Perception, 1993, volume 22, pages 537-547

Apparent relative size and depth of moving objects

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Received 7 September 1991, in revised form 10 August 1992

Abstract. The effects of the relative velocities of moving objects on their apparent relative size and depth were investigated with the aid of square patterns generated on a CRT display by a microcomputer. The observer matched the apparent sizes of squares, arranged in two or more rows that moved with different velocities, and made judgments of the apparent relative depth of the rows. In many conditions, squares moving more slowly were perceived as larger in size than those moving faster, regardless of the kind of depth responses, but in some conditions which contained strong depth cues the size responses seemed to be affected by perceived depth. The size-change effect of moving objects is discussed from the viewpoint of size-depth relationship.

1 Introduction

Changes in perceived size have been found for moving objects (for example, Ansbacher 1944). Recently, the effects of temporal modulation on apparent spatial frequency have been investigated with sine-wave gratings used as stimuli. It was found that fractional shifts in apparent periodicity were induced by grating drift (Virsu et al 1974; Parker 1981, 1983). These results showed that the greater the speed of the stimuli the smaller their apparent size (the greater the apparent spatial frequency). Virsu et al (1974) suggested that this effect was based on the temporal properties of inhibitory interactions, whereas Parker (1981, 1983) stated that it arose for the improvement in some other visual information processing, for example pattern-discrimination performance. But the causes of this effect are not yet clear.

We believe that the effect is related to perceived depth and that it does not result from lower-level processes. The logic for this hypothesis is given below.

The relative movements of images across the retina have been regarded as one of the cues to depth perception (Nakayama 1985). Some investigators have shown that, although velocity gradients could provide information for 'unsigned depth' (ie depth separation of elements), they were insufficient for perceiving the direction of depth (Gibson et al 1959; Farber and McConkie 1979; Ono et al 1988). Rogers and Graham (1979) used dot patterns which had velocity gradients linked to head movements or to movements of the monitor. Their results showed that under these conditions motion parallax could be an accurate relative-depth cue. However, Braunstein and Andersen (1981) investigated the effectiveness of velocity gradients of moving objects on relative-depth perception without head movement. They showed that faster objects were judged as closer with a high degree of accuracy in the combined conditions of high speed (10.4 deg s^{-1}) and long duration (10 s) of presentation with free fixation. These results indicate that the relative movement of objects does not necessarily provide accurate relative-depth information, but is nevertheless closely connected to perceived relative depth.

It has been hypothesized that there is a relationship between perceived distance and the perceived size of an object (Kilpatrick and Ittelson 1953; Epstein et al 1961).

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In this relationship, the perceived size of an object is dependent not only on its visual angle but also on its perceived distance. Among objects subtending the same visual angle, the one that appears to be farther is perceived to be larger. In most of the previous experiments concerning this size-distance relationship, two kinds of stimuli, one presented in a large open field (Holway and Boring 1941; Leibowitz et al 1967; Brislin and Leibowitz 1970; Shallo and Rock 1988) and the other presented stereoscopically, have been used. In these latter studies, oculomotor information about the stimuli, such as convergence and accommodation, seemed to provide cues to their depth or distance (Leibowitz and Moore 1966; Oyama and Iwawaki 1972; Komoda and Ono 1974; Oyama 1974). In most studies, changes in perceived size were caused by large changes in perceived distance. Small changes of size with small changes of depth may also occur. Such small changes of size can be observed when we look simultaneously at two stereogram pairs which have crossed and uncrossed disparities, respectively.

It seems reasonable to predict that, when objects subtending the same visual angle are moving with different velocities, the faster objects will be judged smaller than the slower ones because we perceive faster objects as being closer. In the present study the apparent relative size and depth of objects moving with different velocities were measured in order to establish whether this prediction was correct. If apparent-size shifts were found to depend only on relative stimulus velocities and had nothing to do with depth responses, it would be proper to assume, as did previous investigators, that size shifts have a basis at a low level. But if it is found that size and depth responses are related to each other, then our hypothesis is the more plausible.

We performed two consecutive experiments to resolve this question.

2 Experiment 1

In this experiment, we investigated the relationship between the apparent relative size and the apparent depth of moving objects using stimuli consisting of two rows of squares moving horizontally. We measured changes in the apparent relative size of the squares in the rows by a matching method. The subjects also made depth judgments about the stimuli.

2.1 *Subjects*

Six male subjects participated in this experiment. All were naive regarding the purpose of this experiment except one of the authors (HK).

2.2 *Stimuli*

The stimulus patterns were generated by a microcomputer (Macintosh II) and presented on a high-resolution CRT monitor (480 × 640 pixels). The CRT screen, located 1 m away from the subject's eye(s), subtended 10.0 deg × 13.2 deg.

The stimulus patterns, shown in figure 1a, were two rows of squares, both moving horizontally in the same direction. Test and comparison squares were presented either in the top row or in the bottom row. The sides of the test squares subtended 2.12 deg. The sides of the comparison squares could be varied in size between 0.04 and 5.3 deg in steps of 0.04 deg. The adjacent squares in a row were separated by 5.3 deg between their centers, and the top and bottom rows were positioned 4.24 deg apart between centers.

In this experiment, the velocity of the comparison squares, v_c, was kept constant at 2.8 deg s^{-1} and the velocities of test squares, v_t, were chosen at random from four velocities; 2.8, 7.0, 13.9, and 26.3 deg s^{-1}, corresponding to shifts of 2, 5, 10, and 20 pixels in a frame of 15 ms on the monitor screen. The direction of movement of the squares was to the right in half of the displays and to the left in the remaining half.

The luminances of the squares and of the background were 22.5 and 0.07 cd m^{-2}, respectively. The experimental booth was dimly lit. The head of the subject was supported by a chinrest. The height of the subject's eye(s) was level with the center of the monitor.

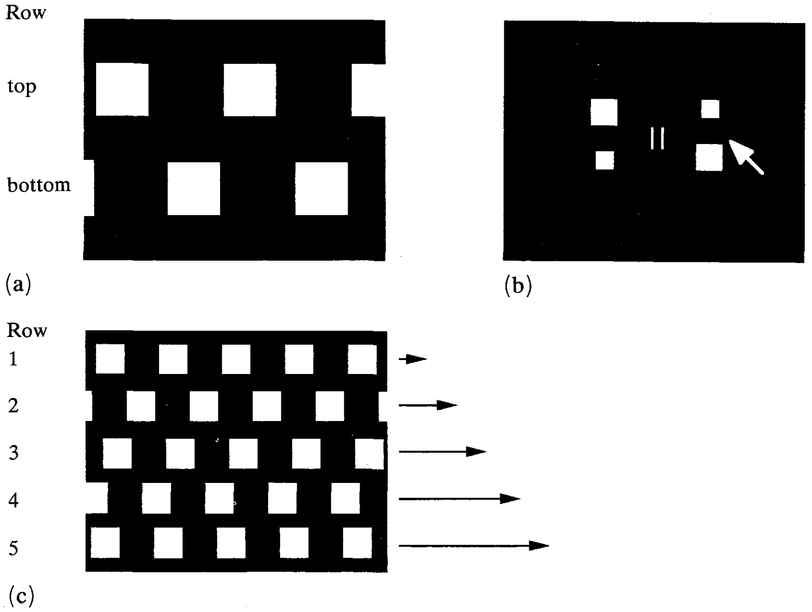

Figure 1. Illustration of (a) an example of the stimulus pattern in experiment 1, (b) the size response display used by subjects in experiment 1, and (c) the stimulus pattern of the five-row, horizontal (top slow) condition in experiment 2. The arrow in (b) was positioned by the subject to indicate the response. The arrows in (c) provide a clue to the velocity gradient.

2.3 *Procedure*

The subject matched the apparent size of the comparison square to that of the test square by means of the method of limits. The test and comparison squares were presented for 3 s. A white mask (22.5 cd m^{-2}) was displayed for 0.8 s after the presentation of the test and comparison squares. This white display prevented the subject from using afterimages of the squares. The subject made a response of 'top squares were larger', 'bottom squares were larger' or 'top and bottom squares were equal in size', with the aid of the response display shown in figure 1b. The comparison square in the subsequent stimulus displays were made smaller (or larger) in 0.04 deg steps according to the subject's response. Trials were repeated until the subject's response changed from 'top squares were larger' to 'bottom squares were larger', or vice versa. A mean size of comparison squares obtained from the consecutive 'top large' and 'bottom large' responses was defined as the point of subjective equality of size of the test squares. There were 32 trials [4 (test velocities) × 2 (top test and bottom test) × 2 (ascending/descending) × 2 (repetitions)] for each subject both under binocular and under monocular viewing conditions. These trials were selected at random, and the orders of the viewing conditions (binocular/monocular) were balanced among subjects.

All the subjects also made depth judgments about the stimuli in separate experimental sessions in which the stimuli were presented for 3 s. The subject reported which squares, those in the top or those in the bottom row, appeared closer. The subject had three alternatives to choose from: 'top row was closer', 'bottom was closer', or 'no depth'. In this experiment, the physical size of all the squares was kept constant at 2.12 deg × 2.12 deg. For each subject there were 64 trials [8 (conditions) × 8 (repetitions)] both under binocular and under monocular viewing conditions. These trials were selected at random, and the orders of the viewing conditions (binocular/monocular) were balanced among subjects.

2.4 *Results*

Since all subjects showed similar patterns of response, the data were averaged across the six subjects. Figures 2a and 2b show the mean relative size, defined as the ratio of the size of comparison squares, s_c, to that of test squares, s_t, at the point of subjective equality, as a function of test velocity, in the binocular and monocular viewing conditions, respectively.

From figure 2 it is seen that apparent relative sizes of test squares decreased with increasing velocities, and that squares in the top row appeared larger than those in the bottom row. The relationship between apparent-size shifts and stimulus velocities is consistent with the results of previous studies (Ansbacher 1944; Virsu et al 1974; Parker 1981, 1983). These effects were greater in the monocular condition than in the binocular condition. It is worthwhile noting that every subject was able to perform the size-matching tasks which we used here instead of the spatial-frequency-matching tasks used in previous studies (Virsu et al 1974; Parker 1981, 1983). This indicates that the sides of the squares in the faster rows shrank in apparent size perpendicular as well as parallel to the direction of motion. A supplementary experiment corroborated this finding.

In table 1 the mean percentage of relative-depth judgments across all subjects is shown. The data from 'top closer' and 'bottom closer' judgments are classified into two categories, depending on the stimulus condition: 'correct' was defined as a judgment of the faster-moving squares being closer, and 'wrong' was defined as a judgment of the slower-moving squares being closer. These categories had been used by Braunstein and Andersen (1981).

Both in the binocular and in the monocular viewing conditions, the percentage of 'no depth' responses was largest when the top and bottom rows had the same velocities. When the velocities of the two rows were different, the number of 'no depth' responses decreased but the depth reponses were not always 'correct': in many cases the slower-moving bottom row was judged to be closer. Moreover, many subjects stated that they perceived the two rows as separated in depth but the directions of these depth judgments were ambiguous. These results are consistent with those of previous studies (Gibson et al 1959; Farber and McConkie 1979; Ono et al 1988).

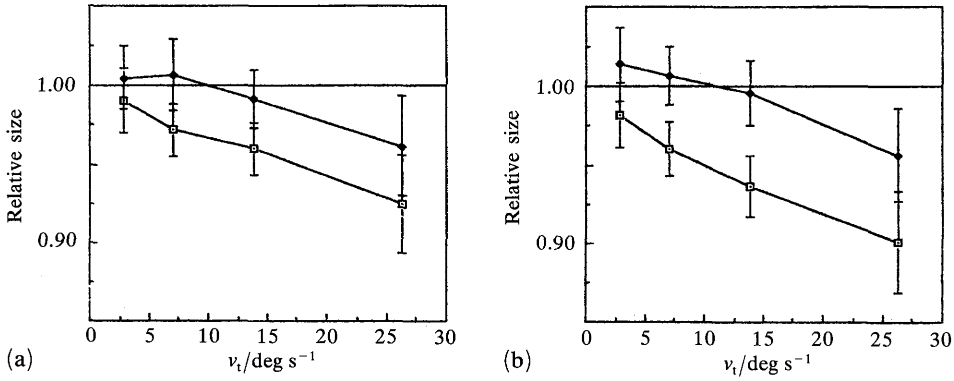

Figure 2. Results of experiment 1. The mean relative size at the point of subjective equality of size as a function of the test velocity in (a) the binocular and (b) monocular viewing conditions. The closed and open symbols show the results of test-top and test-bottom conditions, respectively. Vertical bars represent standard deviations.

In the present experiment, the direction of size changes (ie faster-moving objects being perceived as smaller) is in agreement with a prediction that (i) the subject perceives faster-moving squares to be closer, (ii) the size of the square changes as a function of depth, and (iii) therefore the subjects perceive faster-moving squares to be smaller. But the depth judgments of the subjects did not always conform to this logic.

Table 1. The response rate of relative-depth judgments as a function of test and comparison velocities in experiment 1. (a) denotes responses designated 'correct', and (b) denotes responses designated 'wrong'.

Velocity/deg s^{-1}		Response/%		
top	bottom	'top closer'	'bottom closer'	'no depth'
Binocular viewing				
2.8	2.8	6.3	25.0	68.8
7.0	2.8	6.3 (a)	70.8 (b)	22.9
13.9	2.8	14.6 (a)	68.8 (b)	16.7
26.3	2.8	4.2 (a)	83.3 (b)	12.5
2.8	7.0	8.3 (b)	79.2 (a)	12.5
2.8	13.9	29.2 (b)	62.5 (a)	8.3
2.8	26.3	25.0 (b)	50.0 (a)	25.0
Monocular viewing				
2.8	2.8	12.5	35.4	52.1
7.0	2.8	37.5 (a)	60.4 (b)	2.1
13.9	2.8	43.8 (a)	45.8 (b)	10.4
26.3	2.8	12.5 (a)	70.8 (b)	16.7
2.8	7.0	25.0 (b)	75.0 (a)	0.0
2.8	13.9	35.4 (b)	50.0 (a)	14.6
2.8	26.3	33.3 (b)	50.0 (a)	16.7

3 Experiment 2

In this experiment, the role of perceived depth on the apparent relative sizes of moving objects was further investigated. We used a velocity gradient of moving objects and a long duration of presentation. These conditions resembled those used by Braunstein and Andersen (1981) in their experiment in which relative depth was judged with a high accuracy without observer head movements. The velocities of the stimuli to be compared in size were fixed. The degree of perceived depth was controlled by the number of objects and the orientation of the velocity gradient.

3.1 *Subjects*

Six male subjects, KT, MU, TY, HM, MS, and HS, participated in this experiment. All were naive regarding the purpose of this experiment.

3.2 *Stimuli*

In experiment 2, the stimulus variables were the number of rows and the orientaton of the velocity gradient.

The number of rows was set at two, three, or five. The velocity gradient of these rows increased from top to bottom [called here the 'horizontal (top slow)' condition], or vice-versa [called here the 'horizontal (bottom slow)' condition]. In a third condition, columns, instead of rows, of squares were used as stimuli (called here the 'vertical' condition). In this last case, the velocity gradient increased either from the right to the left or from the left to the right. Each square subtended 1.27 deg. The separation of squares in a row was constant at 2.54 deg between centers. The rows were separated by 1.70, 3.39, and 6.75 deg, corresponding to the five-row, three-row, and two-row conditions, respectively. The velocities were 2.8, 5.6, 8.4, 11.2, and 13.9 deg s^{-1}

for five rows, 2.8, 8.4, and 13.9 deg s^{-1} for three rows, 2.8 and 13.9 deg s^{-1} for two rows, so that the ratios of the velocities were 1:2:3:4:5, 1:3:5, and 1:5, respectively. The relative velocities of the outer rows, which contained the squares which were to be compared in size, were constant regardless of the number of the rows and the orientation of the velocity gradient, as mentioned above. The stimulus patterns of the five-row, horizontal (top slow) condition are shown in figure 1c, as an example.

In the horizontal-movement conditions, the direction of movement of the squares was to the right in half of the presentations and to the left in the remaining half. In the vertical condition we used four combinations [2 (directions of movement: top to bottom/bottom to top) × 2 (orientations of velocity gradient: left to right/right to left)].

The luminances of the stimuli and other conditions of this experiment were the same as those in experiment 1.

3.3 *Procedure*

The moving squares were presented for 10.5 s in each trial. The white mask (22.5 cd m^{-2}) was displayed for 0.8 s after each stimulus presentation. After that, the response display—in which two stationary squares were arranged horizontally or vertically—was presented. The size of one square was changed by the subject and that of the other square was held constant. The subject adjusted the size of the variable square so that the ratio of size between the two squares in the response display was matched to that between the moving squares of the outer rows in the stimulus display. In the same trial, after making the size response, the subject also judged the depth of the test square using a display for depth responses, in which some patterns of perceived depth were drawn.

For each subject there were 144 randomly ordered trials [9 (conditions) × 16 (repetitions)], which were divided into 2 sessions. Only monocular viewing was used.

3.4 *Results*

To examine the results of experiment 2, the depth responses were classified into four categories: 'no depth', 'correct', 'wrong', and 'random'. The category 'no depth' indicates that the subject did not perceive any depth in the stimuli. In the 'correct' category, the rows of squares moving with higher velocities were perceived as closer to the subject. In the 'wrong' category, the rows of squares moving with higher velocities were perceived as farther from the subject. For example, for the display with five rows in the horizontal (top slow) condition (shown in figure 1c), when the subject perceived these squares as if they were arranged on a floor, the response was defined as 'correct', but when he perceived them as if they were on the underside of a ceiling, the response was defined as 'wrong'. In the 'random' category, the direction of the depth judgments was not stable. In the case of the stimuli with five rows, the depth percept was classified as either 'correct' or 'wrong' when the depth was perceived systematically over more than four rows.

In figures 3, 4, and 5 the results of experiment 2 for the vertical, horizontal (top slow), and horizontal (bottom slow) conditions, respectively, are shown. The abscissa represents the number of the rows and the ordinate the mean of the ratio of the perceived sizes of fastest and slowest squares, $s_\mathrm{f}/s_\mathrm{s}$.

The results in the vertical condition, shown in figure 3, show that, for most subjects, the 'correct' depth responses increased as the number of rows increased. In many cases, the ratios $s_\mathrm{f}/s_\mathrm{s}$ are significantly below 1.0, which indicates that the faster-moving squares looked smaller than the slower-moving squares. But this direction of size shift did not always occur with the 'correct' depth responses. These results are consistent with those of experiment 1.

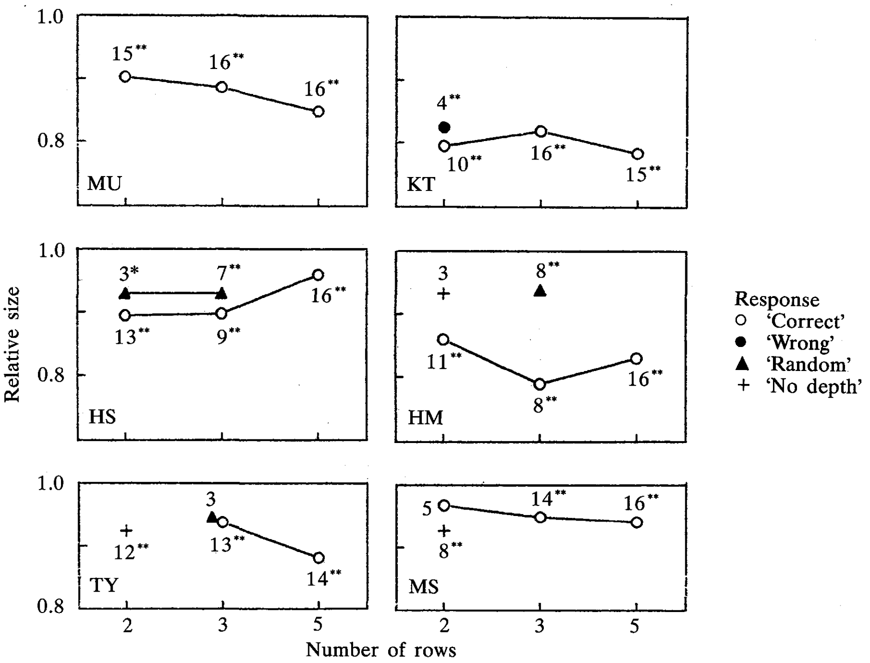

Figure 3. The apparent relative-size ratio as a function of the number of rows in the 'vertical' stimulus condition with monocular viewing for each of the six subjects in experiment 2. Numbers adjacent to the data points show the frequency of response, and the symbols * and ** indicate significance levels of differences of s_f/s_s from 1.0 of $p < 0.05$ and $p < 0.01$, respectively. For clarity, responses recorded less than three times have not been plotted.

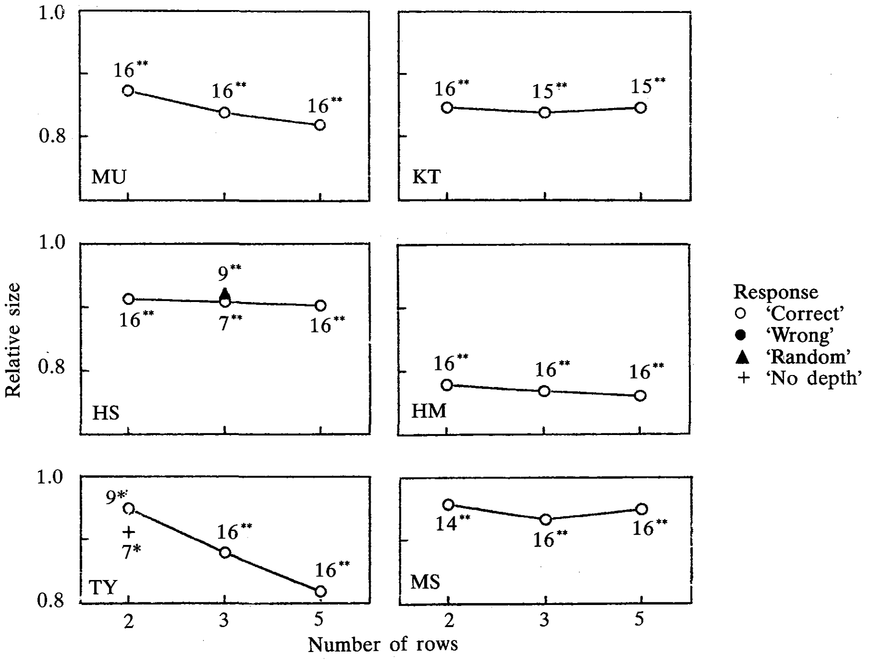

Figure 4. The apparent relative-size ratio as a function of the number of rows in the horizontal (top slow) stimulus condition with monocular viewing for each of the six subjects in experiment 2. Numbers adjacent to the data points show the frequency of response, and the symbols * and ** indicate significance levels of differences of s_f/s_s from 1.0 of $p < 0.05$ and $p < 0.01$, respectively. For clarity, responses recorded less than three times have not been plotted.

The depth responses in the horizontal (top slow) condition, shown in figure 4, were almost all 'correct'. All the ratios s_f/s_s are significantly below 1.0. A tendency for s_f/s_s to decrease as the number of rows increases can be seen for subjects TY and MU, which may be explained as follows. As the number of rows increases, the difference in the depth of squares in the extreme rows increases, and the relative-size differences of these rows increases, though these increasing depth-effects cannot be seen in the depth responses themselves.

The results in the horizontal (bottom slow) condition, shown in figure 5, were different from those in other conditions. In the results for subjects MU, KT, and HS, the ratios s_f/s_s are all below 1.0. For these subjects, 'correct' depth responses were less frequent in this condition than in the vertical and horizontal-(top-slow) conditions, but the overall trend of size responses was almost the same: whether depth responses were 'correct' or not, the faster squares were always judged as smaller than the slower squares. In the results for subjects HM, TY, and MS, on the other hand, s_f/s_s increased as the number of rows increased and some points are above 1.0. For these subjects, 'random' and 'wrong' depth responses were more frequent than for the other subjects and no 'correct' responses were found.

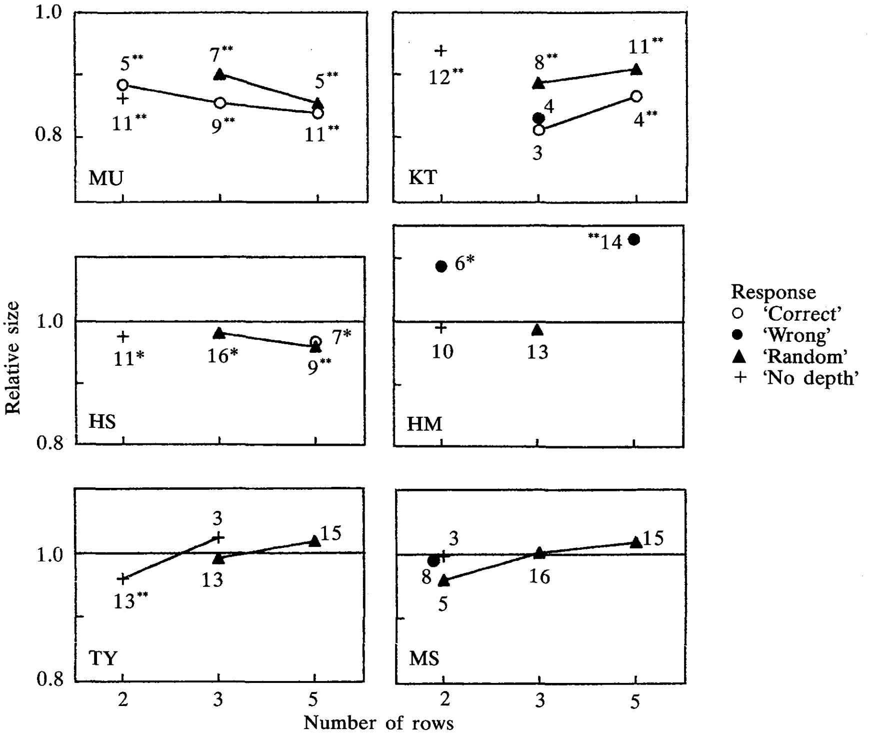

Figure 5. The apparent relative-size ratio as a function of the number of rows in the horizontal (bottom slow) stimulus condition with monocular viewing for each of the six subjects in experiment 2. Numbers adjacent to the data points show the frequency of response, and the symbols * and ** indicate significance levels of differences of s_f/s_s from 1.0 of $p < 0.05$ and $p < 0.01$, respectively. For clarity, responses recorded less than three times have not been plotted.

4 Discussion

In these experiments, the relationship between perceived size and perceived depth of moving objects was not simple. In the two-row conditions (experiment 1), 'correct' size responses (the sizes of faster objects were perceived as smaller than those of slower ones) were always obtained, whether depth responses were 'correct' or not.

It seems that depth judgments were more closely related to the vertical position of the rows of squares: the subjects tended to judge the lower squares to be nearer. Similarly, in many conditions in experiment 2, the values of s_f/s_s were almost significantly below 1.0, whether depth responses were 'correct' or not.

But it is likely that size responses were dependent not only on stimulus velocities but also on the direction of motion and the number of rows. For example, the apparent-size shifts reported by subjects MU and TY in the horizontal (top slow) condition increased with the number of rows (figure 4). Other examples are seen in the size responses of subject HM, which were greater than 1.0 with 'wrong' depth responses in the horizontal (bottom slow) condition (figure 5) and were less than 1.0 with 'correct' depth responses in the vertical and the horizontal (top slow) conditions (figures 3 and 4)—subjects TY and MS also showed a similar trend of responses. These responses seem to be related to perceived depth.

These results indicate that there are at least two factors which cause apparent-size changes. One is the direct effect of relative velocities on apparent sizes and the other is the effect of perceived depth. The latter can be thought of as the indirect effect of velocities, because perceived depth is due to velocity gradients.

It is reasonable to think of perceived distance or depth as being the consequence of differences between perceived size and physical size on the retina. These kinds of explanations are often applied to size illusions of figures (Gregory 1970) and of the moon (Kaufman and Rock 1962; King and Gruber 1962; Rock and Kaufman 1962; Dees 1966). But the judgments of the distance or depth in these examples are often missing from the theories. In the results reported here, the same problem also arises: when objects having the same visual angle were perceived as smaller, they were not necessarily perceived to be closer. How can we explain this?

McCready (1985) argued that it is insufficient to use only one 'perceived size' for the concept of size, and he proposed a distinction between perceived linear size and perceived visual angle. He mentioned contour interactions and oculomotor factors, concerning accommodation and convergence responses, as explanations of departures of perceived visual angle from physical visual angle.

We have also postulated the existence of a 'basic' perceived size or perceived visual angle (Kaneko and Uchikawa 1992). It seems that when the apparent depth of the stimuli was ambiguous, the subjects judged perceived visual angle as apparent size, which was only a synonym for 'size' in these experiments. These responses could be found with the stimuli with two rows. On the other hand, when unambiguous depth was perceived in the stimuli, subjects judged perceived linear size, taking depth into account, as apparent size. These responses were seen in experiment 2 (three-row and five-row stimuli). We think that relative motion in a display yields information for both perceived visual angle and perceived depth, and that subjects use either the perceived visual angle or the perceived linear size as the apparent size of the object, depending on the degree of perceived depth (Ono 1966).

Oyama (1974) investigated the effects of convergence on both perceived size and perceived depth and analyzed their causal relations. He concluded that perceived depth and perceived size were not related causally. Both were determined by convergence. It is likely that our results, in part, support his conclusion because the 'correct' size responses did not necessarily coincide with the 'correct' depth responses. The effect of the number of rows on the degree of size change may also be explained as the result of two direct relations—between velocities and perceived size, and between velocities and perceived depth. But some data in experiment 2—for example s_f/s_s for subject HM in the horizontal (bottom slow) condition, which is greater than 1.0 with 'wrong' depth responses—seem to show mutual relations between perceived depths and perceived sizes. Therefore it would be better to assume that there are two kinds of size perception: perceived linear size and perceived visual angle. The former is the size perception based on perceived depth or distance, whereas the latter is direct size perception determined by velocities or other information.

We have shown that the stimulus configuration, relative velocity, and perhaps perceived depth, of moving objects influence their apparent sizes. And we used the concept of two kinds of perceived size, which McCready (1985) proposed, to explain the complicated size and depth responses in our experiments. But in this explanation the cause of the shifts of perceived visual angle is not yet clear. It may have a basis at a low level, as Virsu et al (1974) suggested. But it seems that size shifts have some benefits for the visual system, because Parker (1981) showed that some neurons continue to signal the veridical spatial frequency of the stimulus even when the subject's perception altered. So we think that the visual system makes the size shifts 'intentionally' and that this is of benefit in maintaining the apparent size of an object constant, independent of its location.

Since Julesz (1964) invented the random-dot stereogram, this has been used as a stimulus in many studies. To investigate motion parallax, the random-dot technique has also been used in many, especially recent, studies. It is obvious that a random-dot technique has many advantages for isolating specific kinds of visual information, such as binocular disparity or motion, in psychophysical experiments. However, it seems that the effects of those sources of information on some features (eg apparent size), which become clear only when the object does not consist of dots but occupies some area, have been overlooked. In our daily lives we usually see objects as having size. Therefore in addition to experiments in which random dots are used, it is important to use, in the investigation of visual processing, patterns having an area.

Acknowledgments. We thank Dr J M Bebko for his help in preparing our manuscript in English.

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