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Dynamic cues to binocular depth

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Abstract

Aim: **Subjects with no clinically measurable stereo-acuity report compelling 'pop-out' depth effects when viewing a 3D stereoscopic video. The purpose of this study was to systematically investigate the effectiveness of static and dynamic stereoscopic stimuli, by isolating cues to depth present in stereoscopic 3D entertainment media.**

Methods: **Stereoscopic stimuli were developed that either featured or lacked changes of disparity and/or of stimulus pattern. A PC-controlled 4-alternative-forced-choice (4AFC) task was used to assess the depth detection thresholds of visually normal subjects, with stimuli presented on a passive polarised stereoscopic monitor at 3 m. Thresholds were determined in four conditions: baseline STATIC (fixed disparity level), STATIC PATTERN CHANGE (fixed disparity level with a change in stimulus pattern), Z-LOCATION CHANGE (disparity increase towards target level with a fixed pattern) and CDOT (disparity increase with pattern change).**

Results: **In total 32 subjects aged 18–41 years were recruited from the University of Liverpool. The mean(±SD) thresholds were: STATIC 183″(±101), Z-LOCATION CHANGE 120″(±60), CDOT 167″(±111) and STATIC PATTERN CHANGE 241″(±129). The conditions which contained a change in z-location yielded a significantly lower threshold than those with fixed disparity ($p > 0.01$), whereas the presence of a pattern change resulted in a statistically significant reduction in threshold ($p > 0.05$). There was no significant interaction between the factors.**

Conclusion: **By directly comparing thresholds for static and dynamic conditions using stimuli presented on the same device with the same settings (such as display duration, size, contrast, colour, display method, luminance, testing protocol), we can conclude that it is the dynamic nature of the disparity information that confers a benefit on individuals' depth detection. The dynamic facet of stereopsis may contribute to the compelling 'pop-out' effect described when viewing 3D entertainment media.**

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Introduction

A large proportion of the population have binocular vision deficits, with the prevalence of strabismus between 2.3% and 3.6% in young children alone.[1–4] These deficits often lead to reduced or absent stereo-acuity when assessed with current clinical methods. At the same time, qualitative work has shown that even in the absence of clinically measurable stereopsis, the experience of compelling 3D volumetric depth is reported when viewing dynamic stereoscopic stimuli such as 3D video.[5–7] The discrepancy between clinical measures and patient reports may be due to the limitations of clinical tests, or additional cues present in stereoscopic entertainment media.

Multiple monocular cues to depth are present in video, which provide the perception of depth considered as compelling as binocular disparity-based depth information.[8] These cues are summarised in Table 1. Table 1 clearly shows that binocular disparity is not the sole cue used to extract depth information; however, it is an important indication of the quality and control of an individual's binocular single vision. In clinical ophthalmological practice, testing currently only assesses one facet of this, namely static binocular disparity. Table 1 shows that motion is useful for the detection of depth order, the determination of shape, and the discrimination of movement through depth. Motion should therefore be considered an important binocular cue.

Motion in depth, present in both monocular and binocular stimuli, provides the impression of movement of a stimulus through depth, towards or away from the observer. The presence of this dynamic facet of stereopsis has been demonstrated in the absence of measurable static stereo-acuity. Of 42 subjects who were unable to identify depth on a static stereo-acuity test which displayed disparities up to 1200″ (Titmus stereotest), 22 were able to identify binocular motion in depth at a threshold of 500″ or smaller.[25,26] Other studies suggest that the presence of dynamic disparity results in the identification of motion in depth, where static disparity demonstrated no depth.[27,28] Furthermore, the time taken to identify which target is closest to an observer is significantly shorter when the target moves through depth, even if the stationary presentation has a

Table 1. Monocular cues to depth divided into those that do not include motion (Static) and those that do (Dynamic)

		Static depth	Dynamic depth
Accommodation		With a high contrast pattern, the apparent distance of a stimulus decreases as accommodation increases.[9] Changes in accommodative demand can be used as a source of ordinal distance information[10]	*No evidence found*
Perspective	Size	The size of familiar objects can provide information on relative distance[11,12]	Individuals are able to determine a change in depth based on the expansion or contraction of an object's border over time[13]
	Linear	The convergence of receding parallel lines gives the impression of greater distance with increased proximity to the vanishing point[14]	*No evidence found*
	Height in field	Typically, objects higher in the visual field are at a greater distance. If a base up prism is worn and adapted to, an object on the ground is perceived as further away[15]	*No evidence found*
	Texture gradient	A change in the texture gradient gives the impression of a change in surface slope. The smaller, denser or more keystoned a texture is, the further away it is perceived[16]	As the texture elements expand or contract, individuals can determine a change in depth over time[13]
Interposition		Most scenes consist of distinct elements. A familiar complete object is perceived as closer to the observer when occluding an object behind[17]	As additional elements are added and occlude those behind, a sense of movement in depth is perceived by the observer[18]
Lighting	Shading	Based on the rational assumption that light falls on an object from above (specifically 26° left from vertical), the visual system interprets depth as concavity or convexity based on shading[19]	*No evidence found*
	Shadows	The visual system has a highly sensitive mechanism for discriminating shadows, which provides information about the location in depth of the object casting the shadow[20]	As an object moves diagonally across a plane while its shadow moves horizontally, the increased separation provides the impression of the object rising from the surface[21]
	Aerial perspective	The scattering of light by dust and water vapour in the atmosphere reduces the contrast of objects at greater distances. A more blurred or lower contrast region will therefore appear more distant than a less blurred, higher contrast region[22]	*No evidence found*
Motion parallax		When an individual point in space is fixated upon and the viewer's eye moves to the right, all objects beyond fixation move to the right, whilst all objects closer than fixation move to the left. Objects further from fixation will also appear to move more slowly than those closer[23]	The Kinetic Depth Effect. A small bar, illuminated from behind and projected onto a screen, will appear as a flat shadow. When this bar is rotated on an axis parallel to the screen however, 3D form becomes apparent[24]

larger amount of disparity.[29] When asked to compare static and dynamic targets, observers matched smaller amounts of disparity when motion in depth was present, compared with a static disparity target.[30] The presence of motion in depth enhances the perception of depth.

Motion in depth (a depth change) contains two binocular cues: changes in disparity over time (CDOT) and interocular velocity differences (IOVD).[31,32] The CDOT mechanism determines the amount of spatial disparity present between the images projected onto each retina, continually monitoring for changes. If the amount of disparity of an object seen in depth increases or decreases over time, the object is perceived to be moving towards (looming) or away (receding) from the observer. The IOVD mechanism does not rely on determining spatial disparity; rather it uses the motion of the images projected onto each retina, and based on any difference between the motion in the left and right eye (speed or direction) perceives motion through depth. It appears also that the CDOT cue is used by most individuals in isolation whereas fewer are able to use the IOVD.[33]

While these studies agree that the presence of motion in depth can demonstrate binocular function in the absence of measurable static stereo-acuity, there are a number of limitations of the methodologies employed, such as the comparison of different disparity ranges and the use of differing presentation methods (computer display vs paper-based testing) between the static and dynamic conditions. Also, previous studies have investigated the perception of motion in depth, rather than depth detection *per se*. Therefore, the aim of this study was to directly compare static and dynamic conditions, using stimuli presented on the same device, to determine whether dynamic cues to depth result in lower thresholds than static cues.

Methods

Screening

Ethics approval was gained from the University of Liverpool Ethics Sub-committee and the study was performed in accordance with the ethics standards laid down in the Declaration of Helsinki. Participants were recruited from the University of Liverpool through the electronic participant recruitment system and informed consent was gained from each subject. Prior to participation in the experiment each subject was screened to meet the inclusion criteria of a visual acuity difference (with any correction) of fewer than 2 lines (logMAR ETDRS VA chart), no manifest deviation as determined

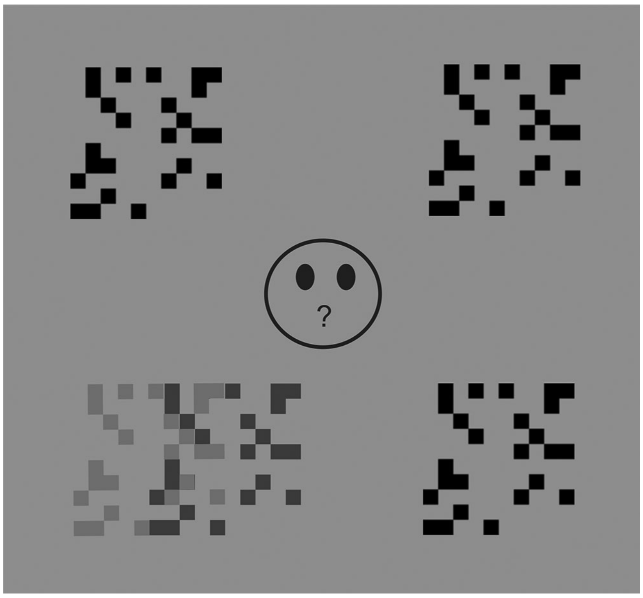

Fig. 1. Schematic of stimuli on screen. The lower left stimulus shows a target stimulus with a disparity between the left and right half-images of 0.05° (10 pixels). When wearing 3D glasses each of the half-images would be presented to each eye individually.

by cover test (near and distance), the presence of motor fusion (prism fusion range) and stereo-acuity (Frisby stereotest) of 85″ or better.

General stimuli and tasks

The experiment was presented on a 22″ film type pattern retarder monitor (FLATRON D2342, LG Electronics), where alternate horizontal lines of pixels (1080) were polarised to the right or left eye in turn when passive 3D circular polarising glasses were worn. The screen was positioned 3 m from the subject, with a horizontal resolution of 1920 pixels distributed over 50 cm, where each pixel subtended 0.005° or 18.1″. The black dots within each patch were presented on a grey background with 99.6% contrast and a mean luminance of 9.75 cd/m^2. The experiment was controlled by a Pentium i3 Windows PC with an NVidia Quadro FX4600 graphics processor, running Psychopy.[34] The subject's head rested on a forehead/chin rest to align their eyes with the centre of the screen and fixation target. The experiment was performed in a dark room with no external light source.

A spatial 4-alternative-forced-choice procedure (4AFC) was used (Fig. 1), with the target random-dot stimulus (presented with crossed disparity compared with 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). In each condition the subject had to choose which of the four patches appeared closest to them in space using a response box. The target patch was always presented with crossed disparity. The instructions were standardised and presented on screen prior to each condition. A fixation target (diameter 0.36° (76 pixels)) was provided in the centre of the screen which provided feedback to the subject upon response, green indicating a correct response and red an incorrect one. The patches subtended 0.5° square (100 × 100 pixels), containing 25 dots of 0.05° square (10 × 10 pixels). All four patches were initially displayed away from the fixation target horizontally by 0.6° (120 pixels) and vertically by 0.68° (135 pixels). The design aimed to maintain all stimuli within a central 5° of fixation (2.46° horizontal and 1.18° vertically from the centre of fixation). The maximum separation of the stimuli on screen was 30 pixels (543″) to avoid overlap of the patches.

The four patches were identical aside from the introduction of disparity in the target patch and were displayed on screen for 1 second in all conditions, followed by the fixation target in isolation. When the subject provided a response the next trial would be presented. A staircase procedure was controlled by Psychopy[34] for each of the conditions; thus the amount of disparity decreased if depth was perceived or increased if the subject could not detect depth (Fig. 2). A three-down, one-up method was used so that the staircase converged to a performance of 79.4% correct in order to determine threshold.[35]

Experimental conditions

The main comparison in the experiment was between the static and depth change conditions, but to further investigate dynamic depth cues we included a CDOT-only condition for comparison. Further, a fourth condition was also introduced as a control for the CDOT condition. The order of presentation of these conditions was randomised for each subject. All stimuli were displayed for a total of 1 second. The features of each condition were as follows:

1. STATIC: Stimulus presented at a fixed amount of disparity. Between each trial the pattern of dots changed.
2. Z-LOCATION CHANGE: Each half-image consisted of the same pattern of dots during the 1 second presentation; however, every 167 ms an increase in the amount of disparity occurred from the initial value of one-sixth of the target disparity. For example, for a target disparity of 60″: in the first 167 ms the disparity was 10″, increasing to 20″ for the next 167 ms, and then up to 60″ for the final 167 ms of the presentation time. Between each trial the pattern of dots changed.
3. CDOT: This condition was similar to the Z-LOCATION CHANGE condition; however, on each change in disparity the pattern of dots making up each patch also changed in the target and control patches.
4. STATIC CHANGING PATTERN: To ensure any differences between the dynamic and CDOT conditions were not due to the changing pattern of dots during presentation, this condition was identical to the STATIC condition with the pattern of dots changing every one-sixth of a second. For example, for a target disparity of 60″: for the first 167 ms the disparity was 60″ with one pattern, for the next 167 ms the disparity remained at 60″ but a different pattern of dots was presented, etc.

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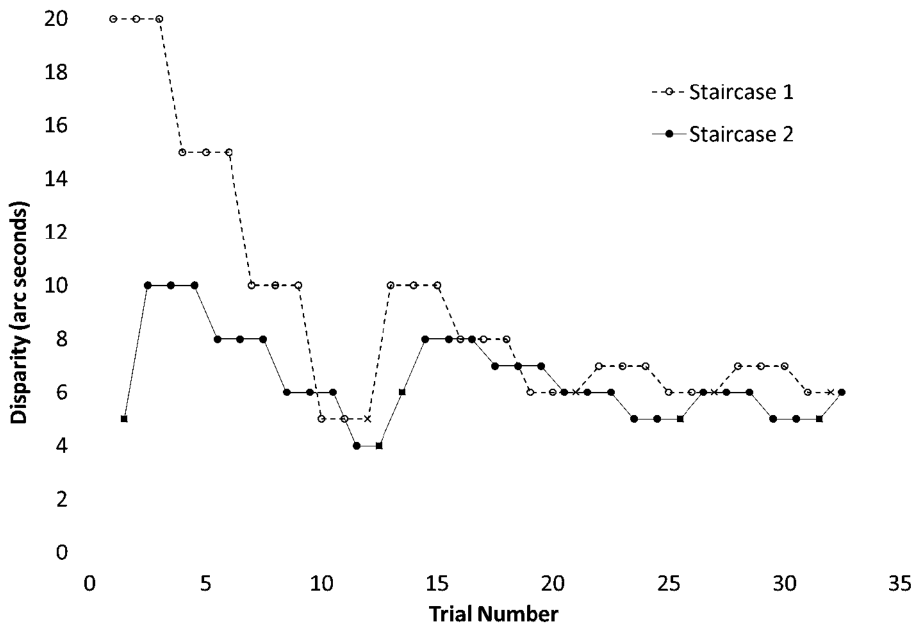

Fig. 2. Example of two staircases converging for one condition using a three-up, one-down procedure. An incorrect response is represented by a cross, as is shown in the plot. Three correct responses are required for the task to become harder (disparity decrease); however, one incorrect answer will make the task easier (disparity increase). This disparity threshold is approximately 6″ in this example.

To exclude any cue from monocular viewing or from motion alone indicating the correct response in the conditions with changing disparity (Z-LOCATION CHANGE and CDOT), lateral motion was introduced into the three distractor patches in the stimuli. The amount of motion was identical to the distance moved by the target patch, occurring every 167 ms; however, rather than the half-images moving in opposing directions to create crossed disparity, the non-target-patch half-images moved in the same direction, thereby providing the same amount of retinal motion but zero disparity change.

Statistical analysis

To obtain stereo-acuity thresholds for each participant a cumulative Weibull function was fitted to the relative frequency of correct responses as a function of disparity level.[36] This procedure finds the best-fitting sigmoidal curve given the data points (i.e. the relative frequencies at each disparity level). Two parameters are fitted for each data set: the location of the curve along the x-axis and the steepness of the curve. Threshold is defined as the disparity level where the observer achieves 72.41% correct. On the x-axis disparity levels are plotted, and on the y-axis the relative frequency of a correct response (Fig. 3). The purpose of the experiment was to design a stimulus that allowed us to compare stereo-acuity between static and dynamic conditions but not to assess the limiting stereo-acuity performance of observers. Hence the stimuli were not optimised to measure the limiting performance, and therefore it was expected that naïve participants would find it difficult to complete the task. To be included in the analysis, it was required that at least one of the four conditions resulted in a reliable Weibull fit (r^2 of at least 0.3), to demonstrate the subject understood the task.

Results

In total 32 subjects aged 18–41 years were recruited, screened and took part in the experiment. The average interocular visual acuity difference was mean (±SD) 0.04 (±0.04) logMAR. Reliability of function fit was analysed for each participant (see example, Fig. 3), 7 of whom were excluded as they did not meet the criteria. The mean (±SD) age of the remaining subject was 25 (±1.2) years.

The mean (±SD) thresholds derived from the psychometric function fits in each condition were as follows: STATIC 182″ (±100″), STATIC CHANGING PATTERN 241″ (±128″), Z-LOCATION CHANGE 120″ (±60″), CDOT 167″ (±109″) (see Fig. 4). The thresholds were analysed using a 2-way ANOVA, with 'pattern type' being one factor (changing/static) and 'disparity type' the other (static/changing). We found two main effects: stereo-acuity thresholds are lower when the disparity information is dynamic ($F(1,80) = 9.33$, $p < 0.01$), and changing the pattern during presentation leads to an increase in thresholds ($F(1,80) = 5.35$, $p < 0.05$) (Fig. 4) There was no significant interaction between the two factors ($p = 0.81$).

Discussion

In previous studies,[6,7] subjects reported compelling depth perception when viewing stereoscopic 3D entertainment media in which a large variety of cues to depth were present in the stimuli. The aim of the current study was to remove monocular cues to depth to investigate the contribution of dynamic disparity information for depth detection.

By directly comparing thresholds for static and dynamic conditions using stimuli presented on the same device with the same settings (display duration, size, contrast, colour, display method, luminance, testing

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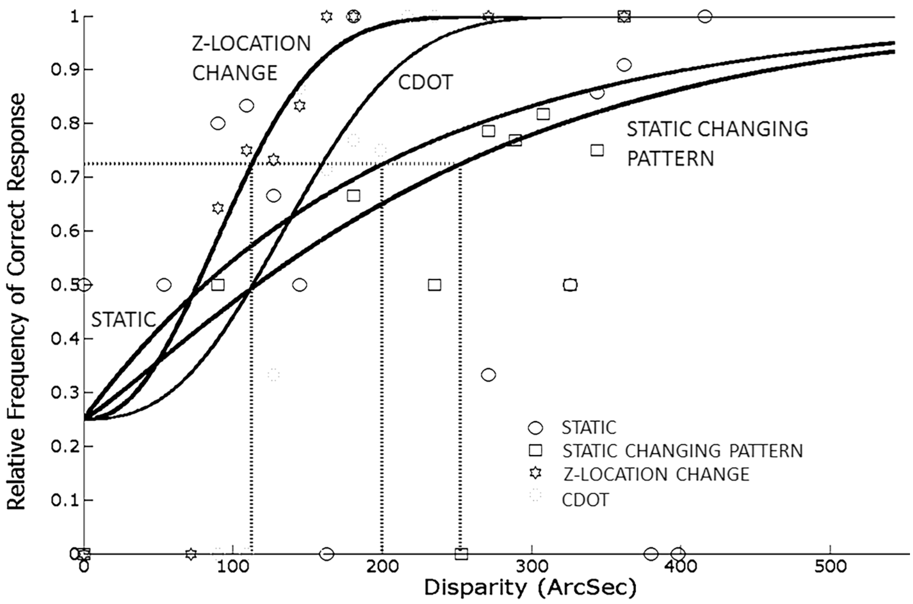

Fig. 3. An example of the fitting procedure demonstrating two good fits (upper two lines) and two poor fits (lower two lines). The diamond and star points are well fitted by the Weibull function ($r^2 \approx 0.8$) whereas the square and circle points do not follow the function to the same degree ($r^2 \approx 0.4$).

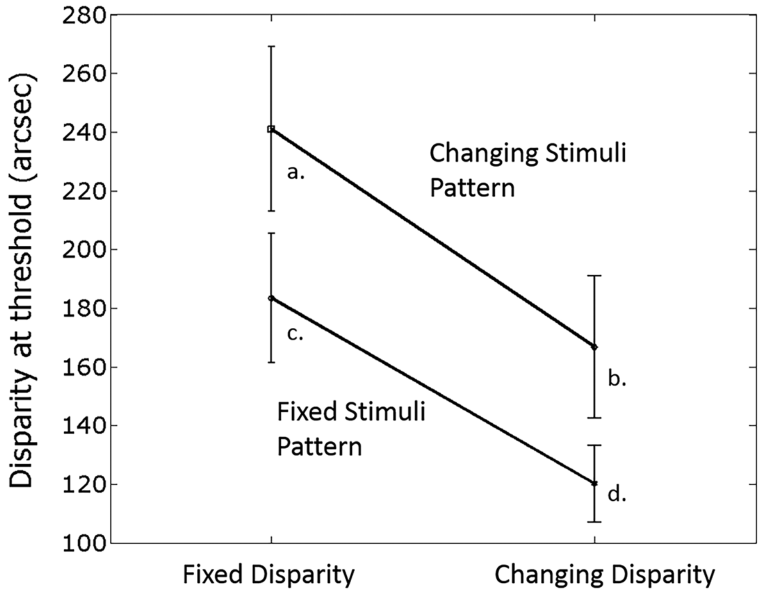

Fig. 4. Plot of mean (error bars = ± SD) threshold disparity for each condition. (*a*) STATIC CHANGING PATTERN, (*b*) CDOT, (*c*) STATIC, (*d*) Z-LOCATION CHANGE.

protocol), we can conclude that it is the dynamic nature of the disparity information that confers a benefit on individuals' depth detection. This finding provides a potential explanation for the observation that those without measurable static stereo-acuity seem to perceive volumetric 3D depth at the cinema,[5,6] and can accurately report changes in depth when these are presented dynamically.[25–28]

The lowest thresholds were found for the Z-LOCATION CHANGE condition (changing disparity/ fixed pattern), which is consistent with the idea that the CDOT cue alone is not solely responsible for depth detection of motion-in-depth stimuli, but that another cue, the IOVD cue, might be utilised, in line with previous reports.[33]

Additional experiments have been conducted to determine whether isolation of the IOVD cue results in the perception of depth. By definition, no disparity information is available in the IOVD cue, as no spatially corresponding points exist between the two eyes; the IOVD cue signals only a change in position. Indeed, of 132 subjects assessed in a subsequent study, only 12

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were able to provide a reliable fit in the IOVD-only condition, with thresholds significantly higher than any other condition.[37]

Of the 32 subjects tested, 7 were not included in the analysis as they did not provide a reliable function fit in at least one condition. As the population of subjects used in this study were not familiar with psychophysical testing methods, it is not unexpected that a considerable proportion did not provide reliable data. A study using similar stimuli to display similar cues found that only half of their 62 subjects provided thresholds for use in analysis.[33] The level of stereo-acuity (e.g. STATIC 185″) measured in the study sample may appear poor; this is due to the design of the stimuli used in the experiment. The aim was not to measure absolute thresholds, but to allow comparison between the different conditions without creating a ceiling effect due to the relatively large pixel size in the display.

By introducing lateral motion to the distractor patches in the stimuli in the CDOT and Z-LOCATION CHANGE conditions, we aimed to ensure the subjects were not responding on the basis of monocular retinal motion alone.[31] Whilst no lateral motion was programmed in the target stimulus, a degree of lateral motion can be perceived in stimuli moving through depth, as the lateral motion is more readily detected than the depth change.[38]

The data presented here provide evidence that the human visual system can utilise dynamic disparity information more effectively than static disparity signals, corroborating work performed by Weldon *et al.*[29] This is distinct from other studies mentioned here, where the ability to detect motion was assessed. Our finding that dynamic disparity processing is superior to static processing warrants further investigation and potential development of a clinical test, to allow the full assessment of binocular potential to assist management decisions. Binocularity may be demonstrable when tested with a dynamic binocular test, where absence of response is found during static assessment.

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