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Relative cues and absolute distance perception

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It is possible, in theory, for the simultaneous occurrence of several different relative cues of distances to increase the veridicality of the perception of absolute distance. To test whether this actually occurs, a three-dimensional display was viewed monocularly while moving the head laterally, under conditions in which some error in perceived absolute distance was expected. The perceived absolute distance of the display was measured with the number of relative cues of distance within the display varied. No systematic reduction was found in the error in perceived absolute distance as a consequence of the variation in the number of relative cues. The study provides no evidence that the potential source of absolute distance information provided by relative cues is utilized by the visual system.

The present study examines whether the perception of the absolute distance of a visual configuration, extended in depth, can be modified by the relative cues generated within the configuration. The study has two parts. First it is shown that a modification of perceived absolute distance by relative cues is possible theoretically. Second, experiments are conducted to determine whether the visual system utilizes information from relative cues in this manner.

THEORY

Relative cues to depth within a configuration can be defined separately from absolute cues to the distance of the configuration from the observer. Instances of the former are binocular disparity, relative motion parallax, and relative size. Instances of the latter are the oculomotor cues of convergence and accommodation and the cue of absolute motion parallax. Equations of the same general form define all of the above relative cues (Gogel, 1978), with two of these cues described using the three-dimensional display shown in Figure 1. The cue of relative motion parallax between the near (D_n) and far (D_f) portions of this display is generated as the head moves laterally a distance K_h from Positions 1 to 2 to 3, and returns. The visual angle at the nodal point of the eye produced between the far and near indicated portions of the display is ϕ_1 at Position 1 and ϕ_3 at Position 3. The horizontal projections of these two angles differ (relative to the bottom, the top is to the left at Position 1 and to the right at Position 3). This difference defines the cue of relative motion parallax (γ_m), which can be specified to a close approximation as

$$\gamma_m = \alpha_n - \alpha_f = K_h(D_f - D_n)/D_nD_f, \qquad (1)$$

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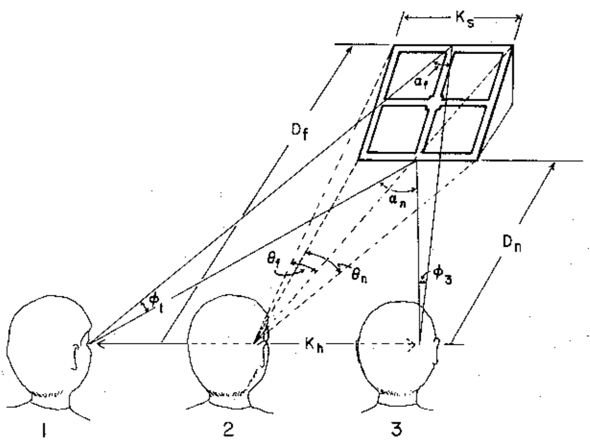

Figure 1. An illustration of two of the relative cues of distance (relative size and relative motion parallax) present in a three-dimensional display viewed while moving the head.

where the angles are in radians, $\alpha_n = K_h/D_n$, and $\alpha_f = K_h/D_f$. The relative size cue is illustrated in Figure 1 for the head at Position 2. The difference between the visual angles θ_n and θ_f subtended by the top and bottom (the near and far portions) of the square display of physical width K_s defines the relative size cue of distance (γ_s) in radians as

$$\gamma_s = \theta_n - \theta_f = K_s\,(D_f - D_n)/D_nD_f, \qquad (2)$$

where $\theta_n = K_s/D_n$ and $\theta_f = K_s/D_f$. It will be noted that Equations 1 and 2 have the same general form, that is, $\gamma = K(D_f - D_n)/D_nD_f$. Other relative cues, for example, relative accommodation and binocular disparity, also have this form. In the well-known case of the binocular disparity occurring between a near and far point of the display, γ is the horizontal difference in the visual angles subtended between these at the two nodal points of the eyes.

According to the general equation for relative cues of depth, a constant $D_f - D_n$ will produce a smaller

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γ the greater the distance of the configuration from the observer. If perceived depth were proportional to γ, a drastic lack of depth constancy would result. Fortunately, a correct perception of absolute distance is capable of modifying the depth perceived from γ in the direction of depth constancy. For example, the absolute distance cue of convergence will modify the perception of depth from binocular disparity in the direction of veridicality (Foley, 1978; Gogel, 1964; Ono & Comerford, 1977; Wallach & Zuckerman, 1963). It would be of importance if the converse also occurred, that is, if relative cues contributed to the veridicality of absolute perceptions of distance (see Foley & Held, 1972; Gogel, 1978). To consider seriously the possibility that relative cues can contribute to the perception of absolute distance, it is necessary to show that this is feasible theoretically. Considering Equations 1 and 2 together, it follows that

$$K_s = K_h \gamma_s / \gamma_m. \tag{3}$$

In Equation 3, γ_s and γ_m are available to the observer from the proximal stimulus, and it might be expected that the observer can sense the lateral motion, K_h, of the head. Thus, from cues of relative depth, the observer can have sufficient information to achieve a correct perception K_s' of the size (K_s) of the near and far edges of the square in Figure 1. Also, from K_s' and the visual angle θ subtended by a horizontal edge, a correct perception D' of the absolute distance D of the edge will occur according to the size-distance-invariance hypothesis (Kilpatrick & Ittelson, 1953), where

$$D_n' = K_s'/\theta_n \text{ and } D_f' = K_s'/\theta_f, \tag{4}$$

with θ_n and θ_f in radians. Thus, theoretically, relative cues can contribute to the accuracy of absolute perceptions of distance if two or more relative cues are available, with at least one of these having a constant K that is known to the observer. Another relative distance cue available from a surface slanted in depth and possibly contributing to the perception of absolute distance is that of relative accommodation (the accommodative difference between the near and far portions of the display). Indeed, it might be supposed that the greater the number of relative distance cues (with two as a minimum), the more likely it is that the relative cues will contribute to the veridical perception of absolute distance. It remains to be shown, however, that the observer can use relative cues in this way.

A test of this possibility has several requirements. One is that errors in using absolute distance cues are present, thus providing the opportunity for these to be reduced by the introduction of relative cues. A situation likely to meet this requirement is the monocular observation of an object in an otherwise dark field presented at a physical distance different from that specified by the specific distance tendency. The specific distance tendency is the tendency, in the absence of strong cues of absolute distance, for the object to appear at about 3 m (Gogel, 1969; Gogel & Tietz, 1973). Under these conditions, an object at a distance of 1 m, for example, will appear at a greater distance, with the perceived distance a compromise between that expected from the specific distance tendency and the available absolute accommodation.

A second requirement is the ability to vary the relative cues available in the display. In the present study, this was accomplished in two ways. One way was to present in a frontoparallel plane either the entire display shown in Figure 1 or only the small center square. In this case, $D_f - D_n$ in Equation 2 is zero and K_s in Equation 3 becomes indeterminate. Another way is indicated in Figure 2 and will be discussed later.

A third requirement is that of measuring the perceived absolute distance of the stimulus as a function of the number of relative cues available. A method called the head motion procedure, illustrated in Figure 3, was applied. This method, described in detail elsewhere (Gogel, 1976, 1977a, 1977b; Gogel & Tietz, 1979), is based on the phenomenon that a physically stationary object, misperceived in distance, will appear to move concomitantly with the head as the head is moved laterally. The apparent concomitant motion will be in the direction of, or opposite to, the head motion, depending upon whether the apparent distance of the object is less or greater, respectively, than its physical distance. Furthermore, if the object is *physically* moved concomitantly with the head until the apparent motion disappears, the magnitude of this physical motion can be used to calculate the perceived distance of the object, as indicated in the figure caption. This method was applied throughout the present study.

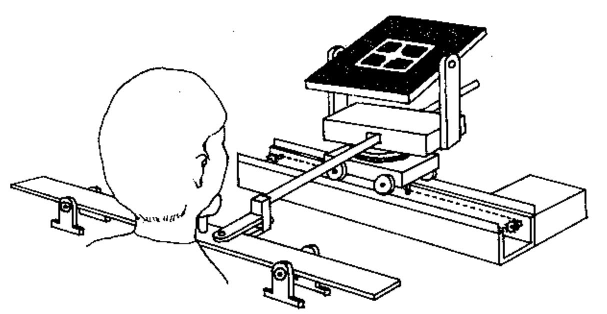

Figure 2. A method of removing the cue of relative motion parallax by turning the stimulus so as always to face the observer despite changes in the direction of the stimulus relative to the observer's head.

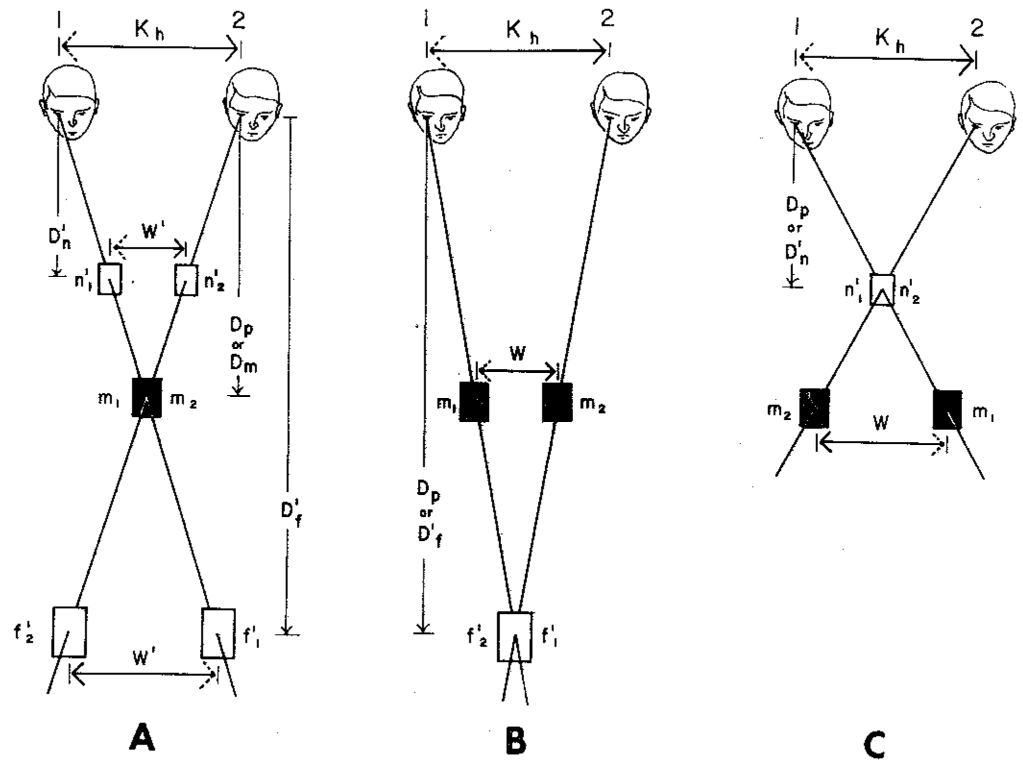

Figure 3. Principles involved in the head-motion procedure. The prime notation and open rectangles indicate perceived extents and perceived positions, and the notation without primes and filled rectangles indicate physical extents and physical positions. The apparent concomitant motion (W′) of the stationary rectangle with or against the head motion (K_h) as a function of the errors in perceived distance shown in A is eliminated in B and C by physically moving the rectangle a distance, W, as the head is moved until the rectangle no longer appears to move. The apparent absolute distance of the rectangle (D′) is calculated from the physical motion (W) required to achieve this null perception using the equation $D' = K_h D/(K_h - W)$, where D is the physical distance of the rectangle from the observer.

EXPERIMENTS

Method

Observers

The same six observers (four men and two women) were used throughout this study. They were graduate students in psychology who were paid for their participation. Each had a near and far acuity (uncorrected) of at least 20/20.

Apparatus

A portion of the apparatus used to present the stimulus and to vary its lateral motion physically by continuous amounts concomitant with the motion of the head is illustrated in Figure 2. At the observation position, a head- and chinrest assembly mounted on ball bearings could be moved left and right through a distance of 12 cm. A click presented from a loudspeaker every 1.5 sec was used to pace the time of arrival at left- and right-cushioned stops. The stimulus was viewed monocularly (an eye patch was over the left eye) from a dark observation booth.

The stimuli were formed by covering an electroluminescent surface with opaque material except for the portions producing the stimulus figure. The luminance of all stimuli was .09 cd/m²; the remainder of the visual field was totally dark. The stimulus was mounted in a holder that permitted it to be slanted in depth with the top edge more distant than the bottom edge, to form an angle of 30 deg with the horizontal plane (see Figures 1 and 2), or to be oriented in a plane frontoparallel to the observer. Throughout this study, the stimuli were square in shape with the centers of the squares physically at 30, 60, or 120 cm from the observer. The sides of the stimuli were 7.3, 14.6, and 29.2 cm at the 30-, 60-, and 120-cm distances, respectively, to maintain a 10-deg visual angle of the diagonal when the slant was 30 deg from the horizontal and a 19.5-deg visual angle of the diagonal when the slant was 90 deg (vertical). The widths of the luminous lines of the figure were .10, .20, and .40 cm, respectively, at the three distances. It will be noted in Figures 1 and 2 that a small inner square was formed at the intersection of the lines dividing the large square into quadrants. The sides of this small square were .25, .50, and 1.0 cm, respectively, at the three distances. The small square sometimes was presented without the remaining portions of the configuration. The displays (represented in Figure 2) will be called the large squares or large stimuli to distinguish them from the cases in which only a small (center) square was present.

As shown by Figure 2, the stimulus in its holder was mounted on a cart that was movable laterally on a track. The cart was attached to a chain-and-sprocket drive, with the drive controlled by a motor variable in speed and direction. The motor was part of an electronic servosystem that physically moved the stimulus laterally concomitant with the physical lateral motion of the head. The position and motion of the head- and chinrest was communicated by a gear-and-chain connection to the servosystem, whose output was controlled by a knob located at the position of either the observer or the experimenter. By adjusting the knob, the physical motion of the stimulus concomitant with the motion of the head could be varied continuously from a motion in the same direction as the head motion to one opposite to that of the head motion. The perceived distance of the stimulus was computed from the physical motion adjusted by the observer to achieve the criterion of no apparent motion of the center square of the display. The apparatus could be adjusted in distance to present the stimuli at the required distance.

To be able to remove the cue of relative motion parallax, the stimulus holder was mounted on a turntable. A rigid bar connecting the stimulus and the head-motion apparatus was pivoted at the head- and chinrest assembly and extended through an opening in the base of the stimulus holder (see Figure 2) so as to rotate the holder on the turntable around a vertical axis without restricting the lateral motion of the cart on its track. When the bar was in place, the stimulus always faced toward the right eye of the observer for all lateral positions of the stimulus and head (see Figure 2). When the bar was not used (disconnected from the apparatus), the turntable was pinned in place and the stimulus did not rotate as the cart moved laterally. In this case, the near and far edges of the stimulus remained parallel to the track for all lateral positions of the stimulus. Also, in this case, the retinal image of the stimulus was not constant as the head moved laterally; instead, it executed a shear transformation, as shown in the upper three drawings of Figure 4. With the bar in place, the shear transformation on the retina was absent and the shape on the eye was always similar to that shown in the middle drawing in the upper portion of Figure 4. Another transformation that occurred at the near (30 cm) distance is the trapezoid transformation shown in the lower half of Figure 4. When the head was to the right or left relative to the large stimulus, one side of the square was closer and therefore larger on the eye than the other. The trapezoid transformation shown in Figure 4 occurred in the absence of the rigid bar and with the display oriented vertically. With a large stimulus slanted in depth, in the absence of the rigid bar, both transformations (shear and trapezoid) occurred simultaneously on the retina as the head was moved relative to the stimulus. Whether the shear transformation was perceived depended upon whether the slant of the display was perceived correctly (Gogel, 1980). The greater the error in perceived slant, the greater the perception of shear. The perception associated with the trapezoid transformation is more difficult to predict. Possibly, it would result in perceived rotation around a vertical axis. The

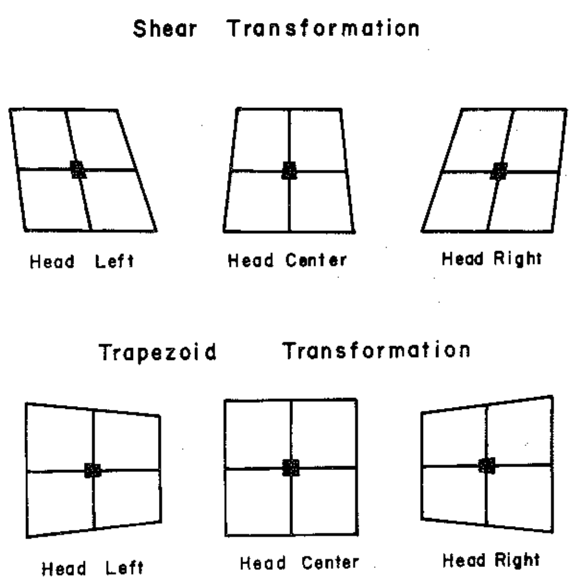

Figure 4. Transformations on the retina involved in a stimulus physically slanted in depth (upper portion) or physically upright (lower portion) as viewed with a moving head.

use of the bar connecting the head and stimulus assemblies eliminated the trapezoid, as well as the shear transformation on the retina, that would have been present in some of the stimuli viewed with a moving head.

Apparent slant was measured in all three experiments. The measurement apparatus, located in the observation booth, consisted of a blue 10.7-cm square plate rotatable by the observer in depth around a horizontal axis using the fingers and palm of the right hand. Reference marks indicated the horizontal and vertical positions of the plate, with the rotation of the plate read by the experimenter from a dial outside the observation booth. White cardboard attached to the left wall of the observation booth provided a light adaptation surface with a luminance of 17.5 cd/m² when the booth light was turned on.

Experiment 1. Either a large stimulus at a 30-deg depth slant from the horizontal plane or a small square alone (in a frontoparallel plane) were presented with centers at 30, 60, or 120 cm. The rigid bar connecting the head- and chinrest assembly with the stimulus assembly was not used. In terms of the number of relative cues and transformations, the large stimuli at the 30 deg slant will be called the complex stimuli and the small squares in the frontoparallel plane will be called the simple stimuli of Experiment 1.

Experiment 2. Only the large stimuli of Experiment 1 slanted in depth at 30 deg from the horizontal plane were used. Again, these were presented at the three distances under two conditions. In one condition, the rigid bar between the head- and chinrest assembly and the stimulus assembly was present, and in the other it was absent. Since the rigid bar removed the cue of relative motion parallax, the presentations using this bar are called the simple stimuli and the presentations in which the bar was omitted are called the complex stimuli.

Experiment 3. Only the large stimuli of Experiment 1 were used at the three distances, and were either slanted 30 deg (top back) or were vertical. Also, the bar connecting the head- and chinrest assembly and stimulus assembly was either present (the simple stimuli) or was absent (the complex stimuli) with either the 30-deg or vertical orientation.

A summary of the stimuli used in the three experiments and the relative distance cues and transformations available with these stimuli are listed in Table 1. The numbers at the left of the table identify the different combinations (conditions) of cues and transformations used in the experiments. Strictly speaking, the notation "absent" does not mean that the particular depth cue was eliminated but, rather, that it was consistent with the stimulus' being in a frontoparallel plane (whether or not it was actually frontoparallel). For example, if the cue of relative motion parallax is listed as absent (Conditions 1, 3, 5, 7, and 8), the lack of relative motion between the near and far parts of the display on the eye indicated that the display was frontoparallel. Relative size and relative accommodation are listed as cues to depth in all situations in which the stimulus was slanted (Conditions 2, 3, 4, 5, and 6). Three relative cues of distance were present under Conditions 2, 4, and 6, two were present under Conditions 3 and 5, and no relative cues were present under Conditions 1, 7, and 8.

Procedure

Experiment 1. The observers were instructed as to what was meant by perceived motion "with" and "against" the head and as to what was meant by the adjustment to the no-apparent-motion (null) criterion. They were always told to fixate the center of the stimulus and to adjust the control knob of the servo-system until this center appeared to move neither right nor left as the head was moved laterally. They were instructed also to use a bracketing technique in arriving at the null adjustment. This involved adjusting the control knob so as to approach the null position from apparent concomitant motions alternately with and against the direction of the head motion, using successively smaller adjustments until the null setting was achieved. Using a drawing to illustrate the shear transformation, the observers were informed

Table 1
Depth Information Available in Conditions Labeled Simple or Complex in Three Experiments

		Relative Cues			Transformations	
Stimuli	Description	Size	Motion Parallax	Accommodation	Shear	Trapezoid
		Experiment 1				
(1) Simple	Small Squares at 90 deg, Bar Absent	Absent	Absent	Absent	Absent	?
(2) Complex	Large Squares at 30 deg, Bar Absent	Present	Present	Present	Present	Present
		Experiment 2				
(3) Simple	Large Squares at 30 deg, Bar Present	Present	Absent	Present	Absent	Absent
(4) Complex	Large Squares at 30 deg, Bar Absent	Present	Present	Present	Present	Present
		Experiment 3				
(5) Simple	Large Squares at 30 deg, Bar Present	Present	Absent	Present	Absent	Absent
(6) Complex	Large Squares at 30 deg, Bar Absent	Present	Present	Present	Present	Present
(7) Simple	Large Squares at 90 deg, Bar Present	Absent	Absent	Absent	Absent	Absent
(8) Complex	Large Squares at 90 deg, Bar Absent	Absent	Absent	Absent	Absent	Present

that the stimulus might appear to distort in the manner indicated, but that this would not interfere with the null adjustment of the center.

After some practice with moving the head laterally in the head- and chinrest and practice with the control knob, the tilt comparison plate, and the light adaptation surface, the booth light was turned off. The observer then began the head movement left and right in time with the metronome, the viewing shutter was raised, and, while continuing the head movements, the observer adjusted the control knob until the fixated center of the stimulus appeared to be stationary. The observer noted the apparent tilt of the stimulus, the shutter was closed, and the booth light was turned on. The occluder was removed from the left eye and, with the right hand, the observer, using a bracketing technique, adjusted the tilt comparison plate to duplicate the slant perceived in the stimulus. Following this, the observer looked at the adaptation surface until the next trial. Four practice trials were given on the first scheduled experimental situation.

The order in which the three distances of the stimuli were presented was counterbalanced between observers in all experiments with all observers always presented with all distances. Both the simple and complex stimuli were shown three times in succession at one distance before changing to a different distance, with the order of presenting the simple and complex stimuli counterbalanced between observers. After completing the presentations at one distance, the observer was asked whether shearing motion was observed in any of these.

Experiment 2. The procedure was very similar to that of Experiment 1. The stimuli were the large stimuli of Experiment 1 slanted in depth (top back at 30 deg from the horizontal plane). The stimuli listed as simple were those in which the rigid bar connecting the head and stimulus assemblies was present. The stimuli listed as complex were without the bar. Half of the observers were presented with a simple stimulus before being presented with a complex stimulus at a particular distance. For the remainder, this order was reversed. Following completion of three successive trials for a stimulus at a particular distance, the observer was asked whether any rotation around a vertical axis in addition to any shear was perceived in the stimulus.

Experiment 3. The procedure was the same as for Experiment 2 except that two, rather than three, trials were completed for each condition with each observer. The large stimuli were slanted in depth 30 deg from the horizontal plane or were vertical, and the bar connecting the head and stimulus assemblies was either present (the simple stimuli) or absent (the complex stimuli). Half of the observers received a vertical before a slanted stimulus at a particular distance, and half received the reverse order. No reports of shearing or rotation were asked for in Experiment 3.

Results

The geometric means of the perceived absolute distances (D′) of the center of the stimulus obtained using the head motion with the six observers (averaged over the several trials at a particular distance) are shown in Figure 5 plotted against the three physical distances (D). On each graph, the stimuli are classified as simple or complex, with the complex stimuli involving more relative cues or more stimulus transformations than the simple stimuli.

The numbers near the data curves of Figure 5 refer to the identically numbered descriptions in Table 1. The dashed line in a drawing indicates the correct perception of absolute distance. The displacement of the data curves above the dashed lines is expected from the specific distance tendency. Figure 5 does not suggest that the errors in perceived absolute distance were less when the complex, rather than the simple, stimuli were used. This is consistent with the analysis of variance of the D′ data using a two-way repeated measures design, with the two factors being physical distance and the classification of the stimuli as simple or complex. Only physical distance (D) was statistically significant [$F(2,10) = 20.5$, $p < .01$, in Experiment 1; $F(2,10) = 13.0$, $p < .01$, in Experiment 2; and $F(2,10) = 10.0$, $p < .01$, in Experiment 3]. Neither the simple-complex factor nor any interactions involving this factor were significant at the .05 level in any of the experiments. The standard deviations of the data points of Figure 5, however, were large. The average of these in centimeters for the simple and complex stimuli, respectively, are 69 and 79 for Experiment 1, 90 and 67 for Experiment 2, 123 and 109 for the slanted stimuli, and 131 and 124 for the vertical stimuli of Experiment 3.

The physically vertical stimuli were almost always judged as being vertical or nearly vertical. The stimuli physically slanted in depth 30 deg from the horizontal plane were always perceived as slanted in depth. In

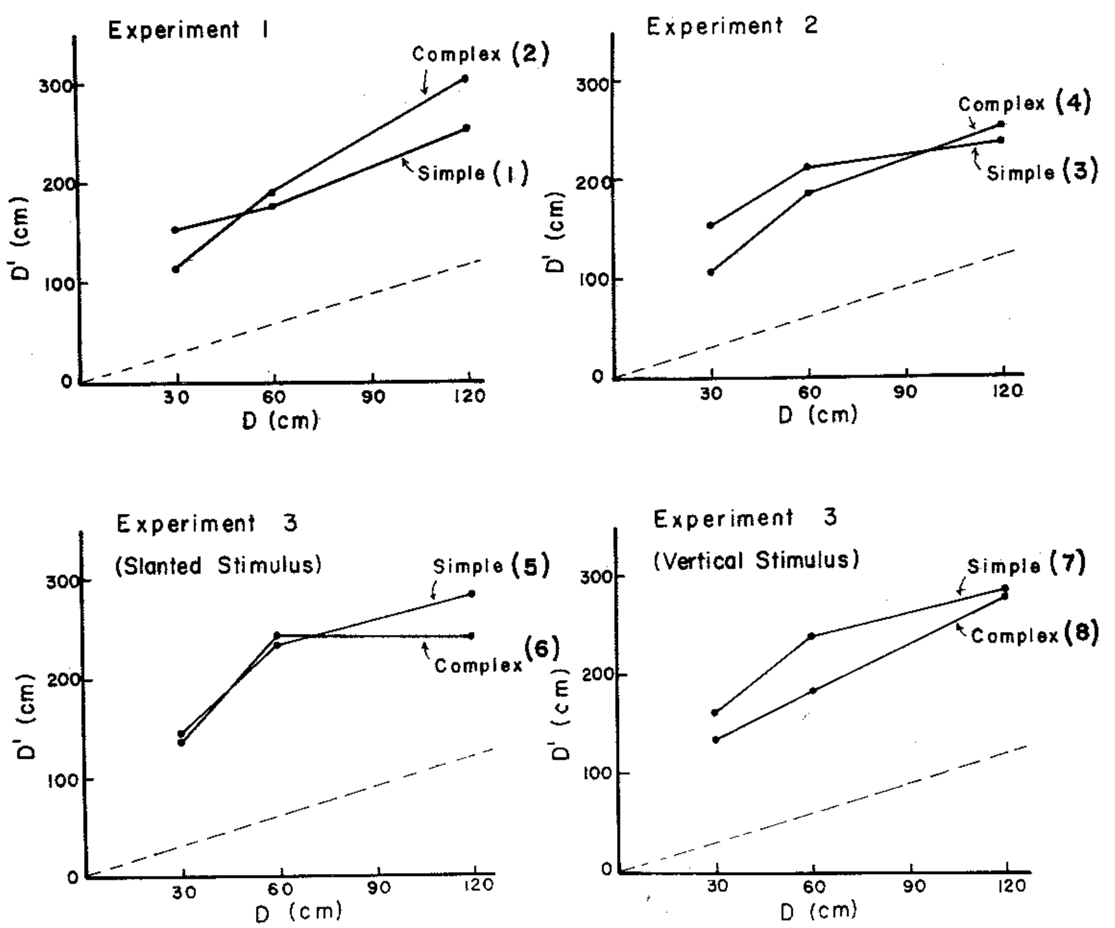

Figure 5. The results obtained from the three experiments indicating the absolute perceived distance (D') of the stimuli (the solid lines) as a function of whether the stimulus condition within an experiment involved more (complex) or less (simple) relative distance cues and motion transformations. The dashed lines indicate the data that would be expected had the perceptions been veridical.

Experiment 1, the average perceived slants of these were 52, 57, and 57 deg from the horizontal at the near, middle, and far distances, respectively. Similar results obtained from Experiments 2 and 3 are shown in Table 2 for the slanted stimuli with (complex) or without (simple) the cue of relative motion parallax. According to an analysis of variance of Table 2, judged slant did not differ significantly as a function of the presence of relative motion parallax [$F(1,5) = 4.2$ and 1.3, respectively, $p > .05$]. The tendency to misperceive the slant of the stimuli in depth is consistent with the frequent reports of shear that occurred in Experiments 1 and 2 for the conditions in which the rigid bar was not used with the large stimuli slanted at 30 deg. Reports of seeing some rotation of the stimuli in Experiment 2 occurred in about half the presentations.

DISCUSSION

Several conclusions are supported by an examination and comparison of the data curves between and within the three experiments. (1) In all three experiments, perceived distance clearly increased with increases in the accommodative (or accommodative convergence) distance. (2) As expected from the specific distance tendency, perceived absolute distance was consistently larger than physical distance. (3) The errors in perceived absolute distance remained essentially unmodified as a function of the presence or absence of either the static (relative size and relative accommodation) or dynamic (relative motion parallax or the trapezoid transformation) cue of relative distance. The present study provides no evidence that observers are able to use the simultaneous information from several relative cues to increase the accuracy of their perceptions of absolute distance. (4) The slanted stimuli were perceived as slanted in depth but as more vertical than their physical slant. Thus, relative distance cues were somewhat, but not totally, effective. Removing relative motion parallax did not substantially change perceived slant, indicating that relative motion parallax was not a very effective cue in the present experiment. The perception of the physically slanted stimuli as slanted is attributed mainly to either the relative size or the cue of relative accommodation, or both. Under other conditions, relative motion parallax is more effective (Hell, 1978; Hell & Freeman, 1977; Rogers & Graham, 1979).

Table 2
Perceived Depth Slant in Degrees from the Horizontal Plane of Stimuli Physically Slanted in Depth at 30 Deg from the Horizontal Plane in Experiments 2 and 3

	Experiment 2						Experiment 3					
	Near		Middle		Far		Near		Middle		Far	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Simple	60	10	59	12	57	11	58	8	54	9	56	10
Complex	55	10	53	13	54	9	52	15	54	10	56	8

The incentive for the present study came from a study by Johansson (1973), who found approximately veridical perceptions of absolute distance at near physical distances, using a four-point display slanted in depth, and viewed while moving the head. He suggested that perspective transformations associated with head motion might have contributed to the results. Absolute distance perception may or may not be veridical, depending upon conditions; but, from the present results, this veridicality, if it occurs, is not the result of relative cues or of the relative transformations associated with observer motions.

Although the present study does not support the hypothesis that relative cues can correct perceptions of absolute distance, it should not be concluded that absolute perceptions of distance are totally independent of relative information. One important effect of relative cues on absolute distance perception is that relative cues can extend the perception of absolute distance beyond that normally expected from absolute cues (Gogel, 1977b). In general, relative cues are more precise than absolute cues, and the perceived depth from relative cues can be added to the perceived distance from absolute cues, resulting in the perception of a visual field far extended in absolute distance. A second way in which relative cues of distance contribute to the perceptions of absolute distance has been demonstrated in regard to the specific distance tendency (Gogel, 1972; Mershon & Lembo, 1977). A single point of light, presented under reduced conditions, will appear near the distance indicated by the specific distance tendency. It will often appear closer than this, however, if a second point at a farther distance is added to the display. In this case, the perceived absolute distance of the first point is modified by the relative cues between the points. Perceptual learning provides a third way in which relative distance information might modify the perception associated with absolute cues. Wallach and Frey (1972) moved a binocularly viewed object from 25 to 80 cm but with size changes corresponding to a path 367 cm long. Later tests of the ratio of perceived size to perceived distance indicated that the perceived distance from oculomotor cues was modified by the perceptual learning associated with the discrepancy between the size and distance information.

Thus there a number of ways in which relative cues can modify absolute perception. The results of the present study, however, do not provide any assurance that one of these is the systematic reduction of errors in perceived absolute distance by relative cues or relative transformations resulting from viewing a three-dimensional display with a moving head.

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