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Last but not least

Ambiguous depth planes: Perceiving depth from motion

Perceiving structure from motion (the kinetic depth effect) is a familiar phenomenon: a stationary pattern of apparently random elements will organize into a coherent three-dimensional structure when set in motion. The resulting percept is usually a three-dimensional object rotating in space. This phenomenon is well known, dating from the work of Wallach in the 1930s, and is often used in animations, such as those in the opening credits of *The Matrix Reloaded*. Julesz (1971) and Braddick (1974) noted that depth could be seen in random-dot textures where one region was moved against a static background. Julesz reported that regions with faster-moving texture were seen as closer to the observer. We have found that presenting such displays for more than a few seconds results in a strong impression of depth and the apparent depth of surfaces changes.

This depth-from-motion illusion was first observed by Jocelyn Faubert when a small square region of texture was drifted in one direction, surrounded by a region containing texture drifted in the opposite direction, and a static background texture (see figure 1). The borders of the drifting texture regions were stationary. Illusory depth was perceived within a few seconds of starting the motion. The innermost square appeared to be a moving surface far away, the moving surround was on an intermediate depth plane, and the stationary background was a third depth plane closest to the viewer. With continued viewing, the three-dimensional arrangement of the moving surfaces changed. The smallest region was closest, with the background at a different depth, and the enclosing moving region at a third depth. The depth arrangements changed every few seconds. We also obtained the illusion when only a central square region contained drifting texture. The central square switched between being closest and furthest from the observer [unlike what was reported by Julesz (1971)]. Overall, the impression of depth was greater when there were two central regions with texture drifting in the opposite directions.

We tested seventeen experimentally naive participants (ten female, seven male) to examine some of the parameters affecting the illusion. Observers were seated approximately 60 cm from the CRT screen. Head movements and viewing distance were not

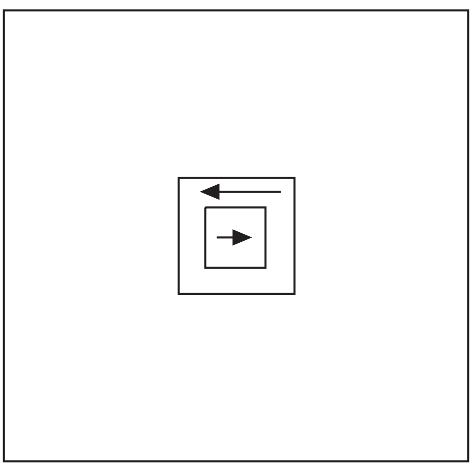

Figure 1. Schematic representation of the display. This represents the two-region condition. The central square was region 1, the moving surround region 2, and the static background region 3. The random-dot texture (50/50 black/white, not shown here) was drifted in one direction in the central square, and the opposite direction in the surrounding region as indicated by the arrows. The drift speed was the same in each region. The one-region condition contained only region 1 in motion. Stimuli were presented on an Apple 13 inch High-Resolution Monitor controlled by a Macintosh IIci computer.

constrained so the participants could freely explore the illusion. Hence, all sizes are reported as distal measures. The two-region display was shown first. If depth was perceived, participants were asked which of the regions (centre, surround, and static background) was closest, farthest, and in the middle. Six of the seventeen participants spontaneously reported an impression of depth in the displays. All seventeen participants reported perceiving different surfaces in depth after prompting. Nine participants saw switching of the depth planes. The number of depth 'switches' in a minute was recorded. Twelve participants reported such switches. The number of switches reported ranged from 1 to 34 in 1 min (mean = 15.1, median = 13.5, not including observations of no depth changes).

The one-region condition was presented next. Eleven participants perceived depth in this display and seven reported switching of the depth arrangement. Ten participants reported depth changes over 1 min, with a range of 3 to 27 switches (mean = 9.8, median = 7, again not including reports of no changes). Two participants reported depth switches in this condition and not in the two-region condition. Four participants who had seen depth changes in the two-region condition reported none in the one-region case. Varying fixation location produced no consistent changes in perceived depth.

The texture elements of the displays were varied in size (1, 2, 4, 8, and 16 pixels per element). The regions were not changed in size, so element size, density, and number were confounded. The participants rated the magnitude of perceived depth by giving a numerical value using the anchors of 0 (no depth) and 100 (depth perceived in original viewing of the two-region display). Figure 2 summarizes the results. Clearly, there was less perceived depth in the one-region display than in the two-region display, and as element size increased, perceived depth decreased.

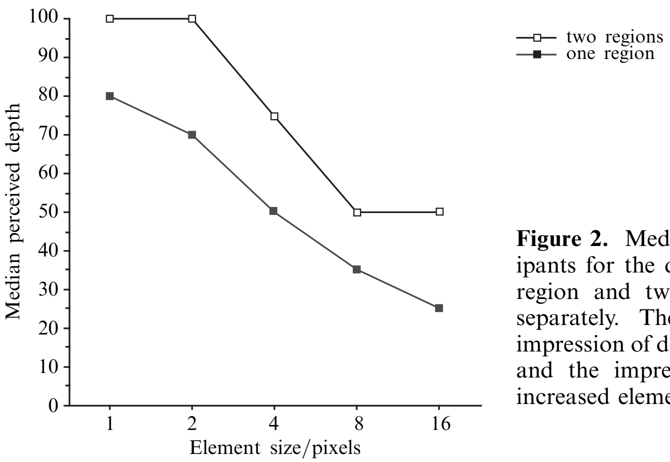

Figure 2. Median depth reported by participants for the different element sizes. The one-region and two-region conditions are shown separately. There is a consistently greater impression of depth in the two-region condition, and the impression of depth decreases with increased element size.

Ultimately, the perceived depth arises because the displays are ambiguous if interpreted as real-world surfaces. Consider the one-region case first. A static background surrounds a moving region. In the real world, we see continuous motion of a region embedded in a stationary background when looking through an aperture like a window. The borders of the region do not move, and the texture does. This is interpreted as self motion or motion of the world outside the window, or some combination of the two. The moving texture has to be going somewhere, so depth is added to the percept. In contrast to Julesz's (1971) report, we found observers saw the moving surface behind or in front of the background.

In the two-region stimulus, an analogous process occurs, although there is not a real-world equivalent like looking through a window. Seeing two regions filled with texture moving in opposite directions produces a strong impression of depth. One might expect to see the collision of two moving fields as some sort of annihilation of the textures, but this was never reported. It is likely that increasing the number of moving regions could increase the impression of depth, but this was not tested.

The observed illusion is inconsistent with what is usually reported for displays comprising a static surround and moving regions. Depth is not usually reported in motion-defined plaids (Adelson and Movshon 1982) or the barber-pole illusion. The surrounding region is usually blank or a solid color in those displays, and the importance of the surround in perceiving the direction of motion was demonstrated by Vallortigara and Bressan (1991). They examined the effect of different aperture arrangements on perception of the barber-pole illusion, and showed that the perceived direction of motion could change if the motion was perceived to be on a different plane from the aperture (see also Vallortigara and Bressan 1994).

It is most interesting that after observing the stimulus for a period of time, there is a bistable depth effect. The effect is similar to plaid motion perception under certain conditions (Adelson and Movshon 1982). When viewing two sinusoidal gratings drifting in different directions there are two possible percepts; seeing the two gratings drifting over one another (transparent motion), or observing a motion that is a combination of the two gratings (coherent motion). The two perceptual states flip back and forth with prolonged viewing. Perhaps the mechanisms underlying bistable plaid motion are similar to those producing the ambiguous depth perceived in the illusion reported here. Some researchers have suggested that perceiving depth and motion in plaid stimuli share common mechanisms (Bowd et al 2000). Given these are processes related to perceiving the third dimension, it is not surprising that there may be a common mechanism at work. Bowd et al (2000) and Vallortigara and Bressan (1991) suggest a role for area MT in processing motion and figure – ground relationships.

The depth illusion reported here likely reflects the visual system resolving ambiguity in a stimulus by following natural constraints. The moving textures produce a conflict in terms of what is encountered in the real world, and this is resolved by adding depth to the percept. Switching of the depth arrangements occurs as the visual system copes with the ambiguity of the stimulus.

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Andrew M Herbert¶, Paula M Beall§, Jocelyn Faubert#

¶ Department of Psychology, College of Liberal Arts, Rochester Institute of Technology, 92 Lomb Memorial Drive, Rochester, NY 14622, USA; e-mail: amhgss@rit.edu; § Department of Psychology, University of Denver, Frontier Hall, 2155 South Race Street, Denver, CO 80208, USA; # École d'Optométrie, University of Montréal, 3744 Jean Brillant, Montréal, Québec H3T 1P1, Canada.

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