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HOW TO REINFORCE PERCEPTION OF DEPTH IN SINGLE TWO-DIMENSIONAL PICTURES*

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ABSTRACT

The physical conditions of the display of single two-dimensional pictures, which produce images realistically, were studied by using the characteristics of the intake of the information for visual depth perception. "Depth sensitivity," which is defined as the ratio of viewing distance to depth discrimination threshold, has been introduced in order to evaluate the availability of various cues for depth perception: binocular parallax, motion parallax, accommodation, convergence, size, texture, brightness, and air-perspective contrast. The effects of binocular parallax in different conditions, the depth sensitivity of which is greatest at a distance of up to about 10 m, were studied with the new versatile stereoscopic display. From these results, four conditions to reinforce the perception of depth in single pictures were proposed, and these conditions are met by the old viewing devices and the new high-definition and wide television displays.

I. INTRODUCTION

The sensation of reality in a picture occurs because of visual depth perception. Therefore, in order to display pictures as if the observer were looking at real objects in three-dimensional space, the physical conditions of the pictures must be matched to the characteristics of the process involved in the intake of information relative to depth perception. The objectives of this paper are to report the results of an investigation on the availability of many cues for visual depth perception, using a common evaluating scale, and to propose ways to reinforce the perception of depth in single two-dimensional pictures.

It is well known that a pair of pictures taken from two laterally separated positions creates the effect of stereoscopic depth perception with binocular cues, such as binocular parallax and convergence cues of the eyeball shown in figure 1 and table 1. However, there are other monocular cues shown in figure 1, such as the accommodation cue of a crystalline lens, motion parallax on moving vision, and pictorial cues. The pictorial cues include transversal size, longitudinal size, texture density and shape, intersection, position of horizon, brightness and shade, air-perspective, and color effect. The study of the comparison of the effectiveness of each of the cues and the study of the interaction between different cues are necessary.

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The availability of cues for visual depth perception has been investigated. Künapas (ref. 1) studied the subjective absolute distance by the method of magnitude estimation as a function of viewing distance up to 4 m and five viewing conditions, where the cues (retinal size, binocular parallax, accommodation, and brightness) were fully provided or partially reduced.

He found that accommodation did not permit any accurate perception of distance, and that retinal image size was one of the most important cues in the judgement of absolute distance from the observer. He also pointed out the similarity of his result and the result of Holway and Boring (ref. 2) that the apparent size at a fixed viewing distance varies with the viewing condition. However, Künapas did not study motion parallax and relative depth perception.

When we view a picture which contains many objects, the space perception in the picture depends on the results of the relative depth perception among the objects.

Stubenrauch and Leith (ref. 3), using holograms, found the interposition cue to dominate over most combinations of other cues (binocular parallax, motion parallax, and retinal size) for perception of normal relief or reversed relief. However, these effectiveness estimations were not measured at large viewing distances.

Furthermore, since the cues on the retina, such as parallax, size, brightness, etc., have different physical attributes, the threshold value of each cue change for depth perception cannot be directly compared with each other.

The author proposes a common scale for evaluating the availability of depth cue, which is defined as the ratio $D/\Delta D$ of the viewing distance D to the detection threshold ΔD of depth difference (depth threshold). We call this ratio scale "depth sensitivity" (refs. 4,5) of vision.

In this way, the effectiveness of various cues can be quantitatively compared with each other as a function of viewing distance.

II. METHODOLOGY

Hypothesis

First, the relationship between depth sensitivity and the detection of quantitative cue change for depth perception of the object's image on the retina was considered from the viewpoint of the hypothesis that the change of cues is transformed into perception depth information while at the same time conserving the information concerning the character of the object on the base of the character as shown in table 1.

For example, when a value R(D) of the cue of binocular viewing direction is inversely proportional to the viewing distance D and is proportional to the constant A (where A is the distance between two pupils), the detection threshold ΔR of the change of the value of a cue such as the binocular parallax is obtained from the depth threshold ΔD as follows:

$$\Delta R = R(D) - R(D + \Delta D) = A/D - A/(D + \Delta D) \qquad (1)$$

Then the depth sensitivity is deduced as

$$D/\Delta D = A/(\Delta R \cdot D) - 1 \tag{2}$$

Second, by dilating on Fechner's Law (ref. 6), it was proposed that depth sensation is based on the sum of the small depth sensation unit dS=K corresponding to the depth thresholds. The depth sensation S(D) is obtained by

$$S(D) = \int_{D_0}^{D} \left(\frac{dS}{dD}\right) dD = \int_{D_0}^{D} (K/\Delta D) dD \tag{3}$$

where K is a transformation constant.

Psychophysical Experiment

The depth sensitivities of the cues of binocular parallax, motion parallax, and accommodation were obtained from the depth thresholds in psychophysical experiments. The characteristics of the cue-change threshold ΔR is induced from the depth threshold ΔD measured under the limited condition, and the depth sensitivities of these cues were calculated. Furthermore, the depth sensitivities of other cues were also calculated by estimating the detection threshold of cue change.

III. EXPERIMENTS I

For measuring the depth threshold, an observer, by using a remote-wire system, moved one of the two black rods (20 arc/min in width, 1 cd/m^2) as illustrated in figure 2, so the difference of depth can be noticed through a slit (40 arc/min in height, 19 arc/deg in width).

Two males (SN 33 yr of age, left V.A. 1.2 corrected, right V.A. 1.2; KI 23, 1.5, 1.5) and one female (NW 23, 1.2, 0.6) having normal streoscopic vision served as subjects in these experiments.

The depth thresholds on the binocular parallax, the motion parallax, and the cue from accommodation were measured as a function of viewing conditions.

The viewing conditions for controlling the depth cues were obtained by combining binocular observation or monocular observation and static observation or lateral moving observation, and observation with natural pupils or artificial pupils (1 mm diameter).

In moving observations, the observer moves the upper body rhythmically to the right and left at different distances and velocities which were measured in real time by an electronic scale wired to the head.

The viewing distance to the fixed rod was 1, 2, 5, and 18 m, respectively. The brightness, the retinal size, and the interval distance of two stimuli were not changed as a function of observation distance.

The measurements were taken for eight trials a day for three days for each person under each condition.

IV. RESULTS I

Binocular Parallax, Motion Parallax, and Accommodation Cues

The depth thresholds with static binocular vision through natural pupils were obtained as shown in table 2, and the symbol (o) in figure 3 indicates the depth sensitivities as a function of distance obtained from the depth threshold of the typical subject (SN).

The cue-change threshold ΔR on binocular parallax shown in figure 4 was calculated from the depth threshold ΔD with binocular vision from equation (1). It was considered that the binocular threshold neither changed as a function of viewing distance, i.e., convergence angle, nor as a function of the size of the pupils.

This was in agreement with the other two observers' results and with those reported by Ogle (ref. 7), Zoth (ref. 8), and Nishi (ref. 9). But Amigo (ref. 10), and Lit and Finn (ref. 11) reported that the threshold slightly increases as the distance decreases to less than 1 m because of the instability of the oculomotor.

The depth sensitivities of this cue shown by the solid line in figure 3 are calculated from equation (2), where a constant value is substituted for ΔR. The maximum distance D_{max} for which the sensitivity falls to zero is $A/\Delta R$.

The depth sensation S_D on binocular parallax is deduced from equation (4) and may be saturated at about 10 m (ref. 12).

$$S_D = \int_{D_0}^{D} \left(\frac{K}{\Delta D}\right) dD = K \int_{D_0}^{D} \left(\frac{A}{\Delta\theta \cdot D^2} - \frac{1}{D}\right) dD$$

$$= K\left[\frac{A}{\Delta\theta}\left(\frac{1}{D_0} - \frac{1}{D}\right) + \log_n \frac{D_0}{D}\right] \tag{4}$$

The depth thresholds for motion parallax with moving monocular vision with a natural pupil at the speed at which the subject could detect the depth are shown by the symbol (■) in figure 3. The depth threshold at a viewing distance of 3 m was measured for different conditions, and it was dependent on the velocity ω_D, but not on the distance d of movement as shown in figure 5(A). The optimum velocity ωa was 6-8° of arc/sec, and at velocities lower than the optimum velocity, the threshold velocity of motion parallax is constant.

Graham (ref. 13) and Zeger (ref. 14) reported on the increase in the threshold as the velocity increases from about 6° to 20° of arc/sec. But in our results shown in figure 5(B), the velocity threshold of motion parallax $\Delta\omega$ is constant at velocities lower than the optimum. This constancy is deduced from the detection model where the minimum parallax is sampled at a constant interval time.

The depth sensitivity of motion parallax calculated from equation (2) is represented by the solid line in figure 3. The sensitivity is $\omega a/\Delta\omega$ and is constant up to the distance at which the optimum velocity of the body movement is obtained, and when the distance is exceeded the sensitivity decreases. The descending curve is obtained by substituting the maximum velocity V_{max} of body movement for A, and $\Delta\omega$ for ΔR in equation (2).

This motion parallax is produced not only by the absolute motion of the observer, but also by the relative motion of the objects, and in the case of moving vision on some riding machine with a speed higher than the motion of the body, the sensitivities of motion parallax at large distances are maintained at the same level as that for short distances and are higher than that for binocular parallax.

The depth thresholds for the blurring cue of accommodation with static monocular vision through a natural pupil are represented by the symbol (Δ) in figure 3, and the depth threshold with vision through the artificial pupil was nearly equal to or slightly greater than the viewing distance.

The depth sensitivity of the natural accommodation cue was also calculated by substituting the pupil diameter during observation for A in equation (2) and by substituting the blurring threshold resulting from equation (1) (similar to the reciprocal of his visual acuity) for ΔR in equation (2).

Other Cues

The depth sensitivities relative to binocular parallax, motion parallax, and accommodation cues obtained from equation (2) are satisfied by the data resulting from the experiment. Therefore, we applied the same method of analysis in obtaining this sensitivity data to the sensitivity data relative to the other cues: convergence, size, slanted shape, texture density, brightness, and air-perspective contrast.

In figure 2, when two objects positioned at a large visual angle are observed in binocular vision, convergence of the line of sight of two eyes results in depth perception. However, the detection threshold of convergence change is larger than the detection threshold of binocular parallax, and the depth sensitivity of convergence was obtained from equation (2) and is represented by dashed line in figure 3.

The depth sensitivity to the cue of the object transversal size shown in figure 3 was calculated from equation (2), where size-S is substituted for A and the ratio of the size change detection threshold $\Delta\theta(\equiv\Delta R)$ to size $\theta = S/D$ in visual angle is constant as reported by Ogle (ref. 15).

This sensitivity agrees with the depth threshold under monocular observation of two square targets (1.8 m^2) measured by Teichner (ref. 16). The maximum distance D_m is determined by the absolute detection threshold of size perception.

The depth sensitivities on the shape of a rectangular object whose upper part inclines at larger distances is represented by

$$\frac{D}{\Delta D} = \frac{S}{\Delta\theta \cdot D} - 1 = \frac{D}{L \cdot \sin\alpha_t} \tag{5}$$

where S is the horizontal length of object, $\Delta\theta$ is the size-cue threshold, L is the height of object, and α_t is the slant threshold.

Freeman (ref. 17) measured the slant threshold of 14 different rectangles without texture by monocular vision. The depth sensitivities calculated from these data varied with height. The optimal depth sensitivity was 78 when D = 135 cm and L = 8 cm. This sensitivity is larger than the data of Teichner, resulting in the difference between the shape cue of one object and the size cue of two separate objects.

In viewing a textured pattern, there are different sizes or density of texture: one is the transversal size or density in a plane rectangular to the depth direction as mentioned above, and the other is the longitudinal size or density along the depth-directional line.

The depth sensitivity on the latter was calculated from equation (6) and is shown in figure 3:

$$\frac{D}{\Delta D} = 2\left(\frac{S \cdot H}{\Delta\theta \cdot D^2} - 1\right) = 2\left(\frac{\theta}{\Delta\theta}\right) \tag{6}$$

where S is the object's longitudinal size on the depth direction, H is the distance between the visual line and the object plane, and the ratio of the longitudinal size θ in visual angle to the size cue threshold $\Delta\theta$ is the same as the ratio of the transversal size cue threshold. This sensitivity is twice as large as that for the transversal size.

The depth sensitivity on the brightness cue shown in figure 3 is deduced from equation (7):

$$\frac{D}{\Delta D} = 2\frac{L \cdot r}{\Delta I \cdot D^2} = 2\frac{I}{\Delta I} \tag{7}$$

where L is luminous intensity, D is the lighting distance, r is the refractory factor of the object, I is the luminance of objects, and ΔI is the cue-change threshold of luminance. This sensitivity is satisfied even at a very small stimulus level at which point Ricco-Piper's law is applied.

When the observer or viewing objects move in three-dimensional space, the projected retinal image changes in position, size, shape (ref. 18), density, and luminance, and the depth perception is effected by those changing velocity.

The depth sensitivity of the air-perspective contrast cue results from the contrast-diminishing function of equation (8), except for the case of blurring or color effect.

$$C = C_0 \exp\left(-\frac{D}{\sigma}\right) \tag{8}$$

where C_0 is the luminance contrast at very small distances and σ is the length constant determined by the air-scattering coefficient.

The sensitivity on this cue illustrated in figure 3 is calculated from equation (9):

$$\frac{D}{\Delta D} = \frac{-C_0}{\Delta C} \cdot \frac{D}{\sigma} \exp\left(-\frac{D}{\sigma}\right) = -\frac{C}{\Delta C} \cdot \frac{D}{\sigma} \tag{9}$$

where ΔC represents the differences in threshold for the brightness contrast deduced from the variation of detection threshold relative to the sine-wave grating pattern given by Watanabe et al. (ref. 19).

V. EXPERIMENTS II

Because of the above-mentioned result that the depth sensitivity of binocular parallax was very high in comparison with other cues, the effects of binocular parallax in other conditions and the interaction effect between binocular parallax and other monocular cues were studied. In Experiments I the change of binocular parallax and retinal size corresponding to moving objects in depth could not be controlled independently. To measure the effects of two coexistent cues, the new versatile stereoscopic display (ref. 20) of the standard TV system in conjunction with a special video processor (fast phase modulation) were used.

In this system, as shown in figure 6, the stereoscopic pictures have been produced with binocular parallax and convergence, controlled temporally and spatially with depth signals in a manner comparable to brightness control signals of video signals – all independent of pictorial cues; for example, size of pattern. The picture is also changed independent of the depth signal.

VI. RESULTS II

The subjects viewed the square pattern in streoscopic vision, of which the size and binocular parallax was changed temporally and simultaneously by the pattern-size and depth-control sine-wave synchronous signals, with variable amplitude and polarity of depth direction, so that the conditions of equally felt depth sensations of motion could be measured. In figure 7, the horizontal axis represents the amplitude in arc-minutes peak-to-peak of oscillation of binocular parallax and the vertical axis represents the amplitude of oscillation of size. The smoothed curves indicate the conditions of those two cues for which equal depth sensation occurred at three levels; that is, depth threshold (Δ) and two suprathreholds (•,▲,□). The data show that the depth sensation from two coexistent cues, changing size and binocular parallax, is a combination of the individual effects of each cue, and when binocular parallax is zero, the changing size cue in monocular vision is more effect than the changing size cue in binocular vision. In other experiments, it was found that the effect of binocular parallax decreased when the objects moved in depth or in the lateral direction.

VII. DISCUSSION AND CONCLUSIONS

The following conclusion were derived from the comparison of the depth sensitivities of various cues and from the interactive effects of depth sensation from two different cues, size changing and binocular parallax.

1. The depth sensitivity relative to binocular parallax is maximum at a distance of up to about 10 m.

2. The depth sensitivity to motion parallax is effective, and this sensitivity on motion at the optimum velocity exceeds that of the binocular parallax at a distance greater than 10 m.

3. The cues from accommodation and convergence are effective for the relative depth perception only at a distance of less than 1 m, but are effective for the absolute depth perception at longer distances.

4. The pictorial cues are effective even at long distances, and the sharp edge of pictures, and clear texture, shade, and gloss of the surface on objects strengthen the sensation of depth.

5. The effects of these cues work together and combine spatially on the wide visual field.

From the investigation of these sensitivities, the following conditions to decrease the sensation of flatness of the display plane of single two-dimensional pictures and to reinforce the depth perception in the picture were found:

1. The effects of binocular parallax must be decreased.

2. The distance of convergence and accommodation must be close to the actual distance of the objects in the picture.

3. The frame of the display must be separated from the images peripherally or depth-wise to be defused.

4. There must be many monocular pictorial cues including the projection of three-dimensional moving objects.

Conditions 1, 2, and 3 are attained by viewing with monocular vision or by positioning the picture image at a distance of about 5 m; conditions 3 and 4, by making the visual angle of picture wide; and condition 4, by using a hi-definition and moving picture.

So, we can point out that the new high-definition and wide television displays (ref. 21) meet these conditions, and these displays produce more realistic picture images than the conventional television.

It is well known that one of the importance conditions for space perception is the size of the viewing field of the display, which gives self-motion perception to an observer, such as when one stands in a "Wander-Room" where wall and ceiling surrounding one rotates; nevertheless, one feels self-motion.

It was found that a visual wide-angle display over 30° induces the sensation of reality because of the integration of the depth cue effects (ref. 22).

The old viewing device called reflectorscope or vue d'optique (in Japanese, nozoki-karakuri, which means "peeking device"), shown in figure 8, in which pictures were viewed through a convex lens or a concave mirror, produces images of the picture realistically.

Concerning the reasons why this device produces reality, Valyus (ref. 24) and Schwartz (ref. 25) pointed out that because of the aberration of the lens or reflector, binocular parallax occurs and results in stereoscopic pictures, and also the difference between the illumination intensities of the binocular images, because of the difference of the diffusion of the screen, results in strereoscopic vision. If these explanations are correct, the disparity and the difference of illumination between the binocular images would increase with the distance from the median line of the picture, and then the depth sensation would depend on position.

However, according to the results of our observations, the depth sensation depends on the nature of objects in the picture, and the depth sensation in monocular vision is equal to or better than that in binocular vision.

Therefore, the actual reason why reality is produced on the old viewing device is that they fulfill conditions proposed in our results in the case of pictures without movement.

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TABLE 1. DEPTH PERCEPTION CUES AND BASES OF CHARACTER FOR TRANSFORMATION. O:OCULOR MOTOR CUE. R:RETINAL IMAGE CUE. B:BINOCULAR VISION. M:MONOCULAR VISION.

Cue	Objective change in 3-D	Image change in retina	Base of character for transformation
Binocular parallax	R.B. Relative distance	Position disparity	Unity
Binocular convergence	O.B. Absolute distance	Position	Optimum
Accommodation (blurring)	O.M. Absolute	Blurring	Optimum
Motion parallax	O.M. Absolute R.M. Relative	Position disparity Velocity	Unity
Transversal size	R.M. Relative Absolute (familiar)	Size	Identity
Longitudinal size	R.M. Relative	Size	Identity
Vertical position	R.M. Absolute		
Size, density	R.M. Slant in depth	Size, density	Uniformity
Shape	R.M. Slant	Shape	Simpleness uniformity
Motion	R.M. Motion	Velocity flow	
Intersection	R.M. Front and Back	Shape	Simpleness
Luminance	R.M. Relative	Illumination	Uniformity
Shade	R.M. Slant	Illumination	Uniformity
Air-perspective	R.M. Relative	Contrast, blurring color	Identity
Color	R.B.M. Aberration	Color disparity	Unity

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TABLE 2. DEPTH THRESHOLDS ON BINOCULAR VISION AS A FUNCTION OF VIEWING DISTANCE

Viewing distance, m	2	3	5	18
Sub. SN	0.5	1.9	5.7	5.1 (cm)
Sub. KI	0.2	0.4	1.2	2.9
Sub. NW	0.8	2.0	6.1	2.9

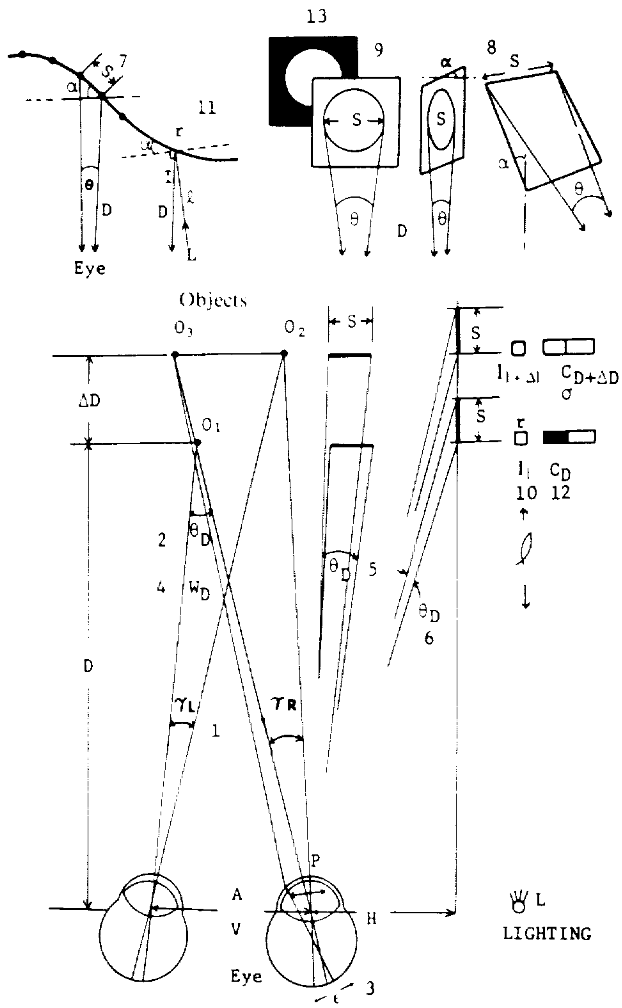

Figure 1.– Illustration of visual cues for depth perception.

1: Binocular parallax $\gamma_L - \gamma_R = \theta_D - \theta_{D+\Delta D}$ at the distance A between pupils.
2: Convergence cue $\theta_D - \theta_{D+\Delta D}$.
3: Blurring cue ε of accommodation on pupil diameter P.
4: Motion parallax $\gamma_L - \gamma_R$ or $\omega_D - \omega_{D+\Delta D}$ at monocular moving vision of distance A or speed V.
5: Transversal size cue $\theta_D - \theta_{D+\Delta D}$.
6: Longitudinal size cue on depth direction axis at distance H.
7: Density cue $[(S/D)\cos\alpha]^{-1}$ of texture on surface at slant α.
8: Shape cue at slant.
9: Intersection cue.
10: Brightness cue $I_l - I_{l+\Delta l}$, $I = r \cdot L/l^2$ of the object with refractory factor r at lighting distance l under lighting L.
11: Shade cue $I\cos\alpha$ on slanted surface.
12: Air-perspective contrast cue $C_D - C_{D+\Delta D}$ of air scattering constant σ.
13: Color effect.

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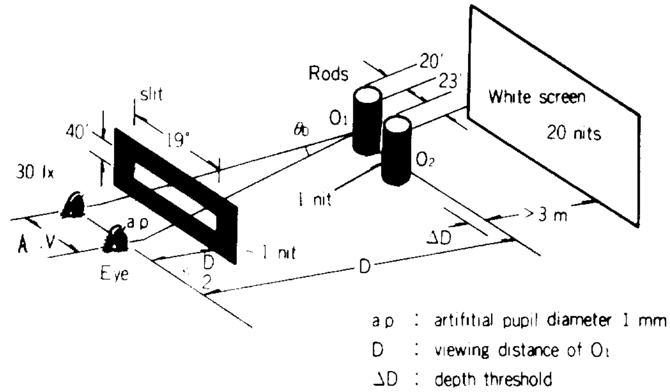

Figure 2.– Apparatus for measuring depth thresholds.

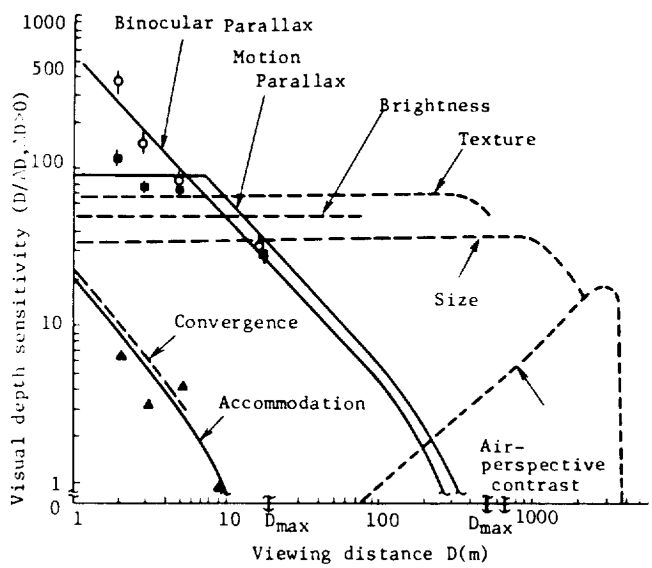

Figure 3.– Depth sensitivities of various cues for visual depth perception as a function of viewing distance. Symbols (o,■,Δ) indicate the averages of five measurements of subject SN and bars on the symbol indicate standard deviations.

Binocular parallax:	A	$= 0.065$ m, $\Delta\theta = 25''$
Motion parallax:	V_{max}	$= 0.8$ m/sec, $\Delta\omega = 4'$/sec, $\omega a = 6°$/sec
Accommodation:	P	$= 0.005$ m of the natural pupil, $\Delta\theta_A = [1/1.2]'$
Air-perspective:	C_0	$= 1$, $\sigma = 1$ km, $\Delta C = 11\%$ of C_D [±1 dB], $C_{min} = 0.02$
Transversal size:	$\Delta\theta_s$	$= 2.5\%$ of retinal size θ_s
Texture/Longitudinal size:	$\Delta\theta_s$	$= 2.5\%$ of retinal size θ_s
Convergence:	$\Delta\theta_s$	$= 10$ min
Brightness:	$I/\Delta I$	$= 0.02$

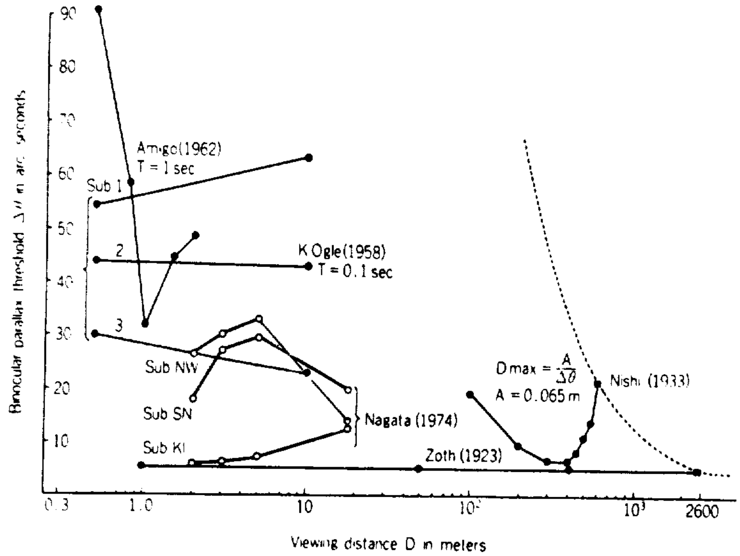

Figure 4.– Thresholds of binocular parallax as a function of viewing distance.

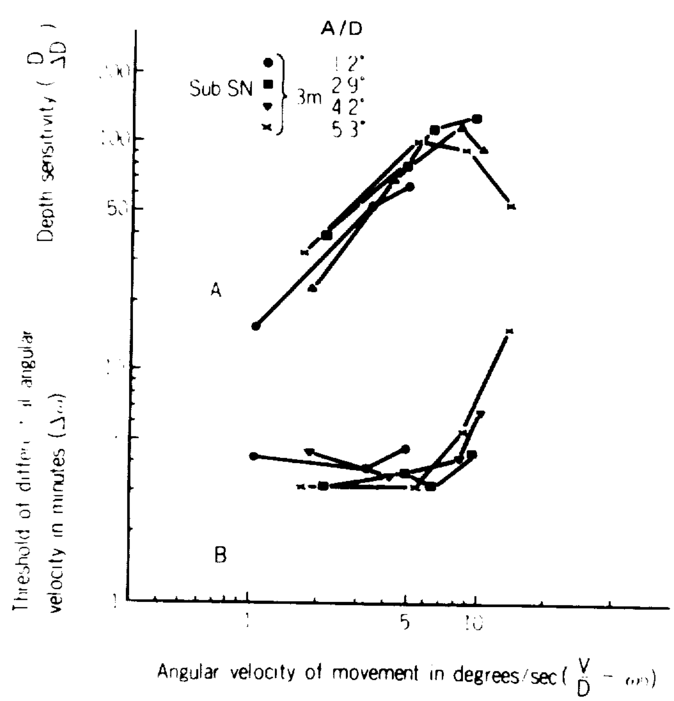

Figure 5.– Depth sensitivities D/ΔD (curves of A) and the threshold of parallax velocity Δω (curves of B) as functions of angular velocity of movement ω_D = V/D and movement distance A at a viewing distance of 3 m.

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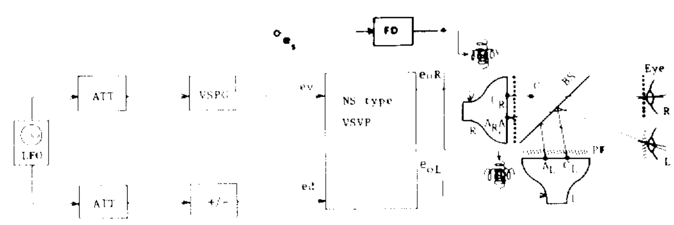

Figure 6.– Diagram of experiments for binocular parallax and size changing cue. LFO:low frequency oscillator. ATT:attenuator. VSPG:variable size square pattern generator. VSVP:versatile stereoscopic video processor. FD:fixed delay. e_v:television video signal of original picture. e_0:phase-modulated video signal for left or right eye. e_d:depth signal for modulation of binocular parallax. e_s:synchronous signal. BS:beam splitter. PF:polarizing filter. $A_{R,L}$; $C_{R,L}$:position of pictures. A;C:perceived position.

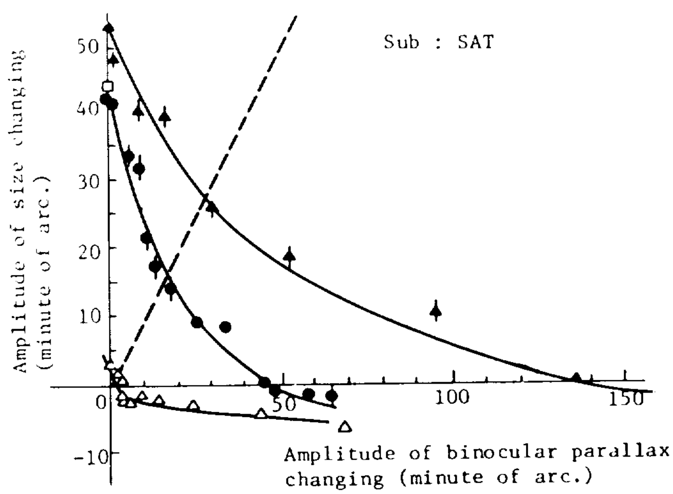

Figure 7.– Interactive effects of depth sensation from two kinds of cue, binocular parallax and changing size cue with oscillating amplitude.

Δ: conditions for the threshold of depth motion perception
•,▲: conditions for equal depth sensation at two levels of suprathreshold
□: condition of only size cue in monocular vision for equal depth sensation with that of ▲
--- : condition in actual moving

Sine-wave oscillation frequency, 1 Hz. Middle size, 6.4 cm (2.71°) x 6.4 cm. Back luminance, 1 cd/m^2; Pattern, 30 cd/m^2. Viewing distance, 1.35 m.

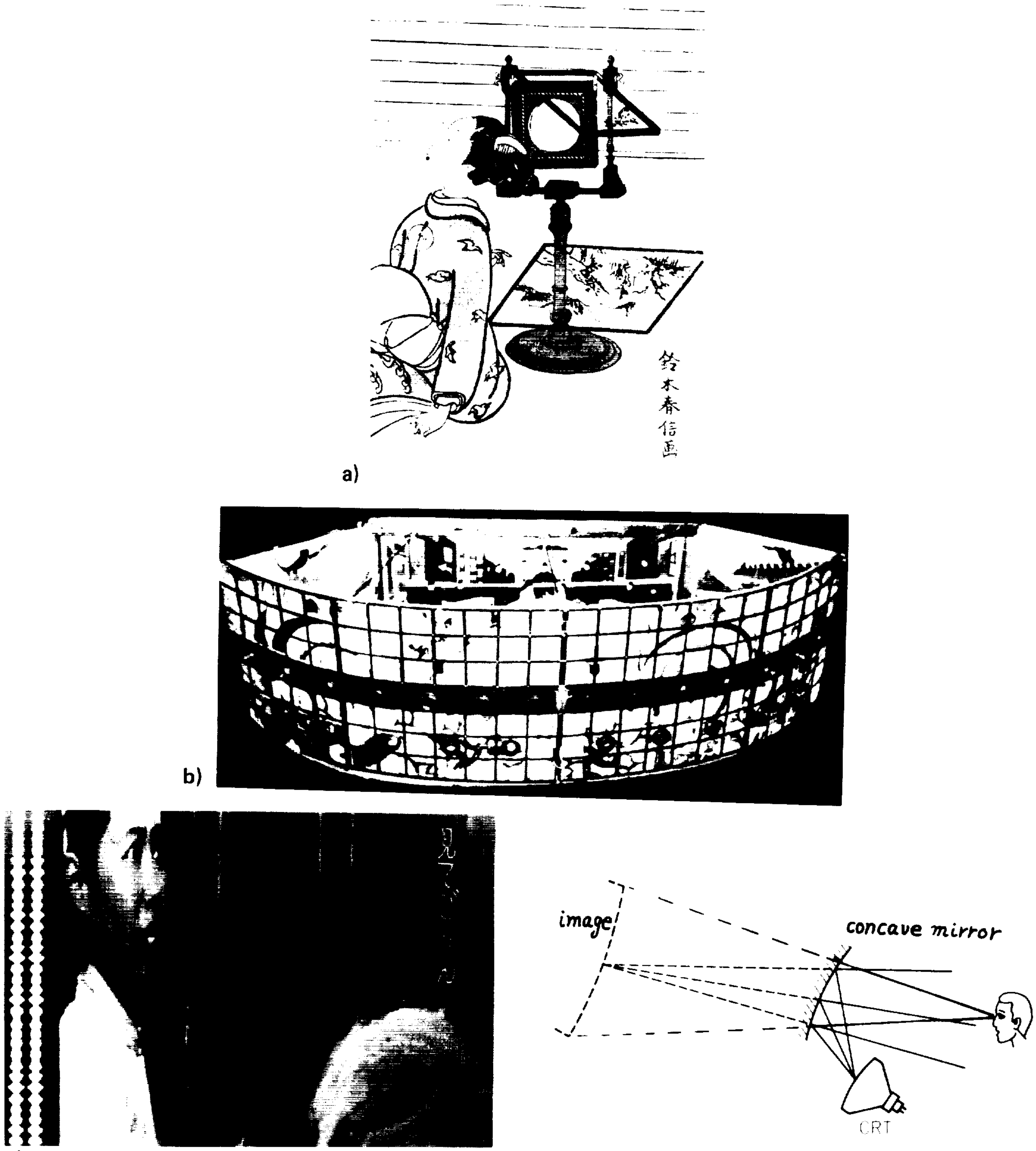

Figure 8.– Old viewing device called vue d optique (nozoki-karakuri) with one lens-mirror (a) and with 24 lenses (b) in Japan and same type (c) in China and one kind (ref. 23) of new wide television system (d).