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The influence of structure from motion on motion correspondence

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Abstract. The visual system has a remarkable ability to reconstruct 3-D structure from moving 2-D features. The processing of structure from motion is generally thought to consist of two stages. First, the direction and speed of features is measured (2-D velocity measurement) and, second, 3-D structure is reconstructed from the measured 2-D velocities (3-D structure recovery). Most models have assumed that these stages occur in a bottom – up fashion. Here, however, we present evidence that the 3-D structure-recovery stage influences the 2-D velocity-measurement stage. We developed a stimulus in which two perceptual modes of motion correspondence (one-way translation versus oscillation), and two perceptual modes of 3-D surface structure (flat surface versus cylinder) could be achieved. We found that the likelihood of perceiving both one-way motion and cylindrical structure increased in similar ways with increasing frame duration. In subsequent experiments we found, first, that a higher likelihood of perceiving one-way motion did not affect the likelihood of perceiving cylindrical structure; and, second, that a higher likelihood of perceiving cylindrical structure increased the likelihood of perceiving one-way motion. These results suggest that the higher, 3-D structure-recovery stage may influence the lower, 2-D motion-correspondence stage. This result is not in accordance with most computational models that assume that there is only one-way, feedforward information processing from the 2-D velocity (energy)-measurement stage to the 3-D structure-recovery stage. Perhaps, one of the roles of feedback processing is to seek consensus of the information processed in different stages.

1 Introduction

Our visual system has a remarkable ability to reconstruct a coherent three-dimensional (3-D) surface when a set of local two-dimensional (2-D) motion cues for depth are presented (Andersen 1989, 1996; Braunstein 1962; Miles 1931; Ramachandran et al 1988; Todd 1998; Todd and Norman 1991; Ullman 1979; Wallach and O'Connell 1953). This is called structure from motion. Ullman's demonstration consists of a pair of coaxial counter-rotating cylinders (Ullman 1979). When static, the display looks like a random collection of dots. Once it moves, however, the observer has a clear impression of one cylinder inside another, rotating in opposite directions. Most models of structure from motion have assumed that there are at least two stages: a 2-D velocity-measurement stage and a 3-D structure-recovery stage. These models also assume that information is passed from the lower, 2-D motion energy-measurement stage (Adelson and Bergen 1985; Van Santen and Sperling 1985) to the higher, 3-D structure-recovery stage, in a bottom – up fashion (eg Marr 1982).

However, this strict two-stage, bottom – up processing model for structure from motion has been challenged. The observation that 3-D structure is perceived even with very short dot lifetime suggests that there is an interpolation process which interacts with structure from motion (Dosher et al 1989; Husain et al 1989; Treue et al 1991). Furthermore, Treue et al (1995) found that a hole (a region with no physical features) can be as wide as one quarter of a rotating cylinder before subjects reliably detect its presence. These empirical findings suggest that there is mutual interaction between structure from motion and surface-representation processes. Considering this finding, Hildreth et al (1995) built a model in which, subsequent to the measurement of 2-D

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direction and speed of motion, reciprocal interactions occur among three relatively high-level component processes in the 3-D structure-recovery stage—feature-based structure from motion, 3-D reconstruction, and temporal integration processes. However, to our knowledge there has not yet been any conclusive evidence of reciprocal interactions between the measurement of 2-D motion (energy) and the recovery of 3-D structure.

In addition, it has been pointed out that there are cases in which 2-D velocity information is not the only cue for structure from motion. Musatti (1924) showed that when a 2-D checkerboard pattern was moved parallel to one of the sides of square checks behind an aperture, 3-D cubes, instead of the 2-D checkerboard, were perceived to rotate. Since the checks at one edge of the aperture were being revealed and those at the other edge concealed, the checks being revealed exhibit expansion while those concealed exhibit compression. Thus expansion and compression at the edges may be used to induce 3-D structure in this stimulus. Braunstein et al (1993) examined perceived orientation in depth and 3-D shape for orthographic projections of rotations of 3-D dihedral angles and found that the perceived magnitude of a dihedral angle cannot be predicted merely by velocity information. Both velocity ratio and image compression are necessary for the prediction.

In the present study, we have obtained results that suggest the 3-D structure-recovery stage[(1)] influences motion correspondence, assumed to occur in the 2-D velocity-measurement process. We created a stimulus with dichotomous motion correspondence (one-way translation versus oscillation), and dichotomous 3-D structure interpretations (flat versus cylindrical surface). In experiment 1, we found that the perception of one-way translation (versus oscillation) and a cylindrical (versus flat) structure increased with increasing frame duration. In experiment 2, the likelihood of perceiving one-way motion was operationally increased. Nevertheless, we did not find any increase in the likelihood of perceiving a cylindrical surface. In experiment 3, we found that the likelihood of perceiving one-way motion was higher in an array containing depth cues which caused the surface to appear cylindrical than in an apparently flat array without depth cues. These results are most plausibly explained as the result of feedback from a higher, 3-D structure-recovery stage to a lower, 2-D velocity-measurement stage. Our results are also inconsistent with computational models which assume that 3-D structure recovery occurs strictly after 2-D velocity has been measured.

2 Experiment 1

First, in order to explore the relation between motion correspondence and 3-D structure recovery, the effects of frame duration on the perceived motion direction and the surface structure were examined.

2.1 *Method*

2.1.1 *Subjects.* Four subjects—two females and two males—were employed. Except for one male who was one of the authors (TW), all the others were naive as to the purpose of the experiment. Each had normal or corrected-to-normal visual acuity and normal color vision.

2.1.2 *Materials and stimuli.* The stimuli were presented on a color video display (Apple M0401, 640×480 pixel resolution, 35 kHz horizontal and 66.7 Hz vertical scanning frequencies) controlled by a Macintosh IIci. The display was placed 57.3 cm from the subject's eyes. The subjects' heads were stabilized by a chin-rest. The computer also collected and recorded the subjects' responses.

[(1)] Since the experiments in the present study were not designed to operationally dissociate the feature-based structure-from-motion process from the surface-reconstruction process, we do not know which process influences the motion-correspondence process. Thus, we combined two processes and refer to them collectively as the 3-D structure-recovery stage.

Figure 1 shows three arrays, each consisting of 5 rows and 5 columns of rectangular elements (0.5 cd m^{-2} in luminance) on a white background (49.0 cd m^{-2} in luminance). The width of the array was either 66.3 or 72.5 deg of visual angle (depending on the frame) and its height was 10.1 deg. These three arrays were cyclically presented as in figure 1. From t_0 to t_1 and from t_1 to t_2 the array shifted rightward by 0.58 deg. From t_2 to t_3 the array shifted back to the same location as at t_0, ie to the left by 1.16 deg. This sequential presentation was then repeated cyclically.

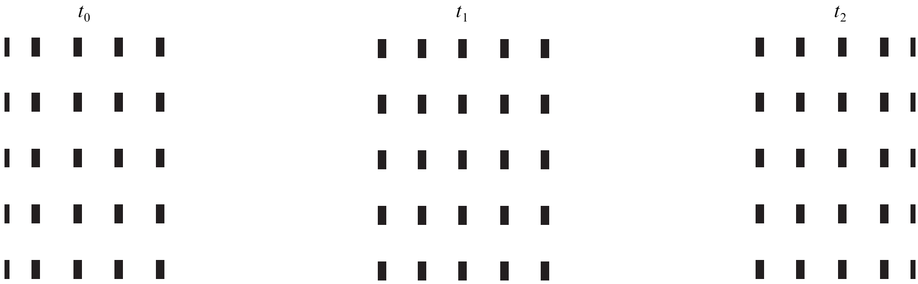

Figure 1. The stimulus used in experiment 1. The three arrays were sequentially presented. The width of the rectangles at the left edge at t_0 and at the right edge at t_2 was half the width of the inner rectangles. The horizontal spacing between the edge rectangles and their neighbors was smaller than the horizontal spacing between the other rectangles.

Local depth cues were introduced only at the edges of the array. A compression/expansion cue (Braunstein 1993; Braunstein et al 1993; Musatti 1924) was depicted by cutting the leftmost and rightmost rectangles to 0.17 deg (half the normal width of 0.33 deg) at t_0 and t_2, respectively. In addition, the horizontal spacing between these rectangles at the edges and their neighbors was 0.37 deg while the spacing between all the other rectangles was 0.55 deg. Thus, when the arrays were sequentially presented, the rectangles at the edges were perceived to move forward on the left and to recede on the right.

2.1.3 *Procedure.* For each trial, a fixation point was presented for 1 s, followed by the sequential presentation of the arrays. The frame duration was varied from 15 to 375 ms in nine steps (15, 60, 105, 150, 195, 240, 285, 330, 375 ms) from trial to trial (therefore perceived speed of motion of the rectangles was higher at a shorter frame duration), while the total duration of the moving array display was a constant 10 s.(2) There were two conditions: a correspondence condition and a surface-structure condition. In the correspondence condition, after the disappearance of the array, subjects were instructed to depress the 'z' key on the keyboard if the overall motion was one-way rightward motion (translation) or to depress the '/' key if the overall motion was oscillation. In the surface-structure condition, the subjects were instructed to respond whether the surface of the array appeared to be cylindrical or flat. In each condition, each of the nine frame durations was repeated 20 times with order of presentation randomized. Two subjects did the correspondence condition first while the remaining two subjects did the surface-structure condition first.

(2) We conducted a preliminary experiment using two naive subjects in which both frame duration and total duration of the moving array were varied (3, 6, and 9 s) with five repetitions. We found basically the same results as in the results of experiment 1. We conducted another preliminary experiment in which the number of total stimulus cycles was a constant 4 and found basically the same results as those in experiment 1. These results indicate that the total frame duration does not influence the correspondence and surface perception. This also suggests that high-level cognitive factors may not significantly influence the subjects' judgments.

2.2 *Results and discussion*

As shown in figure 2, with increasing duration the likelihood of perceiving one-way motion and cylindrical structure diminished. The shapes of the curves for one-way motion and cylindrical structure were similar to each other, although the likelihood of perceiving cylindrical structure was generally higher than that of perceiving one-way motion. Using an array of dots with no depth cues, Watanabe and Cole (1995) found that with relatively long frame durations all the dots were perceived to oscillate, whereas with shorter frame durations only the dots at the edges oscillated while the inside dots moved unidirectionally. The authors concluded that, for long frame durations, oscillation propagates to the center of the array and overrides one-way motion in the whole array. This overriding effect may account for the perception of oscillation with long frame durations in the present experiment.

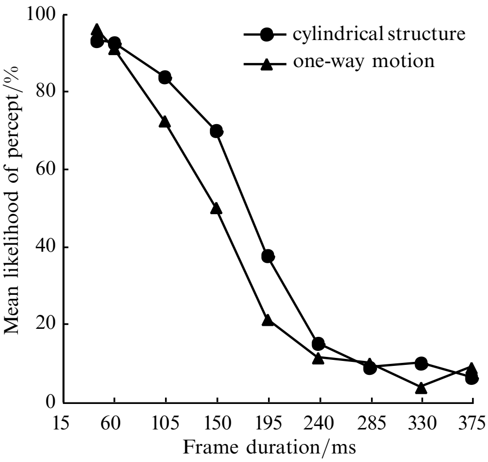

Figure 2. The results of experiment 1. The mean likelihood ($n = 4$) of perceiving a cylindrical surface (filled circles) and the mean likelihood of perceiving one-way rightward motion (filled triangles) are shown as a function of frame duration.

There are several interpretations to these results. The first is that the selection of one-way motion influenced the choice of cylindrical structure. This is in accordance with most computational models which assume feedforward processing from the 2-D velocity-measurement stage to the 3-D structure-recovery stage. Such models would predict that the cooccurrence of one-way motion and cylindrical structure is a result of the influence of one-way motion coded at the 2-D velocity-measurement stage on the cylindrical structure produced at the 3-D structure-recovery stage. However, since the likelihood of perceiving cylindrical structure was higher than that of perceiving one-way motion, the selection of one-way motion, if any, cannot entirely determine the cylindrical structure.

The second possibility is that the similarity in the curves is just coincidental. Maybe they are just typical psychometric curves and there is no direct causal relationship between one-way motion and cylindrical structure.

The last possibility is that the selection of cylindrical structure influenced the choice of one-way motion. This possibility is supported by the subjects' verbal reports that, whenever cylindrical structure was perceived, one-way motion occurred, and by the finding that the likelihood of perceiving cylindrical structure was generally higher than that of perceiving one-way motion.

In experiment 2, we examined the validity of the first possibility—that the selection of one-way motion influenced the choice of the cylindrical structure. If correct, the higher likelihood of one-way motion would influence the likelihood of perceiving cylindrical structure.

3 Experiment 2

3.1 *Method*

3.1.1 *Subjects.* The same four subjects as in experiment 1 were employed.

3.1.2 *Stimuli and procedure.* As illustrated in figure 3, a set of six arrays consisted of red and black rectangles in alternate columns. The luminances of the red and black rectangles and the background were 21.0, 0.5, and 49.0 cd m^{-2}, respectively. One sequence consisted of six frames. In apparent motion, it is known that an object tends to appear to move towards a target of the same luminance (eg Ramachandran and Anstis 1986) or color (Dobkins and Albright 1993, 1998) rather than one which differs in luminance or color. By exploiting this phenomenon, we biased otherwise ambiguous motion such that the columns of red and black rectangles were seen to move to the right as shown in figure 3. Thus, our new stimulus should make it more likely to perceive one-way motion than the black and white stimulus of experiment 1. All the other aspects were identical to those in experiment 1.

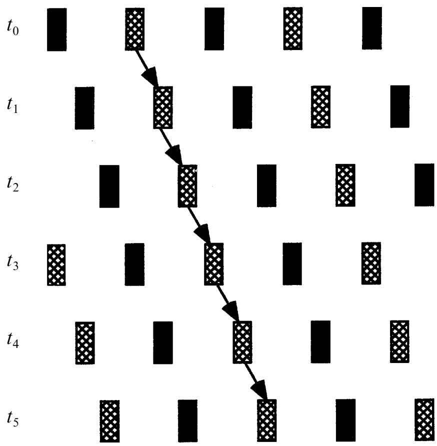

Figure 3. The position of a given row in the array presented in experiment 2 at time t_n. Notice that the rows shown here at different vertical locations were actually presented at the same vertical location but at different times. Black and red (here shown hatched) rectangles are laid out alternately. For all inner rectangles in any given frame, the nearest rectangles in the subsequent frame thus match in color and luminance. One-way motion (as represented by arrows connecting hatched rectangles) is more likely to be observed with this stimulus than with the black rectangles used in experiment 1.

3.1.3 *Results and discussion.* Figure 4a shows the likelihood of perceiving one-way rightward motion relative to frame duration, with the arrays of red and black rectangles (open squares) in experiment 2 and with the arrays of all-black rectangles (filled circles) in experiment 1. Figure 4b shows the likelihood of perceiving cylindrical structure with the arrays of red and black rectangles (open squares) in experiment 2 and arrays of all-black rectangles (filled circles) in experiment 1. As predicted, the likelihood of perceiving one-way motion was higher with a set of arrays of the red and black rectangles than with a set of arrays of the black rectangles only. However, the likelihood of perceiving cylindrical structure did not change significantly between them.

These results do not support the first possibility that the selection of one-way motion determined the choice of cylindrical surface.

In experiment 3, we biased the likelihood of perceiving cylindrical structure in search of evidence for the third possibility—that the selection of cylindrical surface determines the choice of one-way motion.

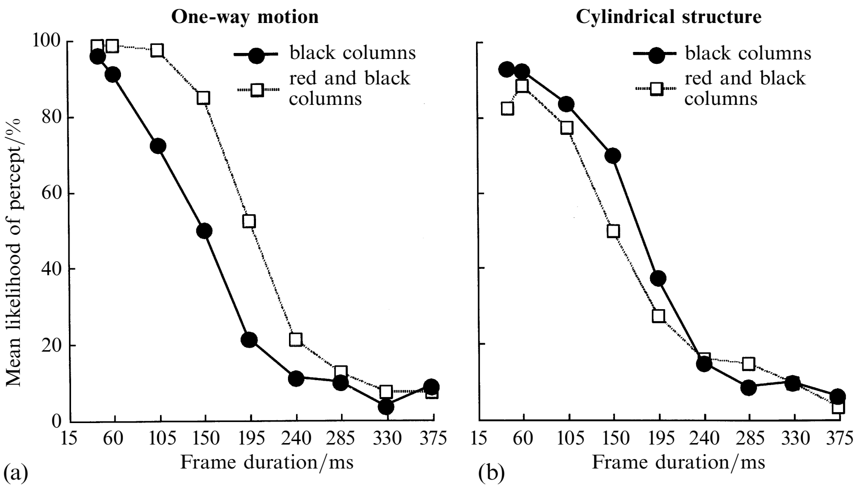

Figure 4. The results of experiments 1 and 2. (a) The mean likelihood ($n = 4$) of perceiving one-way rightward motion for the arrays of all-black rectangles (filled circles) in experiment 1 and red and black rectangles (open squares) in experiment 2 as a function of frame duration. (b) The mean likelihood ($n = 4$) of perceiving cylindrical structure with the arrays of all-black rectangles (filled circles) in experiment 1 and red and black rectangles (open squares) in experiment 2 as a function of frame duration. The results show that, while the likelihood of one-way motion was higher with the array of the black and red rectangles than with the array of all-black rectangles, the likelihood of cylindrical structure did not change significantly between the two.

4 Experiment 3

For the stimuli used in this experiment, the horizontal locations of inner rectangles were randomized, while the rectangles at the edges remained the same as in the first and second experiments. Two sets of frame arrays were used. In the first set, the width of the rectangles along the stimulus borders changed as in the previous experiments, as shown in figure 5a. The other set did not contain the depth cue, as shown in figure 5b. If the selection of cylindrical surface determined the choice of one-way motion, the likelihood of perceiving one-way rightward motion should be higher in the arrays with the depth cues than in the arrays without them.

4.1 *Method*

4.1.1 *Subjects.* The same subjects as in experiments 1 and 2 were employed.

4.1.2 *Stimuli.* In both conditions, the horizontal position of the rectangles, except for those at both edges, was randomly determined from one frame to another. This means that, in contrast to the stimuli in the previous experiments, the inner rectangles did not move coherently from one frame to another. In the set with the depth cue, the width of the leftmost rectangles at t_0 and the rightmost rectangles at t_2 was half that of the inner rectangles (0.33 deg). In the set with no depth cues, all the rectangles were the same width.

4.1.3 *Procedure.* There were four conditions. There were two tasks for each of the two sets. One was to judge whether the array appeared cylindrical or flat. The other was to judge whether the rectangles at the interior of the array appeared to move rightward or in an oscillatory fashion. In each of the conditions, the frame duration was varied in nine steps, just as in the previous experiments. The order of the four conditions was randomized for each subject. The rest of the procedure was identical to that in experiment 1.

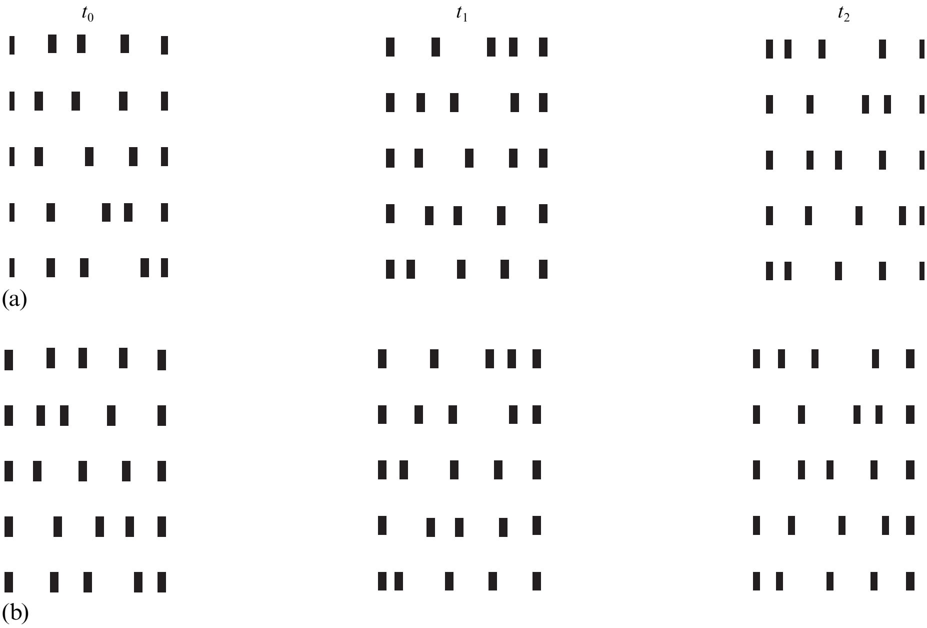

Figure 5. Example of the stimuli used in experiment 3. (a) A set of arrays with the depth cue. The width of the rectangles at the left edge at t_0 and at the right edge at t_2 was half the width of the rest of the rectangles. (b) A set of arrays without depth cues. All the rectangles in the arrays had the same width. In both sets, the horizontal positions of the rectangles, except for those at both edges, were randomly changed from one frame to another throughout the presentation of the stimuli.

4.1.4 *Results.* Figure 6 shows the likelihood of perceiving one-way motion with the arrays containing depth cues (filled triangles) versus no depth cues (open triangles), and the likelihood of perceiving cylindrical structure with the depth cues (filled circles) and without them (open circles). The depth cues increased the frequency of one-way motion perception. These results are in accord with the third possibility, that the selection of cylindrical surface influenced the choice of one-way motion.

Strictly speaking, these results do not rule out the possibility that there is no direct relationship between the one-way motion and cylindrical structure. Indeed, we cannot deny the possibility that the depth cues themselves might directly influence and increase

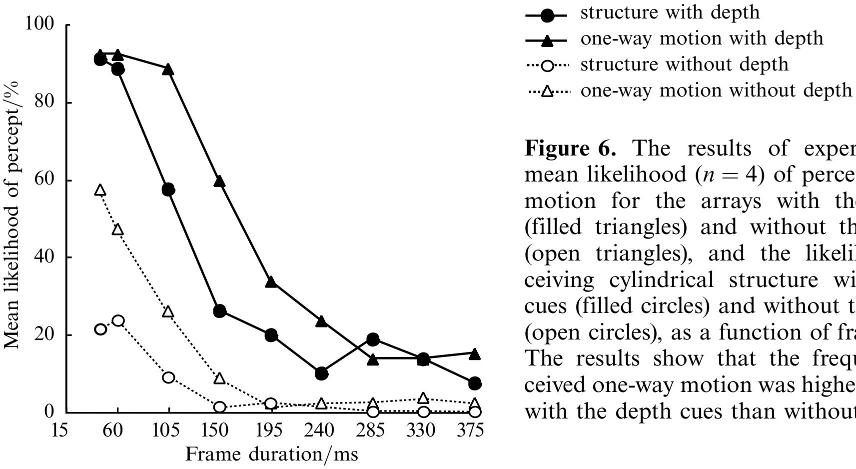

Figure 6. The results of experiment 3. The mean likelihood ($n = 4$) of perceiving one-way motion for the arrays with the depth cues (filled triangles) and without the depth cues (open triangles), and the likelihood of perceiving cylindrical structure with the depth cues (filled circles) and without the depth cues (open circles), as a function of frame duration. The results show that the frequency of perceived one-way motion was higher in the arrays with the depth cues than without them.

the likelihood of perceiving one-way motion as well as cylindrical structure. However, no study has yet reported that these depth cues directly influence motion correspondence. A more likely explanation is that the 3-D structure-recovery stage plays a role in determining 2-D motion correspondence.

5 General discussion

To summarize, in experiment 1 we found a similarity between the likelihood of perceiving one-way motion and perceiving a cylindrical surface on varying frame duration. In experiment 2, the likelihood of perceiving one-way motion did not affect the likelihood of perceiving cylindrical structure. In experiment 3, we found that the presence of depth cues increased the likelihood of perceiving one-way motion.

The results of experiments 2 and 3 suggest that the similarity between the curves for one-way motion and cylindrical structure obtained in experiment 1 could be due in part to the influence that selection of cylindrical structure has over the selection of one-way motion. Motion correspondences such as one-way motion and oscillation are thought to be determined at the 2-D velocity-measurement (energy extraction) stage, whereas 3-D surface structure from motion is thought to be generated at a higher stage. So long as the velocity-measurement stage precedes the 3-D structure-recovery stage, the present study suggests that there may be feedback influence from the 3-D structure-recovery stage on the 2-D velocity-measurement stage.

5.1 *Differences between the present stimuli and the traditional stimuli*

There are several differences between the stimulus used in this study and the typical stimuli currently used to study structure from motion (eg Ullman 1979). First, in the present stimulus, motion correspondence was made ambiguous (one-way motion versus oscillation) so that the influence of 3-D structure on motion correspondence could be observed more explicitly. Second, depth cues were confined to the edges of the array. It has been suggested that depth cues at edges play a crucial role in 3-D structure recovery in a conventional display (Ramachandran et al 1988). Compression as a depth cue has also been linked to the recovery of structure from motion (Braunstein et al 1993). Thus, although there are differences between our display and a conventional stimulus, we believe our stimuli tap the same motion processing stages as those tapped by conventional stimuli.

5.2 *Motion processing is highly interactive*

Most motion models have considered only feedforward processing within the motion module (but see Chey et al 1998; Hildreth et al 1995). However, it has been suggested that the motion system is highly interactive and that reciprocal interactions play an important role in motion processing (eg Watanabe and Miyauchi 1998). There may be, for example, interaction between motion and other submodalities (intermodule interactions). Strong reciprocal interactions have been found between motion and form processes (Anderson and Sinha 1997; Tse et al 1998; Watanabe 1997). Likewise, there may exist interactions between higher and lower stages within the motion module through feedback projections. Nearly equal numbers of feedback projections as those of feedforward projections have been found among the monkey visual cortices (Felleman and Van Essen 1991). More recently, we have shown by means of fMRI (Watanabe et al 1998a, 1998b) and psychophysics (Mukai and Watanabe 1998) that high-level cortical processing influences the 2-D velocity-measurement process.

The results of the present study also support the view that within motion processing a higher-level stage may influence a lower-level stage.

5.3 *Consensus seeking between stages of processing*

What is the purpose of the reciprocal interactions? Recently, Watanabe (1997) found that there are strong reciprocal interactions between motion and form processing and suggested that the role of reciprocal interactions was to maximize coherence between the representations in two modules. The present study suggests that this principle might be applied not only to reciprocal interactions between different modules but also to different stages within the same module (eg motion). The 3-D structure-recovery stage may influence motion correspondence for the purpose of perceiving both cylindrical structure and one-way motion. Unlike traditional stimuli, when our stimulus is perceived as a cylinder, the front surface is seen as opaque, and the rear surface is thus occluded. One-way rightward motion is most consistent with a cylindrical structure in which new rectangles emerge at the left edge, move rightward across the exposed surface, and then disappear at the right edge. On the other hand, when oscillation is perceived, rectangles appear to move back and forth only over the visible surface and are not seen to appear from or disappear into the hidden part of the surface. Thus, oscillation does not particularly support the selection of the cylindrical structure while one-way motion matches the hypothesis. That may be why the higher 3-D structure-recovery stage influences the lower, correspondence stage—in order to increase the match between information at the two stages. In this sense, the principle of consensus seeking between two processes may be applied not only to intermodular interactions but also between stages within a module.

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