Japanese Psychological Research
2001, Volume 43, No. 1, 13–24

Perceived distance of targets in convex mirrors

ATSUKI HIGASHIYAMA[1]
Department of Psychology, Faculty of Letters, Ritsumeikan University, Tojiin-kitamachi, Kita-ku, Kyoto 603-8588, Japan

YOSHIKAZU YOKOYAMA
Department of Psychology, Faculty of Letters, Ritsumeikan University, Tojiin-kitamachi, Kita-ku, Kyoto 603-8588, Japan

KOICHI SHIMONO
Department of Information Processing Engineering and Logistics, Tokyo University of the Mercantile Marine, Ettchujima, Koto-ku, Tokyo 135-8533, Japan

Abstract: We investigated the perceived distance of targets in convex and plane mirrors. In Experiment 1, 20 subjects matched the distance of targets in a real scene to the distance of a virtual target in different mirrors. The matched distances were much larger for convex mirrors than for a plane mirror. In Experiment 2, 20 subjects viewed two targets in a mirror and adjusted their own positions so that the distance to the closer target was perceived to equal the distance between the targets. The mean distance to the closer target was smaller for the convex mirrors than for the plane mirror. In Experiment 3, 20 subjects adjusted the position of a target so that the distance to it in a mirror was perceived to equal the distance designated by the experimenter. The best-fitting power functions showed that the scaling factors were larger for the convex mirrors than for the plane mirror, but the exponents were smaller for the convex mirrors than for the plane mirror. It is suggested that distance in the convex mirrors was perceived to be larger than in the plane mirror, and that the growth of perceived distance in the convex mirrors was slower than in the plane mirror.

Key words: perceived distance, convex mirrors, picture perception, power functions, safe driving.

In this study, we investigated the perception of distance in convex mirrors. There were two motives for this study. The first was the practical utility of the results with regard to the driving of automobiles (e.g., Miura, 1996). In Japan, the external mirrors on automobiles are convex. Convex mirrors provide a wide visual field, but the distance of virtual objects in them is more compressed than in plane mirrors. We do not know how these properties of convex mirrors affect drivers' perceptions of distance. Nevertheless, drivers' handbooks warn us that objects seen in convex mirrors are closer than they appear. For safe driving, therefore, it may be important to examine how perceived distance in convex mirrors differs from that in plane mirrors.

The second motive was the general concern of how well we perceive distance in optically distorted scenes. In convex mirrors, the usual

[1] This study was supported by the research fund provided by Ritsumeikan University, 1998, and by Grant-in-Aid for Scientific Research (# 11871016) from the Ministry of Education, Science, Sports, and Culture in Japan. We thank Hiroshi Ono of York University, who commented on an earlier draft of this paper.

optical relation between objects is distorted. As is shown below, not only virtual distance but also virtual size are compressed in convex mirrors. In other words, the scenes in convex mirrors are miniature versions of real scenes. Optically distorted scenes are also generated with a convex lens and under water. For example, when people use convex lenses to read text, the enlarged letters are localized optically farther away than the real position of the text. However, the letters are usually perceived to be closer than the optical distance. It is also known that the optical distance of an object under water is less than that in air (Adolfson & Berghage, 1974). However, the object under water is reported to be localized at exactly the optical distance (Ono, O'Reilly, & Herman, 1970) or at a greater distance than the optical distance (Kent, 1966; Luria, Kinney, & Weissman, 1967; Ross, 1967). It seems that the visual system corrects such optically distorted scenes by selecting cues that may be appropriate for constructing visual space. In this study, we examined how accurately distance is perceived in convex mirrors and attempted to seek cues that would affect the perception of distance.

Optics of convex mirrors

Before examining perceived distance in convex mirrors, it may be proper to note how rays of light emanating from an object are reflected by a convex mirror. Figure 1 shows a convex mirror (CAB) with a radius of curvature $2f$. Consider the rays of light originating at an end-point P of an object PQ. The ray of light PN, which is parallel to the mirror axis AO, is reflected at point N in the direction of point T, such that points T and N are aligned with the focal point, F. The rays of light PO and QO return along the same course after being reflected by the mirror. It follows that line NF intersects line PO at point P′. Line P′Q′, which is perpendicular to line AO, is called a virtual image of the object PQ.

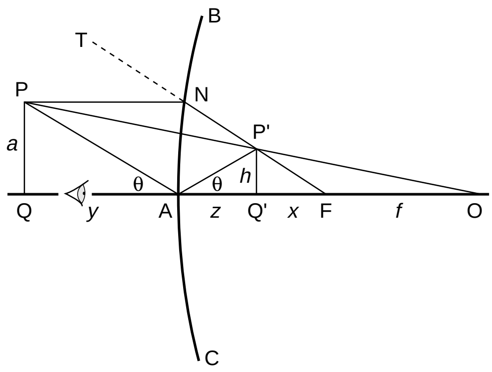

Figure 1. Optics of a convex mirror. See text for definitions of notations.

In this situation, it is readily shown that:

$$1/z = 1/y + 1/f \quad (1)$$

and

$$h = ax/f \quad (2)$$

where x = Q′F, y = QA, z = AQ′, a = PQ, h = P′Q′, and $f = x + z$ (see Figure 1). We call y the real distance of the object and z its virtual distance; we also call a the real size of the object and h its virtual size.

From Equation 1, we can derive several characteristics of virtual distance, z, in convex mirrors. First, it is clear that $1/z > 1/y$, because $f > 0$. This implies that $z < y$ (i.e., a virtual distance is smaller than the real distance). Second, if an object is at an infinitely far distance, we obtain $z = f$. This implies that the virtual image of the object is located somewhere between the mirror surface and the focal point. Third, differentiating z with respect to y, we obtain $dz/dy = f^2/(y + f)^2$. Since f is a constant for a given mirror, z is a negatively accelerated function of y, as is shown in Figure 2. We should last note that when f is infinitely large (i.e., a plane mirror), we obtain $z = y$, implying that real distance is exactly maintained only for a plane mirror.

From Equation 2, we can derive several characteristics of virtual size, h, in convex mirrors. First, we obtain $h < a$, because $x < f$. This implies that the virtual image in convex

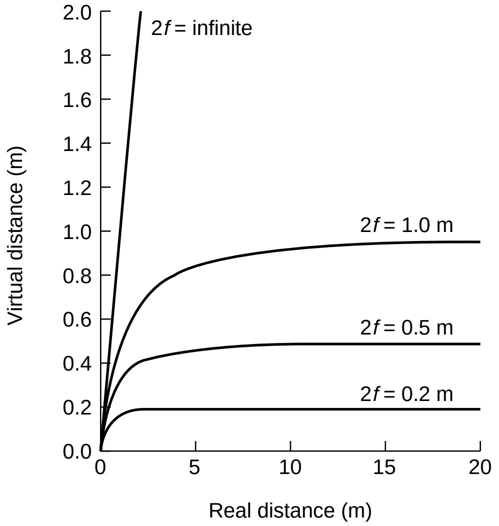

Figure 2. Growth of virtual distance (m) in mirrors as a function of real distance (m). The parameter is the radius of curvature, 2*f* (m).

mirrors is smaller than the real image. Second, since $x/f = z/y$, Equation 2 is transformed into:

$$h = az/y \quad (3)$$

By substituting Equation 1 into Equation 3, we obtain:

$$h = af/(y + f) \quad (4)$$

From Equation 4, it is clear that h decreases as y increases, and we obtain $h = a$ when $y = 0$, and $h = 0$ when y is infinitely large.

Consider, next, the visual angles of a real object and a virtual object, because the relative visual angle is effective as a cue to depth (e.g., Epstein & Landauer, 1969; Gogel, 1969; Levin & Haber, 1993; Toye, 1986). When the eye is placed at position A in Figure 1, the visual angle for the real object is $\theta = \arctan a/y$ and the visual angle for the virtual object is $\theta' = \arctan h/z$. Since $a/y = h/z$, from Equation 3, we obtain $\theta = \theta'$, which implies that the two objects are equal in visual angle.

However, since the eye will usually be placed not at position A but at a position between points Q and A, the visual angles of the two objects are not equal. In this case, the visual angle of the real object is larger than θ, because the viewing distance of the real object is shortened. Conversely, the visual angle of the virtual object is smaller than θ, because the viewing distance of the virtual object is enlarged. Therefore, whenever the eye lies between points Q and A, the visual angle of the real object is larger than that of the virtual object.

Experiment 1. Distance-to-distance matching

In Experiment 1, the distance to a comparison target (a man) in a naturalistic situation was matched to the distance to a standard target (a board) in a convex or plane mirror. If we obtain larger (smaller) distance matches for a convex mirror rather than for a plane mirror, then the perceived distance in the convex mirror is suggested to be larger (smaller) than that in the plane mirror.

In this experiment, three predictions are possible about distance matches for convex and plane mirrors. First, distance matches for a convex mirror may be smaller than those for a plane mirror. This prediction would be confirmed if binocular convergence and accommodation are available as distance cues and if perceived distance is affected by virtual distance in mirrors. As is shown in Figure 2, virtual distance in convex mirrors is much smaller than that in plane mirrors.

Second, distance matches for a convex mirror may be larger than those for a plane mirror. This outcome would be obtained from two possible sources of pictorial information. The one is the relative *linear* size of virtual objects: A target of small linear size is perceived to be farther away than a target of large linear size (Higashiyama, 1977, 1979). According to Equation 4, as an object recedes away from a mirror, its virtual size in the plane mirror remains constant but its virtual size in the convex mirror decreases rapidly. Another is the relative *angular* size of virtual objects: A target of small angular size is perceived to be farther away than a target of large angular size

(Epstein & Landauer, 1969; Gogel, 1969). Since in Experiment 1 the linear size of virtual objects was positively correlated with the angular size, the second outcome may be due to the linear and/or angular size of virtual objects.

The third prediction is that distance matches for a convex mirror may equal those for a plane mirror. This prediction would be confirmed if the target is compared with a nearby object that has a familiar size that is available as a cue to distance (Gogel, 1964; Gogel & Mertens, 1968). Note that in Experiment 1 the target was surrounded by familiar buildings and these objects are transformed in the same way as the target in a mirror, regardless of whether the mirror is convex or plane.

Method

Subjects. Twenty undergraduates volunteered as subjects.

Mirrors and target. Five circular glass mirrors, one plane and four convex, were used. The diameter of each mirror was 52 mm. The radii of curvature of the convex mirrors were 0.2 m, 0.4 m, 0.6 m, and 1 m, and the radius of curvature of the plane mirror was infinite. Each mirror was fitted into a black plastic plate (58 mm diameter × 20 mm deep), like a hand glass. The subjects viewed a virtual image of the target in each mirror. The target was a red-painted board, 15 cm wide and 152 cm tall, and was 10 or 20 m from the mirror. Table 1 shows the virtual distance (z) and virtual size (h) of the target.

Procedure. The experiment was done in an open field (5 m wide × 50 m long) between two four-storey buildings at the university. Subjects stood at the center of the field, grasped the mirror with their preferred hand, and saw in the mirror the reflection of the standard target behind them. Subjects were required not to move around, but they were allowed to move their head, arms, and hands. In the mirror, subjects saw the target, placed 10 m or 20 m behind them. In front of the subject, there was a male experimenter who approached or moved away from the subject. This experimenter was used as the comparison target.

The subjects' task was to give a stop sign to the experimenter when the distance from the subject to the experimenter (a real scene) appeared to be the same as the distance from the subject to the board in the mirror. Subjects observed the standard and comparison targets binocularly. Since they had their back turned toward the standard target, they viewed it in a mirror, while viewing the comparison target directly. The experimenter emphasized that the subject should judge on the basis of "objective distance." By objective distance, we meant the distance that is determined with an appropriate instrument with objective units. The distance between the subject and the experimenter was read by the experimenter with a tape measure. For a given mirror, the subject made two distance adjustments, by approaching and backing away, for each of the two standard distances. The order of mirrors, distances, and

Table 1. Radius of curvature (2*f*) and curvature (1/2*f*) of the mirrors used in Experiment 1, and the distance, z (m), and size, h (m), and visual angle θ' (°) of the virtual image in each mirror of a target 1.52 m tall placed 10 or 20 m from each mirror

		10 m			20 m		
2*f*	1/2*f*	z	h	θ'	z	h	θ'
0.2	5.0	0.099	0.015	2.15	0.100	0.008	1.08
0.4	2.5	0.196	0.030	3.44	0.198	0.015	1.73
0.6	1.67	0.291	0.044	4.28	0.296	0.022	2.16
1.0	1.0	0.476	0.072	5.33	0.488	0.037	2.69
infinite	0	10.000	1.520	8.39	20.000	1.520	4.28

Note: z and h were obtained from Equations 1 and 4, respectively. θ' was obtained under the assumption that the subject's eye is 30 cm away from the mirror.

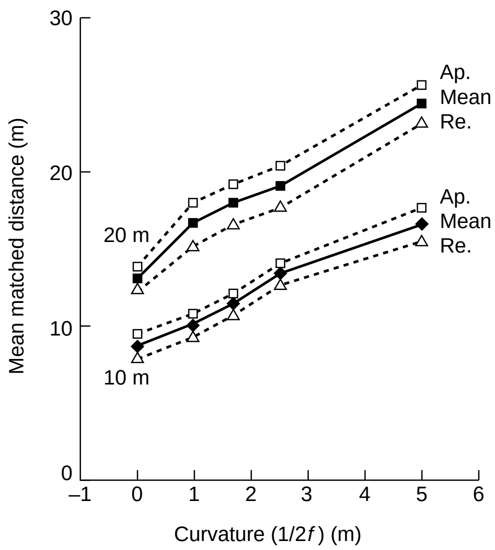

Figure 3. Mean distance matches (m) between the subject and the experimenter as a function of mirror curvature. Filled symbols represent the mean taken across series and subjects. Open symbols represent the mean approaching (squares) or receding (triangles) matches.

series was randomly determined for each subject.

Results and discussion

Figure 3 shows the mean distance matches between the subject and the experimenter as a function of curvature (i.e., the inverse of $2f$, in m), for the two standard distances. The main effect of standard distance was significant, $F(1, 19) = 161.41, p < .001$, indicating the mean distance matches for 20 m were larger than those for 10 m.

The main effect of mirror was significant, $F(4, 76) = 147.48$, $p < .001$, indicating larger mean distance matches for a more convex mirror. This suggests that perceptions of the standard distances were enlarged in more convex mirrors.

The interaction between standard distance and mirror was significant, $F(4, 76) = 9.64$, $p < .001$, suggesting that the mean differences between the distance standards varied with mirrors. For the curvatures of 0.0, 1.0, 1.7, 2.5, and 5.0, the mean differences were 4.3 m, 6.6 m, 6.5 m, 5.6 m, and 7.9 m, respectively.

The main effect of series was significant, $F(1, 19) = 15.7$, $p < .001$. For any mirror, the mean distances for the approaching series were consistently larger than those for the receding series. Additionally, the interaction between standard distance and series was significant, $F(1, 19) = 4.53$, $p < .05$. Figure 3 suggests that the mean difference between the series was larger for the 20-m standard than for the 10-m standard.

Regardless of whether the mirror was plane or convex, the mean distance matches for the 20-m standard were larger than those for the 10-m standard. This means that the standards were correctly discriminated in depth. However, this does not mean that the subjects judged on the basis of virtual distances in each convex mirror, because the virtual distances in each convex mirror were almost the same for the two standards (Table 1). The subjects probably based their judgments on pictorial information in the mirrors.

The finding that the mean distance matches increased as the mirror curvature increased is at variance with the optical prediction on the locations of virtual images in mirrors. Equation 1 predicts that an object in a more convex mirror is localized at a smaller virtual distance (see Table 1). It follows that if the subjects judged distance according to virtual distance in the mirror, then the distance matches would have increased for a less convex mirror. Interestingly, Figure 3 suggests that the object in the plane mirror was perceived to be closer than that in any convex mirror. Pictorial information contained in the mirrored scene, rather than binocular convergence and accommodation, was probably available to perceived distance.

There were the four variables that may have influenced the distance matches (see Figure 1): mirror curvature, virtual size, virtual distance, and visual angle of the virtual object at the subject's eye (real distance of a target was not considered as an available variable, because the subject did not see the real target). By performing several regression analyses, we attempted to find what subset of predictive variables influenced the distance matches and to estimate the independent contribution of each predictive variable. When these four variables were all entered into the equation, the adjusted squared multiple regression coefficient, R^2, was .87, and visual angle, standard coefficient $\beta = -1.45$, $t(5) = 5.02$, $p < .01$, and virtual size, $\beta = 1.68$, $t(5) = 2.84$, $p < .05$, were significant, but curvature ($\beta = 0.02$) and virtual distance ($\beta = -1.24$) were not. Further analyses were performed by entering visual angle and virtual size into the equation and ruling out curvature and virtual distance from it. The results showed that the adjusted R^2 was .76, and visual angle was significant, $\beta = -0.06$, $t(7) = 4.66$, $p < .05$, but virtual size was not significant, $\beta = 0.24$, $t(7) = 1.07$, $.30 < p < .40$. Accordingly, the visual angle of virtual objects is suggested to have been the most influential variable on perceived distance in this experiment.

Experiment 2: Distance-to-depth matching

In Experiment 2, we explored how perceived distance grows in convex and plane mirrors. Subjects viewed two fixed targets at different distances in a mirror and adjusted their position so that the distance from the subject to the closer target was perceived to equal the depth between the targets. In short, the subject matched distance to depth. This task was what we call the multiple method or the bisection method.

From these distance-to-depth matches, we determined how rapidly perceived distance grows within a given mirror, but could not determine whether perceived distance in a convex mirror is larger than, smaller than, or equal to that in a plane mirror. There were two predictions regarding the growth rate of perceived distance. One is that perceived distance in a convex mirror grows at the same rate as that in a plane mirror, because in spite of distorted images in convex mirrors subjects are capable of perceiving changes in distance from pictorial information. The other is that the scale for distance in a convex mirror is more negatively accelerated than that in a plane mirror, because, as shown in Figure 2, virtual distance in convex mirrors increases with a negative acceleration, while virtual distance in plane mirrors grows linearly.

Method

Subjects. Twenty undergraduates volunteered as subjects.

Mirrors and targets. We used one plane mirror and two convex mirrors, 0.2 m and 0.4 m in radius of curvature. These mirrors were the same as those in Experiment 1. Two sets of three equilateral triangles (30 cm, 40 cm, and 50 cm in side) were cut out from white card and were used as the targets seen in the mirrors. Two triangles were set erect on the ground by means of supports, one behind the other, at a separation (depth) of 7 m or 15 m. All combinations of triangle size and separation were used (see below).

Procedure. The experiment was done in an open field where no objects were seen around the targets, except for a fence at the far end of the field. Subjects stood in the center of the field, grasped a mirror in their preferred hand, and viewed in the mirror the two targets behind them. The targets were aligned with the subject.

For a given trial, the subject was asked to approach or move away from the targets, so that the distance between the subject and the closer target was perceived to equal the depth between the targets. The experimenter emphasized that subjects should base their judgments on “objective distance.” The experimenter measured the distance from the subject to the closer target.

For each subject, 12 trials (3 mirrors × 2 depths × 2 series) were imposed. Each of the nine (3 × 3) possible target size combinations was randomly assigned to nine of the 12 trials and three further combinations were randomly selected for the remaining three trials. For a given mirror, the subject made the approaching

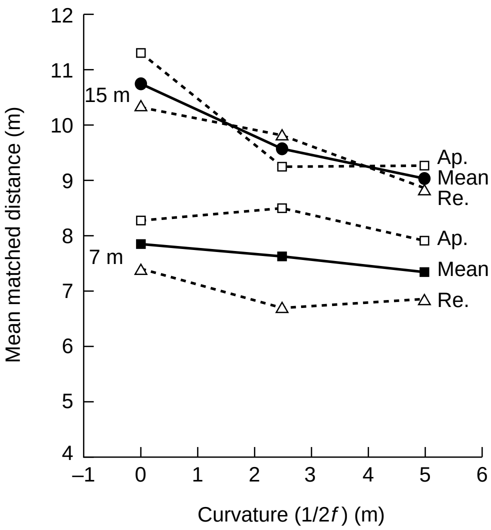

Figure 4. Mean distance matches (m) of the closer target as a function of mirror curvature. Filled symbols represent the mean taken across series and subjects. Open symbols represent the mean approaching (squares) or receding (triangles) matches.

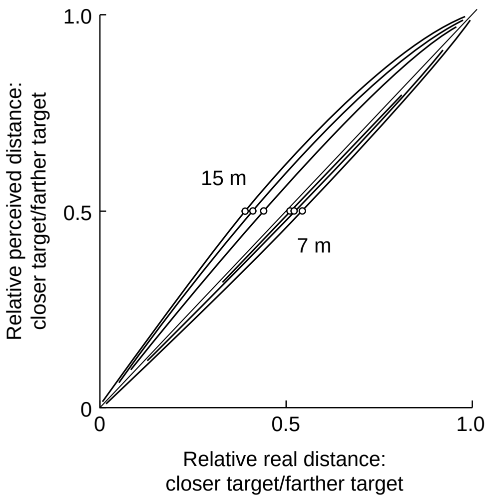

Figure 5. Replotting of the data of Figure 4. The abscissa is the real-distance ratio of two targets and the ordinate is the perceived-distance ratio of the two targets. The left, center, and right circles plotted for each depth represent the strongly convex, moderately convex, and plane mirrors, respectively.

and receding adjustments for each of the two depths. The order of the mirrors, depths, and series was randomly determined for each subject. In the analysis of the data, mirror, depth, and series were treated as experimental variables, but triangle size was not.

Results and discussion

Figure 4 shows the mean distances of the closer target as a function of mirror curvature. The main effects of depth, $F(1, 19) = 20.03, p < .001$, and mirror, $F(2, 38) = 9.85, p < .001$, were significant, but the interaction of depth and mirror was not. The main effect of series was not significant; the interaction of series and other factors was not significant.

For the 7-m depth, the mean distances to the closer target were 7.9 m, 7.6 m, and 7.4 m for the plane, moderately convex, and strongly convex mirrors, respectively; for the 15-m depth, the mean distances were 10.8 m, 9.6 m, and 9.0 m, respectively. Clearly, the mean distances for the small depth were all larger than 7 m, but the mean distances for the large depth were all less than 15 m. These results suggest that the scale for distance differed between the small and large depths.

To obtain a scale for each combination of the depth and mirror, we constructed Figure 5, in which the abscissa is the real distance ratio of the closer target to the farther target and the ordinate is the perceived distance ratio of the closer target to the farther target. The data points were taken from the mean distances in Figure 4. Figure 5 shows that the perceived distance for the 15-m depth grew with a negative acceleration but the perceived distance for the 7-m depth grew with a slightly positive acceleration.

Assuming a power function, $D' = aD^n$, between real distance, D, and perceived distance, D', we estimated the exponent n according to the equation $n = \log i/\log S_i$, where i is the perceived-distance ratio and S_i is the real-distance ratio (Cook, 1978). In this experiment, $i = 0.5$ and S_i was determined empirically – for example, for the 7-m depth observed with the plane mirror, $S_i = 7.9/(7.9 + 7.0)$. For the small depth, the n values obtained were 1.09, 1.06, and 1.04 for the plane, moderately convex, and strongly convex mirrors, respectively; for the large depth, the respective n values were 0.80, 0.74, and 0.71, respectively. The scaling factor, a, was not uniquely determined in this experiment.

The main findings in this experiment were that, for both depths, the growth of perceived distance in the convex mirrors was slower than that in the plane mirror, and that for the small depth the perceived distance increased almost linearly with real distance, but for the large depth the perceived distance increased with a negative acceleration. The first finding may reflect the growth of virtual distance in mirrors, because, as shown in Figure 2, the growth of virtual distance is more compressed in convex mirrors than in plane mirrors. The second finding supports the results of Gilinsky (1951) and Cook (1978), who scaled distance with partition methods.

Experiment 3. Distance-to-numeral matching

In Experiment 3, we scaled distance more directly. The subject was told a target distance by the experimenter and was required to adjust the target position to produce the distance. The scales obtained from the distance matches were compared among different mirrors.

Method

Subjects. Twenty undergraduates volunteered as subjects.

Mirrors. We used one plane mirror and two convex mirrors, 0.2 m and 0.6 m in radius of curvature. These mirrors were the same as those used in Experiment 1.

Procedure. The experiment was done in the same open field as in Experiment 1. The subject stood at the end of the field, looked into a mirror held in the preferred hand, and saw a male experimenter who approached or moved away from the subject. The subject was required not to move around, but was allowed to move head, arms, and hands. For a given trial, the subject was told the distance to be estimated – 10, 20, or 40 m.

The subject's task was to give a stop sign to the experimenter when the distance between the subject and the experimenter was perceived to equal the distance designated by the experimenter. On hearing the stop sign, the experimenter stopped walking and measured the distance to the subject. The experimenter emphasized that the subject should judge on the basis of "objective distance."

Our method resembles the method of magnitude production (e.g., Gescheider, 1985; Stevens, 1975). Yet, there was a critical difference between the two: In our method, the target distances were designated in objective units (i.e., in meters), whereas in the method of magnitude production the magnitudes assigned by the experimenter are dimensionless, pure numbers.

There were 18 trials (3 mirrors × 3 designated distances × 2 series) for each subject. For a given mirror, the subject made the approaching and receding adjustments for each of the three designated distances. The order of mirrors, designated distances, and series was randomly determined for each subject.

Results and discussion

Figure 6 shows the results. The ordinate represents the designated distance, D', and the abscissa represents the mean distance matches, D. The main effect of mirror was significant, $F(2, 28) = 89.11$, $p < .001$, indicating that a more convex mirror produced smaller distance matches. This suggests that the target in a convex mirror was perceived to be farther away than the same target in a plane mirror.

The main effect of designated distance was significant, $F(2, 28) = 109.72$, $p < .001$, indicating that a larger designated distance yielded larger distance matches. This suggests that the subjects could readily discriminate between the three.

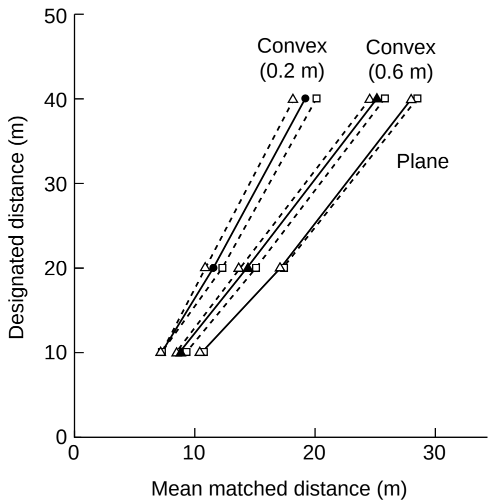

Figure 6. Designated distance (m) as a function of the mean distance matches (m). Filled symbols represent the mean taken across series and subjects. Open symbols represent the mean approaching (squares) or receding matches (triangles).

The main effect of series was significant, $F(1, 14) = 7.90, p < .05$, indicating that for every combination of mirror and designated distance, the approaching series produced larger distance matches than the receding series; the overall mean difference between the series was 0.85 m.

The interaction of mirror and designated distance was significant, $F(4, 56) = 7.49, p < .001$. In Figure 6, this interaction is seen as the differences in the slope of the plots for the three mirrors. The slope for the 0.2-m convex mirror is steeper than that for the plane mirror and the slope for the 0.6-m convex mirror is between the two. The least-square lines fitted to the data in Figure 6 were $D' = 2.5D - 8.4$ for the 0.2-m convex mirror ($r^2 = .999$), $D' = 1.8D - 5.9$ for the 0.6-m convex mirror ($r^2 = .999$), and $D' = 1.7D - 9.0$ for the plane mirror ($r^2 = .999$).

To compare results with those obtained in Experiment 2, we fitted, with the least-square criterion, power functions to the same data and obtained $D' = 0.62D^{1.41}$ for the 0.2-m convex mirror ($r^2 = .999$), $D' = 0.61D^{1.30}$ for the 0.6-m convex mirror ($r^2 = .999$), and $D' = 0.34D^{1.43}$ for the plane mirror ($r^2 = .999$). The obtained exponent was not simply related to mirror curvature, but the exponents for the convex mirrors were smaller than the exponent for the plane mirror. A simple relation was obtained between scaling factor and curvature: the scaling factor was larger for a more curved mirror. These results suggested that the growth of perceived distance in the convex mirrors was slower than that in the plane mirror, and that the distance in the convex mirrors was perceived to be larger than that in the plane mirror.

To clarify what variables influence the perceived distance, we first performed a regression analysis by using, as predictive variables, mirror curvature, virtual size, virtual distance, and visual angle of the virtual object at the subject's eye. The data for these variables is shown in Table 2. The results of the analysis showed that the adjusted R^2 was .65 and only visual angle, $\beta = -1.51$, $t(4) = 3.28$, $p < .05$, was significant – curvature ($\beta = -0.57$), virtual size ($\beta = 1.08$), and virtual distance ($\beta = -0.61$) were not significant. Therefore, visual angle was included in the subsequent analyses. When visual angle and curvature were selected as the predictors, the adjusted R^2

Table 2. Designated distance D′ (*m*), adjusted distance D (*m*), curvature (1/2*f*), virtual distance z (*m*), virtual size h (*m*), and visual angle θ′ (°) of the virtual image in Experiment 3

D′	*D*	1/2*f*	*z*	*h*	θ′
10	7.23	5.00	0.099	0.024	3.43
20	11.68	5.00	0.099	0.015	2.13
40	19.34	5.00	0.099	0.009	1.29
10	8.70	1.67	0.290	0.058	5.65
20	14.46	1.67	0.294	0.036	3.43
40	25.30	1.67	0.297	0.021	1.97
10	10.76	0.00	10.76	1.75	8.99
20	17.42	0.00	17.42	1.75	5.64
40	28.41	0.00	28.41	1.75	3.49

Note: *D* corresponds to y in Figure 1.

was .64, and visual angle, $\beta = -1.12$, $t(6) = 4.02$, $p < .01$, and curvature, $\beta = -0.72$, $t(6) = 2.60$, $p < .05$, were significant. With visual angle and virtual size as the predictors, the adjusted R^2 was .62, and visual angle, $\beta = -1.11$, $t(6) = 3.87$, $p < .01$, and virtual size, $\beta = 0.70$, $t(6) = 2.46$, $p < .05$, were significant. But, with visual angle and virtual distance as the predictors, the adjusted R^2 was .56 and only visual angle, $\beta = -0.83$, $t(6) = 3.34$, $p < .05$, was significant – virtual distance was not ($\beta = 0.53$). It is thus suggested that visual angle was the most influential variable on perceived distance, curvature and virtual size were somewhat influential but weak, and virtual distance had no influence on perceived distance.

General discussion

A major finding of this study was that the perceived distance of a target in convex mirrors was larger than perceived distance in a plane mirror. In particular, Figure 6 indicated that the perceived distance for the 0.2-m convex mirror was 1.8 times as large as the perceived distance for the plane mirror, whereas the perceived distance for the 0.6-m convex mirror was 1.2–1.4 times as large. Figure 6 also indicated that this enlargement of perceived distance in convex mirrors was more prominent at farther distances. Therefore, the warning in drivers' handbooks proved to be valid: A car behind is localized at farther distance in an external convex mirror than in the inside plane mirror.

The enlargement of perceived distance in convex mirrors is explained by the hypothesis that a virtual object of small linear or angular size is perceived to be farther away than a virtual object of large linear or angular size. However, it is difficult to predict the perceived distance in convex mirrors by the virtual distance of objects in convex mirrors.

Ross (1967) found an effect that is similar to the enlargement of perceived distance in convex mirrors. She had several divers judge target distance under water. Although a target under water is localized optically at about three-quarters of its real distance, the judged distance was much greater than the optical distance. Kent (1966) and Luria et al. (1967) also found that the perceived distances of targets under water were larger than the optical distances. It is interesting that regardless of whether a scene is transformed by a convex mirror or water, the target is perceived to be further from where it should, optically, be localized.

The second finding of this study is that the growth of perceived distance in convex mirrors was more compressed than that in plane mirrors. In Experiment 2, as the mirror curvature increased, the exponent of the power function decreased from 1.09 to 1.04 for the 7-m standard and from 0.80 to 0.71 for the 15-m standard. Similarly, in Experiment 3, the exponents for the convex mirrors (1.30 and 1.41) were smaller than the exponent for the plane mirror (1.43). Therefore, another warning to the drivers of automobiles may be needed: It may be difficult to discriminate relative distances of automobiles seen in convex mirrors.

The slow growth of perceived distance in convex mirrors reminded us of depth perception in pictures and photographs (Bengston, Stergios, Ward, & Jester, 1980; Hagen, Jones, & Reed, 1978; Ogasawara, 1973; Smith, 1958a, 1958b; Smith & Gruber, 1958; Wohlwill, 1965). A scene in a convex mirror is a three-dimensional miniature of the real scene, whereas a scene in a photograph is a projection of the real scene onto a plane surface. We think that both mirrored and photographed scenes share the feature of poor information about depth.

Early studies (Ogasawara, 1973; Smith, 1958a, 1958b; Smith & Gruber, 1958) suggested that perceived depth in photographs varies with viewing distance from the photographs. For example, Smith and Gruber (1958) compared perceived depth in a photograph of a scene with perceived depth in the real (photographed) scene. When the optical array entering the eye from a photograph approximated the original array entering the lens of the camera (i.e., equivalent optical array), the perceived depth in the photograph equaled that in the real scene. In addition, when the optical array entering the eye from the photograph was magnified (or diminished) by shortening (or enlarging) the viewing distance of the photograph, the perceived depth in the photograph was shortened (or enlarged).

However, two recent studies suggested that even if a photograph of a scene produces the same optical array at the eye as does the real scene, the perceived depth in the photograph is likely to be less than that in the real scene. Bengston et al. (1980) demonstrated that even under an equivalent optical array, as the size of the optical array decreased, the perceived depth in photographs was shortened. Hagen et al. (1978) had the subjects judge distances under four monocular views: usual view of a real scene, view of the real scene through a peephole, view of the real scene through a rectangular slot, and view of a slide photograph of the real scene. When the judged distance was represented as a linear function of real distance, the slope for the usual view was steeper than those for the other views.

Finally, we should refer to the great variability in exponent of the power function. The mean exponent was 0.91 in Experiment 2, and 1.38 in Experiment 3. This difference may be accounted for in terms of scaling method. In Experiment 2 the subjects produced two equal-appearing distances, whereas in Experiment 3 the subjects produced target distances that were given by the experimenter. It has been shown (Stevens, 1975; Stevens & Galanter, 1957; Stevens & Guirao, 1962) that methods which require subjects to judge differences of sensory magnitudes (e.g., partition judgments) generate a different scale from methods which require them to judge ratios of sensory magnitudes (e.g., method of magnitude production). That is, in linear coordinates, the partition scale is concave downward if plotted against the magnitude-estimation scale. Our results seem to be consistent with the results of Stevens and his colleagues.

One may also account for the difference of exponent in terms of array of stimulus targets. In Experiment 2 there were two targets aligned in depth, whereas in Experiment 3 a single person was observed as a target. The two-target array is likely to induce the equidistance tendency (Gogel, 1956): The perceived depth of two targets appears to be shortened when the directional separation of the targets is small under reduced viewing of cues to distance. Although binocular disparity may be available in the two-target situation, the equidistance tendency probably overcomes the depth information delivered by binocular disparity. We thus suggest that the scale for distance in mirrors is affected not only by mirror curvature but also by scaling method and target array.

References

Adolfson, J., & Berghage, T. (1974). *Perception and performance under water*. New York: John Wiley & Sons.

Bengston, J. K., Stergios, J. C., Ward, J. L., & Jester, R. E. (1980). Optic array determinants of apparent distance and size in pictures. *Journal of Experimental Psychology: Human Perception and Performance*, **6**, 751–759.

Cook, M. (1978). The judgments of distance on a plane surface. *Perception and Psychophysics*, **23**, 85–95.

Epstein, W., & Landauer, A. A. (1969). Size and distance judgments under reduced conditions of viewing. *Perception and Psychophysics*, **6**, 269–272.

Gescheider, G. A. (1985). *Psychophysics*. Hillsdale, NJ: Lawrence Erlbaum Associates.

Gilinsky, A. S. (1951). Perceived size and distance in visual space. *Psychological Review*, **58**, 460–482.

Gogel, W. C. (1956). The tendency to see objects as equidistant and its inverse relation to lateral separation. *Psychological Monographs*, **70**, Whole No. 411.

Gogel, W. C. (1964). Perception of depth from binocular disparity. *Journal of Experimental Psychology*, **67**, 379–386.

Gogel, W. C. (1969). The sensing of retinal image. *Vision Research*, **9**, 1079–1094.

Gogel, W. C., & Mertens, H. W. (1968). Perceived depth between familiar objects. *Journal of Experimental Psychology*, **77**, 206–211.

Hagen, M. A., Jones, R. K., & Reed, E. S. (1978). On a neglected variable in theories of pictorial perception: Truncation of the visual field. *Perception and Psychophysics*, **23**, 326–330.

Higashiyama, A. (1977). Perceived size and distance as a perceptual conflict between two processing modes. *Perception and Psychophysics*, **22**, 206–211.

Higashiyama, A. (1979). The perception of size and distance under monocular observation. *Perception and Psychophysics*, **26**, 230–234.

Kent, P. R. (1966). Vision under water. *American Journal of Optometry and Archives of the American Academy of Optometry*, **43**, 553–565.

Levin, C. A., & Haber, R. N. (1993). Visual angle as a determinant of perceived interobject distance. *Perception and Psychophysics*, **54**, 250–259.

Luria, S. M., Kinney, J. S., & Weissman, S. (1967). Estimates of size and distance under water. *American Journal of Psychology*, **80**, 282–286.

Miura, T. (1996). *Kodo to shikaku-teki chui* [Behavior and visual attention]. Tokyo: Kazama Shoten.

Ogasawara, J. (1973). Shashin ni okeru kyori, okisa, katachi no chikaku [Perception of distance, size, and form in photographs]. *Japanese Psychological Review*, **16**, 1–17.

Ono, H., O'Reilly, J. P., & Herman, L. M. (1970). Underwater distance distortion within the manual work space. *Human Factors*, **12**, 473–480.

Ross, H. (1967). Water, fog and the size-distance invariance hypothesis. *British Journal of Psychology*, **58**, 301–313.

Smith, O. W. (1958a). Comparison of apparent depth in a photograph viewed from two distances. *Perceptual and Motor Skills*, **8**, 79–81.

Smith, O. W. (1958b). Judgments of size and distance in photographs. *American Journal of Psychology*, **71**, 529–538.

Smith, O. W., & Gruber, H. (1958). Perception of depth in photographs. *Perceptual and Motor Skills*, **8**, 307–311.

Stevens, S. S. (1975). *Psychophysics*. New York: John Wiley & Sons.

Stevens, S. S., & Galanter, E. H. (1957). Ratio scales and category scales for a dozen perceptual continua. *Journal of Experimental Psychology*, **54**, 377–411.

Stevens, S. S., & Guirao, M. (1962). Loudness, reciprocality, and partition scales. *Journal of the Acoustical Society of America*, **34**, 1466–1471.

Toye, R. C. (1986). The effect of viewing position on the perceived layout of space. *Perception and Psychophysics*, **38**, 483–495.

Wohlwill, J. F. (1965). Texture of the stimulus field and age as variables in the perception of relative distance in photographic slides. *Journal of Experimental Child Psychology*, **2**, 163–177.

(Received Jan. 21, 1999; accepted Nov. 6, 1999)