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Research Article

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Depth Perception, Binocular Integration and Hand-Eye Coordination in Intact and Stereo Impaired Human Subjects

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Abstract

A series of tests was devised to assess stereoscopic depth processing, motion parallax depth processing, binocular integration and hand-eye coordination in normal, stereoblind, and stereo deficient subjects. Using a random-dot stereoscopic display viewed through a stereoscope we established that of the 262 subjects tested, 177 were categorized as having normal stereoscopic depth perception, 28 as being stereo deficient and 57 as being stereoblind. These three groups of subjects processed motion parallax information for depth equally well, but the stereoblind and stereo deficient subjects had significantly longer reaction times. On the hand-eye coordination tests the stereoblind subjects performed significantly less well than did normal and stereo deficient subjects, whose performance on these tests was similar. Our binocular integration tests revealed significantly less integration in stereoblind subjects than in normal and stereo deficient subjects. The tests we have devised will be useful for the accurate assessment of various forms of treatment for amblyopia and strabismus for the reinstatement of depth perception, hand-eye coordination and binocular integration.

Introduction

One of the central requirements of higher living organisms is the ability to derive the third dimension from the two dimensional images that fall on the retinal surface. Several neural mechanisms have evolved to accomplish this [1,2]. Notable among these are stereopsis and motion parallax. Motion parallax is predominantly a monocular cue whereas stereopsis, a binocular cue, relies on the disparity of the images that fall on the retinae of the left and right eyes. The basic neural mechanisms of these depth cues have been extensively studied [3-5].

In the course of evolution several mechanisms have emerged for the processing of depth information [5]. The accurate assessment of depth is a central requirement for survival. Due to the fact that the images that form on the retina are two-dimensional, the extraction of depth information is a particularly demanding task.

Of the several mechanisms that have evolved perhaps the most intriguing is stereopsis, which requires selective neural connections from disparate regions of the two retinae to binocularly drive neurons in the brain [6]. The processing of disparity information yielding stereoscopic depth perception has several attributes that render it effective [7]. These include the ability to detect small differences in depth at close distances from the eye and to accomplish this rapidly so that motor responses can be made accurately with dispatch [8-11].

For the processing of depth based on motion parallax either the observer or the visual scene has to be in motion. The extraction of depth from motion parallax requires integrating information over time which takes longer than acquiring information gained from disparity, but has the advantage of working well over extended distances [12,13]. Even this mechanism can be quite rapid in some species, as for example in frogs that catch flies in motion by flicking their tongues. Individual variability in the use of disparity and motion parallax cues has been studied recently by Nefs et al. [14]. They have identified two independent mechanisms for motion-in-depth perception.

The neural mechanisms that process stereopsis and motion parallax, which are remarkably effective, contribute differentially to processing of depth cues [4,8,15-20]. It is well known that stereopsis is especially effective at relatively short distances from the observer, is extremely sensitive to small depth differences, can assess relative depth very rapidly and can do so under static viewing conditions [10,21]. Motion parallax is effective over a large range of distances. Due to the fact that differential motion is the central cue, which has to be integrated over time, the computation depends on motion velocity and hence typically takes longer to process and is not effective under static conditions [9,22].

Depth cues also play an important role in hand-eye coordination. The mechanism of stereopsis, in particular, is central for making fine adjustments in motor control, such as in threading needles, for example. A related attribute for effective visual processing involves the ability to integrate the inputs from the two eyes not only for stereoscopic depth perception, but also for unifying the inputs from the two eyes into veridical single images.

The prime aim of the research on which we report here was to create a comprehensive battery of tests that can reliably assess depth perception based on stereopsis and motion parallax, hand-eye coordination and binocular integration in normal, stereo deficient and stereoblind subjects. The portion of this battery that examines stereopsis and motion parallax has been extensively tested in both monkeys and humans as reported in our previous publications [23,24]. None of the individual clinical tests presently in use studies all of these capacities [24]. The clinical tests that presently assess stereoscopic depth perception use several different methods which include the use of stereoscopes, color filters and polarizers to present displays separately to the two eyes and auto stereograms as detailed in the

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Discussion section. Not all of these tests use random-dot stereograms which provide no other cue than disparity. In our tests for stereopsis and motion parallax we used a stereoscope which appears to be the most foolproof device as confirmed by our experiment in which all the normal subjects readily fused the left and right eye images and readily perceived depth based on disparity.

In our battery of tests we utilize a few well-established procedures. However, most of tests we have devised are novel. In the Discussion section we compare our tests with others and point out what the advantages are in our procedures. Our tests will serve a useful purpose in future work for the integrated assessment of depth processing, hand-eye coordination and binocular integration in intact subjects and in subjects with deficiencies in stereoscopic depth processing due to varied etiologies. Furthermore, our tests will provide a reliable means for assessing the effects of various forms of treatment to reinstate stereoscopic depth perception. The integrated test for assessing stereoscopic depth perception and motion parallax using random-dot stereograms will also enable investigators to identify the brain areas involved in the processing of these depth cues using imaging procedures.

Methods

We tested 262 subjects of which 177 had normal stereoscopic vision, 57 were stereoblind and 28 were stereo deficient. Some of the tests we devised were developed during the conduct of the experiment. Therefore not all subjects participated in all parts of the test battery. For each of the figures shown the number of subjects tested is therefore always specified. Administration of the entire battery of tests took 1.5 to 2.0 hours. The majority of the subjects were students at MIT. Subjects were initially recruited by emails and posters throughout MIT and pre-screened using our Quick Stereo Test to obtain reasonable number of stereoblind and stereo deficient subjects. Subjects of prime interest were those who do not see the displays in depth as shown in the *Magic Eye* books. This accounts for the fact that the percent of stereoblind subjects in our sample is above the national average, which comprises of approximately 5-10% of the population. In our sample nearly 20% of the subjects were stereoblind, as determined by their results on the stereopsis test. A significant percent of subjects who had reported that they did not perceive depth in the *Magic Eye* books did have stereoscopic depth perception as revealed by our methods that used a stereoscope. The reason for this is that failure to see depth in autostereogram displays can be due not only to stereo blindness, but an inability by the oculomotor system to converge or diverge the eyes when viewing such displays. Use of a stereoscope circumvents this problem. None of the normal subjects we tested exhibited any problem in fusing identical images presented to the left and right eyes through the stereoscope.

This research was approved by MIT's Committee on the Use of Humans as Experimental Subjects. The experimental procedures and the purpose of the experiment were explained to each subject. A written informed consent form was obtained from all individuals who participated in the study.

The battery of tests we used was as follows:

Visual acuity test

Visual acuity was assessed using the Snellen chart. Subjects were asked to read the letters on each line in succession on the basis of which we established their acuity under binocular, left and right eye viewing conditions. A difference value for the acuity of each eye was plotted providing a comparison among subjects with and without stereoscopic vision.

Eye movement tests: tracking and vergence

We asked each subject tested to track the green top of a rod held by the experimenter which was moved first in a fronto-parallel plane and then toward and away from the subject's eyes to assess vergence movements. While doing so, the experimenter watched the eyes of the subjects to determine whether the two eyes moved in unison when the rod was moved in the fronto-parallel plane and converged and diverged properly when the rod was moved toward and away from the subject. Since the eyes were viewed at a close distance of 2-3 feet, this could be reliably assessed by the experimenter. This test took only a few minutes and most subjects tested performed well on it.

Stereopsis and motion parallax tests

Stereopsis and motion parallax were assessed using procedures in which subjects viewed random-dot displays that appeared on a monitor through a stereoscope. The basic condition is depicted in Figure 1. The tests carried out were as follows:

The quick stereo test: In the interest of quickly screening subjects at the onset of the experiment for stereoscopic depth perception, we have devised a static test which for many of the subjects was administered prior to the detailed dynamic tests described below. The "Quick Stereo Test" has the advantage of determining in less than five minutes how well subjects can process disparity cues for stereoscopic depth perception. Subjects viewed the display through the stereoscope (Figure 1). The red frame of the display, which subtended 9.8 by 9.8 degrees of visual angle, was on throughout the test. Each trial began with the appearance of a central fixation spot followed by the appearance of a random-dot array presented to each eye. The first presentation was a control condition in which a capital letter appeared made visible by virtue of darker shading as shown in Figure 2A. The subject had to state what letter was shown. None of the subjects tested had any trouble identifying the letter shown made visible by darker shading. The next series of displays was presented in succession with the letters presented made visible by virtue of disparity. Figure 2B depicts this condition. When viewed through a stereoscope, readers with intact stereoscopic vision should

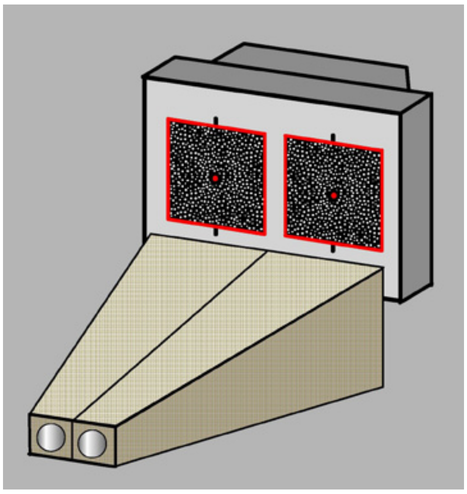

Figure 1: Display system for testing stereopsis and motion parallax. The two displays, one for the left and the other for the right eye are rocked back and forth along a central vertical axis as depicted in Figure 3A.

perceive a letter of similar overall size as the one shown in Figure 2A. Three levels of disparity were used in successive steps measuring 8.40, 5.04 and 1.68 minutes of visual angle. Subjects with stereoscopic vision identified these letters with ease whereas stereo deficient subjects had difficulties at the lowest disparities and stereoblind subjects failed in identifying any letter presented with disparity.

When this test was developed a number of normal subjects were also tested under monocular viewing conditions. None of the subjects so tested were able to perceive the letters indicating that the test does not contain monocular cues.

Analysis of stereopsis and motion parallax using dynamic displays: To assess stereopsis and motion parallax, the procedure we devised was to use a dynamic display which was viewed by the subjects through the stereoscope. The random-dot stereograms were rocked back and forth along a vertical axis for each of the left and right eye displays. The fulcrum of the rotation was in the center of the display. This arrangement is depicted for the single perception of the display in Figure 3A. A dynamic viewing of this is available on our website (http://web.mit.edu/bcs/schillerlab/) both in the header display and in RESEARCH, section 1L. Based on a three-dimensional model, a computer program was written to provide the differential motion in the rocking display to have a small region within it move at a different rate than the background thereby creating a percept of a protruding square in depth. On each trial the subject's task was to press one of the four corresponding pushbuttons on a box placed on the table under the stereoscope, using two fingers of each hand placed to be in touch with the four pushbuttons. The four pushbuttons corresponded to the four locations at which the target appeared on the screen, with the left far button representing the left top location of the target on the screen display, the right far button the right top target location, the near left button representing the bottom left and the near right button the bottom right target location. The subjects practiced this task and all performed well. Correct choices were indicated by a brief beep. Subjects were encouraged to guess when they could not discern the location of the target on the screen. They were given one second to respond after which the next trial started. Failure to press a button within the one second period was considered an incorrect response. This procedure allowed us to collect both percent correct and latency data.

Three basic conditions were used with this dynamic display: (1) Only disparity cues were presented, (2) Only differential motion cues were presented and (3) The two cues were presented together.

In the first dynamic test one level of disparity and one level of differential motion were used (10 minutes of visual angle for disparity and 4.5 degrees per second of differential velocity for motion parallax). The stimulus appearing in depth was a small square that was presented randomly in one of four locations that had a size of 1.3 x 1.3 degrees of visual angle. The center of each square was at an eccentricity of 3 degrees from the fixation spot.

This test enabled us to assess stereoscopic vision and motion parallax. Stereoblind subjects performed at chance when only disparity cues were provided. These subjects also were unable to specify the letters on the Quick Stereo Test.

In the second set of tests the magnitude of the disparity and the magnitude of the differential motion were varied systematically, each presented singly, which enabled us to obtain psychometric functions. Subjects, who were stereoblind, as assessed on the initial test, were not examined with different degrees of disparity for the stereo test since they could not see any depth under disparity conditions but were examined on the varied magnitudes of differential motion. On the motion parallax test many subjects were tested under both monocular and binocular viewing conditions.

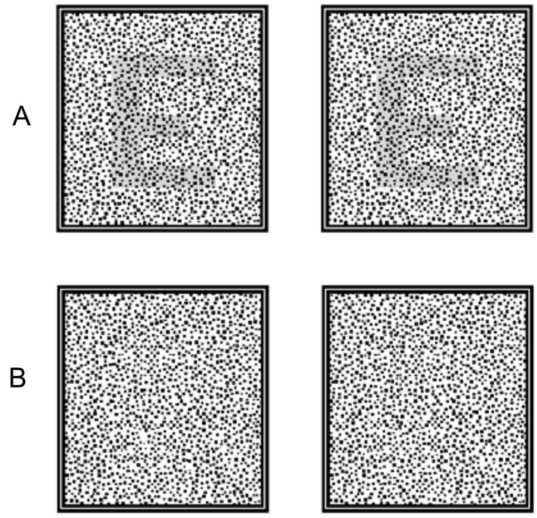

Figure 2: Example of the quick stereo test. A: Shows the letter E when the cue provided is shading. B: Shows the letter H visible only by virtue of disparity when viewed through a stereoscope.

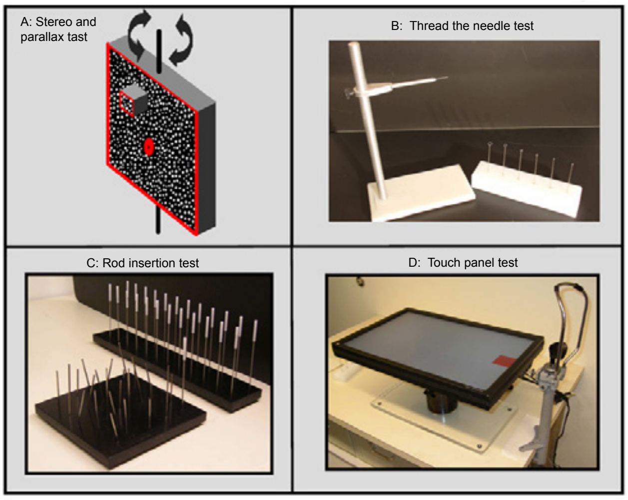

Figure 3: A: Example of a display when the images presented to the two eyes on the monitor are fused. The display rocks back and forth along the vertical axis shown by the vertical lines as also depicted in Figure 1. B: The device used for the thread the needle test. The diameters of the loops range between 0.8 and 6.3 millimeters. The test is carried out under both binocular and monocular viewing conditions. C: The rod insertion task in which the rods with the plastic tops have to be inserted into each of the 25 tubes successively. The task was performed four times, twice under binocular and twice under monocular conditions. For each repetition the unit containing the tubes was rotated 90 degrees. D: The device used for the touch panel test. Subjects were asked to place their head into the head holder on the right. Upon pressing the touch panel where the red square is located, a small black spot appeared briefly at one location on the panel. The task was to reach out and touch the dot. Thirty-six dots were shown in succession tested twice under both binocular and under monocular viewing conditions. In addition to obtaining time of completion data, this test allowed us to generate accuracy scores based on the difference between the location of each dot and where the subject touched the screen.

Hand-eye coordination tests

Three tests were used to assess hand-eye coordination. Subjects were tested binocularly and monocularly, with the latter using their preferred eye. During monocular testing one eye was covered with an eye patch. Figure 3B-D provides photographs of the devices used for this test.

Thread-the-needle test: The thread-the-needle test, shown in Figure 3B consists of a horizontally oriented rod at the end of which the attached pin measures 0.6 millimeters in diameter. The unit was placed on a table with the pin at a height of 25 cm from the table top. Next to this unit were six "needles" whose eyes varied in size, with internal diameters of 6.3, 4.0, 2.9, 2.0, 1.1 and 0.8 millimeters. Each needle measured 9 centimeters from base to the eye. The task of the subject was to take each needle from the receptacle, starting with the one with the largest eye, and thread them successively onto the pin. They were told to perform the task as quickly as they could and that their performance would be timed. Subjects were tested under binocular conditions as well as under monocular conditions using their preferred eye. The length of time to complete the task was recorded. Subjects were tested twice under both binocular and monocular conditions using an ABBA sequence.

Rod insertion test: Figure 3C provides a photograph of the devices used for this test. Twenty-five pins are provided shown in the right section of the figure. The task of the subject was to take each pin in succession and insert it into the tubes shown on the left of the figure. The 25 tubes of varied lengths are secured to the base and protrude at various angles. Subjects were tested under binocular and monocular conditions. For monocular conditions we asked them to use their preferred eye. The other eye was covered with an eye patch. Subjects were tested twice under both binocular and monocular conditions using an ABBA sequence. For each test the base holding the tubes was rotated 90 degrees. The prime measure obtained was the time it took subjects to insert the 25 rods into the tubes for each condition.

Touch panel test: A horizontal touch panel measuring 52 by 32.5 centimeters was used as shown in Figure 3D. Subjects were seated in front of the panel and placed their heads into the chin and head rest attached to the table. The top of the touch panel was 26 centimeters above the table and was 16 to 18 centimeters below the eye. Subjects were told that using their preferred finger, their task was first to touch the area lit up as a small red square close to the edge of the panel nearest to them. Doing so resulted in the disappearance of this square and the appearance of a small 5 millimeter diameter black spot that appeared at random locations which they had to touch with their forefinger. Upon doing so the black dot was extinguished and the red square appeared again. Upon touching it, another black spot appeared at a different location and the process was repeated. Thirty-six black spots appeared in succession. Subjects were instructed to perform as quickly and accurately as possible. Each subject was tested twice under both binocular and monocular viewing conditions using 36 trials for each using an ABBA sequence. To assure rapid performance, each black spot upon being activated by touching the red square remained on for 850 milliseconds. The measures on this test were accuracy and time of completion. Accuracy was assessed by obtaining the location of each touch on the panel relative to the actual location of the black spot.

Binocular integration tests

Binocular integration was tested using displays that were viewed on the monitor through the stereoscope. The frame arrangement was similar to the one used for the dynamic stereo and motion parallax displays described in the Quick Stereo Test section above and remained on throughout. The stimuli presented inside the frame subsequent to fixation of the central fixation spot were either identical for the two eyes or were different. The ability to integrate these images when they were different for the two eyes was assessed. The stimuli were presented at high contrast using images that were made visible by both light increment and decrement by virtue of having stimuli that consisted of black and white lines as shown in Figures 4-9. To minimize binocular rivalry, the stimuli were presented briefly for 16.7 milliseconds; we have established in previous work that brief presentations minimize rivalry [25,26]. The following binocular integration tests were administered:

Displays with simple figures: The figures used were a cross, a wheel

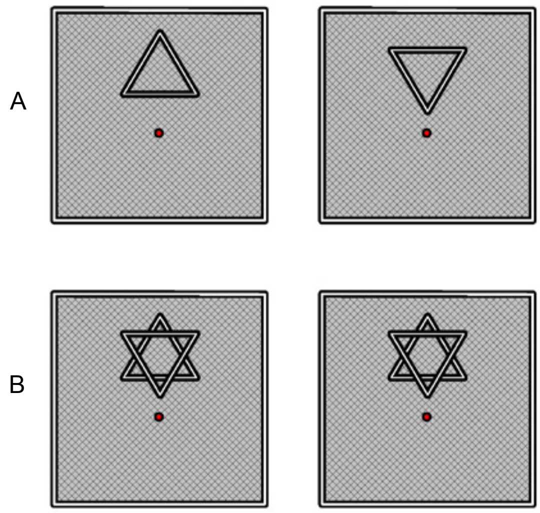

Figure 4: Example of the test for binocular integration using a figure. A: Shows a right-side up triangle presented to the left eye and upside-down triangle shown to the right eye. When integrated, the Star of David is seen. B: The Star of David shown to both eyes.

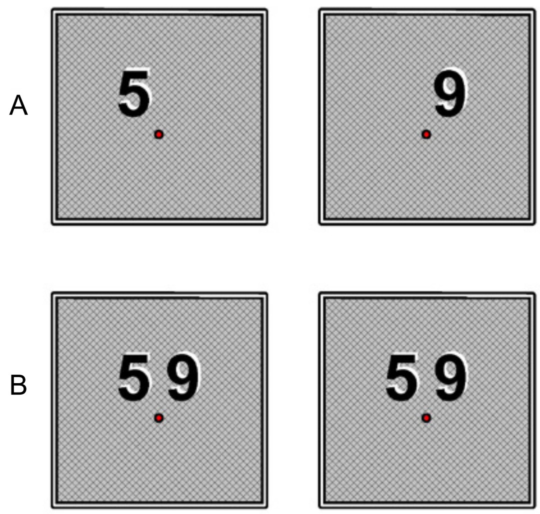

Figure 5: Example of the test for binocular integration using numbers. A: Number 5 is presented to the right eye and 9 to the left eye. When integrated, 59 was seen. B: 59 was shown to both eyes.

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and the Star of David. Each figure has been set up to consist of two elements which could be presented together to both eyes or could be presented separately to each eye. For the cross the separate presentation consisted of a vertical line to one eye and a horizontal one to the other. For the Star of David a triangle pointing upwards was presented to one eye and a triangle pointing downward was presented to the other eye as shown in Figure 4. For the wheel, the spokes were presented to one eye and the ring to the other. Six presentations were made, for three of them the total figures were presented binocularly, and for three of them they were presented monocularly with the two elements of the figure presented to separately to the two eyes. Subjects were asked to report what they had seen. They could see either the three full images (the cross, the wheel and the Star of David) or they could see half-images (a horizontal or vertical line, a right-side up or upside-down triangle, and a star or ring). Subjects with stereoscopic vision mostly integrated these percepts by reporting correctly the integrated percept. The majority of stereoblind subjects failed to integrate the separately presented images. Which image they preferentially perceived enabled us to determine which eye was dominant.

Displays with numbers: A set of numbers was presented in a fashion a similar to that just described. Examples of these numbers as presented appear in Figure 5. The numbers were presented either singly to each eye or were presented in pairs. Eight conditions of presentation were used. For one of these conditions the two numbers were presented binocularly. For four of the eight conditions a single number was presented to either the left or right eyes, with 7 and 3 presented successively to the left eye and 4 and 8 presented successively to the right eye. For the remaining three conditions interocular presentations were made with 7 and 4, 5 and 9, and 3 and 8 presented to the left and right eyes in successive steps. If integrated, the numbers reported were 74, 59 (as shown in Figure 5) and 38. Integrated responses always involved reporting two numbers, for example 59 for Figure 5A as well as for Figure 5B. When for the paired presentations subjects reported a single number (as either 5 or 9) for Figure 5, that indicated lack of integration.

Displays with words: A series of four- or six-letter words was used which were presented either binocularly or with alternate letters presented separately to each eye as shown in Figure 6. Nine conditions of presentation were used. For binocular presentation the words were TEST, CHAIRS, STURDY and BLUEST. For interocular presentation the letters were interdigitated showing to the left and right eyes as follows: C A R and H I S, B U S and L E T, S U D and T R Y (as shown in Figure 6).

Displays with rotating wheels: This test assesses integration of motion information between the eyes. The procedure capitalizes on the principle of proximity in perceived motion. The direction in which we perceive a rotating wheel with identical spokes is determined predominantly by the proximity with which successive spokes appear as made evident in movies and on TV where it is common to see wheels rotating backwards in forward moving vehicles when the speed is such that in successive frames a spoke appears closer to a previously shown spoke that is actually a consequence of the unseen rotation between frames. This can be mimicked in its most basic form using the conditions shown in Figure 7. The entire display has 24 potential spoke locations of which eight are shown simultaneously at any given time. If spokes 1, 4, 7, 10, 13, 16, 19, and 22 appear initially and are followed by spokes 2, 5, 8, 11, 14, 17, 20 and 23, and so on, as specified in Figure 7A, clockwise rotation is perceived. If the second set of spokes shown is 3, 6, 9, 12, 15, 18, 21, and 24, and so on as indicated in Figure 7B, rotation will be seen to take place counterclockwise. Each sequence in these cases has three steps and then returns to the first step providing continuous clockwise or counterclockwise motion. Figure 8A-C shows these steps for clockwise rotation when identical stimuli are presented to each eye.

If one now presents such a sequence interocularly as shown in Figure 8D-F, binocular integration will result in perceiving the rotation of the wheel as being clockwise. If this display is viewed monocularly, the perceived rotation is counterclockwise. Similarly therefore, in subjects who fail to integrate between the eyes under interocular viewing conditions, rotation will be perceived as being counterclockwise. Most subjects with stereoscopic vision, as seen in the Results section, perceived clockwise motion whereas the majority of stereoblind subjects perceived counterclockwise motion.

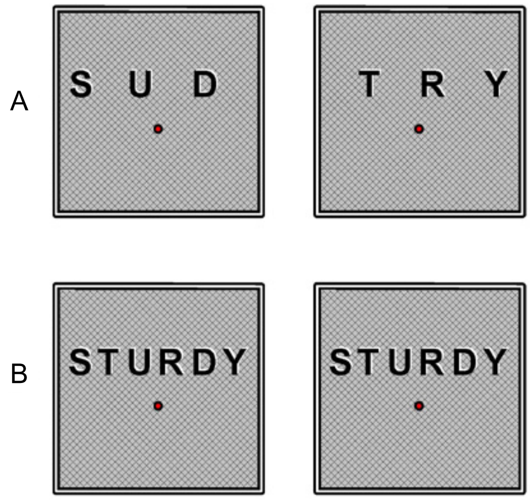

Figure 6: Example of the test for binocular integration using words. A: The word S U D was presented to the left eye and T R Y to the right eye. The letters presented to the left and right eyes were set up in an interdigitated fashion; as a result, when integrated the word STURDY is perceived. B: The word STURDY presented to both eyes.

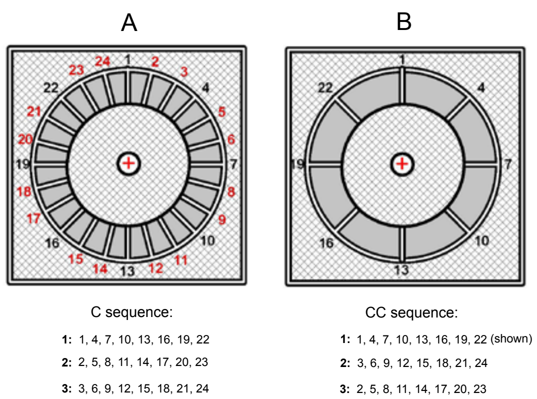

Figure 7: The procedure used to test whether a wheel shown is perceived to rotate clockwise or counterclockwise. In each frame shown in sequence eight spokes appeared. A: Shows all the spokes used in the test. B: Shows the first sequence used. The numbers listed for three consecutive sequences for clockwise (C) and counterclockwise (CC) rotation are depicted below the figure.

These four tests can provide a reliable and satisfactory assessment of the extent to which subjects can integrate binocularly. Comparing the extent of integration between normal and stereo deficient individuals can provide further useful information about the relationship between such integration and depth perception.

Results

A total of 262 subjects were tested in this study of which 177 were categorized as having normal stereoscopic vision (mean age=28.6; SD=11.2; N=176; no info=1 (F=96; M=81)), 28 as being stereo deficient (mean age=34.1; SD=13.4; N=28 (F=16; M=12)) and 57 as being stereoblind (mean age=36.8; SD=13.5; N=56; no info=1 (F=31; M=26)). Some of the subjects were tested on the entire battery of tests we had devised, but a small subset of them was tested only on some of them. The reasons for this were that (1) some of the tests were developed during the conduct of the experiment and (2) some of the subjects were not able to participate in the entire battery of tests.

In assessing stereo blindness, the results we obtained with the Quick Stereo Test were entirely consistent with the detailed tests: All subjects who failed to identify the letters made visible by disparity on the Quick Stereo Test also failed on the detailed dynamic stereopsis task. The data we present here assessing stereopsis and motion parallax are based on the dynamic tests. In the following results, the significance of differences in reaction time latencies was evaluated using a t-test for the difference between two independent means (assuming unequal variances of the two samples). The significance of differences in percent correct performance was assessed using a z-test for the difference between two independent proportions.

Visual acuity test

During the initial portions of the testing procedure each subject's acuity was tested on the Snellen chart. Subjects were tested under both monocular and binocular conditions. Figure 9 shows the left and right eye differences in acuity on the Snellen chart both for the number of subjects and the percent of subjects. Overall, no difference between left and right eye acuities was found in 64% of intact, normal subjects (IN), 59% of stereo deficient subjects (SD) and 23% of stereoblind subjects (SB). The percent of normal and stereoblind subjects with equal acuity in the two eyes was significantly different ($z=3.06$, $p < 0.05$). A difference in acuity between the two eyes greater than 10 was found in 7.9% of normal subjects, 31.8% of stereo deficient subjects and 44.3% of stereoblind subjects. The percent of normal and stereoblind subjects with acuity differences greater than 10 was also significantly different ($z=2.14$, $p < 0.05$). Figures 13-16 depict these differences in detail.

Eye movement test

Tracking eye movements of subjects, as described in the Eye Movement Tests subsection of the Methods section, showed that all subjects had good pursuit movements when the distance of the moving display from the observer was kept constant. All normal subjects also had excellent vergence movements when the rod with the green top was moved toward and away from them. Of the stereo deficient and stereoblind subjects, 17.4% of the 23 stereodeficient and 34.0% of the 47 stereoblind subjects tested showed deficits in vergence movements.

Stereopsis and motion parallax tests

The results obtained using the dynamic display in which one of four regions appeared made visible either by virtue of disparity or by motion parallax are shown in Figures 10 and 11.

Figure 10 shows latency and percent correct performance obtained for stereopsis. For this test only disparity cues were provided using four levels: 1.68, 3.36, 6.72 and 10.08 minutes of disparity. Data are shown for intact, normal subjects (IN), stereo deficient subjects (SD) and for stereoblind subjects (SB). The stereoblind subjects were tested only on the highest disparity where their performance was at chance level. This was the case because on some trials the stereoblind subjects did not

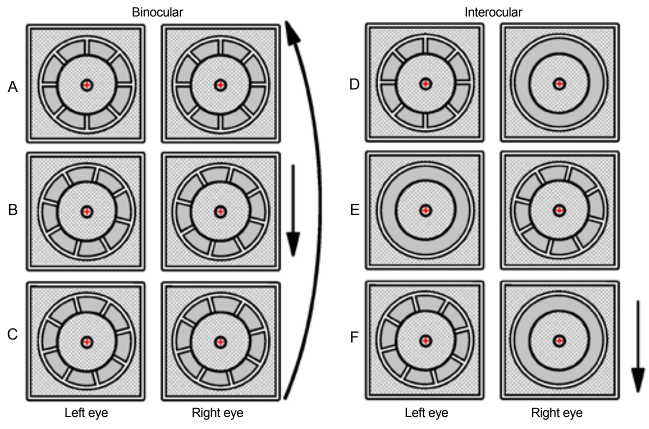

Figure 8: Three sequences of the rotating wheel are shown, A, B, C for binocular and interocular presentations. These sequences are presented repeatedly. As shown for binocular viewing, clockwise rotation is perceived. Under interocular presentation conditions clockwise rotation is perceived when the input to the two eyes is integrated and counterclockwise rotation is seen when they are not integrated. Under monocular viewing conditions counterclockwise rotation is perceived.

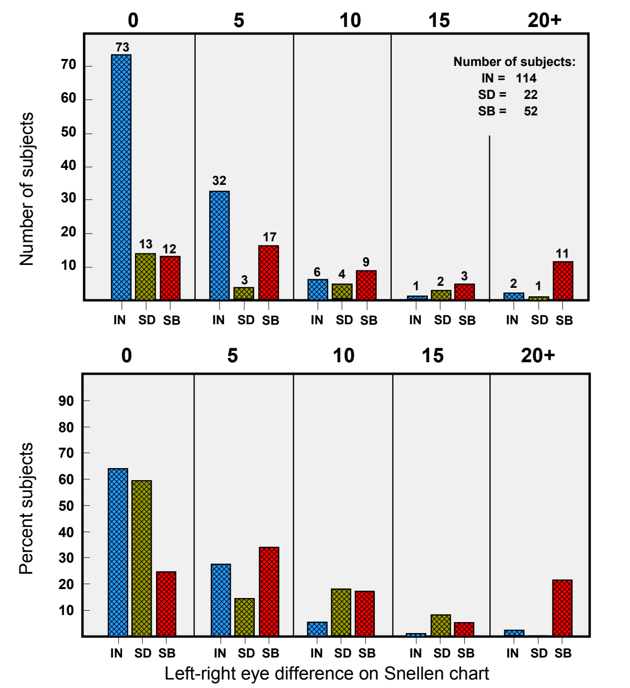

Figure 9: The distribution of normal (IN), stereo deficient (SD) and stereoblind (SB) subjects for left and right eye differences in acuity as measured on the Snellen chart shown both for number of subjects and percent of subjects in our sample.

make a choice by pressing one of the four push buttons. When subjects did not perceive the target, as was especially the case for stereoblind subjects when only disparity cues were provided, they naturally often hesitated in pressing a button before the time to do so expired. Hence these subjects showed a higher incidence of not pressing the buttons. When the targets were perceived by subjects, they pressed the buttons with increasing latencies as the task became more difficult as can be seen and is noted for Figure 10. The differences in performance between the normal and stereo deficient subjects were significant beyond the 0.01 level for both percent correct and latency performance except for the lowest disparity value for latency.

Figure 11 shows performance by normal, stereo deficient and stereoblind subjects when tested for motion parallax using five different levels of motion parallax differences. Percent correct performance was quite similar among the three groups of subjects. Surprisingly, the latencies of both the stereoblind and stereo deficient subjects were significantly longer than the latencies of intact subjects. The differences were statistically significant beyond the 0.01 level. The standard error scores for the data shown in Figure 11 appear in Table 1. These standard error scores are shown separately because the error bars are very close to each other or are overlapping and cannot be discerned.

On the motion parallax test, 42 normal subjects, 28 stereoblind subjects and 11 stereo deficient subjects were tested under both binocular and monocular viewing conditions. The mean latency difference between the binocular and monocular viewing conditions was very small for all three groups. For normal subjects the latencies under monocular viewing conditions were faster by just 5.68 milliseconds than under binocular viewing conditions. For stereoblind subjects the latencies under monocular viewing conditions were faster by just 8.87 milliseconds than under binocular viewing conditions. For the stereo deficient subjects the latencies under monocular viewing conditions were faster by just 1.15 millisecond. These small differences were not statistically significant. These findings indicate that the overall longer latencies for motion parallax in stereoblind and stereo deficient subjects compared with normal subjects, as shown in Figure 11, are not due to possible conflicts of input from the two eyes. For the stereo deficient subjects this is further supported by the fact that this group has obtained high integration scores on the binocular integration test described below and in Figures 13-15.

Examination of the latency differences for paired and single presentation of stereopsis and motion parallax on the first task as described in the Methods section in which one level of disparity and

Standard Error Scores for Motion Parallax Latencies

	1.0	1.7	2.5	3.0	4.5
IN	8.6	7.3	6.8	6.7	7.4
SD	16.6	19.2	20.8	18.5	21.9
SB	14.6	13.3	13.4	12.6	13.8

Percent correct

	1.0	1.7	2.5	3.0	4.5
IN	4.8	2.8	1.8	1.5	1.1
SD	12.2	9.6	5.9	5.0	3.0
SB	7.3	6.5	4.7	4.2	2.8

Table 1: Standard error scores on the motion parallax text for intact, stereo deficient and stereoblind subjects for the data shown in Figure 11. The bold numbers indicated the motion parallax values in degrees per second differential velocity as in Figure 11.

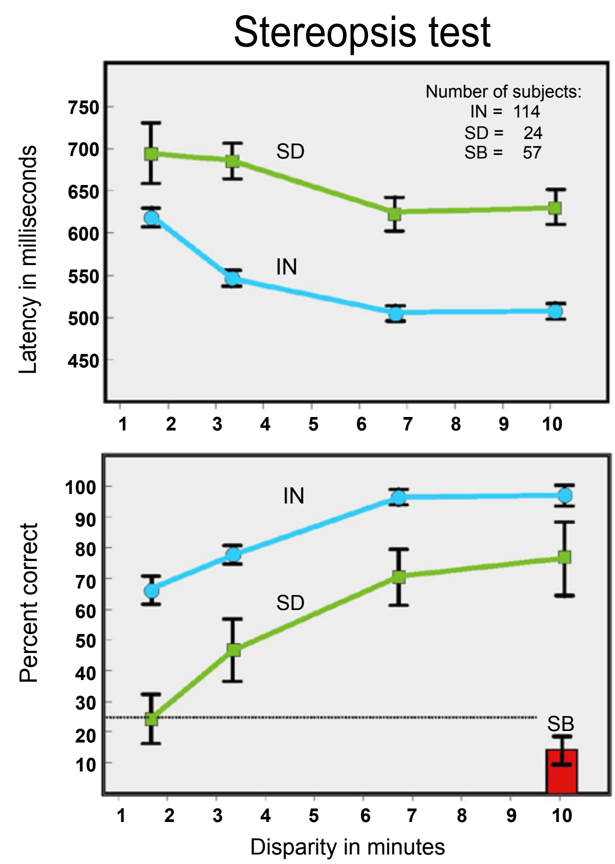

Figure 10: Performance on the stereopsis test showing percent correct performance and response latencies for normal (IN), stereo deficient (SD) and stereoblind (SB) subjects using four different levels of disparity. The black bars show the +/- standard error values for each condition.

motion parallax were used and were presented in a randomized order for providing only stereo cues, only parallax cues and the combination of the two, revealed significantly faster reaction times to the paired presentations for intact, normal subjects. We do not present a figure for these data. The latencies and standard deviations were as follows: disparity plus parallax, 488.5 ms, SD = 87.6; disparity only, 523.4 ms, SD = 101.4; parallax only, 518.2 ms, SD = 88.7. The latency differences between paired and single presentations were significant beyond the 0.005 level. These findings are in agreement with previous work we have reported showing that in normal subjects when three depth cues, disparity, parallax and shading are presented in various combinations, the combined presentation of all three cues yields significantly faster reaction times than the presentation of single or paired cues [24]. That reaction times are faster when both disparity and motion parallax cues are presented than when these cues are shown singly, has been established in our previously published studies carried out in normal human and monkey subjects, indicating that the brain can advantageously integrate these cues [23,24].

Hand-eye coordination tests:

Summary data on the three hand-eye coordination tests for intact, normal subjects (IN), stereo deficient subjects (SD) and stereoblind subjects (SB) are shown in Figure 12. For the Thread-the-needle and the Rod-insertion tests, latency differences are shown for monocular

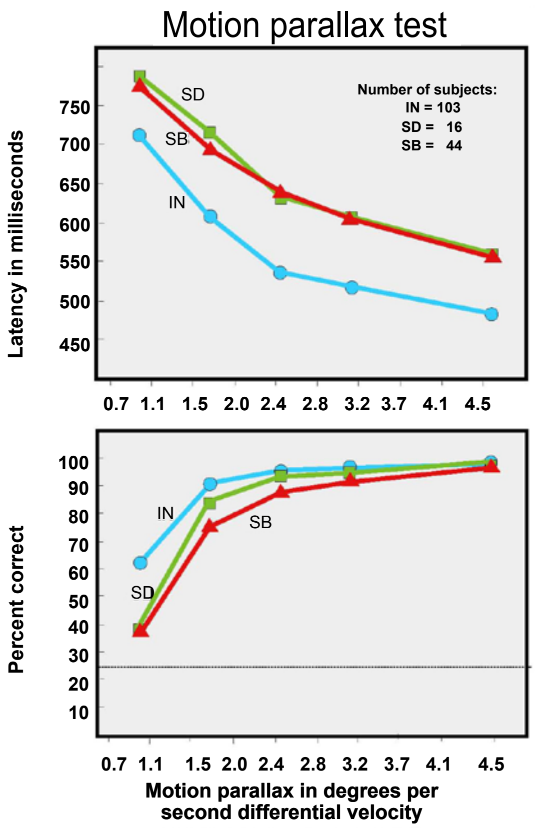

Figure 11: Performance on the motion parallax test showing percent correct performance and response latencies for normal (IN), stereo deficient (SD) and stereoblind (SB) subjects using five levels of differential velocities.

and binocular conditions of presentation. Stereoblind subjects showed significantly less time difference in performance under monocular and binocular viewing conditions than did normal and stereo deficient subjects ($p < 0.01$). The differences between normal and stereo deficient subjects were not significant.

For the touch panel test the differences in the error scores are plotted, expressed as the difference between the center of the black dot that appeared on the touch panel and where the subject touched the panel with the tip of the finger. The smaller difference between monocular and binocular conditions for the stereoblind subjects was significant beyond the 0.01 level (t=3.94, dF=134).

In normal subjects the mean time scores for completing the Thread-the-needle test under binocular and monocular viewing conditions was 15.7 and 28.1 seconds (SEM = 0.36 & 1.15), for completing the Rod-insertion test under binocular and monocular viewing conditions was 85.1 and 119.8 seconds (SEM = 2.32 & 5.39) and for completing the Touch-panel test under binocular and monocular viewing conditions was 28.7 and 46.9 seconds (SEM = 1.25 & 1.93).

In stereo deficient subjects the mean time scores for completing the Thread-the-needle test under binocular and monocular viewing conditions was 18.1 and 30.8 seconds (SEM = 1.24 & 3.14), for completing the Rod-insertion test under binocular and monocular viewing conditions was 86.1 and 118.6 seconds (SEM = 5.88 & 14.29) and for completing the Touch-panel test under binocular and monocular viewing conditions was 28.7 and 46.9 seconds (SEM = 2.41 & 4.03).

In stereoblind subjects the mean time scores for completing the Thread-the-needle test under binocular and monocular viewing

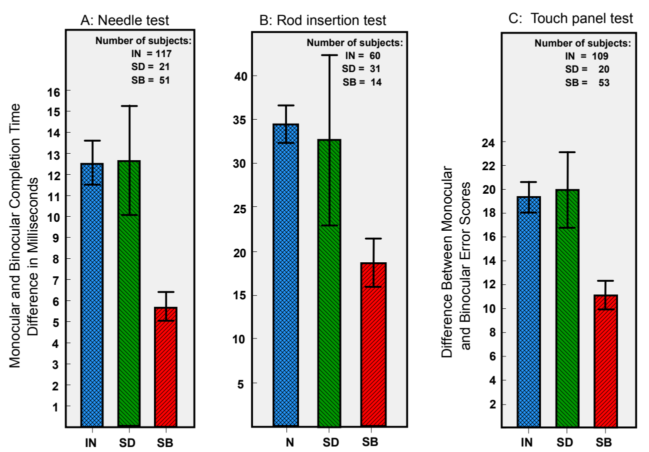

Figure 12: A: Time completion differences between monocular and binocular viewing conditions on the needle test. B: Time completion differences between monocular and binocular viewing conditions for the rod insertion test. C: Differences in the error scores between monocular and binocular testing conditions on the touch panel test. The black bars show the +/- standard error values.

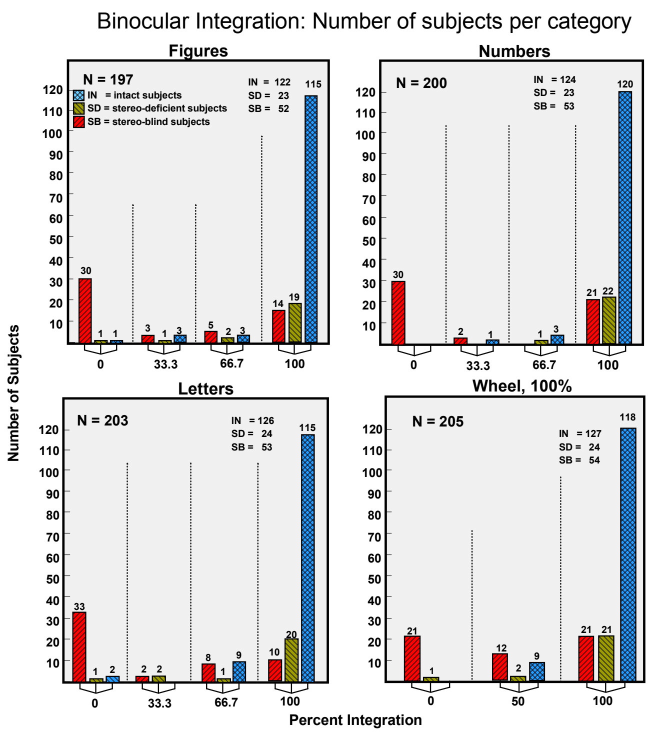

Figure 13: The distribution of the number of normal (IN), stereo deficient (SD) and stereoblind (SB) subjects on the four binocular integration tests. For each test performance was broken down into percent integration categories. For the wheel test integration three categories were created, 0, 50 and 100% integration. For the other tests four categories were used: 0, 33.3, 66.7 and 100% integration.

conditions was 21.6 and 25.8 seconds (SEM = 1.43 & 1.51), for completing the Rod-insertion test under binocular and monocular viewing conditions was 97.9 and 113.8 seconds (SEM = 6.80 & 8.85) and for completing the Touch-panel test under binocular and monocular viewing conditions was 34.1 and 45.1 seconds (SEM = 1.78 & 1.90).

The differences between normal and stereoblind subjects in mean completion times under binocular viewing conditions were statistically significant on the Thread-the-needle test (t=5.35, dF=165, p<0.01), on the Rod-insertion test (t=3.39, dF=87, p<0.01) and the Touch-panel test (t=3.94, dF=134, p<0.01). The differences between normal and stereo deficient subjects in mean completion times under binocular viewing conditions were not statistically significant on these three tests.

Binocular integration tests

For each of the four binocular integration tests, the figures, the numbers, the letters and the wheel rotation, we obtained a percent integration score for each subject. Figure 13 shows the distribution of the number of normal (IN), stereo deficient (SD) and stereoblind (SB) subjects. Figure 14 displays the same data expressed in terms of the percent of subjects. Figure 15 shows the summary data on the integration tests plotting the percent of IN, SD and SB subjects who integrated 100% and 0%. Almost 94 percent of the normal subjects integrated 100%, whereas nearly 54 percent of the stereoblind subjects failed to integrate. The stereo deficient subjects integrated almost as well as did the normal subjects. Better than 31 percent of the stereoblind subjects integrated 100% indicating that this is a heterogeneous population.

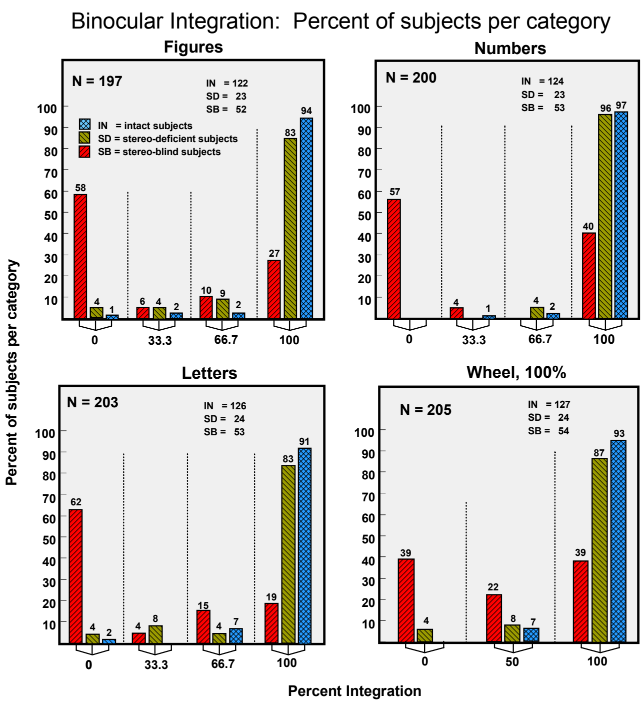

Figure 14: The percentage of normal (IN), stereo deficient (SD) and stereoblind (SB) subjects on the four binocular integration tests. For each test performance was broken down into percent integration categories. For the wheel test integration three categories were created, 0, 50 and 100% integration. For the other tests four categories were used: 0, 33.3, 66.7 and 100% integration.

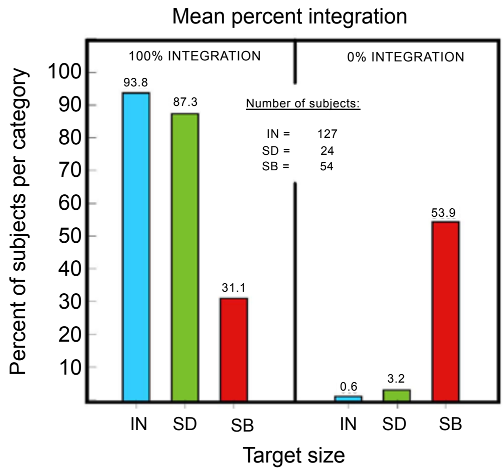

Figure 15: Mean percent of normal (IN), stereo deficient (SD) and stereoblind (SB) subjects on the four binocular integration tests who integrated 100 and 0 percent.

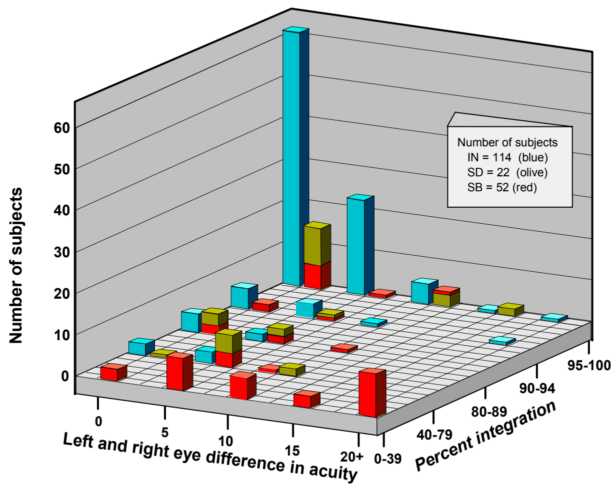

Figure 16: Distribution of the number of subjects based on percent of overall integration on the four binocular integration tests as a function of the differences in acuity between the left and right eyes.

To obtain reliable data on binocular integration we have devised four tests which use different but overlapping procedures. The first, as described below uses figures, the second numbers, the third words, and the fourth apparent motion. Using four tests provided us with high reliability in assessing binocular integration. The performance of normal subjects was consistent on these four tests as shown in Figures 13-16. Stereoblind and stereo deficient subjects showed significantly less binocular integration.

Figure 16 provides a closer look at the relationship between left and right eye acuity differences and percent integration performance in normal (IN in blue), stereo deficient (SD in green) and stereoblind (SB in red) subjects. These data show that most normal subjects had small differences in acuity between the two eyes and integrated well. Stereoblind subjects were widely distributed, but overall had significantly greater differences in acuity between the eyes and exhibited much less integration as already specified in Figure 15. The stereo deficient subjects were also widely distributed. As already noted in the Visual Acuity subsection of the Results section, the difference in acuity between the two eyes was significantly higher in stereoblind and stereo deficient subjects than in normal subjects with intact stereoscopic vision.

Discussion

We have developed a comprehensive battery of tests to assess depth perception based on stereopsis and motion parallax, hand-eye coordination and binocular integration in normal and stereoblind subjects. The tests we have devised as described in the subsections of Stereopsis and motion parallax tests, Hand-eye coordination tests and Binocular integration tests in the Methods section, are novel. The data we have presented here are based on the testing of 262 subjects of whom 177 were normal, 57 stereoblind and 28 stereo deficient. Our results establish the fact that the tests we have devised can be effectively used to assess depth perception based on stereopsis and motion parallax, hand-eye coordination and binocular integration in intact subjects and in subjects whose stereo vision is compromised.

The Quick Stereo Test permits us to determine in less than five minutes how well subjects can process disparity cues for depth perception. This pre-screening procedure enables us to readily identify subjects who lack stereopsis. Such subjects would then not need to be exposed to detailed testing of stereopsis using several levels of disparity (see Figure 10). The stereopsis and motion parallax tests using dynamic displays permit assessment of stereopsis only, motion parallax only and the combined presentation of these two depth cues. The use of random-dot stereograms, as developed by Julesz [27], is outstanding for this purpose as it can isolate cues to selectively activate mechanisms that process only disparity or only motion parallax [28]. We have published several papers studying normal humans as well as monkeys using this stereopsis and motion parallax test [23,24,26,29].

An interesting finding, as shown in Figure 11, was that on the motion parallax test stereoblind and stereo deficient subjects had significantly longer response latencies than did normal subjects. To determine whether this increased latency may be due to conflicting inputs from the two eyes, we tested 81 subjects under both monocular and binocular viewing conditions (42 normal, 28 stereoblind and 11 stereo deficient). The differences between monocular and binocular viewing conditions were very small as specified in the Results section. We therefore conclude that the increased latencies on the motion parallax test in stereoblind and stereo deficient subjects is not due to problems in integrating input from the two eyes. This is further supported by the fact that in our sample 87.3 percent of the stereo deficient subjects integrated 100% on our binocular integration tests.

The tests we have devised will therefore be useful for further work in which differences are to be assessed in accurate detail for depth perception in afflicted subjects with different etiologies. Most importantly, these tests will be able to accurately assess how effective corrective treatments for stereo deficiencies are when such treatments are administered at various times during development. Such work will establish the critical periods not only for stereopsis but also for binocular integration. The critical periods for these two capacities may well be different in time and in duration.

It is estimated that 5 to 10% of the population in the United States is stereoblind [30]. Most commonly deficits in or a total loss of stereopsis are long-standing, often brought about by amblyopic and strabismic conditions that were present already at birth or have arisen quite early in life. However, the inability to process disparity can also arise later in life due to a variety of factors, such as the partial or complete loss of vision in one eye, brain infarcts and accidents to the oculomotor system that result in the misalignment of the two eyes producing deficits in conjugate and vergence eye movements. Such deficits often arise due to accidents and war injuries. Detailed testing of individuals who have lost stereoscopic depth perception due to accidents and injuries sustained in combat is central for the assessment of improvement in depth perception during rehabilitation.

The prime source of stereo blindness and stereo deficiency is amblyopia and strabismus, which most commonly appears early in life. Numerous publications have examined the consequences of these two deficiencies and procedures to correct them [31-37]. Most of these studies have concentrated on differences in acuity between the two eyes and in how treatment procedures can improve acuity; a fraction of these studies have also examined stereoscopic depth perception [36,38-40].

Several methods have been used to assess stereopsis [1,2,4,30,40,41]. Although variations of stereograms are used commercially (Titmus stereo test, TNO stereo test), these require the use of polarizing glasses. Some disadvantages for using these glasses are: The first is that when the displays are presented on a monitor, the inputs to the two eyes are presented in successive frames thereby reducing the frame rate to each eye by half. Thus if a 60 Hz monitor is used, as a result of the alternating frames to the left and right eyes, the frame rate becomes just 30 Hz. This reduces the effectiveness with which motion information can be analyzed, especially for motion parallax. Another shortcoming of the polarizing system is that the processing of wavelength information is compromised. Most notable is the fact that there is more cross-talk, or bleeding as some call it, at short wavelengths. Also, discomfort for the subject, such as subjects who are color-blind, already wear corrective glasses, and report headaches for those who move their heads while wearing these glasses. Using a stereoscope circumvents these problems.

Furthermore, stereoscopic presentations work extremely well in experiments performed on monkeys whose visual system is similar to that of humans, the results of which have provided important information about depth processing in the visual system. DeAngelis and Uka [41] used random-dot stereograms to show that 93% of MT neurons are selective for horizontal disparity. In previous studies [24,25,42], various depth cues have been identified in area V4 and MT.

Another method that has been used to assess stereoscopic depth perception is to test subjects using autostereograms. While this mode of presentation for assessing stereopsis is quite popular as evidenced by the success of the *Magic Eye* books, the problem is that many individuals who cannot see the three-dimensional displays actually turn out to have normal stereoscopic vision. They do not see the displays because they lack adequate control to converge or diverge their eyes which is necessary for perceiving depth in autostereograms [43]. This seems to be especially the case in children. Autostereograms are also ill-suited for the presentation of dynamic displays designed to assess motion and motion parallax.

Stereopsis and motion parallax have been studied in normal and stereoblind and stereo deficient subjects by several investigators using methods different from the ones we devised. Richards [44,45], Richards & Lieberman [46], van Ee & Richards [47], van Ee [48] tested MIT students with devised planar and volumetric tests using polarized glasses to test for stereopsis, degree of disparity, as well as motion parallax of 2-D dots corresponding to the vertices in 3-D shapes and categorized subjects with stereo abilities to cross, uncross, or zero vision. Rogers & Graham [28,49] devised a random dot stereogram that can be seen through an oscilloscope to test for threshold sensitivities of observers' moving heads.

Our finding is in agreement with Melmoth et al. [50] and Suttle et al. [51] who used entirely different procedures to assess latencies showing that stereoblind and stereo deficient subjects had longer response latencies on the motion parallax test that did normal subjects. Melmoth tested normal subjects under binocular and monocular conditions and determined that subjects are slower under monocular conditions; Suttle measured slower eye-hand coordination timing with amblyopic children than in normal children.

Given the relatively high incidence of stereo blindness, which in the majority of cases is due to amblyopia and strabismus that occurs early in life, developing procedures to reinstate stereopsis is a major task. Evidence obtained in research on both humans and animals has established that there is an early critical period before which corrective measures need to be taken to succeed in reinstating stereopsis. What the time is during development and what the duration is of the critical period has been open to debate [30,32,52,53].

The tests we report here will be useful in future work for the assessment of depth perception in normal and afflicted individuals. Particularly important will be to determine at what stage of development treatment procedures for amblyopia and strabismus can be effective in reinstating stereopsis. We believe that our tests are well-suited for the reliable and accurate assessment for not only stereopsis, but also for assessing motion parallax, hand-eye coordination and binocular integration. Another important future task will be to determine where in the brain of normal and treated individuals stereopsis and motion parallax are processed and how the brain is organized in individuals who have been successfully treated and those who have not been treated. We are presently pursuing this kind of work using fMRI imaging, the results of which we plan to publish in the near future. One of the areas involved in the processing of both disparity and motion parallax cues for depth perception is the middle temporal area (MT) which has been established in both normal human and in monkey subjects using single-cell recording methods as well as fMRI mapping procedures [4,8,9,16,17,41,54].

Readers interested in obtaining detailed information about the equipment and the computer programs we used in this study are encouraged to contact us.

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References

1. Howard IP (2002) Seeing in depth. In: Basic Mechanisms, Vol 1. Porteous Publishing, Thornhill, ONT.
2. Howard IP, Rogers BJ (2002) Seeing in depth. In: Depth Perception, Vol 2. Porteous Publishing, Thornhill, ONT.
3. Poggio GF, Poggio T (1984) The analysis of stereopsis. Annu Rev Neurosci 7: 379-412.
4. Cumming BG, DeAngelis GC (2001) The physiology of stereopsis. Annu Rev Neurosci 24: 203-238.
5. Pettigrew J (1978) Stereoscopic visual processing. Nature 273: 9-11.
6. Parker AJ, Cumming BG (2001) Cortical mechanisms of binocular stereoscopic vision. Prog Brain Res 134: 205-216.
7. Bradshaw MF, Parton AD, Eagle RA (1998) The interaction of binocular disparity and motion parallax in determining perceived depth and perceived size. Perception 27: 1317-1331.
8. DeAngelis GC, Ohzawa I, Freeman RD (1991) Depth is encoded in the visual cortex by a specialized receptive field structure. Nature 352: 156-159.
9. Chowdhury SA, DeAngelis GC (2008) Fine discrimination training alters the causal contribution of macaque area MT to depth perception. Neuron 60: 367-377.
10. Harris JM, McKee SP, Smallman HS (1997) Fine-scale processing in human binocular stereopsis. J Opt Soc Am A Opt Image Sci Vis 14: 1673-1683.
11. Roy JP, Komatsu H, Wurtz RH (1992) Disparity sensitivity of neurons in monkey extrastriate area MST. J Neurosci 12: 2478-2492.
12. Cao A, Schiller PH (2003) Neural responses to relative speed in the primary visual cortex of rhesus monkey. Vis Neurosci 20: 77-84.
13. Zhang Y, Weiner VS, Slocum WM, Schiller PH (2007) Depth from shading and disparity in humans and monkeys. Vis Neurosci 24: 207-215.
14. Nefs HT, O'Hare L, Harris JM (2010) Two independent mechanisms for motion-in-depth perception: evidence from individual differences. Front Psychol 1: 155.
15. Roe AW, Parker AJ, Born RT, DeAngelis GC (2007) Disparity channels in early vision. J Neurosci 27: 11820-11831.
16. Born RT, Bradley DC (2005) Structure and function of visual area MT. Annu Rev Neurosci 28: 157-189.
17. DeAngelis GC, Cumming BG, Newsome WT (1998) Cortical area MT and the perception of stereoscopic depth. Nature 394: 677-680.
18. Freeman RD (1999) Stereoscopic vision: Which parts of the brain are involved? Curr Biol 9: R610-613.
19. Nadler JW, Angelaki DE, DeAngelis GC (2008) A neural representation of depth from motion parallax in macaque visual cortex. Nature 452: 642-645.
20. Xiao DK, Marcar VL, Raiguel SE, Orban GA (1997) Selectivity of macaque MT/V5 neurons for surface orientation in depth specified by motion. Eur J Neurosci 9: 956-964.
21. Kontsevich LL, Tyler CW (2000) Relative contributions of sustained and transient pathways to human stereoprocessing. Vision Res 40: 3245-3255.
22. Mikami A, Newsome WT, Wurtz RH (1986) Motion selectivity in macaque visual cortex. II. Spatiotemporal range of directional interactions in MT and V1. J Neurophysiol 55: 1328-1339.
23. Cao A, Schiller PH (2002) Behavioral assessment of motion parallax and stereopsis as depth cues in rhesus monkeys. Vision Res 42: 1953-1961.
24. Schiller PH, Slocum WM, Jao B, Weiner VS (2011) The integration of disparity, shading and motion parallax cues for depth perception in humans and monkeys. Brain Res 1377: 67-77.
25. Schiller PH, Carvey CE (2006) Demonstrations of spatiotemporal integration and what they tell us about the visual system. Perception 35: 1521-1555.
26. Schiller PH, Slocum WM, Weiner VS (2007) How the parallel channels of the retina contribute to depth processing. Eur J Neurosci 26: 1307-1321.
27. Julesz B (1960) Computer aid in producing double-image random dot stereograms. Bell System Technical Journal 39: 1125-1162.
28. Rogers B, Graham M (1982) Similarities between motion parallax and stereopsis in human depth perception. Vision Res 22: 261-270.
29. Zhang Y, Schiller PH (2008) The effect of overall stimulus velocity on motion parallax. Vis Neurosci 25: 3-15.
30. Sekuler R, Blake R (1994) Perception. McGraw-Hill, New York.
31. Bacal DA (2004) Amblyopia treatment studies. Curr Opin Ophthalmol 15: 432-436.
32. Hess RF, Mansouri B, Thompson B (2010) A new binocular approach to the treatment of amblyopia in adults well beyond the critical period of visual development. Restor Neurol Neurosci 28: 793-802.

33. Moseley MJ, Fielder AR, Stewart CE (2009) The optical treatment of amblyopia. Optom Vis Sci 86: 629-633.
34. Rutstein RP, Fuhr PS (1992) Efficacy and stability of amblyopia therapy. Optom Vis Sci 69: 747-754.
35. Scott WE, Kutschke PJ, Keech RV, Pfeifer WL, Nichols B, et al. (2005) Amblyopia treatment outcomes. J Aapos 9: 107-111.
36. Spierer A, Raz J, Benezra O, Herzog R, Cohen E, et al. (2010) Treating amblyopia with liquid crystal glasses: a pilot study. Invest Ophthalmol Vis Sci 51: 3395-3398.
37. Wallace DK, Chandler DL, Beck RW, Arnold RW, Bacal DA, et al. (2007) Treatment of bilateral refractive amblyopia in children three to less than 10 years of age. Am J Ophthalmol 144: 487-496.
38. Kani W (1978) Stereopsis and spatial perception in amblyopes and uncorrected ametropes. Br J Ophthalmol 62: 756-762.
39. Rowe FJ (2000) Long-term postoperative stability in infantile esotropia. Strabismus 8: 3-13.
40. Shotton K, Elliott S (2008) Interventions for strabismic amblyopia. Cochrane Database Syst Rev CD006461.
41. DeAngelis GC, Uka T (2003) Coding of horizontal disparity and velocity by MT neurons in the alert macaque. J Neurophysiol 89: 1094-1111.
42. Schiller PH (1993) The effects of V4 and middle temporal (MT) area lesions on visual performance in the rhesus monkey. Vis Neurosci 10: 717-746.
43. Wilmer JB, Backus BT (2008) Self-reported Magic Eye stereogram skill predicts stereoacuity. Perception 37: 1297-1300.
44. Richards W (1970) Stereopsis and stereoblindness. Exp Brain Res 10: 380-388.
45. Richards W (1971) Anomalous stereoscopic depth perception. J Opt Soc Am 61: 410-414.
46. Richards W, Lieberman HR (1985) Correlation between stereo ability and the recovery of structure-from-motion. Am J Optom Physiol Opt 62: 111-118.
47. van Ee R, Richards W (2002) A planar and a volumetric test for stereoanomaly. Perception 31: 51-64.
48. van Ee R (2003) Correlation between stereoanomaly and perceived depth when disparity and motion interact in binocular matching. Perception 32: 67-84.
49. Rogers B, Graham M (1979) Motion parallax as an independent cue for depth perception. Perception 8: 125-134.
50. Melmoth DR, Finlay AL, Morgan MJ, Grant S (2009) Grasping deficits and adaptations in adults with stereo vision losses. Invest Ophthalmol Vis Sci 50: 3711-3720.
51. Suttle CM, Melmoth DR, Finlay AL, Sloper JJ, Grant S (2011) Eye-hand coordination skills in children with and without amblyopia. Invest Ophthalmol Vis Sci 52: 1851-1864.
52. Fawcett SL, Wang YZ, Birch EE (2005) The critical period for susceptibility of human stereopsis. Invest Ophthalmol Vis Sci 46: 521-525.
53. Marg E (1982) Prentice-Memorial Lecture: Is the animal model for stimulus deprivation amblyopia in children valid or useful? Am J Optom Physiol Opt 59: 451-464.
54. Rokers B, Cormack LK, Huk AC (2009) Disparity- and velocity-based signals for three-dimensional motion perception in human MT+. Nat Neurosci 12: 1050-1055.