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ORIGINAL ARTICLE

Differences in stereoacuity between crossed and uncrossed disparities reduce with practice

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Abstract

Introduction: Stereoacuity, like many forms of hyperacuity, improves with practice. We investigated the effects of repeated measurements over multiple visits on stereoacuity using two commonly utilised clinical stereotests, for both crossed and uncrossed disparity stimuli.

Methods: Participants were adults with normal binocular vision ($n = 17$) aged between 18 and 50 years. Stereoacuity was measured using the Randot and TNO stereotests on five separate occasions over a six week period. We utilised both crossed and uncrossed stimuli to separately evaluate stereoacuity in both disparity directions. A subset of the subject group also completed a further five visits over an additional six week period. Threshold stereoacuity was determined by the lowest disparity level at which the subjects could correctly identify both the position and disparity direction (crossed or uncrossed) of the stimulus. Data were analysed by repeated measures analysis of variance.

Results: Stereoacuity for crossed and uncrossed stimuli improved significantly across the first five visits ($F_{1,21} = 4.24$, $p = 0.05$). The main effect of disparity direction on stereoacuity was not significant ($F_1 = 0.02$, $p = 0.91$). However, a significant interaction between disparity direction and stereotest was identified ($F_1 = 7.92$, $p = 0.01$).

Conclusions: Stereoacuity measured with both the TNO and Randot stereotests improved significantly over the course of five repetitions. Although differences between crossed and uncrossed stereoacuity were evident, they depended on the stereotest used and reduced or disappeared after repeated measurements. A single measure of stereoacuity is inadequate for properly evaluating adult stereopsis clinically.

KEYWORDS
crossed disparity, Randot, stereoacuity, stereopsis, TNO, uncrossed disparity

INTRODUCTION

Stereopsis is commonly measured in the clinic by eye care practitioners to assess the integrity of the binocular vision system.[1] The measurement of stereopsis is particularly ubiquitous in the examination of children where it is used to screen for binocular vision defects such as amblyopia, to aid with diagnosis and management of these conditions and to assess the effectiveness of therapeutic intervention.[2–4] The evaluation of stereopsis in adulthood can also be informative as to an individual's ability to perform motor skills satisfactorily.[5]

There is evidence suggesting that there are differences in the ability of individuals to extract stereoscopic depth from a visual scene depending on whether the disparity induced on the retina is crossed or uncrossed. Richards[10] proposed a mechanism for stereoscopic depth discrimination that involved distinct pools of cortical disparity detectors sensitive to crossed, uncrossed and on-fixation disparities, which gained traction thanks to similar theories and support from other early neurophysiological investigations.[11–15]

Blake and Wilson[16] summarised more contemporary thinking concerning the physiology of stereoscopic processing that a continuum of overlapping, multi-channel disparity tuned cells are responsible for the perceptual appreciation of depth in humans. Supportive evidence for this has been reported from psychophysical experiments, physiology and modelling.[17,18]

Superior stereoacuity using crossed disparity stimuli rather than uncrossed has been reported by several researchers,[19–23] although not universally.[18,24] Studies using infants have demonstrated that sensitivity to crossed disparity arises prior to uncrossed, supporting the idea that crossed and uncrossed stereopsis may be processed separately by the visual system.[25,26]

Richards[10] suggested that as many as 30% of individuals in the general population may be 'stereoanomalous', that is, less able to perceive stereoscopic depth in either the crossed or uncrossed direction, and postulated this was due to a lack of the relevant discrete disparity processors. Similarly, marked differences between individuals in their capacity to perceive stereoscopic depth were reported by Jones,[15] who described six cases of stereoanomaly in 30 subjects, and more recently by Hess et al.[27] who, using web-based random dot stimuli, reported that 32% of their participants had 'below normal' stereopsis and suggested this may be attributable to the model proposed by Richards.[10]

Nevertheless, the true proportion of adults that are stereoanomalous remains a matter of conjecture. It has also been suggested that brief stimulus presentations, as opposed to real neural deficiencies, may lead to an overestimation of the prevalence of stereoanomaly in adults, and thus, its true prevalence is significantly lower.[28–30]

The clinical significance of crossed and uncrossed disparity stimuli in adults remains ambiguous. Most studies that evaluated clinical stereoacuity presented stimuli in crossed disparity, presumably following the recommendations of the respective test manufacturers.[2,6,31,32] Potential differences in the ability of individuals to perceive crossed and uncrossed disparities may therefore limit the generalisation of results from such studies.

The large range and types of clinical stereotests available introduce additional variables which may impact findings.[33] Whether stereotest stimuli are based on local (contour) or global (such as random dot) features,[34–36] the presence or absence of monocular and binocular cues to depth,[37,38] the method of dissociation (such as the use of polarising or red-green anaglyph filters),[39,40] the levels of stereoacuity (the number, range and magnitude of disparity levels) assessed[41,42] and testing protocols[9,43] can all potentially influence measured stereoacuity values. Such differences between stereotests pose a problem for researchers and clinicians in determining the best stereotest to use when quantifying stereoacuity. Relatively poor agreement between individual measurements of stereoacuity across different clinical stereotests has been established.[43]

Key points

- Stereoacuity measured clinically with the TNO and Randot stereotests improves with repeated measurements, plateauing by the fifth visit.
- Differences in stereoacuity between crossed and uncrossed stimuli become negligible or disappear after a period of practice.
- Single clinical measures of stereoacuity are inadequate for evaluating an individual's stereoscopic capabilities.

Moreover, like other visual tasks such as motion discrimination,[44] luminance contrast detection,[45] texture discrimination[46] and other hyperacuity tasks such as Vernier acuity[47–49] and line orientation discrimination,[50] stereopsis can be improved through repeated practice over the course of hundreds and sometimes thousands of trials in psychophysical experiments.[51–55] Perceptual learning in stereoacuity occurs both with[56] and without[57] feedback on performance, although stronger learning effects occur when feedback is given.[58]

Establishing universally recognised, accurate normative stereoacuity values is crucial for clinicians to be able to judge whether an individual's stereoacuity is within the expected range, and to inform whether further investigation or treatment may be warranted. Many normative studies utilising clinical stereotests rely on a single measurement of stereoacuity from their participants.[6,8,59] If a practice effect on stereoacuity can be demonstrated clinically (without the need for hundreds of trials), such data may not be representative of a true normative range of stereoscopic ability.

The aims of this study were twofold. Firstly, to investigate differences between stereoacuity measured with crossed and uncrossed disparity stimuli using two different clinical stereotests. Secondly, to assess the impact of repeated measures on clinically measured stereoacuity.

METHODS

Subjects

Adult participants were recruited from the local student and staff population at the University of Huddersfield. Prior to testing, subjective refraction was performed on all

FIGURE 1 The left panel shows an example of one of the Randot Wirt circle targets mounted onto the presentation stand, whereas the right panel shows one of the TNO targets. The targets are shown without the respective polarised/anaglyph filters.

subjects to ensure the best possible near correction was worn during testing.

Subjects with visual acuity poorer than 0.00 LogMAR in either eye, those with an interocular visual acuity difference of more than 0.10 LogMAR or anisometropia of greater than 1.00D (calculated from the dioptric spherical equivalent for each eye) or with stereoacuity of less than 500 arc seconds (arc s) determined using the Randot test presented with either crossed or uncrossed disparity, were excluded. Subjects with manifest strabismus, poorly controlled heterophoria (determined subjectively) or suppression (complete or intermittent) were also excluded. All testing was conducted by the first author (RC), a registered optometrist.

Sample size and power calculations determined that a sample size of 15 would be sufficient to detect a moderate to high effect size ($\eta^2 = 0.1$) with five (repeated) measurements at 80% power and 95% confidence, using the software G*Power (Heinrich-Heine-Universität Düsseldorf, psychologie.hhu.de).[60] The sample size thus determined was comparable to another similar study.[24]

In total, 21 adult subjects were recruited between 18 and 50 years of age. Of these, four were excluded from the study at the first visit; two due to anisometropia of greater than 1.00D, one for reporting a history of patching and one for a poorly controlled near exophoria. A final total of 17 subjects completed the study. Each subject attended for data collection on five occasions separated by a minimum of two days across a six week period. A subset of 11 subjects completed a further five visits, totalling 10 separate data collection sessions across a three month period.

Approval for the study was obtained from the University of Huddersfield Human Subjects Ethics Committee and the investigation adhered to the principles of the Declaration of Helsinki. Written informed consent was obtained from each subject before participating and after all the risks and procedures were fully explained.

The project was risk assessed, and local safety protocols pertaining to the COVID-19 pandemic were strictly adhered to, including the wearing of personal protective equipment by both the principal investigator and participants. Thorough cleaning and disinfecting of the research area took place between each data collection session.

Test targets

Stereoacuity was measured using two commonly used clinical stereopsis tests[61]; the Randot stereotest (2017 edition, Stereo Optical, stereooptical.com) and the TNO stereotest (18th edition, Lameris, lameris-group.nl). Both have been advocated as good choices to verify the presence of differences between crossed and uncrossed stereothresholds clinically.[21]

The TNO stereotest utilises random dot stereograms, considered desirable as they avoid monocular cues to depth.[62] The Randot test includes local, contoured Wirt circle targets (on a background of random dots). Although such contour targets have monocularly visible lateral displacement cues, only the two largest Wirt circle disparity levels (400 and 200 arc s) suffer in this way; thus, the finer disparity levels can be considered free of effective monocular cues.[38,63] These targets have shown close relation to stereothresholds measured with psychophysical tests, although the presence of useful binocular non-stereoscopic cues has been reported.[37] The TNO stereotest uses red and green anaglyphs to reveal a 'Pacman' shape in depth. Conversely, the Randot test utilises polarisation to separate the retinal images.

The stereotests were separated into their constituent parts for use in this study. Individual squares of each test figure from plates V, VI and VII of the TNO stereotest and the Wirt circle targets from the Randot stereotest were carefully cut out and attached to white cards of equal size. For presentation, the test cards were mounted onto a small stand in front of a plain white background (Figure 1).

To create 10 equivalent levels of disparity between the two stereotests, four of the TNO targets were presented at both 40 and 60 cm. The Randot targets were all presented at a 40 cm test distance (Table 1).

Testing was performed in a clinical test room under typical light levels of approximately 750 lux (measured with a Konica Minolta model T-10A Illuminance Photometer, konicaminolta.eu). Unattenuated luminance of the test targets was relatively constant between 146 and 153 cdm^{-2} for the TNO targets and between 63 and 66 cdm^{-2} for the Randot targets across all sessions (measured with a Konica Minolta LS-150, Luminance Meter; konicaminolta.eu).

TABLE 1 Stereoacuity levels presented for each stereotest

TNO (arc seconds)	Randot (arc seconds)
480	400
240	200
160[a]	140
120	100
80[a]	70
60	50
40[a]	40
30	30
20[a]	25
15	20

[a]To achieve these disparity levels, the target was presented at 60 cm.

Procedure

Subjects were first familiarised with the task and the sensation of crossed and uncrossed depth using a large disparity random-dot (500″ circle) target from the Randot stereotest, presented in both crossed and uncrossed disparity. Near fixation disparity was assessed at each visit at 40 cm with the NV-100 near Mallett unit (Grafton Optical, graftonoptical.com) to confirm vergence stability. No subject included in the final data analysis exhibited a horizontal or vertical fixation disparity at any session. A chin rest was used to restrict head movement so as to minimise potential monocular cues from motion parallax, and to maintain the working distance at a fixed amount.

Stereotest presentation was randomised at each visit. For each stereotest, the test cards were presented individually in a pseudo-random order, both in terms of the magnitude and direction of their disparity. Each disparity level and direction (i.e., crossed or uncrossed) was presented once before repetition. The presentation order (within each repetition) was randomised for each subject. Thus, at each test visit, every disparity level was presented twice for each stereotest and disparity direction.

For each test card presentation, subjects were asked to indicate the correct depth Wirt circle target (Randot) or orientation of the 'Pacman' (TNO) and whether the depth direction of the target was in front of or behind the plane of fixation. Crossed and uncrossed disparity was achieved by altering the test plate orientation (by 180°). Subjects wore the appropriate filters (i.e., either polarising or anaglyphs) over any near refractive correction (worn in a trial frame) if required.

No time limit was imposed for each presentation, and participants were asked to guess if they were unsure. Feedback on performance was not provided. Subjects were allowed breaks as needed. Data collection was performed by a single examiner (RC). Three subjects returned for an additional testing session where one eye (chosen at random) was occluded, to evaluate their performance under monocular viewing conditions.

TABLE 2 Mean (SE) stereoacuity using crossed and uncrossed stimuli across the first five visits for each stereotest

Visit		Crossed stimuli (arc seconds)	Uncrossed stimuli (arc seconds)
1	Randot	37.06 (5.70)	53.24 (10.15)
	TNO	58.24 (11.94)	49.71 (12.16)
2	Randot	35.00 (9.65)	40.00 (5.65)
	TNO	50.29 (12.19)	37.94 (5.29)
3	Randot	30.00 (6.43)	32.94 (4.67)
	TNO	35.29 (3.33)	33.24 (3.75)
4	Randot	30.00 (6.43)	36.47 (6.65)
	TNO	30.29 (4.30)	25.29 (1.78)
5	Randot	30.88 (6.38)	28.53 (4.20)
	TNO	25.29 (1.91)	28.53 (3.54)

Data analysis

At each visit, stereoacuity was defined as the smallest disparity at which subjects correctly identified both the position (the correct orientation of the 'Pacman' or the correct Wirt circle) and relative depth direction (in front of or behind the fixation plane) on both presentations. Thus, the guess rates for a correct response at each disparity level were 2.78% and 1.56% for the Randot and TNO stereotests, respectively.

Stereoacuity across the different stereotests, depth directions and visits were analysed using a three-way repeated measures ANOVA with a significance level of 5%. Where required, the levels of statistical significance included a correction for departures from sphericity.[64] *Post-hoc* pairwise comparisons were also used as appropriate.

Although the number of data points was relatively few, Bland–Altman plots were also constructed to explore the test–retest agreement between stereoacuity measures at different visits.[65]

RESULTS

Table 2 lists, for each stereotest and disparity direction, mean (±SE) stereoacuity (arc s) averaged across all subjects for each of the first five visits. Figures 2 and 3 plot mean (±SE) stereoacuity (arc s) against visit number for the Randot and TNO stereotests, respectively. In each figure, the solid lines and closed symbols represent crossed disparity and the dashed lines and open symbols uncrossed disparity.

In general, stereoacuity for both crossed and uncrossed disparities appeared to improve over the course of the first five visits, although with some variation between the stereotests. To test this trend statistically, a three-way, within-subjects analysis of variance (ANOVA) was conducted with main effects of visit, stereotest and disparity direction. This analysis revealed a significant effect of visit ($F_{1,21} = 4.24$, $p = 0.05$) and a significant interaction between stereotest and disparity direction ($F_1 = 7.92$, $p = 0.01$). No other terms

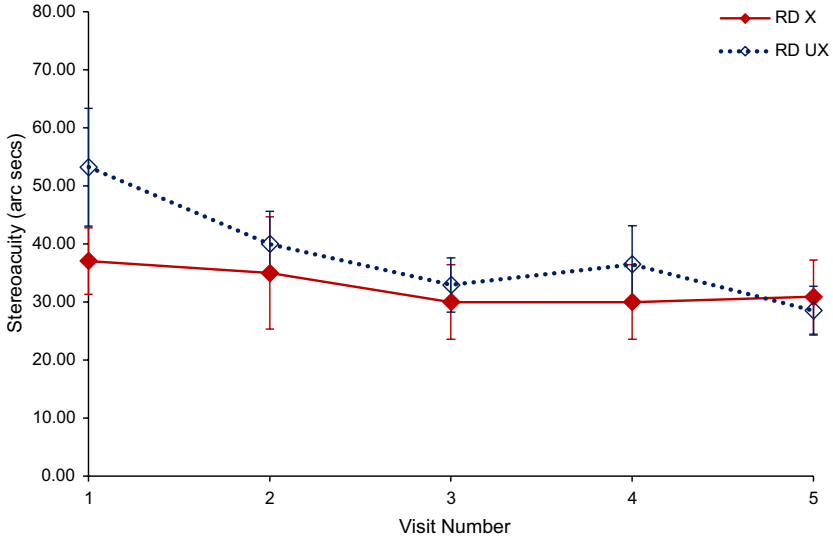

FIGURE 2 Mean stereoacuity (±SE) across all subjects over the first five visits for the Randot stereotest. The solid lines and closed symbols represent crossed (RD X) disparity and the dashed lines and open symbols uncrossed disparity (RD UX).

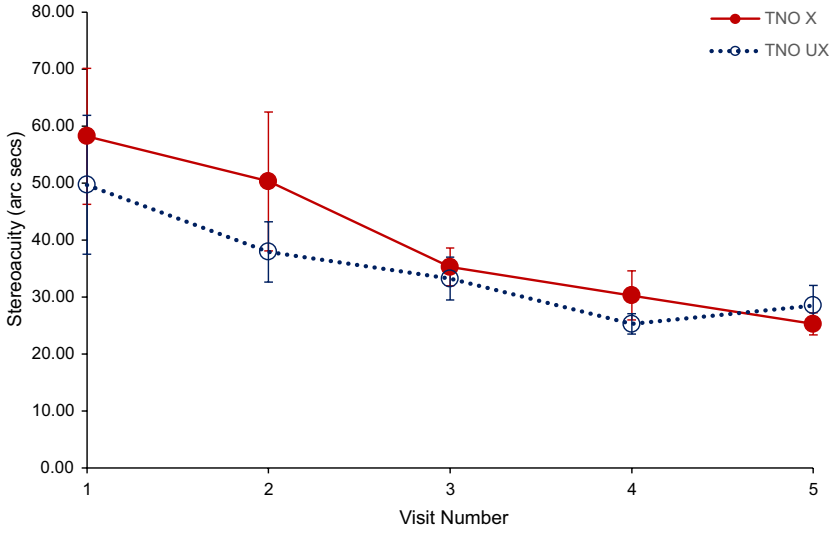

FIGURE 3 Mean stereoacuity (±SE) across all subjects over the first five visits for the TNO stereotest. The solid lines and closed symbols represent crossed disparity (TNO X) and the dashed lines and open symbols uncrossed disparity (TNO UX).

were significant, although the three-way interaction between visit, stereotest and disparity direction was close to significance ($F_{2,81} = 2.59$, $p = 0.07$). Huynh–Feldt corrections were utilised where required due to violations of sphericity in the data.

To further investigate the outcome of the three-way ANOVA, one-way within-subjects ANOVAs were conducted separately for each stereotest and disparity direction. These analyses revealed a significant effect of visit for the TNO stereotest presented with crossed disparity stimuli ($F_{1,56} = 4.34$, $p = 0.03$), but a non-significant effect with uncrossed disparity stimuli ($F_{1,45} = 2.65$, $p = 0.11$). Results for the Randot stereotest showed a non-significant trend effect of visit for uncrossed stimuli ($F_{1,71} = 2.70$, $p = 0.09$), but no significant effect of visit for crossed disparity stimuli ($F_{1,59} = 0.94$, $p = 0.38$). Huynh–Feldt corrections were utilised where required due to violations of sphericity in the data.

Although the one-way ANOVAs revealed a significant effect of visit for only the TNO crossed stimuli condition, limited *post-hoc* pairwise comparisons were also conducted for the two borderline results (TNO and Randot uncrossed conditions). Not surprisingly, given the results shown in Figures 2 and 3, the main differences in stereoacuity occurred between visits one and four or five depending on the condition. For example, stereoacuity in the TNO crossed stimuli condition was significantly different between visits one and four ($p = 0.01$) and visits one and five ($p = 0.02$), indicating a continual improvement in stereoacuity across these visits.

TABLE 3 Mean (SE) stereoacuity using crossed and uncrossed stimuli at visits five and 10 for each stereotest for the subset of 11 subjects who completed 10 visits

Visit		Crossed stimuli (arc seconds)	Uncrossed stimuli (arc seconds)
5	Randot	25.45 (1.87)	22.73 (1.18)
	TNO	25.45 (2.61)	33.18 (5.15)
10	Randot	20.91 (0.87)	25.45 (1.87)
	TNO	23.64 (2.81)	24.09 (3.00)

For the subset of 11 subjects who completed an additional five visits, mean stereoacuity remained relatively stable and did not differ significantly between visits five and 10. Table 3 shows the mean (±SE) stereoacuity (arc s) for both stereotests and disparity directions for each visit. The difference in stereoacuity between visits five and 10 varied from approximately 7% (TNO crossed stimuli) up to about 27% (TNO uncrossed stimuli). This compares to a variation in stereoacuity between visits one and five that ranged from 17% (Randot crossed stimuli) to 57% (TNO crossed stimuli).

In addition to the observed changes in mean stereoacuity, the standard error of the mean is also reduced with repeated measurement (Table 2 and Figures 2 and 3), suggesting that the variance in stereoacuity also declines with repeated testing. To demonstrate the relative differences between visits more clearly, Bland–Altman analyses were performed. Figure 4 shows a representative example. The top panel plots the difference in Randot (crossed disparity) stereoacuity between visits one and two against the average, whereas the bottom panel shows the results for visits four and five. In both panels, the mean difference is depicted by the solid line, whereas the upper and lower limits of agreement (95% confidence intervals) are shown by the broken lines.

Of note is the marked reduction in the 95% confidence intervals between the visits, consistent with the decrease in variance between stereoacuity measurements between the initial two visits and later visits four and five. This reduction is consistent across both stereotests and with both crossed and uncrossed stimuli.

The three-way ANOVA revealed a significant interaction between stereotest and disparity direction ($F_1 = 7.92$, $p = 0.01$). Figures 2 and 3 suggest that any differences between stereoacuity with crossed and uncrossed stimuli (on both stereotests) are mostly confined to the initial visits. To investigate this statistically, crossed and uncrossed thresholds for each visit and stereotest were compared using paired *t*-tests. Uncrossed stereoacuity was significantly poorer than crossed with the Randot stereotest at visits one ($p = 0.05$) and four ($p = 0.03$), but not at any other visit. No significant differences were revealed at any visit for the TNO stereotest.

Three subjects returned for an additional testing session as a control and viewed the stimuli under monocular conditions, whilst wearing the appropriate filters. Test stimuli were presented in the same way as the experimental condition, in both crossed and uncrossed directions. No subject was able to identify the form (position) or depth of the target stimuli correctly at any of the disparity levels on the TNO stereotest. However, two of the three subjects identified the correct 400 and 200 arc s Wirt circle targets on the Randot stereotest in both disparity directions, consistent with previous reports of the presence of monocular cues in this test.[38,63] However, as all subjects achieved a stereoacuity of at least 100 arc s across all test conditions with this stereotest, any monocular cues present did not contribute to the results.

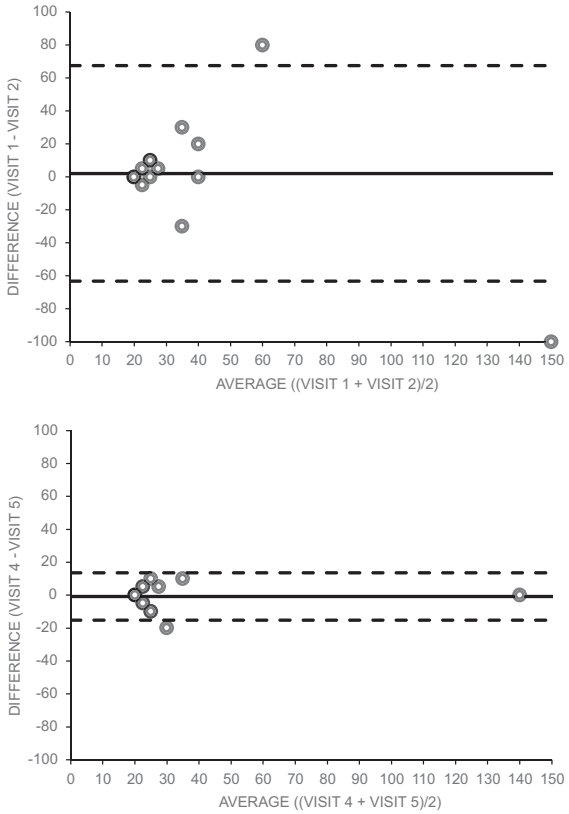

FIGURE 4 Bland–Altman plots of agreement in stereoacuity (arc seconds) using the Randot stereotest (crossed disparity stimuli) comparing visits one and two (top panel), and visits four and five (bottom panel). The mean difference is represented by the solid black line, and the upper and lower limits of agreement (95% confidence) are represented by the broken lines.

DISCUSSION

Lab-based psychophysical experiments have demonstrated a learning effect on stereothresholds, typically over the course of hundreds and sometimes thousands of trials.[52–54,56,66] The ability to improve stereothresholds through repeated measures with clinical stereotests is less well established. No statistically significant difference in crossed stereoacuity was noted by Antona et al.[41] with either the TNO or Randot stereotests across two visits (no

more than one week apart). Similarly, utilising the Zeiss i-Polatest (gebker-optik.com/gebker-optik/zeiss-i-polatest), Alhassan et al.[67] found no significant difference in stereothreshold between two measurements using both crossed and uncrossed disparity at a near testing distance. In a sample of 139 children, Adler et al.[68] found that Randot stereoacuity improved by one disparity level on average on the first repetition (with an average gap between measurements of eight days), but no significant improvement was found on the second.

Our results confirm the presence of a significant practice effect in clinical measurements of stereoacuity and show that up to five measurements are required to achieve stability (Figures 2 and 3), after which further measurements produce no significant change (Table 3). The presence of a practice effect is underscored by the reduction in standard error with repeated measurement (Figures 2 and 3) and further illustrated by the Bland–Altman analysis (Figure 4).

The effect of repeated measures on stereoacuity seems limited to the TNO stereotest and not the Randot test (Figures 2 and 3). However, a potential limitation of our study is that the finest disparity level on the Randot stereotest (20 arc s) may have been too easy and created an artificial floor in the results, as several participants were able to achieve this finest disparity level with both crossed and uncrossed stimuli at their initial visit. Conversely, at the first visit, no subject was able to achieve the finest disparity level (15 arc s) with the TNO stereotest, presented with either crossed or uncrossed stimuli. A greater disparity range with the Randot stereotest may have revealed a significant learning effect.

Our results question the validity of data from studies that rely upon a single clinical measure of stereoacuity from their participants.[6,8,59] When considering normative values of a clinical measure, it would seem prudent to first account for any improvement that can be made by simple repetition. Studies that fail to do this may therefore be underestimating their reported stereoacuity.

Adler et al.[68] advocated the benefit of repeat testing using the Randot stereotest in children, although only once. It is plausible that other investigators may have found significant improvement had they repeated their measurements on more than two occasions.[41,67] The clinical implications of our results are clear; to be assured that a clinical measurement of an individual's stereopsis is as close to their true stereoscopic ability as possible, it is necessary to repeat the measurement several (four or five) times.

Knowledge of the repeatability of a clinical test is essential to be sufficiently confident that any change in measurement with repeated measures is a real alteration of performance and not attributable to natural variation.[68] Taking multiple measurements before establishing a threshold to mitigate for any test–retest discrepancy for clinical tests has been advocated.[69] The shared limitations of clinical stereotests, including their discrete disparity levels and high guess chances, are well known.[70,71] A change of two disparity steps has been suggested as the minimum required to be confident that any change in clinically measured stereoacuity is attributable to more than just test–retest variability.[72]

Bosten et al.[73] evaluated the test–retest repeatability of the TNO stereotest (using crossed stimuli only) and reported a Spearman's rank correlation coefficient of 0.57, suggesting that stereoacuity measures with this test across two visits are only moderately repeatable. Coefficients of repeatability of ±54 arc s for the TNO and ±23 arc s for the Randot stereotest (both with crossed stimuli) across two visits have been reported.[41]

Leat et al.[74] found a mean difference in Randot stereoacuity between two measurements (taken on the same day) of 1.1 arc s. By comparison, the mean difference in Randot stereoacuity between the first two visits (crossed stimuli) from the present study was 2.1 arc s, which reduced to 0.9 arc s between visits four and five. The calculated test–retest coefficients of repeatability[75] between visits one and two and visits four and five for the Randot stereotest (crossed disparity condition) were ±66.8 arc s and ±14.8 arc s, respectively. For the TNO stereotest, the calculated coefficient of repeatability between visits one and two was ±50 arc s, reducing to ±30 arc s between visits four and five. We, therefore, propose that studies evaluating the test–retest repeatability of clinical stereotests based on only one repetition are unlikely to have isolated the relative contributions of practice effects and test–retest variability.[23,41,74]

The question as to whether differences exist between clinically measured crossed and uncrossed stereoacuity is more complex. Superior stereoacuity with crossed versus uncrossed disparity stimuli has been reported by numerous researchers in lab-based studies. Using a modified three-rod apparatus, Lam et al.[19] reported a mean crossed stereoacuity of 4.8 arc s and a mean uncrossed stereoacuity of 7.2 arc s in a sample of 72 young adults. Manning et al.[22] observed markedly superior crossed disparity detection in a sample of 85 adult subjects, whereas Woo and Sillanpaa[21] found a mean absolute crossed stereothreshold of 5.6 arc s versus a mean uncrossed stereothreshold of 14.5 arc s utilising a stereotest made from lantern flashlights. Utilising computer-generated Gaussian stimuli, Bosten et al.[73] found a small (mean difference of just 3 arc s) yet significant difference between crossed and uncrossed stereoacuity on a large sample of 1060 young adults.

In a clinical setting, inconsistencies in measured stereoacuity with crossed and uncrossed disparity stimuli are less well established. Using a newly developed contour-based distance stereotest (visotec.co.nz/distance-stereoacuity-test), Ale Magar et al.[23] reported significantly superior stereoacuity with crossed disparity stimuli (mean of 92.5 arc s) than uncrossed (mean of 105.0 arc s) in a sample of 25 children older than 10 years of age. Superior crossed stereoacuity using the Frisby stereotest has also been reported in younger children less than 10 years of age.[7]

Conversely, Momeni-Moghadam et al.[76] reported no significant difference between stereoacuity measured using the TNO stereotest with crossed disparity stimuli

(mean of 92.3 arc s) and uncrossed stimuli (97.5 arc s) in a sample of 174 adults. Crossed and uncrossed stereothresholds measured with the Frisby stereotest (frisbystereotest.co.uk) by Costa et al.[77] in a group of 24 adults aged 15–24 years were similarly comparable (mean stereothreshold of 6.3 arc s with crossed disparity stimuli, versus 5.3 arc s with uncrossed). Although finding some adult subjects to have superior crossed or uncrossed stereoacuity, Larson[24] reported that on average, there was no significant difference in the ability of their participants to detect crossed versus uncrossed disparities using either the Frisby or TNO stereotests.

Our data suggest that although there may be differences between stereoacuity measured with crossed and uncrossed disparity, these differences are not only relatively small, but appear negligible or disappear after repeated measures (Figures 2 and 3). With the Randot stereotest, it appears that stereoacuity measured with uncrossed stimuli is initially inferior to stereoacuity measured with crossed stimuli, but this difference becomes less evident with each subsequent visit (Figure 2). For the TNO stereotest, the reverse appears to be true; stereoacuity measured with crossed stimuli is initially inferior to stereoacuity measured with uncrossed stimuli (albeit not significantly), but similarly, this difference diminishes with each subsequent visit (Figure 3).

The ability of practice to improve the relative performance of a stereoanomalous observer closer to that of a normal observer has already been demonstrated psychophysically with large disparities greater than 0.5°.[57] The results of our study suggest that this phenomenon may also be possible with the much finer disparity stimuli found on clinical stereotests. Alhassan et al.[67] found that an initially significant difference between crossed and uncrossed stereoacuity (poorer uncrossed stereoacuity) at the first session of measurement disappeared in a second session. Studies reporting significant differences between stereoacuity with crossed and uncrossed stimuli, but relying on only a single measure of stereoacuity, may therefore be limited.[7,23] It is possible that such studies may have found no significant difference between crossed and uncrossed stereoacuity had they simply repeated their measurements.

The younger age of the participants recruited by Ale Magar et al.[23] and Anketell et al.[7] may also partly account for the conflicting results with other researchers not finding significant differences between crossed and uncrossed stereoacuity.[24,76,77] It is similarly plausible that differences in crossed and uncrossed stereothresholds are most apparent at absolute threshold, and thus, the typical range of clinical stereotests limits the ability to consistently reveal significant differences.[21]

None of the participants of this study could be labelled grossly 'stereoanomalous'. If the proportion of adults thought to exhibit gross stereoanomaly in one of the disparity directions is as high as has been previously suggested,[10] then a proportion of the individuals recruited for this study should have demonstrated more remote stereoacuity using either crossed or uncrossed stimuli even after a period of practice, albeit the relatively low number of participants is likely to have limited such an outcome.

The agreement of stereoacuity measures using different clinical stereotests is a further discussion point. In a sample of 74 adults, Antona et al.[41] reported a mean stereoacuity of 52 arc s with the TNO stereotest versus a mean of 29 arc s with the Randot stereotest (using crossed disparity stimuli). Several reasons why the global TNO targets may be 'harder' than the local Randot Wirt circle targets have been proposed, including a higher cognitive load provoked by complications of correspondence and matching of random dot stereograms in the virtual cortex, the need for form perception to operate for the distinction of the 'Pacman' shape as opposed to the simple forced-choice detection task of the Wirt circles, the use of anaglyph versus polarised glasses to elicit dissociation of the retinal images and the relative size of the test elements.[39,78–80]

Comparable with the results of Antona et al.,[41] at visit 1, the mean stereoacuity with crossed disparity stimuli was 37.06 arc s with the Randot stereotest and 58.25 arc s with the TNO stereotest. We see no evidence of the more remote stereoacuity, some authors have reported in adult subjects of 90 arc s or more with the TNO stereotest,[73,76] although the lower number of subjects in our study should be noted.

Averaged across the first five visits, the three-way ANOVA revealed a significant interaction between the test and depth direction, suggesting that there may be differences between the stereoacuity measured by the two stereotests, depending on the depth direction. However, these differences were not significant after repeated measurements. By visit 5, mean stereoacuity with uncrossed disparity stimuli is identical for the Randot and TNO stereotests, and mean stereoacuity with crossed disparity stimuli was far more comparable between the two tests than at the first measurement (Table 2). We propose that with repeated measurements, the agreement between the TNO and Randot stereotests would be better than has been reported elsewhere.[41,43]

The extra disparity levels on the TNO stereotest, created by virtue of altering the test distance to 60 cm, resulted in a reduction of the angular size of the random dot elements, which may have impacted the relative difficulty of the task.[43] The measured size of the smallest dots was approximately 0.25 mm in diameter, resulting in a calculated change in angular size of the dots at the test distances of 40 and 60 cm from 2.14 to 1.43 arc min, respectively. Therefore, the angular size of the smallest TNO dots at 60 cm was well within the visual acuity capability of all participants. As a result, changing the test distance of the TNO to 60 cm did not make the dots unresolvable, and so was not likely to impact the difficulty of the task at this distance.

As the purpose of this experiment was to evaluate stereotests in a clinical setting, unlimited viewing time was permitted. Although vergence cues may have contributed,[28–30] stimuli were presented in random order, and subjects were asked to not only indicate the position or

orientation of the stereoscopic stimuli, but additionally to stipulate the depth direction (crossed or uncrossed). Any resulting vergence cues would have had to identify correctly the figure from the background to contribute to a correct response.

In conclusion, utilising a single clinical measure of stereoacuity to determine stereoscopic ability is not supported by the results of our study. A practice effect on stereoacuity is demonstrable clinically, and thus, multiple measures (up to five) on separate days are required to ensure that the true level of stereoscopic ability has been determined, with both crossed and uncrossed stimuli.

Our data suggest that differences between crossed and uncrossed stereoacuity may be present on initial testing but reduce or disappear after a period of repeated measurements. To be assured that any discrepancy between crossed and uncrossed stereoacuity is genuine, multiple measurements should be taken to consider any improvement that can be made with practice.

AUTHOR CONTRIBUTIONS

Robin Clayton: Conceptualization (lead); data curation (lead); formal analysis (lead); funding acquisition (lead); investigation (lead); methodology (lead); project administration (lead); resources (lead); software (lead); validation (lead); visualization (lead); writing – original draft (lead); writing – review and editing (lead). **John Siderov:** Conceptualization (supporting); formal analysis (supporting); supervision (lead); writing – review and editing (supporting).

CONFLICT OF INTEREST

The authors report no conflicts of interest and have no proprietary interest in any of the materials mentioned in this article.

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