Eye Movements, Strabismus, Amblyopia, and Neuro-Ophthalmology

Space Perception of Strabismic Observers in the Real World Environment

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PURPOSE. Space perception beyond the near distance range (>2 m) is important for target localization, and for directing and guiding a variety of daily activities, including driving and walking. However, it is unclear whether the absolute (egocentric) localization of a single target in the intermediate distance range requires binocular vision, and if so, whether having subnormal stereopsis in strabismus impairs one's ability to localize the target.

METHODS. We investigated this by measuring the perceived absolute location of a target by observers with normal binocular vision ($n = 8$; mean age, 24.5 years) and observers with strabismus ($n = 8$; mean age, 24.9 years) under monocular and binocular conditions. The observers used the blind walking-gesturing task to indicate the judged location of a target located at various viewing distances (2.73–6.93 m) and heights (0, 30, and 90 cm) above the floor. Near stereopsis was assessed with the Randot Stereotest.

RESULTS. Both groups of observers accurately judged the absolute distance of the target on the ground (height = 0 cm) either with monocular or binocular viewing. However, when the target was suspended in midair, the normal observers accurately judged target location with binocular viewing, but not with monocular viewing (mean slant angle, 0.8° ± 0.5° vs. 7.4° ± 1.4°; $P < 0.001$, with a slant angle of 0° representing accurate localization). In contrast, the strabismic observers with poorer stereo acuity made larger errors in target localization in both viewing conditions, though with fewer errors during binocular viewing (mean slant angle, 2.7° ± 0.4° vs. 9.2° ± 1.3°; $P < 0.0025$). Further analysis reveals the localization error, that is, slant angle, correlates positively with stereo threshold during binocular viewing ($r^2 = 0.479$, $P < 0.005$), but not during monocular viewing ($r^2 = 0.0002$, $P = 0.963$).

CONCLUSIONS. Locating a single target on the ground is sufficient with monocular depth information, but binocular depth information is required when the target is suspended in midair. Since the absolute binocular disparity information of the single target is weak beyond 2 m, we suggest the visual system localizes the single target using the relative binocular disparity information between the midair target and the visible ground surface. Consequently, strabismic observers with residual stereopsis localize a target more accurately than their counterparts without stereo ability.

Keywords: distance perception, strabismus amblyopia, binocular depth, space perception, vision directed action

Patients with constant strabismus often have reduced visual acuity (VA) in the deviating eye, whereas patients with intermittent or alternating strabismus often have good VA. Sometimes, the VA of patients with constant strabismus can be improved when treatments for strabismus and amblyopia are implemented. However, in all cases, binocular vision may not recover to the normal level, and the strabismic patients can have residual amblyopia and reduced stereopsis.[1] Reduced visual functions can impair one's welfare as humans are very dependent on vision. For example, studies with induced defocus in normal observers have shown that blur can impair visual recognition during driving[2] and basketball shooting performance.[3] Reduced stereopsis has been shown to adversely affect visuomotor tasks, such as negotiating floor-based obstacle or raised surface during walking.[4,5] Refer also to Grant and Moseley,[6] who provided a comprehensive review of visuomotor deficits in prehension, walking, driving, and reading that are experienced by strabismic and amblyopic observers.

In this study, we focus on the space perception of strabismic observers with relatively good VA (see Table). In particular, we sought to discover how these strabismic observers perceive the location of a single visual target on the ground, or suspended in midair, in the intermediate distance range (>2 m). This question is of interest because, while much research has characterized strabismic observers' binocular depth perception and motor action deficits in the near space,[6–11] few studies have investigated its characteristics in the intermediate visual space where many actions related to goal-oriented target localization occur.[12,13]

Whether visual space perception in the intermediate distance would be adversely affected was unclear at the outset of our study. One could argue that it would not be deficient, since our strabismic observers had almost equal visual acuity in

Table. Visual Characteristics of the Strabismic Observers

Subject	Age	Sex	Visual Acuity	Refractive Error	Stereoacuity Threshold	Suppression	Eye Alignment	History
S1	24	M	RE: 20/15 LE: 20/20	RE: −4.75 LE: −0.75	Local: 100 Global: (–)	Intermittent LE	10 ILXT	Myopic correction
S2	31	F	RE: 20/15 LE: 20/15	RE: −1.50 − 0.75 × 060 LE: −0.75	Local: 70 Global: 250	Intermittent alternating	20 AIXT with 4 RHP (RE > LE)	Surgery
S3	24	F	RE: 20/20 LE: 20/20	RE: −2.25 LE: −1.25	Local: 40 Global: 250	Intermittent RE	Aligned but decompensates when fatigue with variable magnitudes of RET and RHT	Surgery for congenital RHT with RET
S4	22	F	RE: 20/25 LE: 20/30	RE: −1.75 − 2.25 × 170 LE: +1.50 − 2.75 × 180	Local: (–) Global: (–)	Alternating	Far: 10 LXT with variable RHT Near: intermittent	Surgery for ET; vision therapy
S5	23	M	RE: 20/20 LE: 20/20	RE: −3.00 − 0.25 × 175 LE: −3.00 − 0.50 × 175	Local: 200 Global: (–)	Far: LE Near: (–)	Far: 15 LET Near: 15 AIET (LE > RE)	Surgery; bifocal lens; alternating patching
S6	24	F	RE: 20/15 LE: 20/20	RE: −6.00 LE: −6.00 − 0.50 × 005	Local: 20 Global: (–)	LE stimulus fainter	4 IRET	Untreated until age 12; progressive lens
S7	24	F	RE: 20/20 LE: 20/20	RE: −6.00 LE: −7.50	Local: 140 Global: 250	(–)	Far: 12 AXT Near: 8 AXT (RE > LE)	Surgery for RXT; vision therapy
S8	27	F	RE: 20/15 LE: 20/15	RE: −1.00 LE: plano	Local: (–) Global: (–)	Alternating	16 AET (LE > RE)	Undiagnosed until age 23; untreated

Unless otherwise specified, the eye alignment and suppression data for the observers are for far and near distances. History was obtained through self-report. Stereoacuity is specified in arc sec. Eye alignment is specified in prism diopters. Note: The visual characteristics provided above reflect the observers' subjective (online) responses during the various tests conducted. As a result, some of the reported visual characteristics deserve further considerations. For instance, observers with alternating strabismus, for example, S7 and S5 (at near), could report no suppression, even though they were experiencing interocular suppression, by virtue of having rapid alternation of their strabismus. Furthermore, observers with large angle alternating strabismus, for example, S4, S7 and S8, could obtain depth cues from rapid alternation. Therefore, observer S7's reported stereoacuity could be an overestimation of her stereo ability (false positive). (–) for stereopsis indicates not measurable; (–) for suppression indicates no suppression; RE, right eye; LE, left eye; for eye alignment: XT, exotropia; ET, esotropia; RHT, right hypertropia; A (before the type of strabismus), alternating; I (before the type of strabismus), intermittent.

each eye, which allowed their visual systems to sample optically reliable monocular depth cues. One could further argue that their deficient binocularity would be irrelevant, because the singular visual target used in our experiment was placed at the intermediate distance range where the absolute binocular distance information of the target, derived from accommodation, absolute binocular disparity (vergence angle), and/or absolute motion parallax, is unlikely to be effective. This is because, while accommodation, absolute binocular disparity, and absolute motion parallax provide reliable depth information in the near distance space, they become ineffective in the intermediate distance space.[14–18] Consider the absolute binocular disparity information derived from vergence angle as an example. Arguably, when one fixates at a suspended target binocularly, the visual system can use the two eyes' convergence angle to code its egocentric distance. However, there is a limiting distance after which the convergence angle becomes too small to be a reliable signal to code a suspended target.[19] For instance, an observer with an interpupillary distance of 6.5 cm makes a convergence angle of 44.69 arc min for a target at 5.0 m, and a convergence angle of 40.63 arc min for a target at 5.5 m. The difference between the convergence angles at the two distances is approximately 4 arc min, which is too small to be coded reliably by the vergence eye movement system. These two arguments might, thus, reasonably lead one to propose that the strabismic observers, as well as observers with normal binocular vision (control group), will perform equally well, or badly, in judging the absolute distance of a target in the intermediate distance range.

Yet, several studies have shown that relative binocular disparity information can affect relative depth judgment in the intermediate distance range.[20–24] This being the case, would it be possible that the visual system also uses the *relative* binocular depth information in the intermediate distance range to judge the *absolute* (egocentric) distance between the observer and target? A recent study of observers with normal binocular vision from our laboratory reveals that this is possible, at least in the reduced cue environment where the predominant visual depth cues were texture gradient and relative binocular disparity.[24] We showed that the relative binocular disparity between a target suspended in midair and the ground surface was used to improve the accuracy of perceived absolute distance.

If the visual system also capitalizes on the relative binocular disparity information of the suspended target and the ground surface in the full cue environment where there are ample other monocular cues, as used in the present study, we can hypothesize that strabismic observers with poor stereopsis will not be able to judge accurately the location of a suspended target in the intermediate distance range. Extending this rationale, we can further hypothesize that the strabismic observers will perform no differently from observers with normal binocular vision when the target is located on the ground. This is because there is no binocular visual advantage when the relative binocular disparity between the target and ground is zero. Here, we tested these hypotheses using the blind walking-gesturing task,[25] which is a visually-directed task modified after the blind walking task by Thomson,[26] and confirmed the predictions in the affirmative.

METHODS

Observers

A total of 16 naïve observers participated in the study. They were classified in two groups, normal (mean age, 24.5 years) and strabismic (mean age, 24.9 years), in accordance with their binocular visual status ($n = 8$ in each group). Their visual acuity was measured with the Snellen visual acuity chart, interocular suppression with the Worth-4-dot test, and stereoacuity with the Randot Stereotest. The Randot Stereotest uses contour (local) stimuli and random-dot (global) stimuli to measure stereopsis. The contour stimuli have gradations of relative binocular disparity that range from 400 to 20 arc sec, while the random-dot stimuli have only two intervals of relative binocular disparity steps, 500 and 250 arc sec. It has been observed clinically, that some strabismic and/or amblyopic patients are unable to perceive stereo depth with the random-dot stimuli even though they can perceive stereo depth with the contour stimuli. Thus, testing with both types of stimuli could provide an indication of the extent of deficits caused by strabismus and/or amblyopia.[27] The aforementioned visual parameters were obtained on the day the observers provided their informed consent to participate in the study.

We classified observers as having clinically normal binocular vision if they had normal or corrected to normal visual acuity of at least 20/20 and equal in each eye, no strabismus, no suppression on Worth-4-dot test, ability to perceive depth with the random-dot stereogram (up to 250 arc sec), and contoured stereogram (up to 20 arc sec). The other eight observers classified as strabismic (see Table) had constant, alternating or intermittent strabismus with exotropia, esotropia or hypertropia. Six of the eight strabismic observers had stereoacuity ranging from at least 20 to 200 arc sec and several could not perceive depth with the random-dot stimuli. The stereoacuity of the other two strabismic observers was beyond the upper-limit measurable with the Randot Stereotest (400 arc sec). Please note that observer S6 with 20 arc sec of stereoacuity was classified in the strabismic category because she had intermittent strabismic at near and far, did not perceive depth with the random-dot stereogram, and reported fainter image in one eye on Worth-4-Dot (implying low grade suppression).

We also measured each observer's eye height for use in our data analysis. The eye height is the length from one's feet on the ground to the eye. To measure the eye height, we instructed the observer to stand upright on a level floor and look straight ahead. The vertical distance (height) from the observer's feet (with flat heel shoes) to his/her eye level is the eye height. We found the mean eye height for the normal observers to be 156.8 ± 1.8 cm and the mean eye height for the strabismic observers to be 156.9 ± 1.6 cm.

The research conducted followed the tenets of the Declaration of Helsinki and was approved by the institutional review board (IRB). Informed consent was obtained from the subjects after explanation of the nature and possible consequences of the study.

Stimuli

The experiments were conducted in a well-lighted hallway with full cues. The predominant monocular cues to depth afforded by the hallway were the texture gradient cue from the square carpet tiles on the floor and the linear perspective cue from the parallel walls of the hallway. The targets were white Styrofoam spheres of different physical sizes. The Styrofoam spheres were made of high-density foam that has a smooth, durable surface, and could be readily purchased at most arts-and-crafts stores. They were placed at four viewing distances, 2.73, 4.15, 5.51, and 6.93 m, respectively, to subtend a constant visual angle of 0.52°. At each viewing distance, the target could be located at one of four heights above the floor: 0 (i.e., on the floor), 30, 67, and 90 cm. For the targets suspended above the floor, transparent fishing lines that were not visible to the observers were used to suspend the targets from the ceiling. In this way, the targets above the floor were seen as floating in air and not in direct physical contact with any other surfaces. The targets that were 0 and 67 cm above the floor served as the test targets, while those at the other two heights (30 and 90 cm above the floor) served as catch trial targets. The purpose of having the catch trials was to prevent observers from guessing that all the test targets had the same height.

Design

The test conditions implemented on each group of observers were the monocular and binocular viewing conditions. An opaque eye patch was used to occlude the observer's nondominant eye in the monocular condition. Eye dominance was determined using a variation of the Ring test, where the observer was asked to sight a distance target, one eye at a time, through a hole formed by both hands held at arm's length. The eye that perceived the target as being more centered in the hole was defined as the dominant eye.[28,29] Each test condition, with 32 trials in a session, was performed on a different day. The order of the trials performed within a session was randomized. For each observer, the two separate sessions used different randomization sequences. The test order of the two viewing conditions was counterbalanced between the observers in each group.

Two blocks of trials, separated by a 10- to 20-minute break, were performed during a test session. Each block comprised 12 test trials and four catch trials that included the following: four target distances on the ground (one trial each), four target distances at 67 cm height (two trials each), two target distances at 30 cm height (one trial each), and two target distances at 90 cm height (one trial each). The last two combinations served as catch trials and the complementary distance/height combinations not tested in the first block were tested in the second block. The same combinations of test trials were tested in the second block.

Procedures

We measured the observers' responses using the blind walking-gesturing task, which is based on the classic blind walking task.[26,30–33] The blind walking task is a common procedure for measuring an observer's space perception. In this procedure, the observer is asked to judge the target distance and to respond by walking briskly in blindfold to where he/she judged (remembers) the target to be located. Blindfolding prevents visual feedback and walking briskly minimizes introspection, thus, providing a measure of visually-directed response. We modified the blind walking paradigm by adding the extra action of indicating the judged height of the target.[25,34] Therefore, in our study, for the target suspended in midair, the observer judged the target's location (Fig. 1a) and responded by walking blindly to traverse the remembered target distance. Upon reaching the remembered destination, he/she used his/her hand to gesture the remembered target height (Fig. 1b). The blind walking-gesturing task essentially reduces to the classic blind walking task when the target was

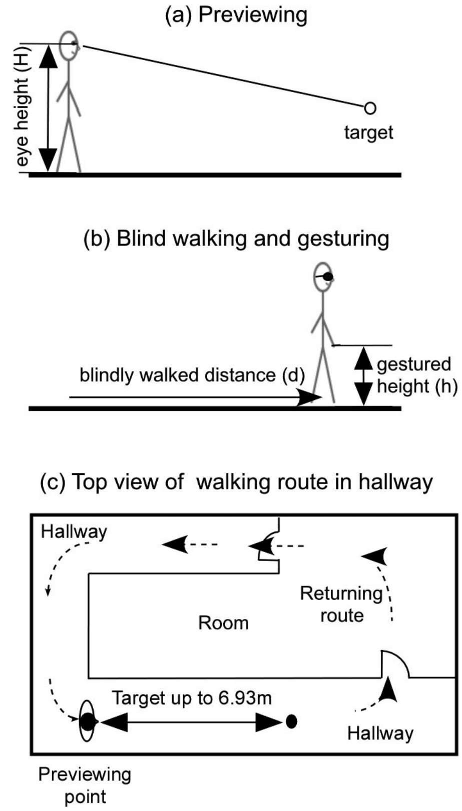

Figure 1. Illustration of blind walking-gesturing task and procedure. (**a**) Previewing to judge the target's location. (**b**) Walking blindly to the judged location and gesturing the perceived target height. (**c**) Walking back to the preview location after completing the task.

on the floor, because the observer indicated that the target height was on the floor. To familiarize the observer with the blind walking-gesturing task, we provided the observer with several practice trials before the test days (after obtaining his/her informed consent). A few practice trials that served as "warm-ups" also were given to the observer before commencing the proper experiments on the two test days (sessions).

To begin a test trial, the observer was led to the starting point and instructed to stand facing the wall opposite the test area. He/she waited for the experimenter to place the target at the designated location, and only turned around with eyes closed to face the test area when instructed. He/she then opened his/her eyes and judged the target's location. While he/she was not restrained by a head/chin rest, he/she was instructed nevertheless to stand upright and minimize body movements while viewing the target. Only vertical (up/down) head rotation was permissible. The observer also was told he/she had unlimited viewing duration. The observer informed the two experimenters when he/she was ready to respond and pulled a blindfold tied around the forehead over his/her eyes. In the meantime, one experimenter having quickly removed the target to allow the observer to walk unobstructed verbally informed the observer to start walking. When the observer reached the destination, he/she "froze" to allow the experimenter to measure his/her walked distance and gestured target height. This ended a trial. The observer, still in blindfold, was led by the other experimenter to walk for several more meters beyond the testing area (variable distance to prevent feedback) to enter a large room at the end of the hallway before removing his/her blindfold. This room had another door that led the observer back (in a loop) to the starting point (and facing the wall, Fig. 1c).

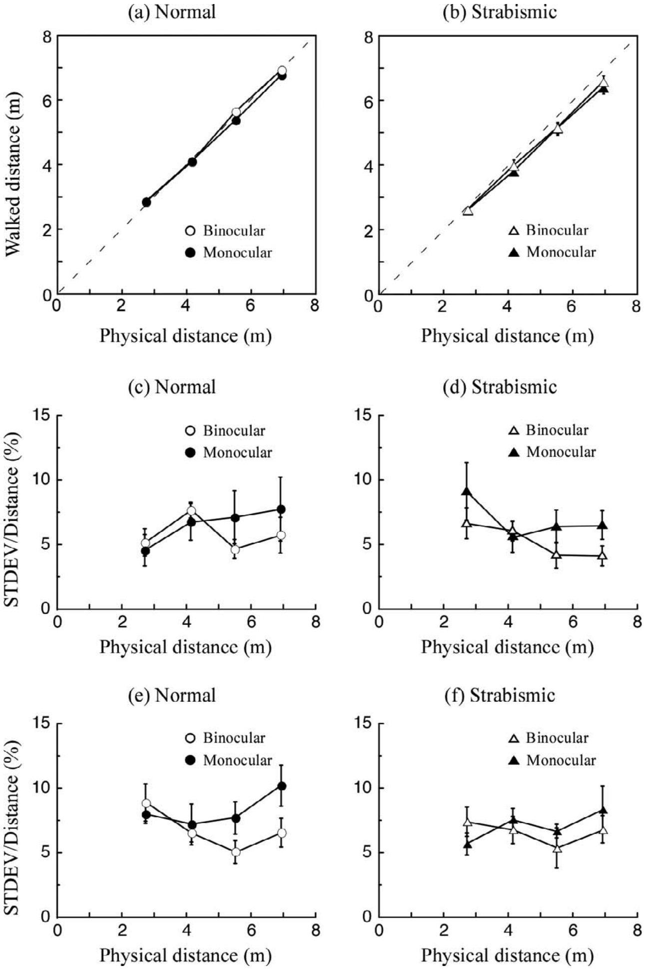

Figure 2. (**a–d**) Mean results in which the observers judged the test target on the floor with the blindfolded walking task. (**a**) Normal group's mean blind walked distance. (**b**) Strabismic group's mean blind walked distance. (**c**, **d**) Respectively, for the normal and strabismic groups, plot the ratio of the mean SD of the repeated walked distance with respect to the mean walked distance as a function of the physical target distance for the results in (**a**) and (**b**). (**e**, **f**) Respectively, are plotted in a similar manner as (**c**) and (**d**) for the walked (horizontal) distances when the test target was suspended 67 cm above the floor.

Statistical Analysis

We applied ANOVA with repeated measures (mixed model with two within-subjects factors [viewing × distance] and a between-subject factor [group]) to the walked distance for the normal and strabismic groups (average data are depicted in Figs. 2a, 2b for target on the ground and Figs. 2e, 2f, 3 for suspended target). The same analysis also was applied to the ratio data of the standard deviation of the repeated walked distances at each target distance, divided by the mean walked distance (SD/distance ratio; Figs. 2c, 2d).

RESULTS

Judging a Target on the Ground

We asked observers to judge the distance of a target on the floor and then walk blindly to the judged location. Figures 2a

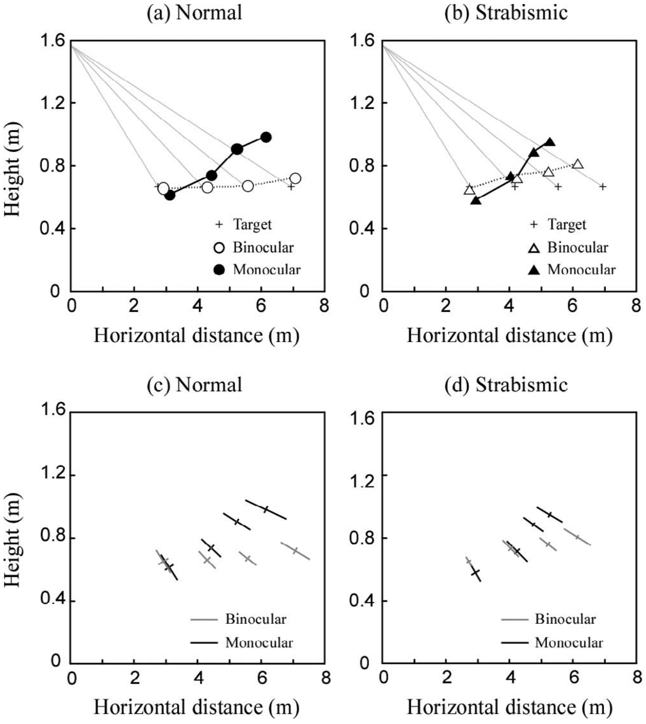

Figure 3. Mean results in which observers judged the location of a test target suspended above the floor (67 cm) with the blind walking-gesturing task. (**a**, **b**) The normal (*circles*) and strabismic (*triangles*) groups' mean judged target locations. The *plus symbols* depict the physical targets' locations. (**c**) The normal group's average standard deviations of the judged locations. The center of each oblique cross indicates the mean judged target location. The longer limb of the cross that points toward the average eye location at the *y*-axis represents twice the standard deviation of the eye-to-target-distance. The orthogonal limb represents twice the standard deviation of the angular-size-width. (**d**) Similar to (**c**) for the strabismic group.

and 2b depict the average walked distances, respectively, for the normal and strabismic groups. Clearly, the data points for each group fell along the diagonal line, indicating accurate egocentric distance perception. Also, the data points from the monocular and binocular viewing conditions were similar. The outcomes of ANOVA analysis did not reveal a significant difference between the monocular and binocular viewing conditions ($F[1, 14] = 2.985$, $P = 0.106$), or an interaction effect between the viewing condition and target distance ($F[1.829, 25.604] = 0.641$, $P = 0.522$, Greenhouse-Geisser correction). There was only a marginal difference between the two groups ($F[1, 14] = 4.120$, $P = 0.062$). Overall, our findings showed that monocular depth information is sufficient for accurate absolute distance judgment of targets located on the ground. While these findings were consistent with those of others who tested observers with normal vision, to our knowledge ours are the first to show that strabismic observers respond similarly.

Can the visual system use the binocular depth information to improve the precision of its performance? To answer this question, we first calculated each observer's SD/distance ratio. We then averaged the SD/distance ratios of all observers and plotted the averaged ratio as a function of the target distance in Figures 2c and 2d, respectively, for the normal and strabismic groups. The outcomes of the ANOVA analysis did not reveal a significant difference between the monocular and binocular viewing conditions, that is, there was no binocular advantage (main effect of viewing condition: $F[1, 14] = 3.380$, $P = 0.087$; interaction effect of viewing condition × target distance: $F[3, 42] = 1.980$, $P = 0.132$). The ANOVA analysis also failed to reveal a significant difference between the normal and strabismic groups ($F[1, 14] = 0.014$, $P = 0.909$). Finally, the ratios in Figures 2c and 2d did not significantly vary with the target distance ($F[3, 42] = 0.298$, $P = 0.826$).

Judging a Single Target Suspended Above the Ground

Observers judged the location of the suspended target, and then walked blindly to the judged location and gestured the remembered target height upon reaching the destination. Figures 3a and 3b, respectively, plot the normal and strabismic observers' mean judged locations of the test targets (height = 0.67 m). To quantify the overall difference in performance, we calculated the average judged eye-to-target distances (eye-to-target distance = $[d^2 + \{H - h\})^2]^{1/2}$, where d is the walked distance, H is observer's eye height, and h is the gestured height). The outcomes of a 3-way ANOVA confirm that the normal observers are significantly more accurate than the strabismic observers ($F[1, 14] = 6.269$; $P = 0.025$), the accuracy is significantly better with binocular viewing than with monocular viewing ($F[1, 14] = 5.608$; $P = 0.033$), and judged eye-to-target distance increases significantly with the physical eye-to-target distance ($F[1.686, 3.600] = 516.495$; $P < 0.001$, Greenhouse-Geisser correction). The two interaction effects involving the eye-to-target distance also are significant (observer group × eye-to-target distance: $F[3, 42] = 8.377$; $P < 0.001$; viewing condition × eye-to-target distance: $F[3, 42] = 44.481$; $P < 0.001$), indicating that the effects of observer group and viewing conditions increase with target distance.

We noted, with further examination of the normal group's data (Fig. 3a) that the judged locations with binocular viewing (open circles) overlap with the physical target locations (plus symbols), indicating accurate judgment. In contrast, the judged locations of the two farthest targets (filled circles) with monocular viewing were nearer and higher than the physical target locations. To quantify the difference between the two viewing conditions, we calculated the average judged eye-to-target distances and found no distance underestimation for the near targets, but significant distance underestimation for the two farthest targets. The outcomes of a 2-way ANOVA revealed a significant interaction effect between viewing condition and eye-to-target distance ($F[3, 21] = 20.666$; $P < 0.001$). Figure 3b also shows a similar binocular viewing advantage for judging the suspended targets in the strabismic group's data for the two farthest targets (interaction effect between viewing condition and eye-target distance: $F[3, 21] = 24.414$, $P < 0.001$). However, for the two farthest targets in the strabismic group, the judged locations were inaccurate under both viewing conditions, with the monocular viewing condition suffering the larger distance underestimation.

Additionally, the slope of the data in Figures 3a and 3b are revealing of how viewing conditions differentially compress perceptual space in the intermediate distance range. Noticeably, while the slope of the data with binocular viewing for the normal observers in Figure 3a can be approximated by a horizontal line (mean slant angle, 0.8° ± 0.5°) indicating little space compression and accurate target localization, the data with monocular viewing are fitted by a slanted line (mean slant angle, 7.4° ± 1.4°). The slant angle is significantly larger in the monocular viewing condition ($t[7] = 5.901$, $P < 0.001$) indicating a larger space compression. For the strabismic group, the slant angle also is larger in the monocular viewing condition (binocular, 2.7° ± 0.4°; monocular, 9.2° ± 1.3°; $t[7] = 4.968$, $P < 0.0025$) indicating larger space compression in the monocular condition. Comparing between the two groups,

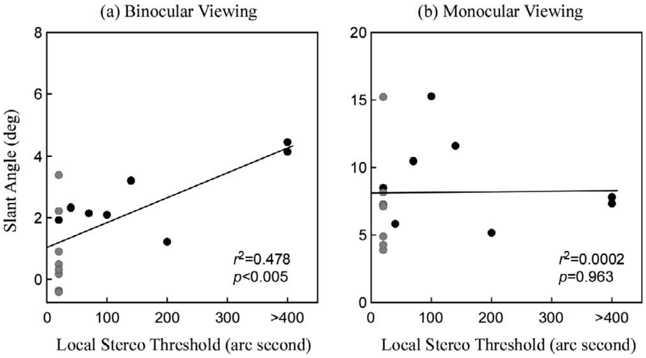

Figure 4. Slant angle as function of local stereo threshold (normal observers, *gray circles*; strabismic observers, *black circles*). The slant angle reliably increases with stereo threshold in the (**a**) binocular viewing condition, but not in the (**b**) monocular viewing condition.

we found a significant difference between the groups with binocular viewing ($t[14] = 2.999$, $P < 0.01$). The two groups, however, performed similarly with monocular viewing ($t[14] = 0.995$, $P = 0.337$) wherein the binocular disparity cue was eliminated.

To further verify the contribution of binocular depth information to perceived location, we examined whether there was a reliable correlation between the strabismic observer's slant angle and stereo threshold. Our analysis revealed that with binocular viewing, the slant angle increased significantly with the observer's stereo threshold ($r^2 = 0.606$, $P < 0.05$). In contrast, with monocular viewing, the slant angle was independent of stereo threshold ($r^2 = 0.073$, $P = 0.518$). To extend the analysis, we pooled normal and strabismic observers' data in the same graphs (Fig. 4). Figure 4a shows that the slant angle reliably increased with stereo threshold in the binocular viewing condition ($r^2 = 0.479$, $P < 0.005$). This tendency, however, was absent in the monocular viewing condition (Fig. 4b, $r^2 = 0.0002$, $P = 0.963$). Admittedly, while the correlation data supported our hypothesis, the analysis was based on a small sample of eight observers in each group. Therefore, the trend lines in both graphs were influenced by the two observers without measurable stereoacuity from the strabismic group. However, it is noteworthy that the slant angles were larger with monocular viewing than with binocular viewing, as accentuated by the differently scaled vertical axes in Figures 4a and 4b, which underscores the role of binocular vision in increasing the accuracy of space perception.

Precision of Performance

To determine the source of variability in the performance, we analyzed each observer's data in polar coordinates with the origin at his/her eye level. We calculated the standard deviations of the eye-to-target distance response component and of the angular declination response component at each physical target location. These standard deviations then were averaged among observers, multiplied by 2 (to increase visibility when plotted on the graphs) and shown in Figures 3c and 3d, respectively, for the normal and strabismic groups. In the graphs, the eye-to-target variability line is plotted with the appropriate length along the average projection line and the angular declination variability line orthogonal to it. Clearly, the precision of the angular declination is better (smaller variability) than the precision of the eye-to-target distance. This observation of better precision for angular declination together with the fact that an observer judges angular declination correctly even as he/she incorrectly judges the eye-to-target distance, underscores that the angular declination information is reliably coded and used for constructing our perceptual space. In addition, Figures 3c and 3d show that the precision of the eye-to-target distance becomes worse as the target distance increases. Confirming it, the outcomes of ANOVA analysis show the precision decreases significantly with the target distance ($F[3, 42] = 13.160$, $P < 0.001$), that the binocular advantage is only moderate ($F[1, 14] = 4.046$, $P = 0.064$), and there is no significant difference between the normal and strabismic observers ($F[1, 14] = 1.786$, $P = 0.203$). On the other hand, application of the same statistical analysis to the precision of the angular declination data did not reveal that precision changes significantly with target distance ($F[3, 42] = 0.453$, $P = 0.716$), or with viewing condition ($F[1, 14] = 0.004$, $P = 0.949$). It also did not reveal a significant difference between the normal and strabismic observers ($F[1, 14] = 1.160$, $P = 0.300$).

We also calculated the ratio of the standard deviation of the walked horizontal distance to the mean walked distance for the suspended target, in an analysis similar to that for the judged target distance on the ground in Figures 2c and 2d. The analysis for targets above the ground is shown in Figures 2e and 2f for the normal and strabismic groups, respectively. A comparison shows that the ratios in Figures 2e and 2f (above the ground) are larger than those in Figures 2c and 2d (on the ground; $F[1,14] = 6.517$, $P < 0.05$), confirming that the precision of performance is worse when the target is seen above the ground. It also is interesting to note that in Figures 2e and 2f the ratios appear slightly smaller in the binocular than monocular viewing conditions, a trend consistent with the notion that binocular depth information improves the precision of performance. However, ANOVA analysis does not show a significant difference between them (main effect of viewing condition, $F[1, 14] = 3.228$, $P = 0.091$; interaction effect of viewing condition × target distance, $F[3, 42] = 2.343$, $P = 0.087$). It also fails to reveal significant differences between the normal and strabismic observers ($F[1, 14] = 0.669$, $P = 0.427$) and target distance ($F[3, 42] = 1.888$, $P = 0.146$).

DISCUSSION

Overall, our findings provided a quantitative assessment of the spatial abilities of strabismic observers beyond the near visual space compared to observers with normal vision. Similar to normal observers, strabismic observers judged absolute distance accurately when the target was placed on the floor with monocular and binocular viewing. However, unlike the normal observers, they misjudged the absolute location when the target was suspended in midair, with monocular viewing being worse than binocular viewing. During binocular viewing of the suspended target, there exists a positive correlation between the overall error of judged locations and the observer's stereo threshold. Therefore, the advantage of binocular viewing indicates the important role of relative binocular disparity information for locating a target beyond the near space, as predicted in the Introduction.

We should add that our data could be influenced by two other vision-related factors. The first is the fact that several of our observers had previously been treated for their strabismus (S2, S3, S4, S5, and S7). It could be that they also had amblyopia accompanying their strabismus. Therefore, besides the reduced stereoacuity, the previous existence of amblyopia in these observers could potentially contribute to their poor task performance in our study.[11] The second factor is a possible underestimation of the stereoacuity deficits of several observers because we only tested their stereopsis at near (40 cm) rather than at distance (6 m), and we only tested stereoacuity one time during recruitment day rather than repeated the testing during the experimental days. While near and distance stereoacuity would remain similar for observers whose angles of deviation were similar at near and far distances, the same might not be true for observers with intermittent exotropia (S1 and S2).[35] It has been found that, at least in children, stereoacuities of intermittent exotropes vary over the course of a single day.[36] Additionally, observer S5 exhibited interocular suppression at distance, suggesting that his stereoacuity at distance would be far worse (or not measureable) than what we have reported in the Table had we measured his stereopsis at distance. Thus, an argument could be made that our data would be more directly comparable with distance stereoacuity, since we tested targets at the intermediate distance range (2.73–6.93 m). However, the counter argument could be made that testing stereoacuity at 6 m alone would not be completely representative either.

More generally, our empirical findings can be considered in the larger context of the ground theory of space perception. According to the ground theory, the visual system uses the ground surface as a reference frame for localizing objects.[23–25,33,34,37–42] The visual system can construct accurate ground reference frame representation with monocular depth cues (e.g., texture gradient information on the floor).[30,37,42] Therefore, when the target is on the ground where there are ample monocular depth cues, both groups accurately judged the target distance. As a result, the advantage of binocular depth information for locating a target on the ground is minimal. However, an extra computational step is required to correctly determine the egocentric location of the suspended target. Specifically, the visual system must find a reliable, relative distance between the target and the ground surface reference frame. This can be done by scaling the relative binocular disparity between the target and the ground according to the egocentric distance on the ground surface.[24,43,44] Consequently, when the visual system cannot obtain reliable binocular depth information, either because the observers were strabismic or monocular, the midair location of the target cannot be judged accurately.

The current findings also added to the growing body of works on how impaired stereopsis impedes one's daily activities, such as reaching, grasping, walking, and driving.[4–6,9,45,46] In general, space perception, including perceived distance derived from binocular disparity, is used to guide or direct actions.[47] To guide an action, the perceptual system continuously processes stimulus information to update the space representation during action. The updated space representation acts as an online feedback to guide the motor system's movements, until the goal is achieved. Take the example of a person using his/her sight to continuously guide the action of his/her hand reaching for a cup on the table. To guide the hand action, the perceptual system first constructs a space representation and stores it in the working memory system. The working memory system provides the initial "instruction" to the motor system to start the action. During the action, the working memory system continuously updates the space representation (memory) and uses the updated representation to direct the motor system's next movement. In contrast, the blind walking-gesturing task used in the current study is an example of a visually directed action. The perceived target location is stored in the working memory system. While blind walking, the traversed distance is registered and used to update the observer's online target distance. When the updated target distance becomes zero, the observer stops walking. Clearly, there are some fundamental differences between visually guided and visually directed actions. However, in reality, we often combine these two operations to achieve the goal in reaching and/or navigation.

Finally, our findings along with those of others (see review by Grant and Moseley 2011)[6] serve as a reminder that poor stereopsis as a result of childhood disorders of strabismus and/or amblyopia persists into adulthood, and affects everyday perception and actions in the near and intermediate visual space. It is notable that at the time of testing none of our observers would be classified as amblyopic when referenced to the American Academy of Ophthalmology's guideline for visual acuity deficit.[48] Moreover, several of our strabismic observers were never treated. Therefore, our study also highlights the fact that poor stereopsis can exist in strabismic individuals whose visual acuity is normal by clinical standards. Fortunately, recent advances in cortical plasticity research have shown the ability of adult animals to recover from the effects of early visual deprivation.[49–51] Consistent with this, human psychophysical studies show that perceptual learning can improve the monocular vision of the weak eye.[52–55] Also taking the psychophysical approach, other works from our laboratory have shown that adults with strabismus and/or amblyopia who underwent the push-pull perceptual learning paradigm to recalibrate the interocular excitatory-and-inhibitory balance exhibited improved stereopsis.[56–58] Future work will investigate if this improvement translates into more accurate use of the relative binocular disparity information for space perception in the intermediate distance range.

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References

1. von Noorden GK, Campos EC. *Binocular Vision and Ocular Motility: Theory and Management of Strabismus*, 6th ed. St. Louis: Mosby; 2002.
2. Owens DA, Tyrrell RA. Effects of luminance, blur, and age on nighttime visual guidance: a test of the selective degradation hypothesis. *J Exp Psychol Appl*. 1999;5:115–128.
3. Applegate RA, Applegate RA. Set shot shooting performance and visual acuity in basketball. *Optom Vis Sci*. 1992;69:765–768.
4. Buckley JG, Panesar GK, MacLellan MJ, Pacey IE, Barrett BT. Changes to control of adaptive gait in individuals with long-standing reduced stereoacuity. *Invest Ophthalmol Vis Sci*. 2010;51:2487–2495.
5. Vale A, Buckley JG, Elliott DB. Gait alterations negotiating a raised surface induced by monocular blur. *Optom Vis Sci*. 2008;85:1128–1134.
6. Grant S, Moseley MJ. Amblyopia and real-world visuomotor tasks. *Strabismus*. 2011;19:119–128.
7. Hou C, Pettet MW, Norcia AM. Acuity-independent effects of visual deprivation on human visual cortex. *Proc Natl Acad Sci U S A*. 2014;111:E3120–E318.
8. McKee SP, Levi DM, Movshon JA. The pattern of visual deficits in amblyopia. *J Vision*. 2003;3:380–405.
9. Grant S, Melmoth DR, Morgan MJ, Finlay AL. Prehension deficits in amblyopia. *Invest Ophthalmol Vis Sci*. 2007;48:1139–1148.
10. Niechwiej-Szwedo E, Goltz HC, Chandrakumar M, Wong AM. Effects of strabismic amblyopia on visuomotor behavior: part II. Visually guided reaching. *Invest Ophthalmol Vis Sci*. 2014;55:3857–3865.
11. O'Connor AR, Birch EE, Anderson S, Draper H, FSOS Research Group. The functional significance of stereopsis. *Invest Ophthalmol Vis Sci*. 2010;51:2019–2023.
12. Henson DB, Williams DE. Depth perception in strabismus. *Br J Ophthalmol*. 1980;64:349–353.
13. Kani K. Stereopsis and spatial perception in amblyopes and uncorrected ametropes. *Br J Ophthalmol*. 1978;62:756–762.

14. Beall AC, Loomis JM, Philbeck JM, Fikes TJ. Absolute motion parallax weakly determines visual scale in real and virtual environments. In: *Proceedings of Conference on Human Vision, Visual Processing, and Digital Display.* Bellingham, WA: Society of Photo-Optical Instrumentation Engineers; 1995:288–297.
15. Fisher SK, Ciuffreda KJ. Accommodation and apparent distance. *Perception*. 1988;17:609–621.
16. Gogel WC, Tietz JD. A comparison of oculomotor and motion parallax cues of egocentric distance. *Vision Res*. 1979;19: 1161–1170.
17. Leibowitz HW, Owens DA. Anomalous myopias and the intermediate dark focus of accommodation. *Science*. 1975; 189:646–648.
18. Viguier A, Clement G, Trotter Y. Distance perception within near visual space. *Perception*. 2001;30:115–124.
19. Cutting JE, Vishton PM. Perceiving layout and knowing distances: the integration, relative potency, and contextual use of different information about depth. In: Epstein W, Rogers S, eds. *Handbook of Perception and Cognition, Vol 5; Perception of Space and Motion*. San Diego, CA: Academic Press; 1995:69–117.
20. Allison RS, Gillam BJ, Vecellio E. Binocular depth discrimination and estimation beyond interaction space. *J Vision*. 2009; 9:10, 1–14.
21. Loomis JM, Philbeck JW. Is the anisotropy of perceived 3-D shape invariant across scale? *Percept Psychophys*. 1999;61: 397–402.
22. Palmisano S, Gillam B, Govan DG, Allison RS, Harris JM. Stereoscopic perception of real depths at large distances. *J Vision*. 2010;10:19, 1–16.
23. Wu J, He ZJ, Ooi TL. Perceived relative distance on the ground affected by the selection of depth information. *Percept Psychophys*. 2008;70:707–713.
24. Wu J, Zhou L, Shi P, He ZJ, Ooi TL. The visible ground surface as a reference frame for scaling binocular depth of a target in midair. *J Exp Psychol Hum Percept Perform*. 2015;41:111–126.
25. Ooi TL, Wu B, He ZJ. Distance determined by the angular declination below the horizon. *Nature*. 2001;414:197–200.
26. Thomson JA. Is continuous visual monitoring necessary in visually guided locomotion? *J Exp Psychol Hum Percept Perform*. 1983;9:427–443.
27. Cooper J, Feldman J. Random-dot-stereogram performance by strabismic, amblyopic, and ocular-pathology patients in an operant-discrimination task. *Am J Optom Physiol Opt*. 1978; 55:599–609.
28. Ooi TL, He ZJ. Sensory eye dominance. *J Am Optom Assoc*. 2001;72:168–178.
29. Xu JP, He ZJ, Ooi TL. A binocular perimetry study of the causes and implications of sensory eye dominance. *Vision Res*. 2011; 51:2386–2397.
30. Loomis JM, DaSilva J, Fujita N, Fukusima S. Visual space perception and visually directed action. *J Exp Psychol Hum Percept Perform*. 1992;18:906–921.
31. Philbeck JW, O'Leary S, Lew ALB. Large errors, but no depth compression, in walked indications of exocentric extent. *Percept Psychophys*. 2004;66:377–391.
32. Rieser JJ, Ashmead D, Talor C, Youngquist G. Visual perception and the guidance of locomotion without vision to previously seen targets. *Perception*. 1990;19:675–689.
33. Sinai MJ, Ooi TL, He ZJ. Terrain influences the accurate judgement of distance. *Nature*. 1998;395:497–500.
34. Ooi TL, Wu B, He ZJ. Perceptual space in the dark affected by the intrinsic bias of the visual system. *Perception*. 2006;35: 605–624.
35. Serrano-Pedraza I, Manjunath V, Osunkunle O, Clarke MP, Read JC. Visual suppression in intermittent exotropia during binocular alignment. *Invest Ophthalmol Vis Sci*. 2011;52: 2352–2364.
36. Hatt SR, Mohney BG, Leske DA, Holmes JM. Variability of stereoacuity in intermittent exotropia. *Am J Ophthalmol*. 2008;145:556–561.
37. Wu B, Ooi TL, He ZJ. Perceiving distance accurately by a directional process of integrating ground information. *Nature*. 2004;428:73–77.
38. Gibson JJ. *The Perception of the Visual World*. Boston, MA: Houghton Mifflin; 1950.
39. Sedgwick HA. Space perception. In: Boff KR, Kaufman L, Thomas JP, eds. *Handbook of Perception and Human Performance*. New York, NY: Wiley; 1986:21.1–21.57.
40. He ZJ, Wu B, Ooi TL, Yarbrough G, Wu J. Judging egocentric distance on the ground: occlusion and surface integration. *Perception*. 2004;33:789–806.
41. Ooi TL, He ZJ. A distance judgment function based on space perception mechanisms: Revisiting Gilinsky's (1951) equation. *Psychol Rev*. 2007;114:441–454.
42. Wu J, He ZJ, Ooi TL. The visual system's intrinsic bias influences space perception in the impoverished environment. *J Exp Psychol Hum Percept Perform*. 2014;40:626–638.
43. Gillam BJ, Sedgwick HA, Marlow P. Local and non-local effects on surface-mediated stereoscopic depth. *J Vis*. 2011;11(6):5.
44. Wu J, He ZJ, Ooi TL. Stimulus duration and binocular disparity factors in representing the ground surface and localizing object in the intermediate distance range. Annual meeting of Vision Sciences Society. *J Vis*. 2004;4(8):21.
45. Melmoth DR, Grant S. Advantages of binocular vision for the control of reaching and grasping. *Exp Brain Res*. 2006;171: 371–388.
46. Tijtgat P1, Mazyn L, De Laey C, Lenoir M. The contribution of stereo vision to the control of braking. *Accid Anal Prev*. 2008; 40:719–724.
47. Loomis JM, Da Silva JA, Philbeck JW, Fukusima SS. Visual perception of location and distance. *Curr Direct Psychol Sci*. 1996;5:72–77.
48. Pediatric Ophthalmology/Strabismus Preferred Practice Pattern Panel. *Preferred Practice Pattern: Amblyopia*. San Francisco, CA: American Academy of Ophthalmology; 2012.
49. He H-Y, Ray B, Dennis K, Quinlan EM. Experience-dependent recovery of vision following chronic deprivation amblyopia. *Nat Neurosci*. 2007;10:1134–1136.
50. Harauzov A, Spolidoro M, DiCristo G, et al. Reducing intracortical inhibition in the adult visual cortex promotes ocular dominance plasticity. *J. Neurosci*. 2010;30:361–371.
51. Bavelier D, Levi DM, Li RW, Dan Y, Hensch TK. Removing brakes on adult brain plasticity: from molecular to behavioral interventions. *J Neurosci*. 2010;30:14964–14971.
52. Polat U, Ma-Naim T, Belkin M, Sagi D. Improving vision in adult amblyopia by perceptual learning. *Proc Natl Acad Sci U S A*. 2004;101:6692–6697.
53. Huang C-B, Zhou Y, Lu Z-L. Broad bandwidth of perceptual learning in the visual system of adults with anisometropic amblyopia. *Proc Natl Acad Sci U S A*. 2008;105:4068–4073.
54. Li RW, Klein SA, Levi DM. Prolonged perceptual learning of positional acuity in adult amblyopia: perceptual template retuning dynamics. *J Neurosci*. 2008;28:14223–14229.
55. Levi DM, Li R. Perceptual learning as a potential treatment for amblyopia: a mini-review. *Vision Res*. 2009;49:2535–2549.
56. Xu JP, He ZJ, Ooi TL. Effectively reducing sensory eye dominance with a push-pull perceptual learning protocol. *Curr Biol*. 2010;20:1864–1868.
57. Ooi TL, Su YR, Natale DM, He ZJ. A push-pull treatment for strengthening the "lazy eye" in amblyopia. *Curr Biol*. 2013;23: 309–310.
58. Ooi TL, He ZJ, Su YR. Resetting the interocular inhibitory-andexcitatory balance with a novel video game based on the pushpull perceptual learning protocol. Abstract presented at: 2014 Society for Neuroscience Conference, November 19, 2014; Washington, DC. Program/Poster 819.15/GG1.