1040-5488/02/7912-0771/0 VOL. 79, NO. 12, PP. 771–778
OPTOMETRY AND VISION SCIENCE

ORIGINAL ARTICLE

Stereoacuity at Distance and Near

BONITA P. H. WONG, OD, MSc, RUSSELL L. WOODS, MCOptom, PhD, and ELI PELI, MSc, OD, FAAO

New England College of Optometry, Boston, Massachusetts (BPHW, EP), The Schepens Eye Research Institute and Harvard Medical School, Boston, Massachusetts (RLW, EP)

ABSTRACT: *Purpose.* Because previous studies have reported conflicting evidence, we examined a possible difference in stereoacuity between distance and near, in particular using a random-dot display. We compared distance and near stereoacuities using identical presentation formats at the two distances. *Methods.* Twelve young adults with low, stable refractive errors and apparently normal binocular vision participated. Stereoacuity was determined with a Mentor B-VAT II using Random Dot E (BVRDE) and Contour Circles (BVC) stereograms presented on a standard monitor (25 × 19.3 cm) at 518 cm (distance-habitual) and a small monitor (2.0 × 1.4 cm) at 40 cm (near-habitual). To examine whether accommodation-convergence influenced stereoacuity, testing at 40 cm was repeated with the addition of +2.50 DS lenses and base-in prisms (near-compensated) that created the same accommodation and convergence demands as for distance-habitual viewing. *Results.* The two stereotests produced similar findings. Stereoacuity was not significantly different for distance-habitual and near-habitual viewing of the BVRDE ($p = 0.43$) and BVC ($p = 0.79$) stereotests. Near-compensated stereoacuity was worse than near-habitual (BVRDE, $p = 0.005$; BVC, $p = 0.004$) and distance-habitual (BVRDE, $p = 0.05$; BVC, $p = 0.003$) for both stereotests. Because near stereoacuity with yoked prisms (control condition) was the same as without prism (near-habitual), prism-induced optical distortions cannot account for the difference. *Conclusions.* Stereoacuity was not different at distance and near under normal viewing conditions. The conflict between subject knowledge of target proximity and the optically-induced relaxation of accommodation and convergence, or an inaccurate accommodative-convergence response, might have caused poor near-compensated stereoacuity. (Optom Vis Sci 2002;79:771–778)

Key Words: stereoacuity, distance, proximity

Stereopsis is the binocular perception of depth based on retinal disparity. Monocular cues to depth can be provided by linear perspective, shadows, parallax, and texture among others.[1] Although stereopsis is not essential for perception of depth, stereopsis is advantageous in tasks involving complex visual presentations and hand-eye coordination.[1] Functional mechanisms of stereopsis are still not completely understood.

Local stereopsis involves matching similar features from each monocular view and assigning a disparity to each locus,[2] whereas global stereopsis involves linking patches of binocular views to distinguish figure from ground[3] in stereograms. Random-dot stereograms[4] measure global stereopsis and may be the best test to quantify stereoacuity in the ophthalmic clinic. They consist of a dense array of randomly arranged dots, some of which are displaced laterally in the two monocular views to produce a binocular disparity. Each eye receives one half-image (dichoptic stimulus), and cyclopean depth perception is formed only when corresponding elements in the monocular images are fused. Although slight pattern differences between random-dot stereograms may be evident with monocular viewing, observers are unable to discern the stereoscopic figure in the absence of any obvious contour and do not sense depth unless the plates are viewed binocularly.[5]

Observation distance affects visual functions that, like stereoacuity, might be expected to be unaffected by distance. For example, the critical flicker frequency was worse at near and improved maximally at about 1 m.[6] Accommodation and convergence was suggested to increase the size of the receptive field, which results in worse spatial and temporal resolution. Freeman[7] found that there was a better letter acuity for a distant target at 300 cm than a near target subtending the same visual angle at 30 cm. The better distance acuity was not attributable to the apparent magnitude and awareness of the distance of the stimulus, differences in pupil size, or lens thickness associated with accommodation. It is possible that poor eye alignment may reduce the quality of the binocular percept that might reduce visual acuity and stereoacuity at near. However, changes in suprathreshold perceived depth of random-dot stereograms with fixation distance (30 to 130 cm) were independent of vergence angle and accommodation.[8]

If stereopsis is only a function of binocular disparity, its angular measure should not be affected by observation distance. However, observation distance could affect stereopsis if the visual system uses information, such as accommodation, convergence, and cognitive factors, to estimate the perceived distance and incorporates this information to generate a stereoscopic response.[8–11] Because the visual system uses estimated distance in suprathreshold stereoscopic depth perception, it is possible that such estimates may affect performance at threshold (stereoacuity). Previous studies have reported conflicting evidence for the relationship between stereoacuity and observation distance (Table 1). However, studies that reported a difference in stereoacuity with viewing distance[13, 16, 17, 19, 20] had inadequate control of the viewing condition. The studies that eliminated monocular cues and used the same tests at all distances[12, 14, 15, 21] found no significant change in stereoacuity with viewing distance. Though stereoacuity did not significantly change from 600 to 50 cm, Brown et al.[14] reported a decrease in stereoacuity at 40 cm. Thus, distance and near stereoacuity appear to be the same using haploscopes and alignment tasks,[12, 14, 15, 21] but neither test is clinically available. Distance stereoacuity measured with the Mentor B-VAT II SG and near stereoacuity measured with clinical stereotests (e.g., Randot) are often different.[16, 17, 21] That they are not directly comparable is not surprising because stereoacuity depends on the task and design of the stereotest (which may contain different levels of binocular or monocular cues).

To our knowledge, no study has compared distance and near stereoacuity using random-dot stimuli. Therefore, we measured stereoacuity with the same stereotests (B-VAT stereograms) at distance and near. If distance and near stereoacuity were different, accommodative or convergence state (or both) could be a factor. Hence, we included a third condition in which subjects viewed the near target, but with distance accommodative-convergence demand. Our results support previous studies that similarly controlled monocular cues and used the same stereotests at all distances. We also found evidence that knowledge of target proximity or poor accommodative-convergence control may influence stereoacuity. Reduced stereoacuity due to a difference between the actual and the perceived viewing distance may have important implications in the use of virtual reality head-mounted displays that have built-in lenses and prisms.

METHODS

Subjects

Eighteen subjects aged 18 to 35 years were screened for good visual acuity, small refractive error, and good binocular vision status based on oculomotor functions using routine refractive and functional techniques (Table 2). Contact lens wearers were over-refracted. Lensometer readings were taken for habitual corrections. Six subjects were excluded during the initial screening because they had visual acuity worse than 20/20 (N = 2), suppression (N = 1), abnormal horizontal fixation disparity (N = 2), or abnormal vertical fixation disparity (N = 1). Hence, stereoacuity was measured in only 12 subjects.

The Sheedy Disparometer (Vision Analysis, Walnut Creek, CA) was used at 40 cm to assess binocular stability[22] for two subjects (RC and SU) who experienced eyestrain, headaches, and diplopia immediately after wearing +2.50 DS and base-in prisms (as described below). Because their nearpoint symptoms were only tran-

TABLE 1.
Review of distance and near stereoacuities from previous studies.

	Ogle (1958)[12]	Amigo (1963)[13]	Brown et al. (1965)[14]	Lit & Finn (1976)[15]	Zanoni et al. (1991)[16]	Yildirim et al. (1998)[17]	Kaye et al. (1999)[21]
Better stereoacuity at distance or near?	Same	Distance	Same	Same	Variable (depended on the stereotest)	Near	Variable (same for Align)
Same stereotest at all distances	Same	Same	Same	Same	Different	Different	Different (same Align at 1, 3, and 6 m)
Type of stereotest(s)	HA	HA	HA	Align	BVRDE, BVC, Titmus, TNO, Randot	BVRDE, BVC, Titmus, Randot	Align, Frisby, TNO, Titmus
Monocular cues	Absent	Present	Absent	Absent	Present	Present	Absent
Distances (m)	0.5 and 10	0.33 and 1	0.4 to 6	0.2 to 1.5	0.4 and 6	0.4 and 6	0.4 to 6
Sample size	3	5	3	2	50	112	63
Subject ages (yr)	NR	NR	27 to 30	NR	6.5 to 55	5 to 6 and 19 to 20	5 to 45

Studies that used different stereotests at different distances or did not control monocular cues found different stereoacuities at different distances. Studies that controlled monocular cues and used the same stereotest at all distances found no difference in stereoacuity between distances.

[a] HA, haploscopic apparatus; Align, alignment test of real targets; BVRDE, B-VAT Random-dot E; BVC, B-VAT Contour Circles; NR, not reported.

sient and resolved after several minutes of rest and adaptation, data were included from these two subjects who met all screening criteria specified in Table 2 and did not report further symptoms in the remaining testing period.

Apparatus

The Mentor B-VAT II SG (Mentor O&O, Norwell, MA) was used to display targets on a standard Mentor monitor at distance and a special small monitor (Model 1 M180P45, Thomas Electronics) at near.

The B-VAT image size was calibrated for a nominal 305-cm (10-ft) viewing distance on the hand controller display for distance and near testing. Subjects viewed distance targets at 518 cm (17 ft) on the standard Mentor monitor (25 × 19.3 cm) (Fig. 1A). The size of the B-VAT calibration square on the small monitor (2.0 × 1.4 cm) (Fig. 1B) was manually adjusted to subtend the same visual angle at 40 cm (16 in) as that on the standard monitor from 518 cm; hence, all targets that were subsequently presented had corresponding visual angles. Although the B-VAT is an established method for distance testing, it was necessary to determine the stability of the image size on the small monitor daily using a cathetometer, which measured the calibration square size with an accuracy of 10 μm (Precision Tool & Instrument). The average luminance and maximum contrast levels of both monitors were adjusted to 91 cd/m^2 and 97.5%, respectively.

TABLE 2.
Subjects were screened based on the following criteria for eligibility to participate in our study.

Parameter	Criteria
Age	18–35 yr
Refractive error	≤3.00 DS and ≤−1.50 DC
Visual Acuity[a]	Distance: 20/20 or better
	Near: 20/20 or better
Habitual Rx	±0.50 DS of best correction
Anisometropia	<0.75 DS
Eye suppression	No suppression 2 lines above best VA
Horizontal fixation disparity[b]	Distance: ≤2 min arc
	Near: ≤10 min arc
Vertical fixation disparity[b]	Distance: ≤1 min arc
	Near: ≤1 min arc
Lateral phoria[bc]	Distance: ≤3.0 Δ eso or 5.0 Δ exo
	Near: ≤7.0 Δ eso or 13.0 Δ exo
Vertical phoria[bc]	Distance and near: ≤1.0 Δ

Distance and near targets were presented using the B-VAT II system. For the suppression and associated phoria tests, subjects wore liquid crystal shutter glasses, which presented disparate images alternately to each eye at 60 Hz.

[a] Monocular and binocular visual acuity was defined as the smallest letter size for which at least four of the five isolated Snellen letters were identified.

[b] These inclusion criteria are in the normal range found in the general population.[25]

[c] Von Graefe phoria measurements were measured using a phoropter.[18]

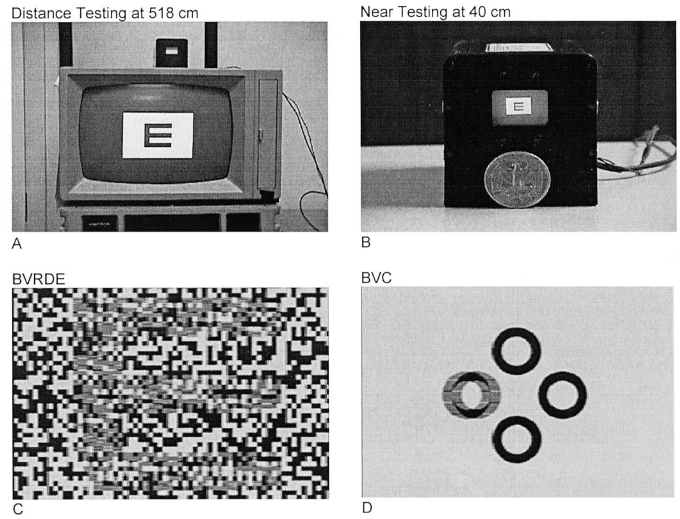

FIGURE 1.
A: Standard Mentor Monitor (Mentor O&O). Note the size of the small monitor placed on top. B: Small Monitor (Model 1 M18000P45, Thomas Electronics). Note the size of the adjacent United States quarter. C: A 6/56 (20/188) Tumbling E in a random-dot pattern with 71 sec arc dot sizes. The task was to identify the orientation of the letter as up, down, right, or left. D: Four black 6/14 (20/47) circles on a white background. The task was to identify the circle that appears to be in front of the others (up, down, left, or right).

Stereoacuity Measurements

Subjects wore liquid crystal shutter glasses that alternately presented dichoptic stimuli at 60 Hz to each eye. Identical presentation formats were used for both viewing distances. Stereotests were administered in dim room illumination. We confirmed that the BVRDE and BVC tests have minimal or no monocular cues to depth perception because stereoacuity could not be measured when testing was conducted with only the dominant eye (N = 4). Testing with the standard B-VAT dot sizes and disparity setting for the BVRDE as reported previously[16, 17] was suprathreshold for most subjects in our study; therefore, the range of disparities had to be altered. Based on a pilot study (N = 4), dot sizes of the random-dot stereograms and the viewing distances were chosen to ensure that an adequate range of disparities (141 to 9 sec arc) was available to determine distance and near stereoacuities of most subjects. The random-dot stereogram used in this study had dot sizes of 71 sec arc that formed a 6/56 Tumbling E (20/188) (Fig. 1C). The BVC stereotest consisted of four black 6/14 (20/47) circles arranged in a diamond configuration against a white background (Fig. 1D).

To better match the psychophysical methods for BVRDE and BVC, Mentor reprogrammed the B-VAT for the BVRDE to permit a four-alternative forced choice (up, down, right, or left) rather than the resident three-alternative forced choice (up, down, or horizontal) used in previous studies.[16, 17] After each presentation, the subject reported the orientation of the Tumbling E for the BVRDE or the location of the elevated circle for the BVC. Stereoacuity was determined using a one-up/one-down staircase procedure that involved increasing and decreasing the disparity. With our configuration of viewing distance and calibration, the available disparities were 141, 106, 71, 35, 18, and 9 sec arc (which corresponded to the nominal disparities of 240, 180, 120, 60, 30, and 15 sec arc displayed on the hand-controller of the B-VAT).

Stereoacuity was measured under three viewing conditions: (1) distance testing with habitual correction (distance-habitual); (2) near testing with habitual correction (near-habitual); and (3) near testing with habitual correction in addition to +2.50 DS lenses and base-in prisms (near-compensated). When viewing a near target, the eyes accommodate and converge. The near-compensated condition was included to optically induce relaxation of both accommodation and convergence such that the accommodation and convergence demands were the same as for viewing a 518-cm (V_D) rather than a 40-cm (V_N) target (Fig. 2). The additional lens power required to equate accommodation was approximately V_N^{-1} (with compensation for vertex distance). The amount of base-in prism (PΔ) required to equate convergence demand was a function of the individual's interpupillary distance (PD) and viewing distances:

$$P^{\triangle} = 100tan\left\{2\left[tan^{-1}\left(\frac{PD}{2V_N}\right)-tan^{-1}\left(\frac{PD}{2V_D}\right)\right]\right\}.$$

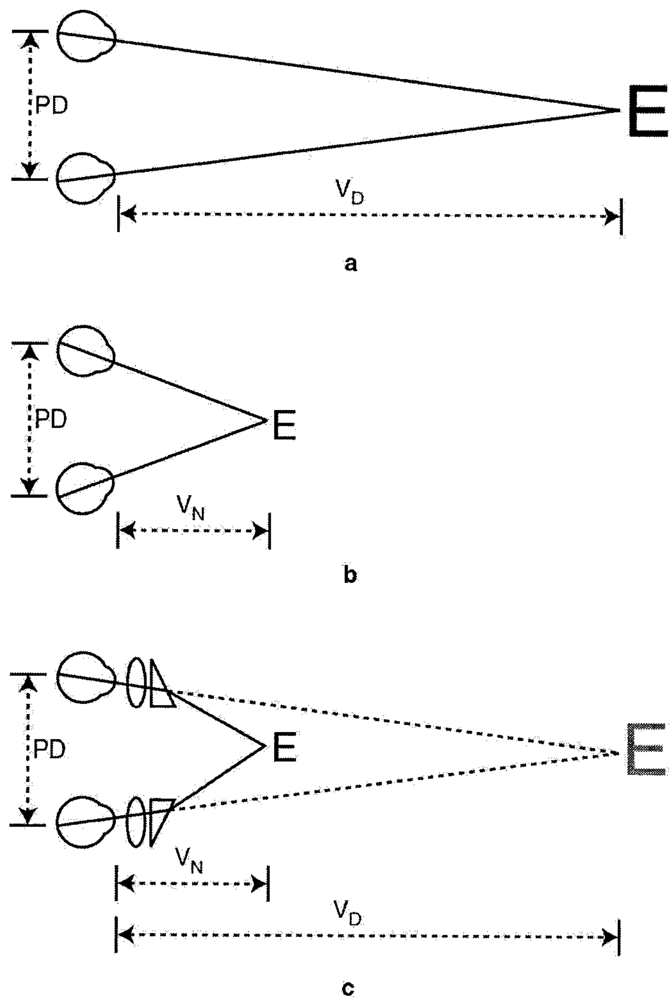

FIGURE 2.
Schematic diagram of the three viewing conditions: (a) distance-habitual viewing at 518 cm (V_D); (b) near-habitual viewing at 40 cm (V_N); and (c) near-compensated viewing at 40 cm with +2.50 DS and base-in prisms. The prism power required to equate the convergence demand in the near-compensated condition for each subject was a function of their interpupillary distance (PD).

Using the small angle approximation, this equation can be simplified to the following:

$$P^{\triangle} = 100PD\left(\frac{1}{V_N} - \frac{1}{V_D}\right).$$

To minimize fatigue and learning effects, subjects began each of the three experimental sessions with a different sequence of testing conditions.

Statistical Analysis

The BVRDE and BVC stereotests used a four-alternative forced-choice, one-up/one-down procedure. Using Probit analysis, the level at which 75% of the responses were correct was considered as the stereoacuity. Stereoacuities beyond the measurable range of the tests were either categorized to be >141 sec arc or <9 sec arc. We examined differences in stereoacuity between the three viewing conditions for all subjects (Wilcoxon signed rank test) and between smaller groups of subjects (Mann-Whitney U test). These nonparametric statistical tests are more conservative than paired and unpaired t-tests, respectively. Statistical significance was considered if $p < 0.05$.

RESULTS

Table 3 summarizes the stereoacuities for the two stereotests, each under three viewing conditions for the 12 subjects. Stereoacuities with BVRDE were worse than with BVC, but the two stereotests showed similar trends under the different viewing conditions. Despite pilot testing and careful selection of the testing conditions, the dynamic range of the B-VAT system was smaller than the range of stereoacuities found among this group of highly selected young subjects under the six test conditions. As can be seen in Table 3, three subjects were able to see the smallest available disparity (9 sec arc) with BVC distance-habitual, whereas seven subjects were unable to see the largest disparity (141 sec arc) with BVRDE near-compensated. Interestingly, two subjects, RC and AN, were in both of these groups. Despite these limitations in the dynamic range, differences between some conditions were apparent.

As shown in Fig. 3A, distance-habitual and near-habitual BVRDE stereoacuities were not significantly different (Wilcoxon signed rank test, $z = 0.78$, $p = 0.43$). For BVRDE, near-compensated stereoacuity was worse than near-habitual (Wilcoxon signed rank test, $z = 2.80$, $p = 0.005$) and distance-habitual (Wilcoxon signed rank test, $z = 1.96$, $p = 0.05$) stereoacuities. As shown in Fig. 3B, distance-habitual and near-habitual BVC stereoacuities were not significantly different (Wilcoxon signed rank test, $z = 0.27$, $p = 0.79$). Like BVRDE, near-compensated BVC stereoacuity was significantly worse than near-habitual (Wilcoxon signed rank test, $z = 2.85$, $p = 0.004$) and distance-habitual (Wilcoxon signed rank test, $z = 2.93$, $p = 0.003$). Subject TL's stereoacuities for all three viewing conditions with the BVC were better than the measurable range; therefore, her data were not included in the analysis of BVC data.

It is possible that the prisms (13 to 15Δ) used in the near-compensated condition introduced distortions that reduced ste-

TABLE 3.
Summary of individual stereoacuities and horizontal fixation disparities.

Subjects	BVRDE Stereoacuity (sec arc)			BVC stereoacuity (sec arc)			Horizontal Fixation Disparity (min arc)	
	Distance-Habitual	Near-Habitual	Near-Compensated	Distance-Habitual	Near–Habitual	Near-Compensated	Distance–Habitual	Near–Habitual
N = 12	518 cm	40 cm	40 cm	518 cm	40 cm	40 cm	518 cm	40 cm
AS	37	21	30	11	10	33	0	0
JR	46	67	117	11	12	20	0	0
SU	125	>141	>141	10	16	62	0	0
RC	54	>141	>141	<9	58	52	0	1 eso
CK	>141	82	>141	11	23	>141	1 eso	1 eso
TW	>141	64	>141	28	14	50	1 eso	1 eso
AN	45	49	>141	<9	10	>141	1 eso	1 eso
LA	59	25	34	17	12	25	0	1 exo
TL	37	23	42	<9	<9	<9	0	1 exo
CA	69	22	>141	30	19	41	0	1 exo
RR	43	23	79	13	16	62	0	1 exo
BW	40	60	>141	15	10	19	1 exo	1 exo

The dynamic range of the BVAT II system (9 to 141 sec arc) was smaller than the range of stereoacuities of these highly selected young subjects.
[a] BVRDE, B-VAT Random-dot E; BVC, B-VAT Contour Circles.

reoacuity. Therefore, as a control experiment, yoked prisms were used to determine the effects of the prisms on visual perception. The three subjects reported that images shifted either to the right or left, but they did not experience noticeable distortion. Their stereoacuities for near-habitual and near-yoked prisms were comparable, and both were better than for near-compensated.

There was no obvious relationship between fixation disparity and stereoacuity (Table 3). However, the five subjects with a near exo-fixation disparity had better near-habitual BVRDE stereoacuity than the four subjects with a near eso-fixation disparity (Mann-Whitney U, $z = 2.2$, $p = 0.028$). No significant difference between these two groups was observed for the near-habitual BVC stereoacuity (Mann-Whitney U, $z = 0.98$, $p = 0.33$). In the near-compensated viewing condition, two subjects (RC and SU) initially reported transient blurring and diplopia. Also, neither of these two subjects had measurable stereoacuity (i.e., >141 sec arc) with near-compensated or near-habitual viewing. We wondered whether this was caused by poor fusion control (e.g., fixation disparity) at near. Fixation disparity normally changes gradually with increasing prism (forced ductions) until the limits of fusional vergence when diplopia results,[22] as demonstrated in curves with flat slopes (Fig. 4). However, subjects RC and SU demonstrated a Type III fixation disparity curve[22] that was flat on base-in side, steep on base-out side, and had a steeper slope (Fig. 5). Both RC and SU had better distance-habitual than near-habitual BVRDE and BVC stereoacuities. Their Type III fixation disparity curves with steeper slopes suggest inefficient prism adaptation, despite normal horizontal fixation disparities of 0 and 1 min arc esophoria, respectively (B-VAT at 40 cm). Note also that the fixation disparities measured with the Sheedy Disparometer were different from the B-VAT results. We suspect that this is a consequence of differences in the fusion lock between the two tests.

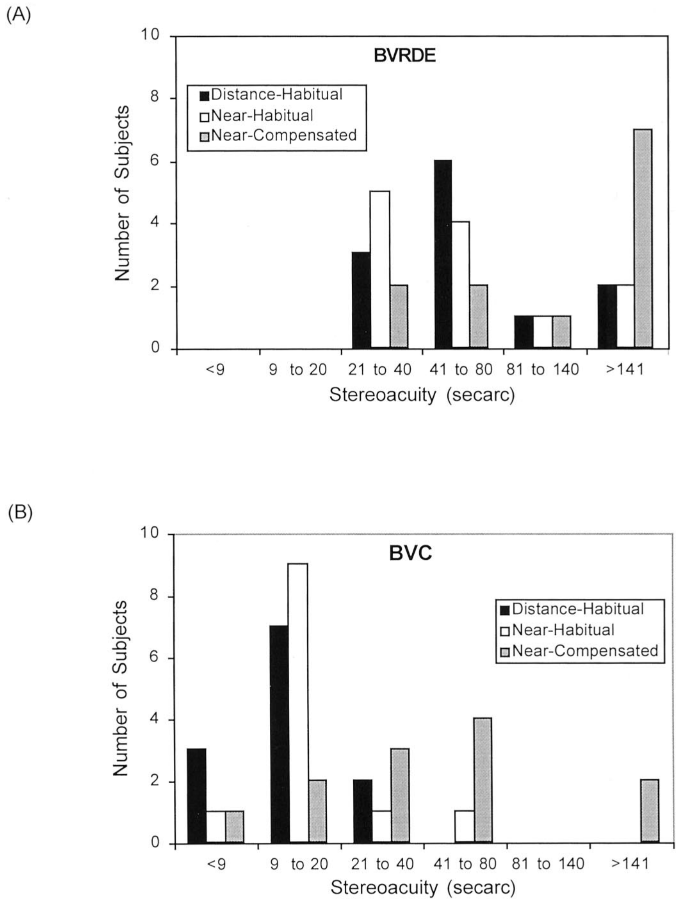

FIGURE 3.
Distribution of stereoacuity for (A) BVRDE and (B) BVC under the three testing conditions of distance-habitual, near-habitual, and near-compensated (N = 12).

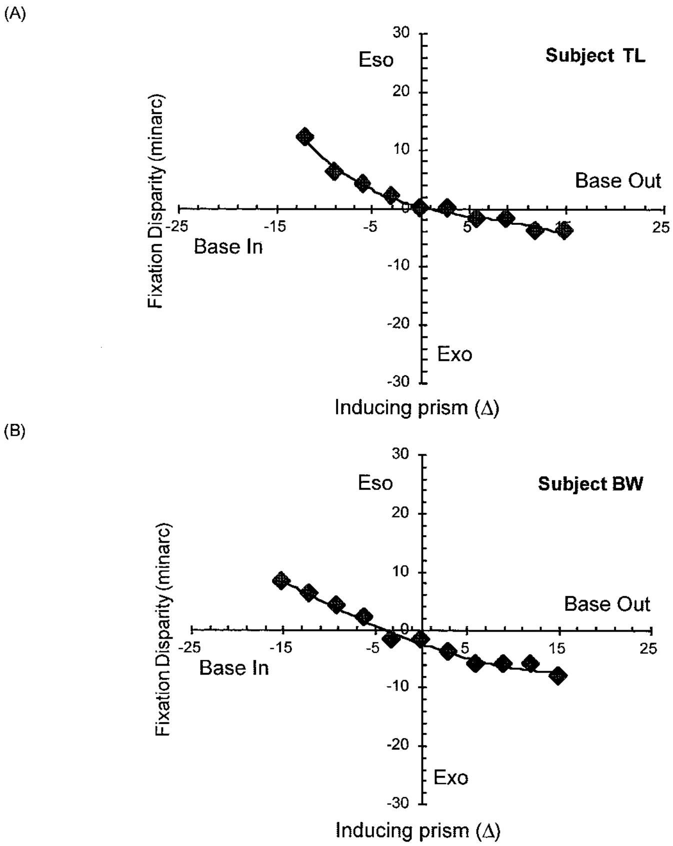

FIGURE 4.
Horizontal fixation disparity curves for two subjects who demonstrated relatively normal near-habitual and distance-habitual stereoacuities. Neither subject reported difficulties with the near-compensated viewing condition. These fixation disparity curves are probably Type I, or possibly Type II, and have low slopes typical of people with good prism adaptation. The fitted curves are third-order polynomials.

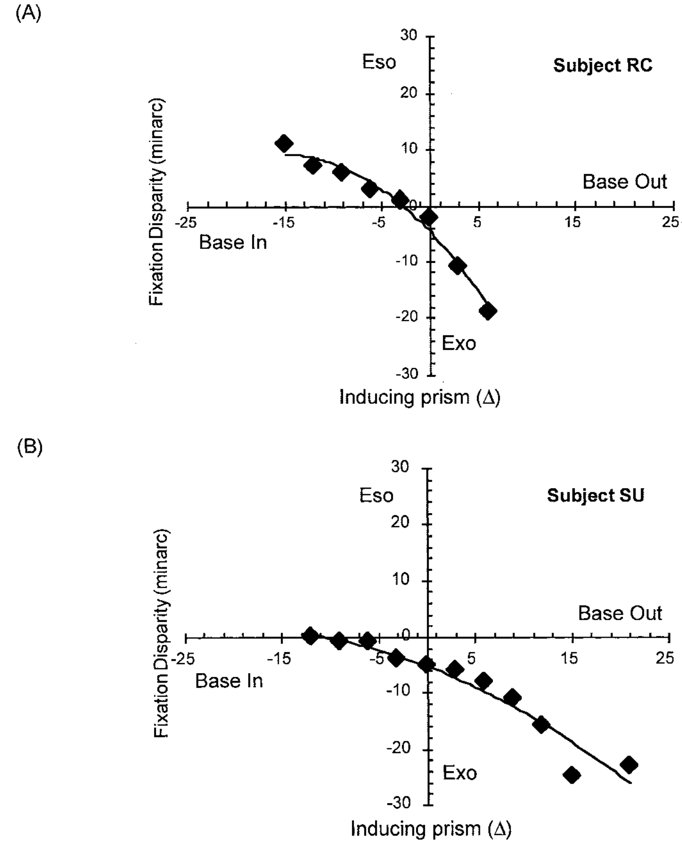

FIGURE 5.
Type III horizontal fixation disparity curves were found for the two subjects who reported intermittent blurring and diplopia in the near-compensated viewing condition. Both fixation disparity curves have steeper slopes than those shown in Fig. 4, suggesting inefficient prism adaptation. The fitted curves are third-order polynomials.

DISCUSSION

Previous studies have shown conflicting evidence regarding the relationship between viewing distance and stereoacuity (Table 1). Measured stereoacuity depends on the design of the stereotest. In addition to binocular cues, some tests contain monocular cues such as linear perspective, shadows, parallax, and texture.[1] Some previous studies have eliminated monocular cues[12, 14, 15, 21]; however, they used haploscopes and alignment tasks that are only available in the research laboratory. Other studies have used different targets at different distances.[16, 17, 21] Our study was the first to use random-dot stereograms to compare both distance and near stereoacuity. For our sample of 12 subjects, we found no statistically significant difference between distance and near stereoacuities when measured using the same stereotests. Our results support Ogle,[12] Jameson and Hurvich,[20] Brown et al.,[14] and Kaye et al.,[21] who suggested that stereoacuity is independent of viewing distance when monocular cues to depth are eliminated.

Accommodation and convergence associated with near did not affect stereoacuity but may allow for more efficient stereoscopic processing because distance testing was qualitatively more difficult for most subjects. Our near-compensated condition (+2.50 DS lenses and base-in prisms) should have positioned the eyes for distance viewing while a near target was presented and relaxed both accommodation and convergence. Near-compensated stereoacuities were significantly worse than distance- and near-habitual stereoacuities. This was not due to the additional lenses (e.g., prism distortion) because near stereoacuity with yoked prisms was the same as without prisms. This linked relaxation of accommodation and convergence should not have blurred stimuli for subjects who are able to efficiently adapt. Subjects with inefficient prism adaptation might experience blur and diplopia, and two of our subjects did report transient difficulties. However, the majority of subjects (N = 10) were asymptomatic. All 12 subjects had visual acuity equivalent to 20/20 or better at distance and near and the random-dot stimuli might be expected to be a good stimulus to accommodation given the relatively small size of the dots (71 sec arc). Unfortunately, we did not measure visual acuity or fixation disparities under the near-compensated condition. It is possible that inaccurate accommodative-convergence responses or small accommodative-convergence fluctuations could have degraded near-compensated stereoacuity, although the effect was stronger than might be expected (Fig. 3 and Table 3).

Fixation disparity refers to small misalignments of the eyes under binocular conditions. The normal population tends to demonstrate Type I fixation disparity curves, and patients with Type III curves tend to have high exophoria and have difficulty with forced convergence.[22] Sustained nearwork for as little as 20 min can increase fixation disparity, inducing stress on the binocular system.[23] It may be that most subjects in our study adapted to the near-compensated condition without significantly affecting fixation disparity, except for RC and SU, whose fixation disparity curves showed comparatively steep slopes that suggest less efficient prism adaptation (Figs. 4 and 5). It would have been insightful to measure fixation disparities through the +2.50 DS lenses and base-in prisms to evaluate the possible contribution to poor near-compensated stereoacuity. The decrease in stereoacuity in those two subjects was more evident with the BVRDE (global stereopsis) than BVC (local stereopsis), although the overall effect was slightly greater for the BVC (Table 3).

Jameson and Hurvich[20] proposed that an observer utilizes all available cues for distance judgements; thus, perceived distance in our study might have provided conflicting signals that reduced near-compensated stereoacuity. Accommodation and convergence have been suggested to contribute to binocular depth perception by providing cues to absolute and relative depth.[8–11] The level of innervation for accommodation or convergence may provide a weak cue to judgement of distance. Fry and Kent[9] reported that changes in vergence induced by base-in and base-out prisms reduced stereoacuity when accommodation was kept unchanged. Similarly, Jiménez et al.[11] reported that small changes in vergence (horizontal prisms of 0.31 to 0.62Δ) reduced the disparity range in which stereopsis of random-dot stereograms occurred and impaired overall depth perception. Also, using random-dot stereograms in experiments with monkeys, viewing distance was shown to modulate the spontaneous activity and responsiveness of neurons in the primary visual cortex area (area V1).[10] Extraretinal cues such as accommodation and vergence were thought to trigger these changes in stereoscopic processing. Conversely, Gonzalez et al.[8] reported that perceived depth of random-dot stereograms was independent of viewing distance, vergence, and accommodation. Estimates of perceived distance may affect stereoacuity because it appears that the visual system uses estimated distance in suprathreshold depth perception.

Depth can be seen in a simple stereogram in about 1 ms, and exposure time is not a significant factor if sufficient luminance is available to allow the observer to see the stimulus.[24] However, random-dot stereograms such as the BVRDE lack obvious visual cues to guide vergence movements to determine depth (global stereopsis), and contour interactions between adjacent dots create a crowding effect that delays the processing of figure.[4] As expected, our subjects responded more quickly to the BVC, which has contours that help align monocular views to easily form an image (local stereopsis), than to the BVRDE. Generally, stereoacuity improved with practice as the subject learned to fuse the BVRDE image, especially with distance testing. Subjects were given unlimited time to determine depth for each presentation. The delay in processing the stereograms at distance was longer than at near even though the stereoacuities were equal at both viewing distances. Subjects had a different sequence of testing conditions for each of the three sessions; therefore, a shorter delay time for processing near stereotests was not a learning effect. Practice seemed to have less influence on performance of the BVC stereotest.

In this study, we found that distance and near stereoacuities were not different under normal viewing conditions. Stereoacuity in the near-compensated condition was worse than with both habitual viewing conditions. Head-mounted displays have wide applications in entertainment, industry, and scientific fields. Peli[25] reported that changes in visual function (i.e., binocular vision, accommodation, and resolution) with short-term head-mounted display use are not statistically different from those with a desktop computer. Head-mounted displays incorporate plus lenses and base-in prisms, much like our near-compensated condition, to help reduce accommodative and convergence demands. The display unit is worn close to the face like a pair of spectacles, but the built-in lenses and prisms cause images to appear at some distance (e.g., 1 m) in front of the wearer. Thus, there is a mismatch between the actual and apparent stimulus positions similar to that found in our near-compensated condition that could affect stereoacuity, at least in some wearers. It would be interesting to investigate stereoacuity with head-mounted displays. However, with current head-mounted display screen resolutions, it may be difficult to display sufficiently small disparities without some manipulation of the stereo-target characteristics (e.g., contrast).

ACKNOWLEDGMENTS

This study was supported in part by NASA grant NLC2-1039 and the T. Backer Fund.

Aspects of this study were presented as a poster at the American Academy of Optometry Meeting 2000, Orlando, Florida: Wong BPH, Woods RL, Peli E. Stereoacuity at distance and near. Optom Vis Sci 2000;77(Suppl):270.

Received February 13, 2002; revision received September 5, 2002.

REFERENCES

1. Reading RW. Binocular Vision: Foundations and Applications. Boston: Butterworth, 1983.
2. Steinman SB, Steinman BA, Garzia RP. Foundations of Binocular Vision: a Clinical Perspective. New York: McGraw-Hill, 2000.
3. Manny RE, Martinez AT, Fern KD. Testing stereopsis in the preschool child: is it clinically useful? J Pediatr Ophthalmol Strabismus 1991;28:223–31.
4. Julesz B. Foundations of Cyclopean Perception. Chicago: University of Chicago Press, 1971.
5. Fricke T, Siderov J. Non-stereoscopic cues in the Random-Dot E stereotest: results for adult observers. Ophthalmic Physiol Opt 1997; 17:122–7.
6. Harvey LO Jr. Critical flicker frequency as a function of viewing distance, stimulus size and luminance. Vision Res 1970;10:55–63.
7. Freeman E. Anomalies of visual acuity in relation to stimulus-distance. J Opt Soc Am 1923;22:285–92.
8. Gonzalez F, Rivadulla C, Perez R, Cadarso C. Depth perception in random dot stereograms is not affected by changes in either vergence or accommodation. Optom Vis Sci 1998;75:743–7.
9. Fry GA, Kent PR. The effects of base-in and base-out prisms on stereo-acuity. Am J Optom Physiol Opt 1944;21:492–507.
10. Trotter Y, Celebrini S, Stricanne B, Thorpe S, Imbert M. Modulation of neural stereoscopic processing in primate area V1 by the viewing distance. Science 1992;257:1279–81.
11. Jiménez JR, Rubino M, Diaz JA, Hita E, del Barco LJ. Changes in stereoscopic depth perception caused by decentration of spectacle lenses. Optom Vis Sci 2000;77:421–7.
12. Ogle KN. Note on stereoscopic acuity and viewing distance. J Opt Soc Am 1958;48:794–8.

13. Amigo G. Variation of stereoscopic acuity with observation distance. J Opt Soc Am 1963;53:630–5.
14. Brown JP, Ogle KN, Reiher L. Stereoscopic acuity and observation distance. Invest Ophthalmol 1965;4:894–900.
15. Lit A, Finn JP. Variability of depth-discrimination thresholds as a function of observation distance. J Opt Soc Am 1976;66:740–2.
16. Zanoni D, Rosenbaum AL. A new method for evaluating distance stereo acuity. J Pediatr Ophthalmol Strabismus 1991;28:255–60.
17. Yildirim C, Altinsoy HI, Yakut E. Distance stereoacuity norms for the mentor B-VAT II-SG video acuity tester in young children and young adults. J Aapos 1998;2:26–32.
18. Carlson NB, Kurtz D, Heath DA, Hines C. Clinical Procedures for Ocular Examinations, 2nd ed. Stamford, CT: Appleton & Lange, 1996.
19. Fruböse A, Jaensch PA. Der einfluss verschiedener faktoren auf die tiefensehscharfe. Ztschr Biol 1923;78:119–32.
20. Jameson D, Hurvich LM. Note on factors influencing the relation between stereoscopic acuity and observation distance. J Opt Soc Am 1959;49:639.
21. Kaye SB, Siddiqui A, Ward A, Noonan C, Fisher AC, Green JR, Brown MC, Wareing PA, Watt P. Monocular and binocular depth discrimination thresholds. Optom Vis Sci 1999;76:770–82.
22. Sheedy JE. Fixation disparity analysis of oculomotor imbalance. Am J Optom Physiol Opt 1980;57:632–9.
23. Garzia RP, Dyer G. Effect of nearpoint stress on the horizontal forced vergence fixation disparity curve. Am J Optom Physiol Opt 1986;63: 901–7.
24. Howard IP, Rogers BJ. Binocular Vision and Stereopsis. New York: Oxford University Press, 1995.
25. Peli E. The visual effects of head-mounted display (HMD) are not distinguishable from those of desk-top computer display. Vision Res 1998;38:2053–66.

Russell Woods
Schepens Eye Research Institute
20 Staniford Street
Boston, MA 02114
e-mail: rwoods@vision.eri.harvard.edu