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Effect of decorrelation on 3-D grating detection with static and dynamic random-dot stereograms

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Abstract

Three experiments examined the effects of image decorrelation on the stereoscopic detection of sinusoidal depth gratings in static and dynamic random-dot stereograms (RDS). Detection was found to tolerate greater levels of image decorrelation as: (i) density increased from 23 to 676 dots/deg^2; (ii) spatial frequency decreased from 0.88 to 0.22 cpd; (iii) amplitude increased above 0.5 arcmin; and (iv) dot lifetime decreased from 1.6 s (static RDS) to 80 ms (dynamic RDS). In each case, the specific pattern of tolerance to decorrelation could be explained by its consequences for image sampling, filtering, and the influence of depth noise.

Keywords: Stereo vision; Correspondence; Stereogram; Surface detection

1. Introduction

In both static and dynamic random-dot stereograms (RDS), 3-D surface structure is visible only after the two monocular images are combined by the visual system (Julesz, 1960, 1964, 1971). In viewing such displays, the stereoscopic depth percept is based solely on the positional disparities of corresponding dots in the two eyes' images. However, there is also a potentially complex correspondence problem to be solved (for a review—see Howard & Rogers, 1995). Since the dots in these RDS are identical in contrast polarity, shape, and size, any dot in the left eye's image could be matched with numerous dots in the right eye's image. While this correspondence problem may often be eased by the presence of clusters of dots that are recognizably the same in the two eyes' images, these dot clusters are not essential for binocular matching. Julesz (1960, 1964, 1971) showed that stereoscopic depth could still be seen when these 'micropatterns' are obscured by large numbers of uncorrelated dots in one or both eyes' images. Using static RDS, which represented a central square lying either in front or behind a surround, he noted that as image decorrelation increases:

> "first the corners of the cyclopean square disappear, but a rounded off area in the centre is still perceived in depth. Loss of stereopsis gradually increases with increasing noise. More and more dots appear at other depth planes than that of the square or its surround. Finally it is impossible to detect an area in the centre as being different to the surround" (Julesz, 1971, pp. 275).

In Julesz's original demonstrations, observers had to detect the 3-D structure of surfaces represented by static RDS with various amounts of image decorrelation. However, this image decorrelation would not only have made binocular matching more challenging, but it should also have influenced stereoscopic surface detection—which requires judgments based on perceived depth and surface structure (Harris & Parker, 1994; Palmisano, Allison, & Howard, 2001). More recent research in this area has attempted to isolate the processes responsible for binocular matching by: (1) using dynamic RDS in which the locations of correlated and uncorrelated dots change continually; and (2) having observ-

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ers detect the presence of interocular correlation rather than changes in depth (Cormack, Stevenson, & Schor, 1991, 1994; Cormack, Landers, & Ramakrishnan, 1997; Livingstone, 1996; Stevenson, Cormack, Schor, & Tyler, 1992; Tyler & Julesz, 1976, 1978). Observers were instructed to indicate which of two stimuli had the greater interocular correlation in a two-interval-forced-choice task. Since displays typically represented a frontal plane surface, stereoscopic surface detection was assumed to play only a minor role in this task. In general, these studies found that sensitivity to interocular correlation depends on a number of stimulus factors, including display duration (Tyler & Julesz, 1976, 1978), contrast (Cormack et al., 1991), dot density (Cormack et al., 1997), and distance of the surface from the plane of fixation (Stevenson et al., 1992).

There is a sizable literature on the effect of image decorrelation on binocular matching. However, the effect of image decorrelation on stereoscopic vision, which involves both binocular matching and disparity-based surface detection, has received far less attention. Julesz's original demonstrations suggest that coarse depth perception is fairly robust to this type of noise. However, it appears that image decorrelation has marked detrimental effects on fine stereopsis (stereoacuity and latency to resolve complex RDS). For example, Christophers, Rogers, and Bradshaw (1993; also cited in Bradshaw, Rogers, & De Brun, 1995) found that the latency to detect a complex spiral shape in depth almost doubled when they decorrelated their static RDS by 30%. Similarly, Cormack and colleagues (1991) found that the smallest horizontal step change in disparity which could be detected in their dynamic RDS increased by approximately a factor of 3–4 as image decorrelation increased from 10% to 70%.

In the current study, we expanded on these previous investigations: examining the effects of dot density, corrugation spatial frequency and corrugation amplitude on the detection of disparity-defined 3-D surfaces in the presence of image decorrelation. In our main experiments, RDS depicted surfaces with sinusoidal modulations in depth and we increased image decorrelation by replacing correlated dots with uncorrelated dots. This study also appears to be the first to explicitly compare the effects of image decorrelation on 3-D surface detection with static and dynamic RDS. Lankheet and Lennie (1996) describe the following differences in the experience of viewing static and dynamic RDS containing Gaussian-distributed additive disparity noise:[1]

> "It should be noted that detecting correlation in (static random-dot patterns) is quite different from detecting it in dynamic random-dot patterns. In (static random-dot patterns) the depth of individual pixels is clearly seen eventually. In dynamic random-dot patterns on the other hand, the short dot life of individual pixels makes their depth very difficult to resolve. As a result, in noisy dynamic random dot stereograms the depth of the noise itself is not perceived: rather than a cloud of points in three dimensions one perceives an uncorrelated image with little or no depth" (pp. 530).

This observation suggests that the detection of 3-D surfaces might be less affected by decorrelation noise with dynamic RDS than with static RDS. Below we outline three possible reasons why detection performance with dynamic RDS might be expected to exceed that found with static displays. The first possibility is that averaging disparity information over time acts to increase the signal-to-noise ratio for a dynamic RDS, since any spurious dot matches occurring when viewing a dynamic RDS would be uncorrelated over time (Allison & Howard, 2000). However, averaging disparity information over time would have little affect on the signal-to-noise ratio for a static RDS, because both the spurious and correct matches would be stable and correlated over time. The second possibility is based on the fact that image decorrelation will only produce stable depth noise when the RDS is static (in the case of dynamic RDS, the short dot lifetimes would make it more difficult to resolve the depth of individual dots). According to this notion, spurious matches in static RDS might be more disruptive to surface detection than spurious matches in dynamic RDS, as the stable depth noise generated by the former would be inconsistent with the perception of a smooth surface (Lankheet & Lennie, 1996). Potentially, any such advantage for dynamic RDS might be nullified by increased difficulties resolving the depths of individual signal dots. However, there is one important difference between the signal and noise dots in dynamic RDS—unlike the transient localized depths represented by noise dots, the global surface structure represented by the signal dots is stable and supported over time. Thus, it is possible that the short dot-lifetimes in dynamic RDS might minimise the effects of local depth noise, but leave the extraction of the global surface structure relatively unimpaired. Finally, the third possibility is that detection performance might be more tolerant to image decorrelation with dynamic RDS, because these displays should have a higher effective density than a static RDS with the same instantaneous dot density—assuming that the dynamic RDS is viewed for a sufficiently long period and the dot lifetime is shorter than the visual integration time (e.g., 26 ms—Lankheet & Lennie, 1996). If true, one might expect differences between static and dynamic RDS to be maximal for sparse, high spatial frequency corrugation displays—as the multiple surface

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[1] In the case discussed by Lankheet and Lennie (1996), all of the dot pairs in their RDS were correlated and originally represented a smooth sinusoidal surface in depth. When Gaussian distributed disparity noise was added to these correlated dots, the result was that the stereo-defined surface appeared jagged—at least when static RDS were used—with the amount of jaggedness depending on the amplitude of this depth noise. Conversely, in the current study, our displays consisted of a mixture of correlated dots (whose disparities represented a smooth sinusoidal surface) and uncorrelated dots. Spurious matches of non-corresponding dots could, however, have indirectly generated depth noise, which would have been very similar to the effects of this additive disparity noise.