A Robust and Reliable Test to Measure Stereopsis in the Clinic

Robert F. Hess,[1] Rifeng Ding,[1] Simon Clavagnier,[1] Catherine Liu,[1] Cindy Guo,[2] Catherine Viner,[3] Brendan T. Barrett,[3] Krupali Radia,[3] and Jiawei Zhou[1]

[1]McGill Vision Research, Department of Ophthalmology, McGill University, Montreal, Quebec, Canada
[2]Department of Vision Science and Optometry, University of Auckland, Auckland, New Zealand
[3]School of Optometry and Vision Science, University of Bradford, Bradford, United Kingdom

Correspondence: Robert F. Hess, McGill Vision Research, Montreal General Hospital, 1650 Avenue Cedar, L11.403, Montreal, Quebec H3G 1A4, Canada;
robert.hess@mcgill.ca.
Jiawei Zhou, McGill Vision Research, Montreal General Hospital, 1650 Avenue Cedar, L11.403, Montreal, Quebec H3G 1A4, Canada;
jiawei.zhou@mcgill.ca.

PURPOSE. The purpose of this study was to develop a convenient test of stereopsis in the clinic that is both robust and reliable and capable of providing a measure of variability necessary to make valid comparisons between measurements obtained at different occasions or under different conditions.

METHODS. Stereo acuity was measured based on principles derived from the laboratory measurement of stereopsis (i.e., staircase method). Potential premeasurement compensations are described if there is a significant degree of ocular misalignment, reduced visual acuity, or aniseikonia. Forty-six adults at McGill University, 44 adults at Auckland University, and 51 adults from the University of Bradford, with an age range of 20 to 65 years old and normal or corrected-to-normal vision participated in this study.

RESULTS. Stereo acuity within this normal population was widely distributed, with a significant percentage (28%) of the population with only coarse stereo (>300 arc seconds). Across subjects, the SD was approximately 25% of the mean. Measurements at two different times were strongly ($r = 0.79$) and significantly ($P < 0.001$) correlated, with little to no significant ($P = 0.79$) bias (0.01) between test and retest measures of stereopsis.

CONCLUSIONS. The application enables measurements over the wide disparity range and not just at the finest disparities. In addition, it allows changes in stereopsis of the order of 1.9 to be statistically distinguished.

Keywords: clinic, stereoacuity, iPod

The primate visual system derives considerable benefit from the overlapping visual fields of the two eyes as a consequence of front facing eyes. Binocular vision in general and stereopsis in particular are fundamental to human vision and visual actions. When binocularity is disrupted early in life due to a strabismus, anisometropia, or a monocular opacity or ptosis, vision can be compromised in the affected eye and stereopsis lost.[1] Hand–eye coordination is disrupted,[2-5] and self-esteem,[6] life style,[7] and career choices are greatly affected. A number of modern approaches to amblyopia therapy set out to restore binocular function as a top priority,[8-16] and their primary outcome measure is ideally binocular fusion and stereopsis rather than monocular acuity. Although these new therapies, unlike the more traditional patching, have been shown to be effective in adults[9-12,14-16] and children,[8,9,13] there is no reliable way to document these changes in stereoscopic performance clinically. The overall goal of this study was to provide a reliable and convenient method with which stereo could be measured in the clinic.

At present, there are no tests for stereopsis that are robust in terms of being able to adequately sample a wide disparity range[17] and provide a measure of measurement variability.[18] The present book tests were primarily designed for children,[19] and they are coarsely quantized, only involve disparity increments, and have a restricted range (20–800 arc seconds). They are certainly adequate for screening, but because each disparity level is often presented only once, they can not provide any measure of variability, something that is needed to address the significance of a change in stereo performance of a clinical population as a result of an intervention, for example, a clinical trial. What we do know is that the test–retest reliability of the present book tests is such that a factor of 4 in stereopsis has to occur for an individual for it to be classified as significant.[18] However, the individual test–retest reliability is a crude way for assessing changes in performance at an individual level because it derives its estimate of variability from population statistics and not the actual variability associated with an individual measurement. To provide a more accurate statistical evaluation of whether two means are different, the iPod stereo test described here, unlike the current clinical book tests, supplies a measure of the variability associated with each measurement.

Here, we describe a new clinically convenient method of measuring stereopsis in adults using a handheld device. This random dot stereo test is accurate, being based on a standard psychophysical procedure; it provides a measure of variability because multiple trials are presented at each disparity; and it allows a wider disparity range to be tested without quantization. We demonstrate its use in three vision departments: one ophthalmological and two optometric. We show that, in the normal population, stereoscopic function is widely distributed, with a significant percentage of the population with only
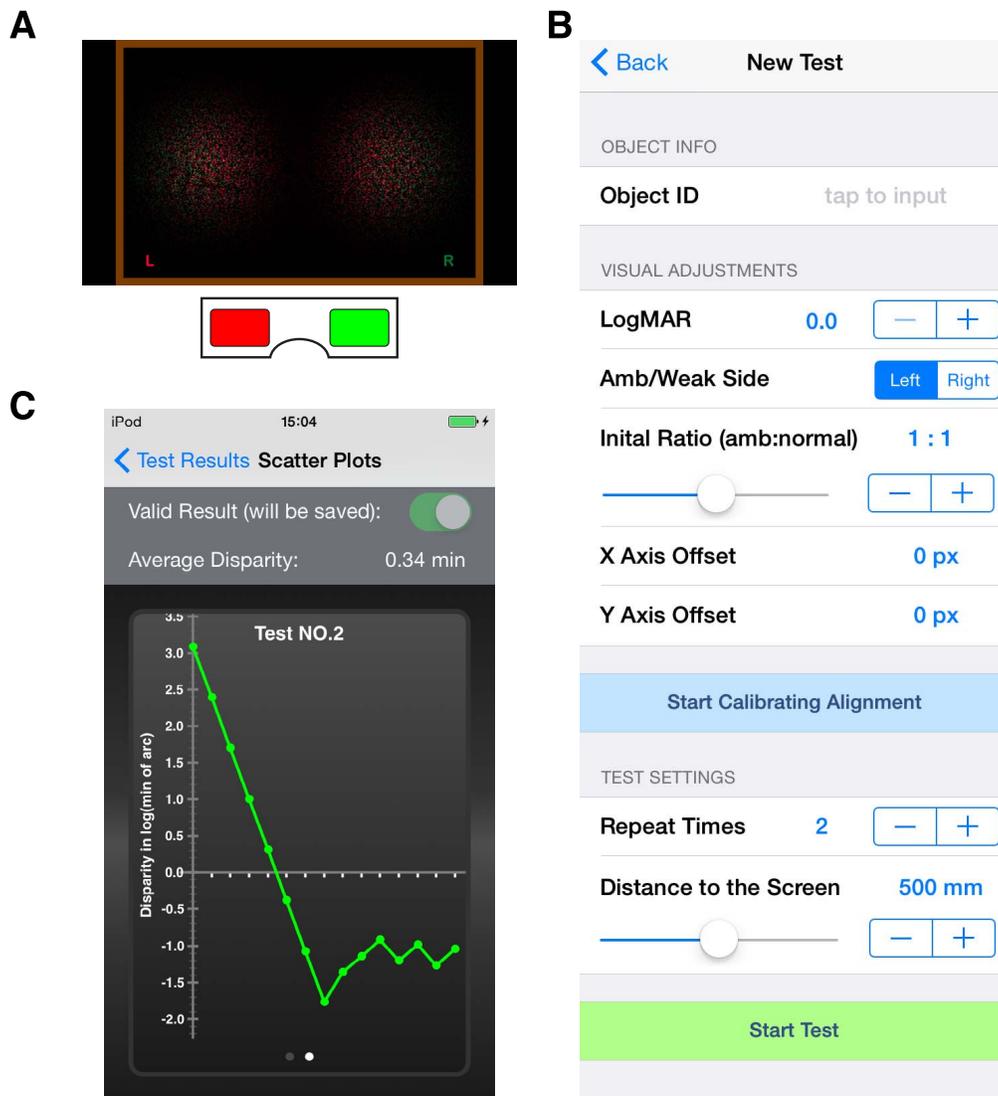
FIGURE 1. Illustration of the Stereogram Test app. (**A**) The 3D stimuli. Observers were asked to answer which disk was behind the screen by taping its position. (**B**) The test settings. (**C**) An example of the results from one staircase estimate.

coarse stereo. This corroborates the findings of an earlier study with a larger sample size using a different but comparable web-based approach.[20] We point out two caveats with regard to the clinical measurement of stereopsis: one being unequal acuity in the two eyes, something well recognized within the clinical fraternity,[21] and the other being unequal image size in the two eyes, something often neglected. We provide a measure of the influence of each of these commonly occurring factors. A compensation for aniseikonia is inbuilt into the current test so that a measure of stereo capability can be obtained that is not contaminated by images size differences due to spectacle-corrected anisometropia.

METHODS

Observers

Forty-six adults at McGill University, 44 adults at Auckland University, and 51 adults from the University of Bradford, with normal or corrected-to-normal (0 logMAR or better) monocular vision participated in this study. The subjects were either staff (clinicians or ancillary) or students at each eye center, and the age range was wide (20–65 years old). An informed consent form was obtained prior to the study, which was approved by the Institutional Review Board of McGill University, the Institutional Review Board of Auckland University, and the Institutional Review Board of the University of Bradford. The described research adhered to the tenets of the Declaration of Helsinki. Except the authors, all subjects were naive to the purpose of this study.

Apparatus and Stimulus

The measurement was conducted by a Mac iPod (model A1367; Apple, Inc., Cupertiono, CA, USA) running the Stereogram Test app, an in-house software for Apple's mobile operating system (IOS) devices that feature 326 pixels per inch (ppi) retina displays (background luminance was zero; i.e., black). The app software was written in Objective-C using the IOS software development kit combined with OpenGL ES 2.0. Observers viewed the stimuli dichoptically through red–green anaglyph glasses at a viewing distance of 50 cm in an environment with normal interior lighting.

Stimuli were two side-by-side static random-dot disks on a dark background, as shown in Figure 1A. The disks were
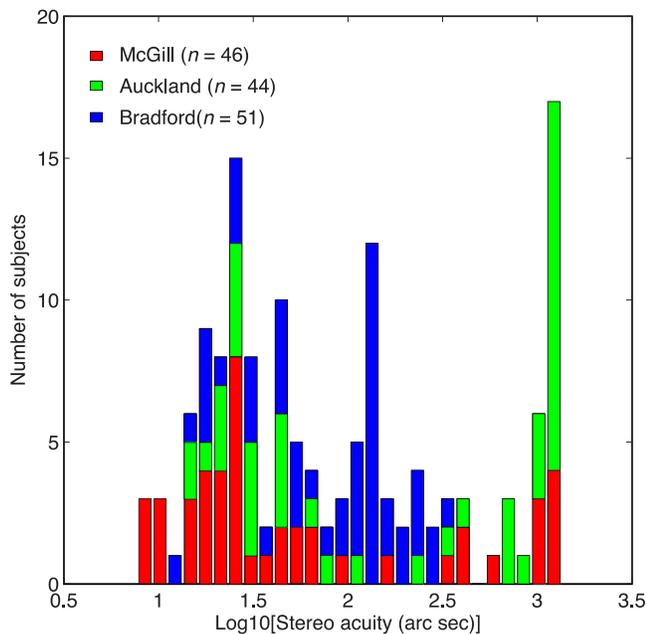
FIGURE 2. Distributions of stereo acuity for 141 normal adults from three clinical testing sites: McGill Ophthalmology ($n = 46$), Auckland Optometry ($n = 44$), and Bradford Optometry ($n = 51$).

Gaussian-windowed to blend the edge to the background. Each disk contained randomly positioned red and green dots, which had a certain offset to generate depth perception (i.e., disparity). Overlapped red and green dots (or overlapped parts of dots, determined by the size of the dots) were blended into an orange color by using the blending functions provided by OpenGL ES to provide subpixel resolution.

The offsets between red and green dots were equal and opposite in the two disks; thus, one of the two disks would be perceived as in front of the screen plane and the other behind the screen plane. In each trial, the observers' task was to tap the disk that was perceived to be behind the screen plane. There was no time limit for responding, as the next trial came immediately after the observers' response.

Procedure

Observers were asked to finish a 10-trial practice before the test. After that, a 5-minute test session, incorporating two separate runs, was used to estimate individuals' stereo thresholds. Each run was driven by a staircase procedure in which the initial offset between red and green dots was set to 40 pixels (corresponding to a stereo acuity of 21.79 arc minutes) and was controlled by a two-down/one-up staircase procedure thereafter. The initial step size was 50%, which changed after the first reversal to 10% in all following trials. Because all of our participants were normal adults, we artificially set the maximal offset between red and green dots to 40 pixels to ensure that it was less than D_{max} (which was approximately 10^4 arc seconds).[22] The staircase was terminated at the fourth reversal point. The stereo threshold and its SE and SD were then calculated based on the last three reversals averaged across in the two test runs (i.e., six reversals in total).

Potential Test Configuration

As shown in Figure 1B, the following configurable parameters were provided in the Stereogram Test app:

1. Visual acuity of the worse eye: This was recorded in logMAR (near distance 50 cm) on the iPod, and a nomogram was provided to estimate what loss in stereo was expected based on the acuity of the worse eye. To assess the effects of lens blur on stereo using this test, two subjects viewed the iPod test with add-on lenses in front of the right eye (2.50–3.00 diopters [D]), which, accounting for the testing distance of 50 cm (i.e., 2.00 D), resulted in a lens blur of between 0.50 and 1.00 D.
2. Aniseikonia: To account for an image size difference due, for example, to spectacle-corrected anisometropia, the size of the pixels could be scaled in front of the more emmetropic eye. A second program was incorporated within this app to measure the degree of aniseikonia. To assess the potential impact of aniseikonia, two subjects undertook the stereo test in which the pixels in one eye's view were scaled in the region of 0% to 20%.
3. Visual alignment: In case of ocular misalignment (e.g., strabismus), an alignment calibration feature can be implemented to allow fusion of the two eyes' images. During the alignment, two half-crosses (one in red and the other one in green) were dichoptically presented to the two eyes. Observers can be asked to align the two half-cross into a perfect whole cross. The degree to which the alignment was stable from run to run can be then assessed, as the alignment offset is provided to the examiner.
4. Repeat times: Participants were allowed to repeat individual test runs in a test session if the staircase results was clearly of an anomalous form indicative of a poor determination as the result of, for example, an early response mistake (finger error).

All the subjects tested in this study had normal visual acuity in each eye, no aniseikonia, and no misalignment of the eyes. These features are described so that the implementation of this test within a clinical population can be assessed.

Result Transformation

As shown in Figure 1C, a plot of disparity as a function of trial number is provided for each test run on completion of the test. The disparity was recorded in pixels during the measurement and was transferred into minute of arc by using the following equation:

$$Disparity = \frac{\tan^{-1}\left(\frac{n \times W_{pixel}}{D}\right)}{\pi} \times 180 \times 60 \, arc \text{ minutes,}$$

where n is the offsets between the red and green dots (in pixels), W_{pixel} is the physical width of a pixel on the display, and D is the distance between the subject's eyes and device's display. In our study, W_{pixel} was 0.0792 mm and D was 500 mm.

RESULTS

The basic result is seen in Figure 2 where we have plotted the results across the three institutions as a bar graph showing the distribution of stereopsis (log seconds of arc) in the normal population sample. The results are not normally distributed,[23] and it is clear that the distribution is broad. Some subjects have relatively good stereo, and others have relatively poor stereo. Approximately 13% of our subjects reached the ceiling offset of 40 pixels (1307 arc seconds) as reflected in the histogram bar corresponding to the largest disparity. This was an order of magnitude below D_{max} for these stimulus conditions,[22] so we
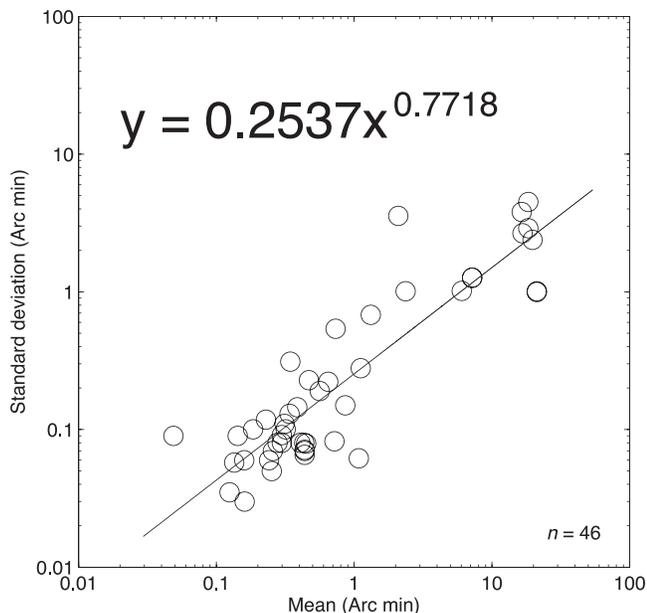
FIGURE 3. The relationship between the measurement means and their associated SD across the sample of subjects tested in McGill ($n = 46$).

conclude their stereo acuity was equal to or worse than this value. This confirms the broad distribution found in a previous study[20] of 600 normal subjects. Although both studies found a very broad range of stereopsis, the current approach provides more fine disparity responses consistent with its better resolution (the previous web-based approach was limited by pixel size).

Figure 3 shows the relationship between the measurement means (average from the two runs) and their associated SD that was only available for the sample of subjects tested at McGill ($n = 46$). The best fitting line on these log/log axes is close to unity (0.7718), suggesting the SD scales with the mean, as expected from our staircase procedure where a relative step size was used. The scaling factor is 0.2537 (the SD = 0.2537 × mean) for the particular staircase parameters used here. What this means is that, given the extent of the measurement variability, two measurement means would be significantly different if they were a factor of 1.9 apart. This was calculated

in the following way. Suppose in one test we find that the threshold is Mean1 and the standard deviation SD1 equals 0.2537 × Mean1 and in a second test we get threshold Mean2, which is δ × Mean1 ($\delta > 1$) and a standard deviation SD2 of 0.2537 × δ × Mean1. To be able to confidently say (i.e., $P < 0.05$) that the threshold in the second test is larger than that found in the first one test, the Z-score between these two tests, which is (Mean2 − Mean1)/sqrt(SD1² + SD2²) or rewritten as (δ − 1)/0.2537/sqrt(1 + δ^2), should be larger than 1.65. This will give us a δ of at least 1.9.

To assess the test–retest reliability, 90 of the subjects were retested across the three locations. In Figure 4A, the stereo measurements of the first test (again the average of two runs) are plotted against those of the retest (the average of two runs). There is a strong ($r = 0.79$) and significant ($P < 0.001$) correlation. In Figure 4B, the reliability is assessed in terms of a Bland-Altman plot with little to no bias between the two measurements (0.01) and no significant difference ($P = 0.79$, 2-tailed paired t-test) between test and retest. The mean absolute difference and 95% confidence interval was 0.01 ± 0.7 log arc seconds.

Reduced Acuity and Stereo

An important issue in clinical stereo testing is the influence of reduced vision, particularly reduced monocular vision.[21,22,24] Patients may have reduced vision in just one eye, such as amblyopes, for whom stereo performance is of particular importance, and it is essential to know to what extent any reduction in stereo performance is simply due to a monocular loss of acuity. There is no way of factoring out such an acuity-based stereo loss by altering the stimulus seen by the other eye,[24] but it is possible to measure the extent of such a dependence and thereby know if the loss of stereopsis is of a magnitude that would be consistent with the loss of acuity. Figure 5B shows the effect of a monocular reduction in acuity (due to lens blur) on stereo performance. Lens defocus of up to 3.00 D was used, and it was verified that this did not produce a measurable degree of aniseikonia (using the test within the app). The solid sloping line is the best fitting line assuming that normal stereopsis is around 6 arc seconds and that normal acuity is 0 in logMAR (i.e., coordinate [0, 0.1]). Results are shown for two normal subjects. The slope of the line of best fit suggests that for every 0.1 logMAR acuity reduction, there is a 36% loss in stereopsis. Although this was measured for the case of monocular acuity loss, it is just as applicable to the case of bilateral acuity loss.[24]
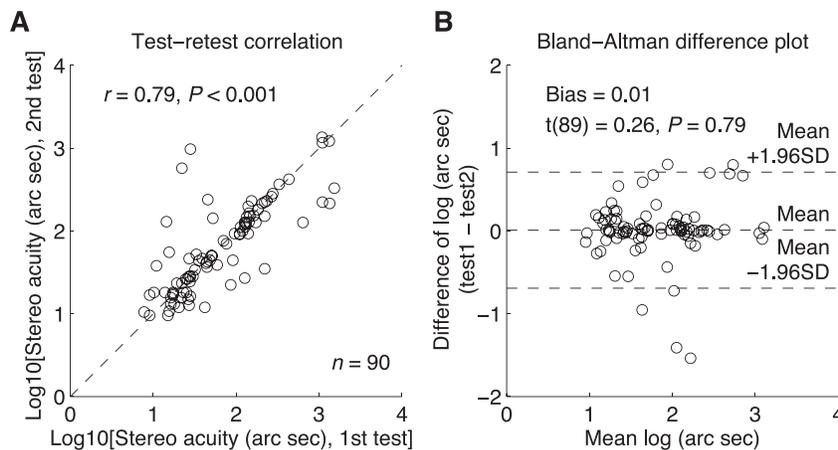

FIGURE 4. Test–retest reliability. (A) Test–retest correlation. Each dot represents results of one subject; the *dashed line* indicates the identity line (slope = 1). Results in the two tests are significantly correlated ($r = 0.79$, $P < 0.001$). (B) Bland-Altman difference plot. The mean difference between the two measures (i.e., the bias), indicated by the *central black dashed line*, is 0.01.
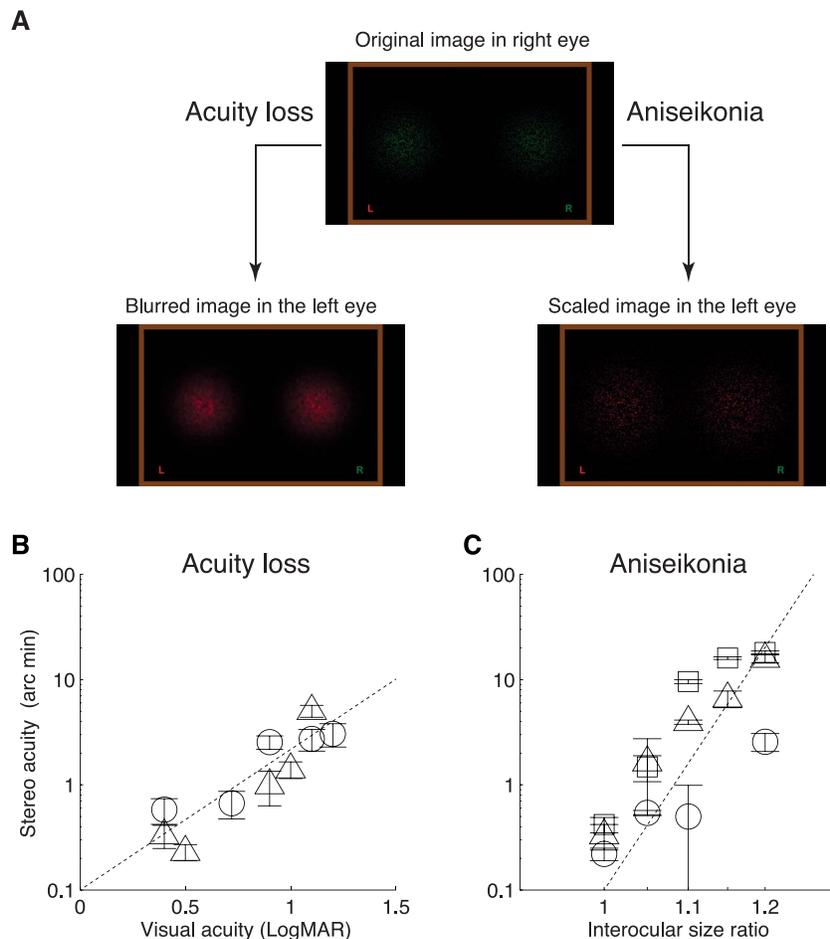
A

Original image in right eye

Acuity loss   Aniseikonia

Blurred image in the left eye   Scaled image in the left eye

B Acuity loss

C Aniseikonia

FIGURE 5. Effect of monocular size scaling and blur on the stereo acuity. (**A**) Illustration of the two conditions in clinical testing: monocular acuity loss and simulated anseikonia. (**B**) Stereo acuity as a function of the visual acuity in the blurred eye. *Different symbols* represent results of two subjects. *Error bars* denote SEM. The best fitting line suggests that for every 0.1 logMAR acuity reduction, there is a 36% loss in stereopsis. The largest defocus lens was 2 D, for which the measured degree of aniseikonia was less than 0.5% and would not have produced a significant loss of stereo (see **C**). (**C**) Stereo acuity as a function of the interocular size ratio. *Different symbols* represent results of three subjects. *Error bars* denote SEM. The slope of this line suggests that every 1% difference in image size between the eyes results in a 33% loss of stereopsis.

Aniseikonia and Stereo

Another issue relevant to stereopsis, and one that is rarely considered, is aniseikonia, resulting from anisometropia corrected with spectacles. It is generally accepted that stereopsis requires matched images in the two eyes and that if the retinal image size difference is too large, stereopsis will suffer. However, image size differences between the eyes are rarely measured, and their effects are rarely considered as a cause of any measured stereo loss. This is an important issue because aniseikonia rather than amblyopia may ultimately limit the extent of benefit that can be obtained from binocular therapy. We incorporated a method by which the interocular image size can be measured, and the pixel display seen by the more emmetropic eye can be adjusted to ensure any such image size changes are factored out of the stereo assessment (Figure 5A). Figure 5C illustrates the relationship between stereo performance and aniseikonia (produced by scaling the size of pixels seen by one eye) for three subjects. The sloping line is the best fitting line assuming normal stereo of 6 arc seconds for images of the same interocular size, (i.e., cross the point [1, 0.1]). The slope of this line suggests that every 1% difference in image size between the eyes results in a 33% loss of stereopsis. This purely optical loss can be completely compensated for in the current test by scaling the pixel size in

the more emmetropic eye, thus permitting valid measurements of stereopsis per se.

DISCUSSION

There is a need for a convenient way to measure stereopsis in the clinic, one that supplies a measure of variability so that valid comparisons can be made between measurements on different occasions and under different conditions for individuals or, in the case of clinical trials, for populations. Here we describe a fast (40–60 trials, taking approximately 3 minutes), convenient, and reliable method using a handheld device based on firmly established laboratory principles offering a compromise between laboratory accuracy and clinical utility. The random dot stimulus offers the best way of ensuring that figural effects are not involved. The two alternative forced choice decision is based on the sign of the disparity that ensures the dipolar aspect of stereo processing is respected, and the staircase measurement method allows one to obtain a sound measure of threshold and its variability. Equally important is the ability to measure over the full disparity range and not just at the finest disparities, because as we demonstrate here and elsewhere[20] that there is a wide range of stereo acuities in the general population. Our staircase algorithm in the adult population gives an SD that is

approximately 25% of the mean, allowing a change in stereopsis of the order of 1.9 to be statistically distinguished for individual measurements across the whole range. This can be improved especially in the coarse disparity range by using a staircase with more trials and a smaller step size; however, this will mean that the measurement will take longer, which may impact on its clinical utility. Knowing the variance associated with individual measurements (i.e., a measure of individual precision) is more valid when comparing individual measurements than relying on the confidence limits derived from a population measure such as the test-retest analysis (i.e., a measure of population precision). Neither measure is appropriate for comparing whether the mean stereo of a population has changed, for example, as the result of a particular therapy.[25] In that case the distribution of the difference between the means before and after the treatment is important.

The test also offers the clinician the opportunity of measuring stereopsis without contamination from image size differences. Because this factor will affect stereo performance, it is essential that its effect be compensated for so that valid estimates of stereo per se can be obtained. This can be done by altering the dimensions of each pixel in the stereo display. Although the effect of reduced monocular or binocular acuity can also negatively impact stereo performance, there is no way to compensate physically for this by adjusting the stereo stimulus. As a consequence, the size of this acuity-based loss can be estimated so that its possible influence can be gauged, allowing stereo losses that are much larger than the estimated acuity-based losses to be considered as primary deficits to binocular function per se. We assume that the low-pass effects of defocus adequately simulate the contrast sensitivity loss found in amblyopia.[26,27]

Interestingly, the subjects tested across three vision departments did display a broad distribution, suggesting that a substantial percentage of the population does not have fine stereopsis. All subjects were wearing their current spectacle prescription, so we cannot explain this broad stereo distribution on the basis of uncorrected refractive errors or indeed undetected ocular anomalies. Furthermore, it is consistent with a number of previous studies. Richards,[28,29] using a similar crossed versus uncrossed discrimination task, estimated that as much as 30% of the normal population are stereo-anomalous for this task. Hess et al.,[20] using a more abbreviated methodology (web-based, self-supervised) but on a much larger (600) sample, found a similar large distribution of normal stereo performance in the normal population. This suggests it is a real effect: one that is consistent with the authors' experience of the difficulty of finding controls within the general population with stereo acuity that is good enough to participate in laboratory studies. However, it should be noted that it is not consistent with population studies[19] using the current stereo tests that rely on a single directional depth increment to define a particular shape. This more primitive task does not utilize the unique bipolar nature of primate stereo processing where separate populations of neurons are tuned to near and far disparities.[30] In fact, these two different approaches to measuring stereopsis might not only rely on different neuronal populations but also possibly different cortical areas; the unipolar task that is currently used essentially involves the discrimination of an absolute disparity, whereas the bipolar nature of the current task involves relative disparities. The former has been identified as occurring in area V1 and the latter in area V2 and beyond.[31]

Acknowledgments

Disclosure: **R.F. Hess**, None; **R. Ding**, None; **S. Clavagnier**, None; **C. Liu**, None; **C. Guo**, None; **C. Viner**, None; **B.T. Barrett**, None; **K. Radia**, None; **J. Zhou**, None

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