Visual Psychophysics and Physiological Optics

A Systematic Comparison of Static and Dynamic Cues for Depth Perception

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Purpose. A clinical diagnosis of stereoblindness does not necessarily preclude compelling depth perception. Qualitative observations suggest that this may be due to the dynamic nature of the stimuli. The purpose of this study was to systematically investigate the effectiveness of static and dynamic stereoscopic stimuli.

Methods. Stereoscopic stimuli were presented on a passive polarized stereoscopic monitor and were manipulated as follows: static disparity (baseline condition), dynamic disparity (change in *z*-location), change in stimulus pattern, change in *z*-location with pattern change, change in *x*-location (horizontal shift), a control (nil-disparity signal). All depth-detection thresholds were measured simultaneously using an adaptive four-alternative-forced-choice (4AFC) paradigm with all six conditions randomly interleaved.

Results. A total of 127 participants (85 women, 42 men; mean [SD] age, 21 [5] years) with visual acuity better than 0.22 logMAR in both eyes were assessed. In comparison to the static disparity condition, depth-detection thresholds were up to 50% lower for the dynamic disparity conditions, with and without pattern change ($P < 0.001$). The presence of a changing pattern in isolation ($P = 0.71$) or a horizontal shift ($P = 0.41$) did not affect the thresholds.

Conclusions. Dynamic disparity information facilitates the extraction of depth in comparison to static disparity signals. This finding may account for the compelling perception of depth reported in individuals with no measurable static stereoacuity. Our findings challenge the traditional definition of stereoblindness and suggest that current diagnostic tests using static stimuli may be suboptimal. We argue that both static and dynamic stimuli should be employed to fully assess the binocular potential of patients when considering management options.

Keywords: stereopsis, stereoacuity, binocular vision, dynamic

Qualitative work has demonstrated that many participants who are diagnosed as stereoblind when assessed using standard clinical tests report an enhanced perception of depth when viewing dynamic stereoscopic stimuli such as three-dimensional (3D) films.[1–3] Although this demonstrates some residual ability to use information from the binocular comparison of retinal images, there are several differences between the characteristics of the stimuli involved. Several stereotests are commercially available for use in the clinic; however, they contain many artefacts preventing accurate threshold measurement of even static stereoacuity.[4] Although clinical stereovision tests involve stationary stimuli with a given static disparity, dynamic 3D stimuli can involve movement across the screen (*x* or *y* location change), variations of the surface pattern of stimuli over time (pattern change), or changes in the amount of simulated depth over time (*z* location change, or *stereomotion*), each of which could affect the observer's ability to extract stereoscopic information. In this study, we set out to evaluate the effectiveness of these stimulus characteristics.

When the two retinal half images of an object fall on corresponding points in each eye (e.g., a fixation target in the central fovea), it has zero disparity (Fig. 1A), and where noncorresponding retinal locations are stimulated, a disparity is present. For a stimulus whose half images are displaced in a temporal direction with respect to each other, the disparity is crossed, and the relevant stimulus feature appears to be closer than the zero-disparity object (Fig. 1B). If such an object were to move laterally across the screen, both of its retinal images would translate at the same velocity (i.e., at the same speed and same direction) such that the disparity does not change over time and the object appears to translate without a change of depth (Fig. 1C). However, for objects that move through depth toward an observer, the amount of disparity relative to the fixation point changes over time, resulting in retinal motion in opposite directions and/or at different speeds in each eye (Fig. 1D).

Disparity change in particular has been considered the most likely candidate for residual stereopsis in those clinically defined as stereoblind (no measurable stereoacuity on standard clinical tests); quantitative work has shown that stereoblind participants are able to correctly identify the approaching or receding motion of stimuli when changes in depth are

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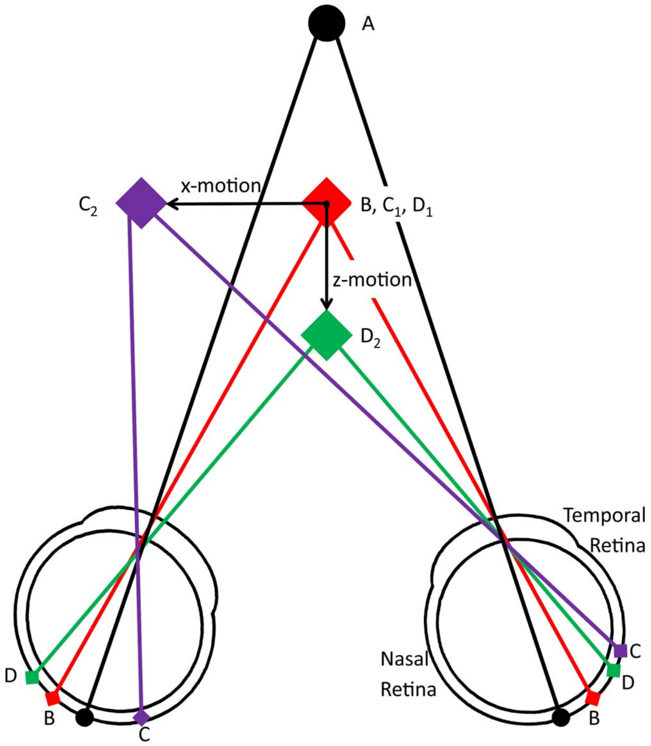

Figure 1. Plan view of various stimuli and their binocular retinal projections. (**A**) The fixation target (stationary, zero disparity). (**B**) A stationary stereoscopic stimulus with a crossed disparity. (**C**) A stimulus moving laterally (*x*-motion) at a constant disparity. (**D**) A stimulus moving in depth (*z*-motion), changing its disparity as its half images translate at different velocities across the retinae. In all cases, subscript 1 denotes the start location at time 1 (**B** on retina) and subscript 2 is the next location at time 2 (**C** and **D** on retina).

simulated stereoscopically in laboratory stimuli.[5–10] However, in these studies observers were asked to judge motion and not depth. In studies measuring participants' abilities to appreciate depth in stereoscopic stimuli, it appears that nonstereoblind observers perceive a greater amount of depth for stimuli involving approaching or receding motion when compared with static stimuli. When asked to match the depth of a static disparity target to one with changing disparity, participants always set a smaller disparity for the moving target.[11] Moreover, when observers were asked to detect depth in an approaching target that began with zero disparity, this was achieved more quickly than a stationary target with a larger disparity, indicating an enhanced sensitivity for dynamic stereoscopic targets.[12] Zinn and Solomon[13] measured the time taken for participants to determine the closest of four binocular targets with various relative disparities as they moved through depth toward the participant. The amount of time taken to determine the closest target did not correlate significantly with static stereoacuity scores as measured with either the TNO test (Lameris Instrumenten, Utrecht, The Netherlands) or Titmus tests. Although this null result appears to suggest that levels of performance with moving and stationary targets are unrelated, the differences between stimuli and procedure for the two tasks make a direct comparison difficult because other stimulus- and task-related parameters may affect performance.

The presence of a changing pattern in dynamic stimuli may result in an improved detection of depth because of the presence of several independent samples and thereby increase the reliability of estimating depth and solving the correspondence problem.[14,15] We aim to further investigate the effect of a pattern change on depth-detection thresholds.

Another element of a dynamic display is lateral motion in addition to disparity. Thresholds for detecting depth are not affected when the lateral velocity is below 2° per second, but worsen exponentially as the velocity increases from 2° to 12° per second. Control experiments found that this effect was not primarily a result of exposure duration or increasing target eccentricity, but the reduced performance is a result of fast lateral motion.[16]

It is important to note also that comparisons of stereoscopic performance between dynamic and static stimuli have been made using fundamentally different test types, for example, computerized or projected disparity change stimuli when compared with book-based tests.[5,7,8] As a direct comparison between clinically used book-based static stereoacuity tests is not possible because each provides a different threshold for the same individual,[17,18] the differing findings of static and dynamic tests may be a result of variations in test design rather than the presence or absence of static and dynamic stereopsis.

In the present study, we investigate the influence of various characteristics of dynamic stereoscopic stimuli on the detection of depth in direct comparison to static stimuli. We include stimuli that either feature or lack changes of disparity, of horizontal location, or of stimulus pattern. By assessing these stimulus characteristics under equivalent conditions, direct comparisons between dynamic and static depth-detection thresholds are possible.

Materials and Methods

Participants

Ethical approval was received from the University of Liverpool Ethics Subcommittee, and the study was performed in accordance with the ethical standards outlined in the Declaration of Helsinki. Participants were recruited from the staff and student population of the University of Liverpool. Prior to participation, informed consent was gained from each participant. The advertised inclusion criteria for the study were for volunteers aged 16 years and older, with vision of at least 0.22 logMAR (that is the level of vision required to legally be able to drive in the United Kingdom).

Apparatus

Stimuli were presented on a 22-inch film-type pattern retarder monitor (FLATRON D2342, LG Electronics, Seoul, Korea), where each alternate horizontal line of pixels (1080) was polarized to either the right or left eye in turn when passive 3D circular polarizing glasses were worn. When correctly aligned with the screen, there was little perceptible ghosting obvious when the display was viewed through the glasses, with crosstalk measured at 4.5%.[19] The screen was positioned 3 m from the participant, with a horizontal resolution of 1920 pixels distributed over 0.502 m, with each pixel subtending 0.005° or 18.1 arc seconds. The display was run at 60 Hz. The experiment was controlled by a Pentium i3, Windows PC (Microsoft, Redmond, WA, USA) with an NVidia Quadro FX4600 (Nivida, Bristol, UK) graphics processor running Psychopy (University of Nottingham, Nottingham, UK).[20] The participant's head rested on a forehead/chin rest to align eyes with the center of the screen and the fixation target.

Stimuli

A four-alternative-forced-choice (4AFC) procedure was used, with the target random dot stimulus (presented with crossed

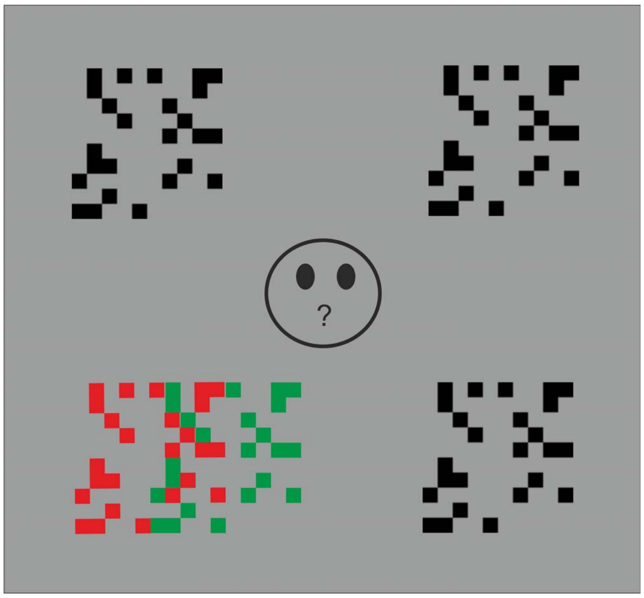

FIGURE 2. Schematic of stimuli on screen. When observed on a three-dimensional monitor while wearing three-dimensional glasses, each half image of the bottom left stimulus in this figure would be presented to each eye individually and appear in front of the screen. The lower left stimulus shows a target stimulus with a disparity between the right (*red*) and left (*green*) half images of 0.05° (10 pixels). (Red and green coloring are for illustrative purposes only.)

disparity compared to the screen) and three distractor stimuli (presented with zero disparity) surrounding a central fixation target (presented with zero disparity) with a diameter of 0.36° (76 pixels; Fig. 2). Within each condition, the three distractor stimuli differed from the target stimulus only in the difference of lateral positions of the left and right half images. The fixation target acted as a feedback mechanism: green coloring indicated a correct response, and red indicated an incorrect response. Each stimulus subtended 0.5° (100 pixel squares), wherein dots of 0.05° (10 pixel squares) were randomly distributed with a density of 25%. The stimuli were precomputed using Matlab (Mathworks, Natick, MA, USA) and presented on a grey background with 98.5% Michelson contrast and a mean luminance of 9.75 cd/m^2. The inner corners of each of the four stimuli were initially separated from the center of the fixation target horizontally by 0.6° (120 pixels) and vertically by 0.68° (135 pixels). The maximum disparity level was 0.15° (30 pixels) to avoid overlap of the left and right half images of the neighboring stimuli, thereby precluding cues to motion-in-depth through unmatched stereopsis.[21,22] All stimuli were visible for a total of 1 second, with the stimuli position and or pattern changed every six frames. This allowed the perception of relatively smooth motion while avoiding the perceived contrast reduction that can occur for rapidly changing patterns.

To determine the contribution of each aspect of dynamic stereoscopic stimuli to the detection of depth, six specific stimulus conditions were included the characteristics of which are shown in Table 1. In each case, the appearance of the four stimulus patches on each trial was designed to be similar, aside from the target stimulus being defined by a separation of the right and left half images.

1. **STATIC.** Target stimuli were presented with a fixed disparity. Both the stimulus' frontoparallel location and its dot pattern were constant throughout.
2. **PATTERN CHANGE.** The left and right eye images were presented with a fixed disparity and location. The dot pattern changed to a novel random array of dots every screen update.
3. **X-LOCATION CHANGE.** Stimuli were presented with a fixed disparity and lateral motion with a total displacement equivalent to half of the target stimulus' disparity. Importantly, each half image moved in the same direction (no disparity change), simulating lateral motion. The dot pattern was fixed.
4. **Z-LOCATION CHANGE.** Target stimuli were presented with a disparity that changed over time (starting at zero and increasing toward the target disparity), but with a constant location and dot pattern. Many observers perceive these stimuli to move laterally as they approach, a percept that is more likely in observers for whom there is substantial suppression of one eye's input.[23] To ensure that this artefactual percept could not be used to provide the correct answer in our 4AFC task, randomized rightward or leftward motion was added to the three distractor stimuli. The two half images of each individual distractor stimulus moved simultaneously in the same direction and by the same distance as the target stimulus' half images.
5. **Z-LOCATION & PATTERN CHANGE.** Target stimuli were presented with a changing disparity (as for the Z-LOCATION CHANGE stimulus), while the dot pattern also changed to a new random array every screen update. As for the Z-LOCATION CHANGE condition, randomized rightward or leftward motion was added to the three distractor stimuli.

In principle, the Z-LOCATION CHANGE condition contains the same information on positional depth as the Z-LOCATION & PATTERN CHANGE condition. However, it also contains a motion-in-depth cue (interocular velocity difference [IOVD]), which provides information on the rate and trajectory of motion in depth.[23–27] To assess the possibility that participants might be tempted to select the stimulus that appeared to move in depth rather than use positional depth signals per se, we included a control condition featuring this cue to motion in depth only. We hypothesized that it would not provide any information on static depth and hence thresholds would not be recordable.

6. **CONTROL.** Target stimuli were identical to those in the Z-LOCATION CHANGE condition in terms of the temporal motion of each retinal half image, the constancy of stimulus pattern, and the lack of overall lateral motion. However, in this condition, left and right half images consisted of different patterns with no binocular correlation. Although this eliminates any coherent binocular disparity signal from the target and distractor patches, it cannot be said that there are no disparity signals present at all. The stimulus itself contains many vertical edges in each eye, and although any arbitrary left–right pair of edges could in principle be said to have a disparity, these would be random and inconsistent, forming a cloud of noisy depth signals centering on zero. Although these signals could not be used to complete the task, it is possible that the IOVD cue might be used to identify which stimulus is moving in depth. To prevent the target patch from being detected by lateral motion because of suppression or diplopia, the distractor stimuli featured nasal motion in each half image.

Procedure

At all times, participants wore their habitual correction appropriate for distance. To ensure that each participant met

Table 1. Characteristics of Each Condition Tested

	Fixed Disparity	Changing Disparity	Fixed Pattern	Changing Pattern	Fixed Lateral Position	Changing Lateral Position	Binocular Correlation	No Binocular Correlation
1. STATIC	✓		✓		✓		✓	
2. PATTERN CHANGE	✓			✓	✓		✓	
3. X-LOCATION CHANGE	✓		✓			✓	✓	
4. Z-LOCATION CHANGE		✓	✓		✓		✓	
5. Z-LOCATION & PATTERN CHANGE		✓		✓	✓		✓	
6. CONTROL		*	✓		✓			✓

* Note that for the CONTROL condition, the lack of binocular correlation means that there is no coherent disparity. However, it is possible that local features may be binocularly matched to produce a noisy "cloud" of disparity signals centering on zero. The dots of the stimuli on the left and right retinae move in the same way as they would in the Z-LOCATION CHANGE and Z-LOCATION & PATTERN CHANGE conditions to reach their target relative displacement (see description of condition 4).

the inclusion criteria, the Early Treatment Diabetic Retinopathy Study (ETDRS) LogMAR chart (Precision Vision™; La Salle, IL, USA) was used to determine if visual acuity level was better than 0.22 logMAR (approximate driving standard visual acuity [VA]) in at least one eye. The stereo fly test circles (Stereo-Optical; Chicago, IL, USA) were used to determine if stereoacuity better than 200 arc seconds was present. If these criteria were met, the participant was included in the experiment.

The experiment was performed in darkness to eliminate environmental distraction. The participants received standardized instructions to maintain fixation on the central target and to use a response box (formatted in the same layout as targets on the screen) to "choose the patch that appears closest to you in space."

Threshold Estimation

In each session, all six conditions were randomly interleaved. Two thresholds were estimated for each condition by separate staircases (Multistair handler functional of Psychopy[20]), one starting at a large disparity (362 arc seconds), and the other at a small disparity (90 arc seconds) to ensure that the starting value did not systematically affect the final threshold. The initial step size was 95 arc seconds, which after three reversals was reduced to 38 arc seconds. After a further two reversals, the step size was halved to the minimum step size of 19 arc seconds. A three-down-one-up method was used so that the staircases converged to a performance of 79.4% correct.[28] The staircase for each condition terminated when eight reversals occurred or if 150 trials were reached. Note that for the CONTROL condition, the variable controlled by the staircase was maximal horizontal retinal displacement, which is applicable to stimuli lacking binocular correlation while being equivalent to retinal disparity in the other conditions.

To obtain depth-detection thresholds for each participant, a cumulative Weibull function (Equation 1) was fitted to the proportion of correct responses as a function of disparity level.[29] Chance level (B) in a 4-AFC experiment is 25%, and the asymptote (A) value was set to 1. The parameters estimated were the steepness of the curve (d) and the location of the curve (c). We use c as our threshold because this represents the disparity level at which observers achieved a 72.41% correct response.

$$f(x) = A - (A - B) \times exp\left(-\left[\frac{x}{c}\right]^{d}\right) \qquad (1)$$

The lower bound of c was set to zero, and the upper bound was set to 1086 arc seconds. As a criterion for exclusion, we used the goodness-of-fit value of the cumulative Weibull function; if $r^2 < 0.3$ in all conditions, the participant was excluded from further analysis. For each comparison, thresholds were only used from participants who provided a reliable response in the conditions included in the planned comparison.

Statistical Analysis

To determine whether dynamic stimuli result in lower depth-detection thresholds than static stimuli, planned comparisons were made between the STATIC versus PATTERN CHANGE, the STATIC versus X-LOCATION CHANGE, the STATIC versus Z-LOCATION CHANGE, and the STATIC versus Z-LOCATION & PATTERN CHANGE conditions. To examine the potential use of artefactual motion-in-depth signals in our depth-detection task (i.e., participants choosing the stimulus that appears to move in depth rather than the stimulus that appeared closer), a comparison was made between the STATIC and the CONTROL conditions, which appeared to move in depth despite having undefined disparity. Because a total of six individual paired comparisons were made using paired t-tests, Bonferroni corrections were applied to maintain a family-wise α of 0.05. The corrected α value was $\frac{0.05}{5} = 0.01$. In addition, a supplementary 2 × 2 analysis of variance (ANOVA) was performed to examine the factorial combination of the two independent variables of pattern (fixed/changing) and depth (fixed/changing).

Results

Screening and the Incidence of Stereoblindness

In total, 127 participants (85 women, 42 men; mean [SD] age 21 [5] years) who passed the screening were assessed. Of these, 19 were excluded on the basis of unreliable performance (see Threshold Estimation in the Materials and Methods section). Table 2 provides an indication of the conditions in which the remaining 108 participants were most and least able to detect depth, with Figure 3 showing threshold performance for each of the conditions.

Do Dynamic Stimuli Result in Lower Depth-Detection Thresholds Than Static Stimuli?

Neither the comparison between the STATIC and PATTERN CHANGE ($t_{43} = 0.37$, $P = 0.71$) conditions nor the comparison between the STATIC versus X-LOCATION CHANGE ($t_{47} = -0.84$, $P = 0.405$) conditions showed a significant difference. However, a different pattern emerged for stimuli that featured motion in depth. A comparison between the STATIC condition

TABLE 2. Number of Observers in Each Condition Who Provided a Satisfactory Weibull Fit and Whose Thresholds Were Subject to Further Analysis ($n = 108$)

	STATIC	PATTERN CHANGE	Z-LOCATION & PATTERN CHANGE	X-LOCATION CHANGE	Z-LOCATION CHANGE	CONTROL
Percentage of satisfactory fit (n)	61 (66)	61 (66)	53 (57)	59 (64)	66 (71)	11 (12)

versus the Z-LOCATION CHANGE condition showed a significant difference between thresholds ($t_{46} = 6.55$, $P < 0.001$), and the Z-LOCATION & PATTERN CHANGE stimulus also yielded a significantly lower threshold than the STATIC condition ($t_{42} = 5.40$, $P < 0.001$). This indicated that the presence of changing disparity enhanced the detection of depth, whereas there was no evidence of any such enhancement for changing stimulus patterns or for stimuli moving laterally.

Factorial Combination of Pattern and Z-Location Change

The factors of Z-LOCATION CHANGE and pattern change were subjected to additional scrutiny in a 2 × 2 within-subjects ANOVA to assess their effects and the possibility of interactions. Of the 108 participants, 27 were able to provide a reliable threshold in each condition included in this analysis. Data are represented in Figure 4. Here, thresholds were lower for conditions involving changing depth, an observation that was confirmed by the presence of a statistically significant main effect of depth ($F_{1,104} = 8.23$, $P = 0.005$). No main effect of pattern was found, as indicated by the similar thresholds for the two plots ($P = 0.947$). The interaction between pattern and depth was not significant ($P = 0.757$), indicating that the enhancements brought by changing depth apply equally to all stimuli regardless of the persistence of the pattern.

Control for the Use of Nondisparity Signals

To assess the potential for motion-in-depth signals (in the absence of disparity signals) to contaminate the measurement of depth-detection thresholds, we used a CONTROL condition that includes the IOVD cue to motion in depth. The median threshold for this condition was at ceiling level, with only 11% of participants able to use this cue reliably (Table 2). This confirms the hypothesized inability of the vast majority of participants to glean any positional depth information from this cue. For the small number of participants who did record thresholds in the CONTROL and STATIC conditions, they were significantly higher than for the STATIC condition ($t_7 = -3.67$, $P = 0.008$).

To ensure that no monocular cues were used to identify the target stimuli, a small subset ($n = 3$) participated in an additional control experiment in which all conditions were viewed as described previously with the additional occlusion

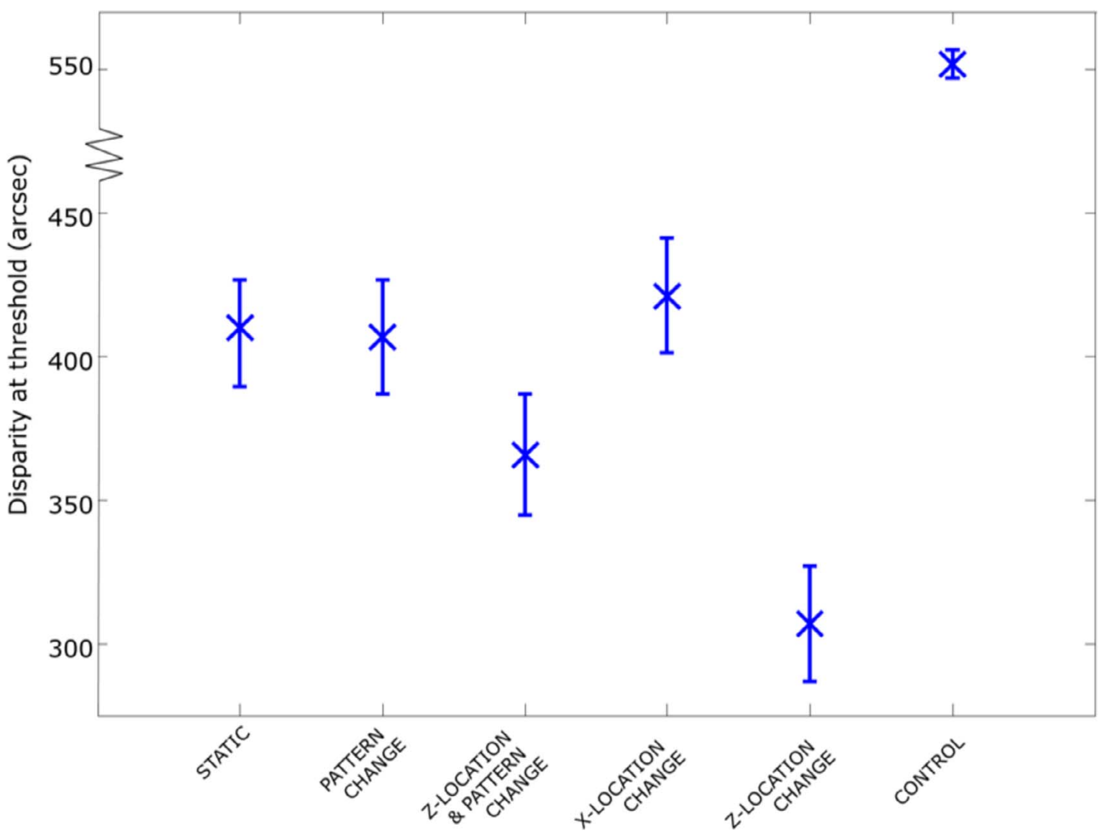

FIGURE 3. Mean (±1 standard error of the mean) depth-detection threshold for patients who met the defined criteria. The number of patients for each condition is as stated in Table 2.

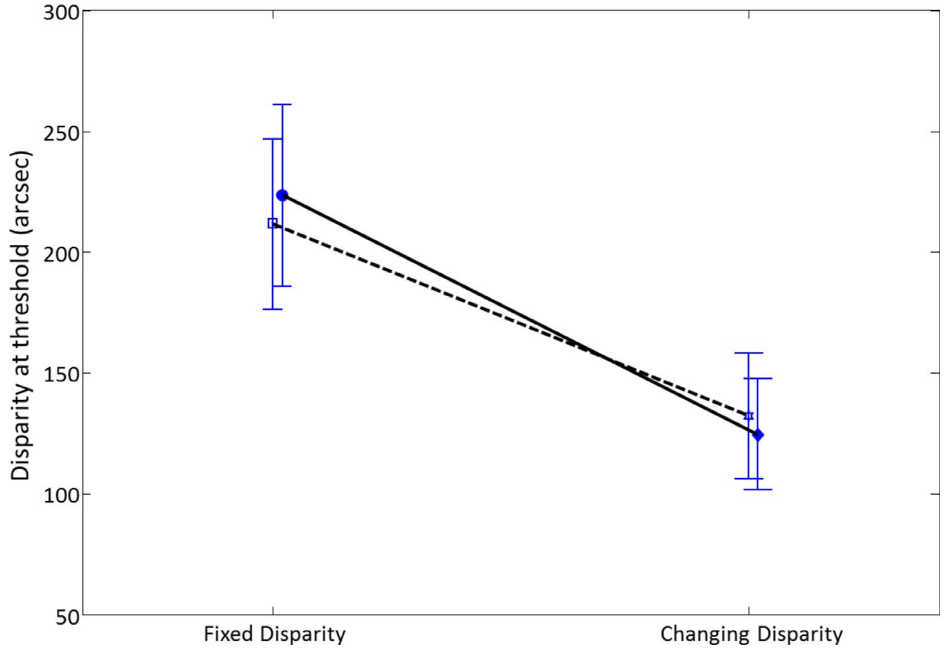

FIGURE 4. Factorial combination of the disparity and pattern factors. *Error bars* represent ±1 standard error of the mean, the *dotted line* signifies the changing pattern conditions ($n = 27$).

of one eye. Under these monocular conditions, no participant was able to perform the task in any condition, demonstrating that there were no informative monocular depth cues present.

DISCUSSION

Dynamic Stereoscopic Stimuli and the Perception of Depth

The experience of depth perception during stereoscopic film or television viewing has been reported in observers lacking clinically measurable stereoacuity.[2] In the aforementioned study, no attempt was made to identify the factors that may contribute to the perception of depth in dynamic displays. The aim of the current study was to isolate the characteristics of dynamic stereoscopic stimuli and to establish their contribution to depth detection. Although there have been reports of dynamic stimuli resulting in better stereoscopic performance[5–8] (in terms of preserved ability to detect stereoscopic motion in depth despite the absence of static stereopsis), to the best of our knowledge our study is the first direct comparison of depth detection between static and dynamic stimuli. We have shown that for some dynamic stimuli, lower thresholds are common for many observers. This advantage for dynamic disparity information is specific to motion in depth and does not occur for patterns moving horizontally or for those that change their surface pattern over time (temporally decorrelated).

Task Difficulty

Of the 127 participants, we excluded 19 from the analysis because they failed to provide reliable responses in any condition. We were interested in testing depth-detection performance in a representative sample of a normal population, where a number of participants are unable to perform psychophysical experiments,[27] whereas these types of studies are often performed on a small set of highly experienced observers.[30] All participants demonstrated the presence of stereoscopic vision during screening (stereo fly test circles <200 arc seconds), but only 61% of participants were able to provide a reliable response in the STATIC condition. The reason for this could again highlight the noncomparability of stereotests, but there are a number of other reasons for this.

It could be suggested that the participants did not understand the task, did not comply with instructions given, or were unable to detect any depth within the 1-second presentation. As shown in Table 2, no condition yielded satisfactory fits for all participants, with 53% to 66% meeting our criterion in the first five conditions, suggesting similar task difficulty across these conditions. The variability in the percentage of reliable fits follow a similar pattern to the thresholds, for example, the most reliable condition was the one in which depth-detection thresholds were lowest.

To further ensure the exclusions were not artefacts of the Weibull fitting procedure, we verified that using the last four reversals of each condition as the threshold for each participant (converging at 79.4%) yielded thresholds similar to fitting the Weibull (threshold is defined as the disparity corresponding to 72.4% correct). The discrepancy between these two methods was always less than 6.5%, and the pattern of the results is not affected by the method used to derive the threshold.

Furthermore, to ensure our arbitrary cut off criteria of $r^2 = 0.3$ did not represent heavy filtering that may bias our results, we repeated the analysis. This demonstrated that the analysis is robust and does not depend on the exact value of r^2 used as a cutoff; the conclusions do not change when an r^2 of 0 is used.

The average level of stereoacuity in the population tested may seem poor (ranging from 180 arc seconds to 351 arc seconds across conditions) when compared with previously published thresholds of less than 5 arc seconds.[31] However, our intention was to test a large sample of observers with differing levels of stereoscopic proficiency. In addition, our experiment was not designed to measure the limits of stereoacuity under optimal conditions[18] but, rather, to examine the relative effectiveness of dynamic versus static cues to

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depth. Even so, 10 participants were able to perform with high precision at one pixel disparity (18.1 arc seconds), the minimum disparity presented. Other potential reasons for the increased thresholds may be in part a result of the depth-cue conflicts present in the stimuli because of the removal of other cues to depth, such as changing size. As is common in studies of stereo/stereomotion, monocular cues to depth are removed with the aim of isolating the cue of interest for investigation. Other factors such as a limited display time, eccentricity of target, and spatial parameters may also contribute to the large thresholds measured in this study.

Disparity thresholds depend on spatial frequency with peak stereoacuity (3 to 4 arc seconds) found at 0.3 cycles per degree when sinusoids are used.[32] Our stimuli are more broadband (in frequency space) and shifted to higher spatial frequencies, well beyond the optimal spatial frequency for stereoacuity. Furthermore, it has been demonstrated that stereoscopic discrimination thresholds increase as eccentricity increases,[33,34] with low thresholds demonstrated when participants can fixate directly on the target and comparator with no time constraint.[35]

Facilitation Specific to Disparity Change

To test whether the detection of depth in moving stimuli was specific to motion in depth rather than to moving stimuli in general, a condition using lateral motion with fixed disparity was included (X-LOCATION CHANGE). We found that unlike changing depth, adding lateral motion to a fixed-disparity stimulus does not improve stereoacuity when compared with a static stimulus with fixed disparity. These findings are in line with previous studies as the velocities used here are below 2°, a level above which depth-detection thresholds worsen.[16] In addition, the effect of changing dot patterns was assessed in a 2 × 2 ANOVA, which showed neither an effect of changing pattern nor an interaction between changing depth and changing pattern. As such, the effect of changing depth is able to account for all examples of enhanced depth detection when compared with the STATIC condition.

A potential confound relating to the *z*-location change conditions (Z-LOCATION CHANGE, Z-LOCATION CHANGE & PATTERN CHANGE) is that the target stimulus did not contain lateral motion, whereas the distractor stimuli did to prevent their identification through monocular viewing. The lack of objective lateral motion in the target stimuli could, in principle, reveal the correct answer. However, it has been documented that observers often perceive such stimuli to have a degree of lateral motion (because of a bias in the perceived speed of one of the half images), just as the distractors do, hence preventing participants from using this cue. Even if this had not been the case, we believe that the use of this cue is unlikely because not only would these two conditions have to be identified out of the six interleaved but also any lateral motion perceived in the motion-in-depth stimuli would need to be ignored, the change in binocular disparity ignored, and solely the difference in lateral motion be identified.

Methods to avoid this potential confound would introduce further confounds; by adding lateral motion to the distractors and target, there would still be a greater amount of lateral motion in the target stimuli. If a random amount of lateral motion were added to the distractors and target patch, a random trajectory for the patch moving in depth would be introduced and hence a lack of standardization of this stimulus condition. A random amount of lateral motion added to the distractors but a constant amount added to the target would result in the speed of lateral translation of the target patch differing from the controls, again providing a method of identifying the target by artifactual means. In addition, and perhaps most important, adding any lateral motion to the target would prevent the research question from being answered; it would produce an oblique trajectory with both x and z motion, preventing the isolation of z-location change.

The possible influence of IOVD on depth detection in the absence of binocular disparity signals was assessed using the CONTROL condition. In this condition, the relative motion of the target compared to distractors is effectively doubled, given that motion of the distractors was equal and opposite to the motion of the target patch. The IOVD cue is most effective in simulating motion in depth when contrasting or relative motion is present.[36] Alongside controlling for monocular and diplopic cues, the use of doubled stimuli provides the opportunity for good performance in this condition if the recognition of motion in depth were reported by the participants rather than depth. Although targets in this condition may have appeared to move in depth, few participants could give reliable responses, and for the latter, thresholds were high. Of the 11% of participants who provided a reliable depth-discrimination threshold, only three were able to provide a threshold below ceiling (543 arc seconds), with a threshold of 161, 477, and 512 arc seconds. It is possible that these three participants interpreted motion toward themselves as being closer in depth than the distractor stimuli because they were asked to identify the patch that appeared closest to them in space. As soon as the target approached it would have appeared closer than the distractors, and as a binocular response was required to correctly identify this, this was defined as a correct response. Feedback was provided in the same manner as in other conditions; we interpreted the identification of the approaching patch as the closest patch as a correct answer and provided positive feedback. Although one participant recorded a threshold of 161 arc seconds (191 arc seconds in Z-LOCATION CHANGE & PATTERN CHANGE and 182 arc seconds in Z-LOCATION CHANGE), the other two participants provided their highest threshold in the CONTROL condition. This lends confidence in our results, confirming that the IOVD cue did not contaminate the conditions in which depth appeared to change over time.

When considering the literature on the ability to detect a change in direction of motion through depth rather than the detection of depth in moving stimuli, several studies have shown examples of stereomotion blindness with intact static depth perception. This has been demonstrated to coincide in specific areas of a single individual's visual field, although normal performance may be possible in other areas. This area can be either a location in a frontoparallel plane or a range of disparities.[37–40] Cases of intact stereomotion perception in areas where participants are unable to detect differences in static depth have also been presented in the peripheral visual field of strabismic participants.[6,10] This evidence is complementary to present findings showing sensitivity to dynamic stereo in the absence of static stereopsis.

Conclusions

We have shown the importance of dynamic stimulus characteristics—particularly of changing disparity—in binocular depth perception. Based on our sample (n = 108) of participants with measurable stereovision, we conclude that this stimulus attribute is a likely candidate to explain some of the discrepancy between some observers' ability to enjoy enhanced depth simulation in 3D movies despite their diagnosis of stereoblindness. Although it has previously been shown that some stereo-deficient participants can *detect motion* in depth from stimuli that approach or recede,[5–10,39,41] this is the first study to show that performance for *detecting depth* is improved under such circumstances, while other dynamic characteristics such as horizontal motion and varying stimulus pattern have no measureable effect.

Our findings have implications for neurobiological models of binocular vision by providing useful constraints on the relative importance of static versus dynamic disparity signals for depth perception. Dynamic disparity changes (condition 4: Z-LOCATION CHANGE) are ecologically valid signals that arise either from self-motion or from object motion toward the observer. Our data show that these dynamic disparity signals are associated with the highest performance for depth detection, consistent with their ecological validity.

Given the omission of changes of disparity, currently used static stereoacuity tests may underestimate the degree of binocular function. With this in mind, the present study constitutes an important first step toward the development of a clinically useful test of dynamic stereoacuity to reflect real-world interactions with depth.[42–46]

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