PERGAMON

Vision Research 40 (2000) 3823–3827

Vision Research

www.elsevier.com/locate/visres

Stereopsis with persisting and dynamic textures

R.S. Allison *, I.P. Howard

Centre for Vision Research, York University, 103 Farquharson, Toronto, Ontario, Canada M3J 1P3

Received 5 May 2000; received in revised form 18 July 2000

Abstract

We measured the percept of changing depth from changing disparity in stereograms composed of random-dot textures that were either persistent or dynamically changed on every frame (a dynamic random-dot stereogram). Disparity was changed between frames to depict a surface undergoing smooth temporal changes in simulated slant. Matched depth was greater with dynamic random-dot stereograms than with persistent random-dot stereograms. These results confirm and extend earlier observations at depth threshold. We posit an explanation based on cue conflict between stereopsis and monocular depth cues.

Keywords: Stereopsis; Cue conflict; Dynamic random-dot stereogram

1. Introduction

Julesz (1971) introduced random-dot stereograms (RDS) for the study of binocular vision, particularly stereopsis. In a RDS, similar random-dot textures are presented to each eye as a stereogram. Disparity can be introduced by displacing the dots in one eye relative to those in the other without changing the statistics and appearance of the monocular textures. Thus, cyclopean stimuli can be created based solely on binocular disparities. This allows for the study of a wide range of cyclopean phenomena. One limitation of RDS stimuli is that, if the cyclopean stimulus moves, motion of individual dots is visible and the shape is no longer strictly cyclopean. Moving cyclopean shapes can be created in a dynamic-random-dot stereogram (DRDS) (Julesz & Payne, 1968). For each and every frame of the motion sequence, the stereogram is created from a new, independent sample of random dots. This removes coherent motion of individual dots and allows one to study of coherent motion of cyclopean shapes. In the present experiments, we measured the percept of changing depth from changing disparity in stereograms composed of random-dot textures that were persistent (RDS) or dynamically changed on every frame (DRDS).

2. Experiment 1: slant and inclination

Cumming and Parker (1994) showed that thresholds for detection of motion-in-depth can be lower for DRDS than for RDS stimuli. This result was unexpected since a DRDS eliminates the interocular velocity signals, which could serve as a cue to motion-in-depth. Other investigators have reported that depth detection or discrimination thresholds can be lower with DRDS stimuli (for example, as Ziegler and Roy (1998) found in a control experiment related to their main study). These earlier findings were anecdotal and at threshold. We were curious if suprathreshold depth perception differed with RDS and DRDS stimuli as well. In the first experiment, we investigated whether suprathreshold percepts of changing slant and inclination are stronger for stereoscopic motion sequences defined by RDS or DRDS stimuli.

2.1. Methods

Computer-generated images were rear-projected onto the screens of a large Wheatstone stereoscope using two Electrohome EDP-58 monochrome projection moni-

* Corresponding author. Fax: +1-416-736-5857.

E-mail addresses: allison@hpl.crestech.ca (R.S. Allison), ihoward@hpl.crestech.ca (I.P. Howard).

0042-6989/00/$ - see front matter
PII: S0042-6989(00)00223-6

tors. The screens subtended 65° height by 75° width at each eye at the viewing distance of 93 cm. Stereoscopic stimuli were presented in a dark room and all surfaces were covered with matte black cloth or paint. The display was composed of 640×480 pixels (width by height) refreshed at 67 Hz. Subpixel interpolation was employed to reduce the aliasing effects of a finite pixel count.

The half images were composed of white dots on a dark background (dot density, 3.36 dots deg^{-2}; dot size, 8 arc min). For each video frame, the same sample of a random distribution was used (persistent texture RDS) or a new sample from the random distribution was chosen (dynamic texture RDS). For both types of texture, disparity was changed between frames (frame rate, 33.5 Hz) to depict a surface undergoing smooth temporal changes in simulated slant, as shown in Fig. 1. Depth in this experiment was defined solely by gradients of disparity. The dots were randomly placed and distributed uniformly across each half-image's display and thus the monocular texture indicated a flat frontal surface. We used equal and opposite horizontal expansion or shear in the two eyes to create a stereoscopic surface changing in slant about a vertical or horizontal axis. After Howard and Rogers (1995), we will adopt the convention of using the term 'slant' to refer to slant about a vertical axis and the term 'inclination' to refer to slant about a horizontal axis. Peak theoretical slant or inclination on each trial was varied between ± 20 and $\pm 40°$ (with a few trials run at $\pm 80°$).

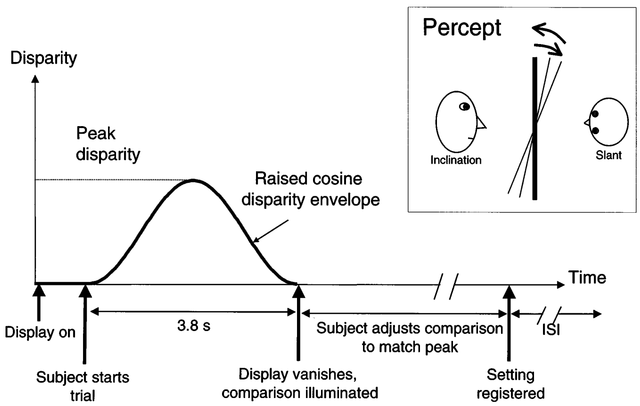


Fig. 1. Procedure and stimulus profile for each trial. The display appeared initially as a fronto-parallel stereoscopic surface. Following initiation by a button push from the subject, the shear or size disparity in the display was increased smoothly according to a single-cycle, raised-cosine profile. The period of the cosine and hence the duration of the motion sequence was 3.8 s. The peak disparity occurred at 1.9 s. The subject adjusted the comparison display until she/he was satisfied and the setting was read into the computer. The inset cartoon shows the subject's percept during the motion sequence.

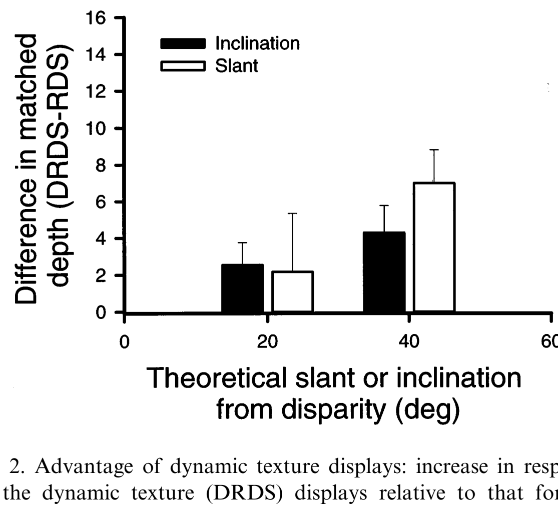


Fig. 2. Advantage of dynamic texture displays: increase in response for the dynamic texture (DRDS) displays relative to that for the persistent texture (RDS) displays. Data is collapsed across repeats and across responses for positive and negative directions of slant or inclination. The advantage of the DRDS stimuli for each observer is defined as the response to the RDS subtracted from the response to the DRDS for each condition. The figure shows this difference between the DRDS and RDS stimuli averaged across the eight observers versus theoretical slant and inclination from disparity (error bars indicate standard error of the mean).

Subjects matched the perceived slant or inclination of the test surface with that of a subsequently presented real surface located directly in front of the subject at a distance of 93 cm and visible through the semi-silvered mirrors when illuminated. The comparison surface contained a variety of depth cues to its true orientation, including absolute and relative disparity, texture gradient, blur and accommodation. The surface was supported on a visible gimbal mounting and could be rotated about either a horizontal or vertical axis by the subject, using a long steel rod. Following each presentation of a test surface, the real surface was illuminated and subjects adjusted its slant or inclination to match the perceived peak slant or inclination of the test surface. After the subject indicated the surface was appropriately adjusted, calibrated voltages from potentiometers attached to the slant and inclination axes of the comparison surface were read into a computer.

2.2. Results and discussion

Fig. 2 shows that mean slant and inclination matches were larger for the dynamic texture than for the persistent texture stereoscopic motion sequence. Perceived peak slant and inclination were larger with dynamic texture than with persistent dots for all eight subjects. For both DRDS and RDS stimuli, perceived slant and inclination were typically less than veridical.

There are several possible reasons why perceived depth in an oscillating stereoscopic surface is increased with dynamic texture. First, the improvement could be due to an increased effective density or luminance achieved by integrating across several frames. Second, it is possible that the correspondence problem could be eased or estimation reliability improved by having several independent samples of the stereoscopic surface available. Third, it may be due to the fact that cue conflict with motion perspective exists in the RDS case but not in the DRDS case.

To investigate whether effective dot density or luminance could be the determining factor, we repeated experiment 1 using a range of dot densities. The procedure, stimulus patterns and profiles were similar to those used in the main experiment, except that only persistent dot displays were used. Dot density was 0.84, 1.68, 2.53, 5.06 or 8.44 dots $\deg^{-2}$. This ten to one variation of dot density had no consistent effect on slant or inclination matches. Thus, we conclude that a simple increase in effective dot density or luminance was not responsible for the improvement in performance in experiment 1.

3. Experiment 2: perspective cue interactions

When depth is specified solely by disparity as in experiment 1, it is always in conflict with other depth cues that indicate a flat frontal surface. The relative contribution of various cues is thought to depend on their relative reliability (Landy, Maloney, Johnston, & Young, 1995). In a DRDS, lack of coherent motion signals presumably weakens the contribution of changing perspective. In experiment 2, we investigated the hypothesis that the increased slant and inclination for DRDS versus RDS stimuli reported in experiment 1 could be explained by cue conflict.

3.1. Methods

DRDS and RDS stimuli similar to those in experiment 1 were used but now slant or inclination was defined by perspective transformations as well as by disparity. The image pairs for each frame were precomputed and the base image transformed to produce surface slants and inclinations that were specified by either: (a) concordant perspective and disparity cues, which indicated the same slant or inclination; (b) conflicting cues, with disparity and perspective indicating equal but opposite slant or inclination; or (c) perspective alone under monocular, left-eye viewing.

Perspective projections to the simulated slanted or inclined planes were constructed from the cyclopean eye (midway between the eyes). Rays were cast from this vantage point through the screens of the stereoscope to the simulated surface. We computed the grey-scale value for each pixel to correspond to the random-dot surface at the intersection with the ray. The resulting perspective transformation was apparent both in the texture gradient and in the outline of the textured disk itself.

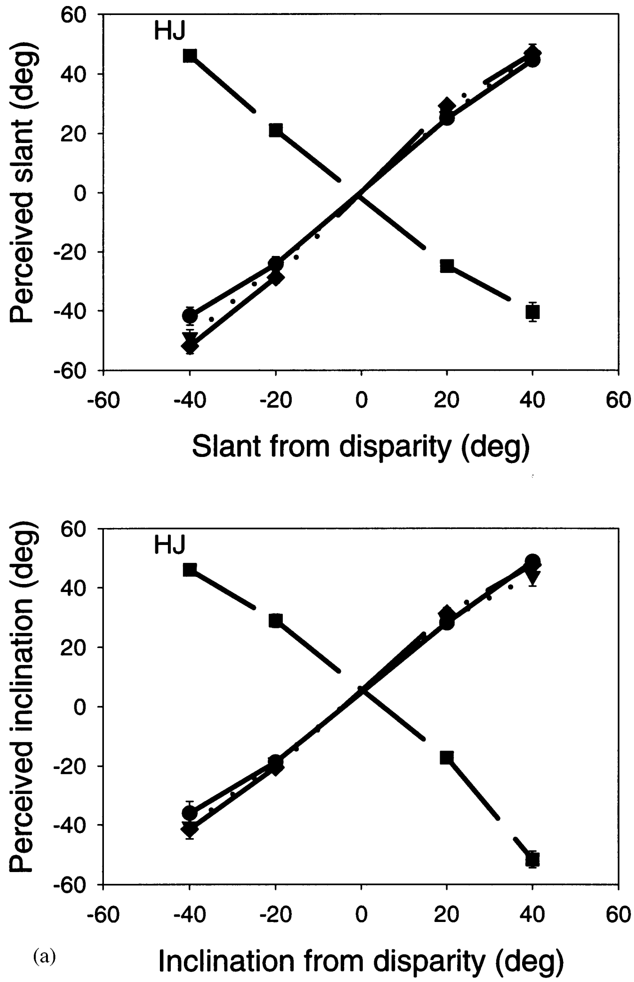
3.2. Results and discussion

For displays with concordant disparity and perspective cues, all five observers indicated strong percepts of changing depth, and matched peak slant and inclination were nearly veridical. When disparity and perspective indicate opposite directions of slant and inclination, the results depended on whether the random-dot texture was persistent or dynamically changing. With persistent texture displays, all observers saw depth according to the perspective transformation under conflict conditions. With dynamic texture, the influence of the disparity cue was more apparent. For example, with the dynamic texture, the observer in Fig. 3a reported slant and inclination matches near the theoretical value predicted from disparity. This was a complete reversal of the subject's results with static texture under conflict conditions, which were near the theoretical value predicted from perspective. Two other subjects also switched from using perspective with persistent texture stimuli to using disparity with dynamic texture stimuli. The responses of the other two subjects were less dramatic: they indicated perceived slant and inclination that was always in the direction predicted by perspective but that was smaller with dynamic versus static texture stimuli. Thus, results for all five subjects are consistent with the subjects relying less on perspective and more on disparity with DRDS rather than RDS stimuli.

Thus, perspective tended to dominate disparity more for persistent than for dynamic textures, which explains why disparity is relatively more effective in a DRDS. But is efficiency of disparity processing improved or are monocular cues weakened by dynamic texture? With monocular viewing of our stimuli, only the monocular cue of changing perspective is available. Fig. 4 shows that, under conditions of monocular left-eye viewing, perceived slant and inclination from changing perspective were smaller for dynamic texture displays than for persistent texture displays. Thus, it appears that the monocular cue of changing perspective is weakened in a DRDS.

4. General discussion

In this study, we found that dynamic texture stereograms can give better suprathreshold stereopsis than persistent texture stereograms, confirming earlier reports at threshold (Cumming & Parker, 1994; Ziegler & Roy, 1998). Experiment 1 showed that this improvement is not due to a simple increase in effective dot density or luminance. Simple increase in dot density (e.g. due to visual persistence) may not be effective since this increases matching ambiguity and matching noise. Increased dot density may also strengthen texture gradient cues.



(a)

Fig. 3. Effect of disparity-perspective cue conflict on slant and inclination matches for (a) one observer and (b) the mean response for the five observers. Disparity and perspective either specified the same slant (concordant) or opposite slant (conflict) for both the RDS and DRDS stimuli. Matched slant and inclination is plotted against theoretically predicted slant from disparity. Thus, for the conflict displays, a slope of + 1.0 indicates matches consistent with disparity and a slope of − 1.0 indicates matches consistent with perspective.

One possibility is that efficiency of stereopsis itself is improved with dynamic texture. This may result from the fact that each frame provides an independent sample of dots with which to make a slant judgement. Thus, we can average over a number of frames in order to get a more reliable low-noise estimate of slant from disparity. As the reliability of the estimate increases, we may tend to weigh it more heavily than the conflicting monocular cues (Landy et al., 1995). Furthermore, the matching problem in a DRDS is similar to that in a RDS of the same density on a frame-by-frame basis, but the DRDS provides several independent samples of dots that may aid in solving the global correspondence problem. Although DRDS frames are independently generated, the visual system integrates over several frames by means of apparent motion processing and visual persistence. Therefore, in practice, the ability to use each frame as an independent sample for matching or slant estimation would be limited.

The results of experiment 3 suggest a cue-conflict explanation for the increased depth with DRDS versus RDS stimuli. Monocular cues to depth in either type of stereogram typically indicate a fronto-parallel surface and therefore conflict with disparity. With a static stereoscopic surface, this conflict is usually resolved in favour of disparity, and stereoscopic depth is obtained. However, when the stereo surface oscillates in depth, cue conflict is enhanced under assumptions of surface rigidity and cohesiveness. At threshold, cue conflict between changing disparity and unchanging perspective is small. The conflict can be increased by using suprathreshold stimuli, as in this study.

Allison and Howard (2000) reported that the influence of conflicting perspective was enhanced when ki-

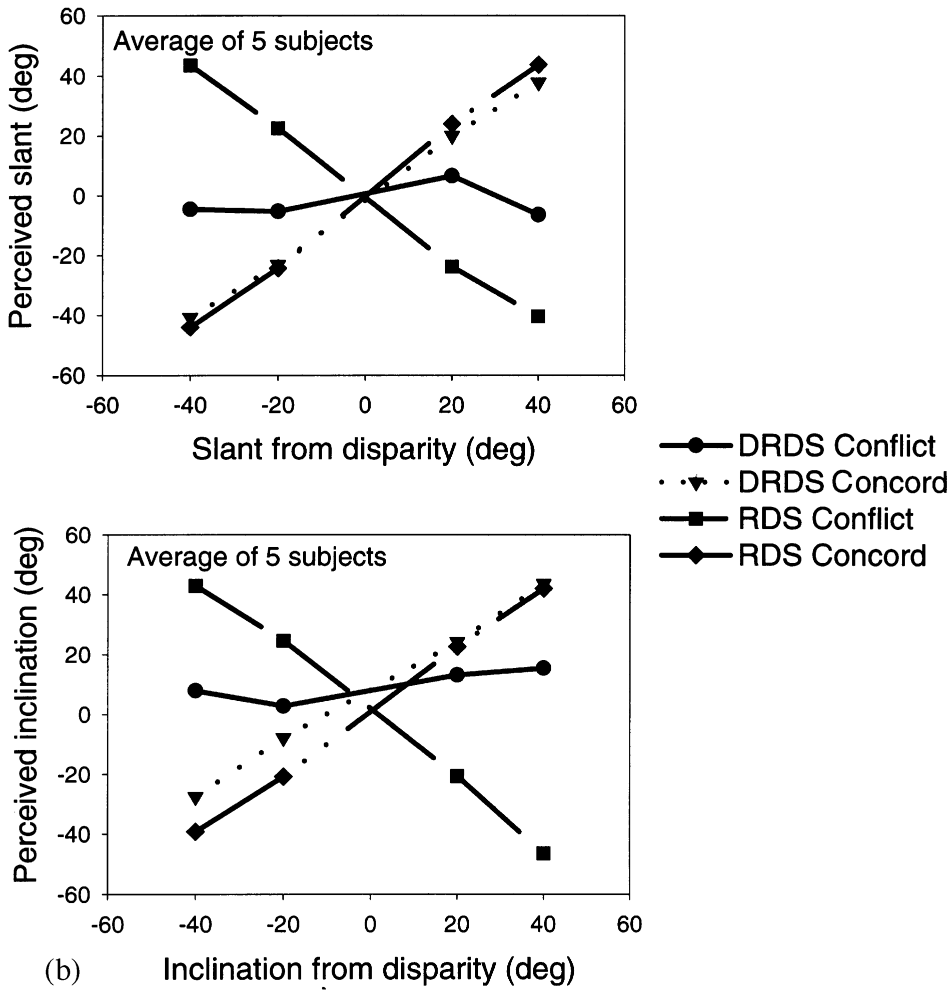


Fig. 3. (*Continued*)

netic slant rather than static slant was simulated. They proposed that this was due to the presence of kinetic or motion perspective cues in the kinetic case. When static disparity indicates a slanted surface and perspective a frontal surface, the texture of the surface is perceived as possessing a texture gradient because only a surface with a real texture gradient can produce such a stimulus. However, this does not violate a strong assumption because real surfaces may be inhomogeneous. Conflict between kinetic perspective and kinetic disparity produces a perceived deformation of the surface, which violates a strong rigidity assumption. Thus, kinetic perspective appears to be given greater weight than static perspective. With dynamic texture elements, disparity-perspective cue conflict is reduced by the elimination of conflicting kinetic perspective. The dynamic texture destroys the coherent monocular motion signals and hence weakens the kinetic perspective cue. While we cannot rule out an improvement in the efficiency of stereopsis, we feel that a cue-conflict account is the most parsimonious explanation of the increase in perceived depth in DRDS versus RDS displays.

Acknowledgements

This work was supported by a CRESTech grant from the Province of Ontario and by NSERC Canada.

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