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Perceived size and perceived distance of targets viewed from between the legs: Evidence for proprioceptive theory

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Abstract

We investigated, using three comparisons, perceived size and perceived distance of targets seen from between the legs. Five targets, varying from 32 to 163 cm in height, were presented at viewing distances of 2.5–45 m, and a total of 90 observers verbally judged the perceived size and perceived distance of each target. In comparison 1, 15 observers inverted their heads upside down and saw the targets between their own legs; another 15 observers viewed them while being erect on the ground. The results showed that inverting the head lowered the degree of size constancy and compressed the scale for distance. To examine whether these results were due to an inversion of retinal-image or body orientation, comparisons 2 and 3 were performed. In comparison 2, 15 observers stood upright and saw the targets with prism goggles that rotated the visual field 180°, while other 15 observers stood upright, but viewed the targets with a hollow frame lacking the prisms. The results showed that, in both goggle conditions, size constancy prevailed and perceived distance was a linear function of physical distance. In comparison 3, 15 observers wore the 180° rotation goggles and viewed the targets by bending their heads forwardly, and the other 15 observers viewed them while wearing hollow goggles and lying on the belly. The results showed a low degree of size constancy and compressed the scale for distance. Therefore, it is suggested that perceived size and perceived distance are affected by an inversion of body orientation, not of retinal image orientation. When path analysis and partial correlation analysis were applied to the whole data, perceived size was found to be independent of perceived distance. These results supported the direct perception model, rather than the apparent distance model.

Keywords: Space; Perception; Size; Distance; Between-leg viewing; Head; Retinal image; Visual cues; Proprioceptive cues; Apparent distance model; Direct perception model

1. Introduction

Proprioceptive information, which is produced by bending the body, tilting the neck, or raising or lowering the eyes, greatly influences visual space perception (Howard, 1986; Lackner & DiZio, 2005). This paper focuses on the perceived size and perceived distance of targets observed from between the legs when bending the upper part of the body forward. One of the earliest careful observations on this subject comes from Helmholtz, 1866/1911, who put it thus:

"But the instant we take an unusual position, and look at the landscape with the head under one arm, let us say, or between the legs, it all appears like a flat picture; partly on account of the strange position of the image in the eye, and partly because,…the binocular judgment of distance becomes less accurate (pp. 8–9)."

He continued,

"It may even happen that with the head upside down the clouds have the correct perspective, whereas the objects on the earth appear like a painting on a vertical surface, as the clouds in the sky usually do."

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These statements suggest that, in observations with the head upside down, perceived depth betweens objects is reduced, although it is not clear whether the absolute perceived distance from the observer to the object is also shortened. One may also infer that, since binocular (stereoscopic) cues are present equally in both parts of the field, the restriction of the perceived distance variation to the lower visual field implies that the perceived size of an object is likely to be based on visual angle.

If a landscape is viewed from between the legs, two orientations change compared to normal upright posture. One is the orientation of the upper body, including the head and chest. The upper body is so inverted that the low back muscles are stretched and the belly muscles are contracted, otolithic stimulation in the inner ears is disturbed and the head is congested with blood. The other is the orientation of the retinal image. By inverting the head upside down, the retinal image is reversed from left to right and is inverted from up to down. Note that when we attempt to see a landscape between our own legs, we have to direct our back to it and bend the body forward. This transformation of the retinal image is equivalent to a 180° rotation of the visual field.

The problem to be addressed in this study is how the visual and proprioceptive sources of information affect perceived size and perceived distance of objects seen between the legs. As has already been cited, Helmholtz accounted for the changes to the perceived size and perceived distance in terms of the information on the retinal image. He assumed that, in the inverted posture, the retinal image is formed on a site that differs from the usual site of stimulation (i.e., the sky, for example, is projected on the upper portion of the retina and the ground is projected on its lower portion), and binocular stereoscopic distance judgment becomes less accurate. As a consequence, perceived depth between objects is compressed, and perceived size of objects is reduced according to size–distance invariance. Meili (1960) similarly interpreted changes of the perceived size of objects when viewed from between the legs. We call this interpretation the "apparent distance theory."

Some may wonder why inversion of the retinal image reduces perceived depth? We think that Helmholtz's account is based on perceptual learning during space perception: we see objects as near unless we learn to see them as far (see Ross & Plug, 2002; pp. 121–122 for review). This idea is restated: (1) most of our experience is of terrestrial scene, viewed from the upright posture, (2) we learn to perceive terrestrial distance accurately in this circumstance, but it is difficult for this learning to transfer to unfamiliar scene (e.g., viewing of the inverted retinal image). As a result, perceived depth between objects is foreshortened when viewing the scene between the legs.

By accurate perceived distance, we mean that perceived distance is proportional to objective distance. In other words, the exponent of the power function, which has been used to construct the scale for distance (Wiest & Bell, 1985), approximates unity. If the exponent is smaller than unity, it means that perceived distance is compressed, whereas an exponent that is larger than unity means that perceived distance is expanded. The apparent distance theory assumes that the exponent of the power function would be smaller than unity only when the retinal images are inverted.

Another theory of 'between legs' perception is based on the changes of proprioceptive information coming from the orientation of the eye, neck, or body (see Ross & Plug, 2002, pp. 153–186; for review). The crucial assumption of the proprioceptive theory is that size constancy is dominant in usual normal posture, but is more reduced the more unusual the posture (Ching, Peng, & Fang, 1963; Hermans, 1954; Holway & Boring, 1940a, 1940b; Suzuki, 1991, 1998; Van der Geer & Zwaan, 1964; Wood, Zinkus, & Mountjoy, 1968). Although no one has ever specified a physiological process underlying this assumption, it seems to us that those authors who emphasize the role of proprioceptive information on perceived size have assumed that perceptual learning regarding size constancy develops under normal posture, and it is deteriorated when this normal posture is changed (Higashiyama, 1996), because the neural context of the judgment circuits is changed.

By usual normal posture, we mean that the eyes are at the primary position, and the head and trunk are kept upright with respect to the direction of the gravity. According to this definition, raising or lowering the eyes produces unusual proprioceptive information of the eye. Also, tilting the head laterally or backward while keeping the trunk erect produces unusual proprioceptive information of the neck. Similarly, bending the trunk forward or lying in a supine position on a bench produces unusual proprioceptive information of the trunk. However, standing on one leg and raising both hands, for example, is not unusual in the light of our definition, because, in this case, observer's head and trunk agree with the direction of the gravity. Orientation of the limbs including the arms and feet is presumably not so crucial in judging size and distance as orientation of the eyes, head, and trunk.

How does the proprioceptive theory explain the high degree of size constancy that is achieved in normal posture? To achieve a high degree of size constancy, we need a visual skill that has been learned from birth onward (Brislin & Leibowitz, 1970), and this skill—a habit that works automatically for objects that we see—has been polished up under normal posture. It is thus possible to say that size constancy is conditioned to normal proprioceptive information (Van der Geer & Zwaan, 1964). This visual skill is assumed to work best under the normal proprioceptive condition in which it has been formed. If an observer receives unusual proprioceptive information by bending the body, tilting the neck, or raising or lowering the eyes, this is degraded, so that perceived size of an object is likely to be based on the visual angle (i.e., a low degree of size constancy). For example, as the viewing distance to an object increases, the size of the object appears constant under normal upright posture; but it appears smaller with the trunk bent forward, because the object at a farther distance subtends a smaller visual angle and the perceived size of the object is likely to be based on the visual angle. Previous studies of size perception mainly investigated the role of the eye or head orientation, and it remains open how the orientation of the trunk affects perceived size.

The proprioceptive theory also assumes that we learn to perceive accurate distance in the natural environment. Specifically, in a situation where several objects intervene between the observer and the target to be judged, he or she has accustomed to perceiving the target distance accurately by making use of visual cues to distance. As for size perception, perceptual learning for distance perception advances under the combination of visual cues with normal posture. Thus, either if visual cues are reduced or if normal posture is changed, it would be difficult to achieve accurate distance judgments.

If the proprioceptive theory is valid and if there is a tendency that we see objects as near unless we learn to see them as far (Ross & Plug, 2002), it is then predicted that depth between objects should appear to be reduced with the trunk bending forward: Perceived distance is represented as a power function with an exponent of less than unity. Although a direct test of this prediction regarding perceived distance has not been made under the condition of bending the trunk forward, the effects of raising or lowering the eyes (Carter, 1977; Hermans, 1954; Thor, Winters, & Hoats, 1970) and the effects of bending the head on perceived distance (Galanter & Galanter, 1973) have been examined. In particular, in the Galanter and Galanter study, the subjects judged distance of targets located at physical distance from a few hundred yards to a few miles. The targets were at different elevations (from horizontal to vertical) against the ocean or against the sky. The exponent of the power function, when fitted to the judged distances, was 1.2 for the horizontal direction (i.e., upright posture) and 0.8 for the vertical direction (i.e., bent neck), supporting the proprioceptive theory.

The proprioceptive theory assumes that the visual skill that is needed to achieve accurate size and distance judgments is conditioned to normal posture. This implies that a process similar to the classical S–R conditioning works in visual space perception. The changes of perceived size or perceived distance that are contingent on postural state may be analogous to, say, saliva secretion that is conditioned to white noise of 60 dB. As is well documented (e.g., Gleitman, Fridlund, & Reiberg, 2004), the amount of saliva secretion, in this case, is maximal to the conditioned noise (i.e., 60 dB) and decreases as the loudness of white noise goes away from the conditioned noise. It is therefore assumed that just as noise intensity is considered to control saliva secretion directly, so proprioceptive state of the eye, neck, or body is an immediate determinant of perceived size and perceived distance. Proprioceptive information affects perceived size without invoking perceived distance or it affects perceived distance without invoking perceived size. This feature of the proprioceptive theory is in contrast with the apparent distance theory, which assumes that the retinal image affects perceived size by taking perceived distance into account.

Both the apparent-distance and proprioceptive theories probably predict that if objects are viewed from between the legs, visual perception of size and distance is less stable compared with when they are observed normally. In between-leg observation, since the retinal image is formed on a site that differs from the usual site of stimulation and the trunk is in a position that differs from its usual upright position, it is difficult for some observers to maintain the habit of seeing the world stably, although other may maintain it well. This implies that individual differences (i.e., inter-observer variability) of perceived size and perceived distance are larger in between-leg observation.

Bearing these theoretical considerations in mind, an attempt was made to clarify the relative effects of visual and proprioceptive factors on perceived size and perceived distance. First, a comparison was made between the effect of bent and upright head, showing how size constancy is reduced and the scale for distance is compressed. It was expected that size constancy would prevail in upright posture in the natural environment (Teghtsoonian & Beckwith, 1978; Teghtsoonian & Teghtsoonian, 1970), while, with the head placed between the legs, underconstancy of size would occur because of the inappropriateness of visual or proprioceptive information. As regards distance in a large open field, perceived distance is often proportional to objective distance for upright posture—doubling objective distance does double perceived distance (Higashiyama & Shimono, 1994, 2004). However, with the head inverted in the informative condition of viewing, doubling of objective distance would be less-than-double perceived distance. This means that perceived depth between objects would be compressed with the head upside down.

To separate visual from proprioceptive factors, a condition in which the observers wore prism goggles making the visual field rotate 180° was compared with a condition in which the observers wore only a frame minus the prisms. Using this comparison, the effect of retinal image orientation on perceived size and perceived distance was examined. We also compared a condition in which the observers wore the 180° rotation goggles with the head upside down, with a condition in which the observers wore empty goggles while lying on the belly with the head upright. Using this comparison, the effect of body orientation on perceived size and perceived distance was studied.

If the retinal image of a landscape is formed in the same orientation as it is in everyday life, the orientation of the retinal image is referred to as normal or upright. For example, in everyday life, the sky is projected on the lower half of the retina and the ground is projected on its upper half. If, however, the sky is projected on the upper half of the retina and the ground is projected on its lower half, the orientation of the retinal image is referred to as inverted. The upright or inverted orientation of the retinal image is used, regardless of body orientation. For example, if we bend the head forward while wearing prism goggles that rotates the retinal image 180°, the retinal image is upright, because, despite the head being bent, the sky is projected on the lower half of the retina and the ground is projected on its upper half.

Finally, the relationship between perceived size and perceived distance was examined in two ways. First, it was assessed whether perceived size and perceived distance agree with the size–distance invariance hypothesis (SDIH), which maintains that the ratio of perceived size to perceived distance is determined as a unique function of visual angle (Epstein, Park, & Casey, 1961; Gogel, 1973; for recent review, see Ross, 2002). If this hypothesis were correct, the ratio of perceived size to perceived distance would be the same in the experimental and control conditions of each comparison.

Next, it was assessed whether perceived size is independent of perceived distance by applying path analysis and partial correlation analysis to the present data. In path analysis, two processing models were examined. One is the apparent distance model, in which it is assumed that perceived size is a combinatory product of the retinal image size of a target and perceived egocentric distance to it, and perceived distance is determined by what is called 'cues,' which include both visual information contained in the optic arrays or retinal images and proprioceptive information contained in eye muscles (Kaufman, 1974; Rock, 1975; McKee & Welch, 1992). Helmholtz's account of between-leg perception is a version of the apparent distance model. Another model is the direct perception model, in which it is assumed that perceived size and perceived distance are influenced directly by exogenous variables, but there is no causal relationship between perceived size and perceived distance (Bertamini, Yang, & Proffitt, 1998; Gibson, 1950; Oyama, 1974; Sedgwick, 1986). The proprioceptive account of the between-leg perception may resemble this direct perception model in that proprioceptive information affects perceived size and perceived distance separately.

A partial correlation analysis was also used to reveal the relationship between perceived size and perceived distance. If perceived size is independent of perceived distance, the partial correlation between the two variables would be zero. This outcome is predicted from the proprioceptive theory, which assumes that both perceived size and perceived distance change with changes in proprioceptive information, but there is no direct causal relationship between perceived size and perceived distance. If, on the other hand, perceived size depends on perceived distance, a partial correlation between the two variables would be significant. This outcome is predicted from the Helmholtz's account of between-leg perception, which assumes that perceived depth is so compressed in the inverted retinal image that the perceived size is reduced according to size–distance invariance.

2. Method

2.1. Participants

Ninety undergraduates volunteered as observers. No special qualifying criteria were imposed, except that visual acuity was normal in unaided or corrected vision.

2.2. Stimuli and optical device

The stimuli were five similar red rectangles of 32×16, 48×24, 72×36, 108×54, and 162×81 cm (height × base). Each target was cut from plywood and stood directly on the ground, with a support on the rear of the target. Each target was presented at a distance of 2.5, 5, 15, 30, or 45 m from the observer. Therefore, there were 25 combinations of targets and distances.

The targets were presented within a 2 m wide × 50 m long ditch. On the left side of the ditch was a five-story building, and on its right side was a 3-m high uniform concrete wall. Since there was no roof above the ditch, the observers, if they wanted, would be able to see the sky from the bottom of the ditch.

Sanwa goggles, equipped with right-angle prisms, were used to produce a 180° rotation of the visual field. A strap was used to hold the goggles steady on the head. When an observer wore the goggles with the head stationary and explored the visual field with both eyes, the visible field size was 44.5° in the horizontal and 31.9° in the vertical dimension.

2.3. Design

The study consisted of three comparisons, each of which included an experimental condition and a control condition. Thirty observers were randomly assigned to each of the three comparisons. In the first comparison, 15 observers of the experimental condition inverted the head and saw the targets between their own legs (i.e., natural viewing with the head upside down). The experimenter asked these observers to bend the head so deeply that they were not able to see the legs. The other 15 observers (control condition) saw the targets while being erect on the ground (i.e., natural viewing with the head upright).

In the second comparison, 15 observers of the experimental condition saw the targets with the prism goggles that rotated the visual field of the observer 180°. In this condition, the visual field of the observer was so greatly limited by the goggle frames that he or she received less visual information (Thouless, 1968). To provide the same reduced visual information as the experimental condition, in the control condition, each of the 15 observers saw the targets with a hollow frame lacking the prisms. The observers in both conditions stood erect on the ground. The experimental condition is referred to as the 'prism-goggle viewing' with the head upright, and the control condition as the 'hollow-goggle viewing' with the head upright. The orientation of the retinal images differed between the two conditions, but head orientation, size of the visual field, and height of the eyes above the ground were the same in both.

In the third comparison, 15 observers of the experimental condition wore the prism goggles and inverted the head (i.e., the prism-goggle viewing with the head upside down). In this condition, the level of observer's eyes was lowered, so that, in the control condition, 15 observers wore the hollow goggle and lay on the belly with his/her chin on the two palms (i.e., the hollow-goggle viewing with the belly on the ground). In this comparison, it was necessary to control the level of the eyes, because it may have an effect on size judgments (Bertamini et al., 1998) and on distance judgments (Harway, 1963; Higashiyama, 1996; Ooi, Wu, & He, 2001). Thus, only the orientation of the head differed between the two conditions, but orientation of the retinal images, size of the visual field, and height of the eyes above the ground were the same in both.

2.4. Procedure

When the observer arrived at the ditch, the experimenter asked him or her to stand at one end of the ditch and direct his or her back to it. On a given trial under natural viewing with the head upright, the observer was asked to turn his/her body to the ditch, to view the target at a preset position, and to verbally judge both perceived size (height) and perceived distance of it. Size and distance were judged in units of centimeters and meters, respectively. After the observer had finished his or her judgments, the experimenter changed the target for the next trial. While assistants were changing targets, the observer again faced directly away from the ditch.

The observer was instructed to judge the objective size and objective distance of the target. By objective size or objective distance, we mean the size or distance of the target that would be obtained if measured with a ruler. Since it is well documented that size judgments are greatly influenced by the instructional variable—apparent, objective, and retinal instructions (Gilinsky, 1955; Leibowitz & Harvey, 1967, 1969), it was necessary to specify the instructions to observers. The main reason why we used the objective instructions in this study is that the objective instructions are natural, clear, and understandable to observers. The retinal instructions, which require judgments based on visual angle of objects, are analytic, artificial, or unusual to most observers, except for the painters, architects, and scientists. The apparent instructions, which require judgments based on subjective size of objects, are ambiguous when we compare two objects at different distances. Some observers interpret apparent size as an impression of objective size we obtain when we look at an object in normal and practical way, and others interpret it as an impression of the visual field an object appears to fill (Joynson, 1948).

Generally, the same procedure was followed by the observers as for natural viewing with the head upright, so only procedures specific to each condition are described below. In the inverted head conditions, the observer faced directly away from the ditch throughout the experiment. Immediately after a target was presented at a preset position, the observer bent the head forward to see the target between his or her own legs. After completing judgments of perceived size and perceived distance of the target, the observer returned to the upright position.

In the prism or hollow goggle conditions, the observer wore the goggles throughout the experiment. After completing size and distance judgments on each trial, in the prism or hollow goggle condition with the head upright, the observer directed his or her back to the target, and in the hollow goggle viewing with the belly on the ground, he or she closed his/her eyes.

The order of the 25 size–distance combinations was randomly determined for each observer. Seven or eight observers in each condition judged size after judging distance for each target, while the remaining observers judged them in the reverse order.

3. Results

Since the distributions of judgments obtained in this study were positively skewed, a geometric mean, instead of an arithmetic mean, was obtained for each of the size–distance combinations. For the same reason, every statistical test used in this study was performed after converting all judgments to logarithmic scores. So, whenever we use the term ‘mean’ in this study, it refers to the geometric mean.

3.1. Comparison 1

Fig. 1 shows the mean size judgments for natural viewing with the head upside down (left panel) and with the head upright (right panel). On log–log coordinates, the abscissa is the viewing distance (in meters) and the ordinate is the mean size judgment (in centimeters) taken across the 15 observers. A three-way (head × size × distance) repeated-measure ANOVA showed that the main effect of distance was significant, $F(4, 112) = 12.3$, $p < 0.001$ and the head × distance interaction was significant, $F(4, 112) = 10.4$, $p < 0.001$. These results suggested that mean size judgments for the upside-down head condition decreased with increasing viewing distance (i.e., underconstancy of size), whereas mean size judgments for the upright head condition remained constant, regardless of viewing distance (i.e., size constancy).

The main effect of size was significant, $F(4, 112) = 328.1$, $p < 0.001$, and the head × size interaction was significant, $F(4, 112) = 2.8$, $p < 0.05$. This interaction

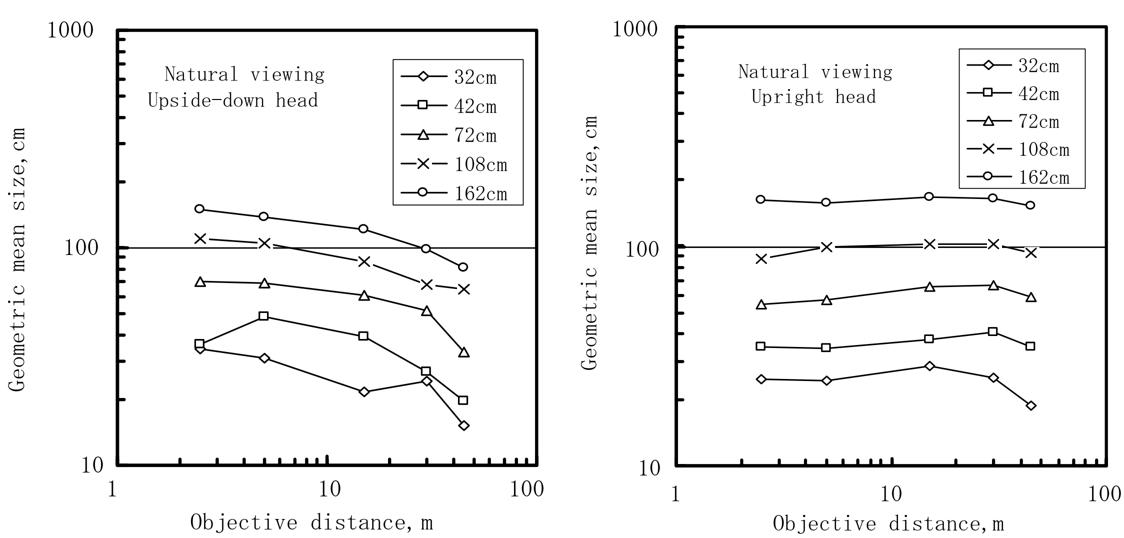

Fig. 1. Geometric mean size judgments (cm) as a function of objective distance (m), with the target size as the parameter. Left, natural viewing with the upside-down head. Right, natural viewing with the upright head.

suggested that mean size judgments for the large targets under the upright head condition were larger than those under the upside-down head condition, but for the small targets, the difference in size judgment between the head conditions was attenuated. It is also noted that mean size judgments in the upright head condition were fairly accurate, but mean size judgments in the upside-down head condition were unquestionably less than the objective size.

Fig. 2 shows the mean distance judgments for natural viewing with the head upside down (left panel) and with the head upright (right panel). On log–log coordinates, the abscissa is the viewing distance and the ordinate is the mean distance judgment (meters) taken across the 15 observers. A three-way (head × size × distance) repeated-measure ANOVA showed that the main effect of distance was significant, $F(4,\ 112) = 472.2$, $p < 0.001$, and the main effect of size was significant, $F(4,\ 112) = 4.8$, $p < 0.01$. This means that: (1) the mean distance judgments increased with increasing viewing distance and (2) the small targets are generally judged to be farther than the large targets.

To reveal the effects of target size on distance judgments, we fitted a power function to the distance judgments. Table 1 shows the results. Note that the exponents of the power function for the upside-down head condition were consistently smaller than those for the upright head condition, but the scale factors for the upside-down head condition were consistently larger than those for the upright head condition. This means that a target at a distance of 15 m or less appeared to be farther away under the upside-down head condition than the upright head condition, but a target at a distance of 30 or 45 m appeared almost at the same distance in the two head conditions. Thus, the depth between objects appears to be much more compressed under the upside-down head condition.

Table 1
Exponents, scale factors and r^2 of power functions fitted to the distance judgments in the natural view condition with the head bent and head upright

Target size (cm)	Upside-down head (r^2)	Upright head (r^2)
32	$y = 1.29\ x^{0.88}$ (0.99)	$y = 0.80\ x^{0.98}$ (1.00)
42	$y = 1.16\ x^{0.91}$ (0.99)	$y = 0.78\ x^{0.99}$ (1.00)
72	$y = 1.11\ x^{0.89}$ (0.99)	$y = 0.78\ x^{0.97}$ (0.99)
108	$y = 1.16\ x^{0.88}$ (0.98)	$y = 0.84\ x^{0.95}$ (1.00)
162	$y = 1.06\ x^{0.87}$ (0.99)	$y = 0.81\ x^{0.96}$ (0.99)
Mean	$y = 1.16\ x^{0.89}$	$y = 0.80\ x^{0.97}$

x, objective distance; y, judged distance; r^2, coefficient of determination.

3.2. Comparison 2

Fig. 3 shows the mean size judgments for prism-goggle viewing with the head upright (left panel) and for hollow-goggle viewing with the head upright (right panel). A three-way (goggle × size × distance) repeated-measure ANOVA showed that the main effect of goggle was significant, $F(1,\ 28) = 4.4$, $p < 0.05$, but the goggle × distance interaction was not significant. These results suggested that, although mean size judgments obtained with the prism goggles were smaller than those obtained with the hollow goggles, the degree of size constancy did not differ between the prism- and hollow-goggle conditions.

The main effect of size was significant, $F(4,\ 112) = 261.2$, $p < 0.001$, but the goggle × size interaction was not significant. This just means that the larger the objective size, the larger the perceived size.

The size × distance interaction was also significant, $F(16,\ 448) = 2.3$, $p < 0.01$. It is probable that the mean size judgments for the large targets (i.e., the 162 cm target) decreased with increasing viewing distance, whereas the mean size judgments for the small targets (i.e., the 32 cm target) increased with increasing viewing distance (see Fig. 3).

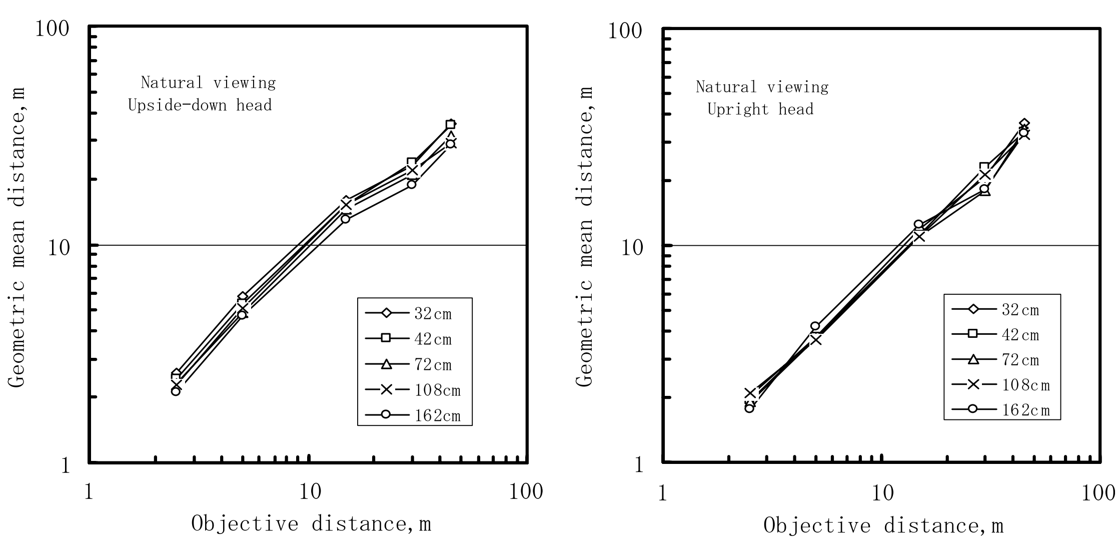

Fig. 2. Geometric mean distance judgments (m) as a function of objective distance (m), with the target size as the parameter. Left, natural viewing with the upside-down head. Right, natural viewing with the upright head.

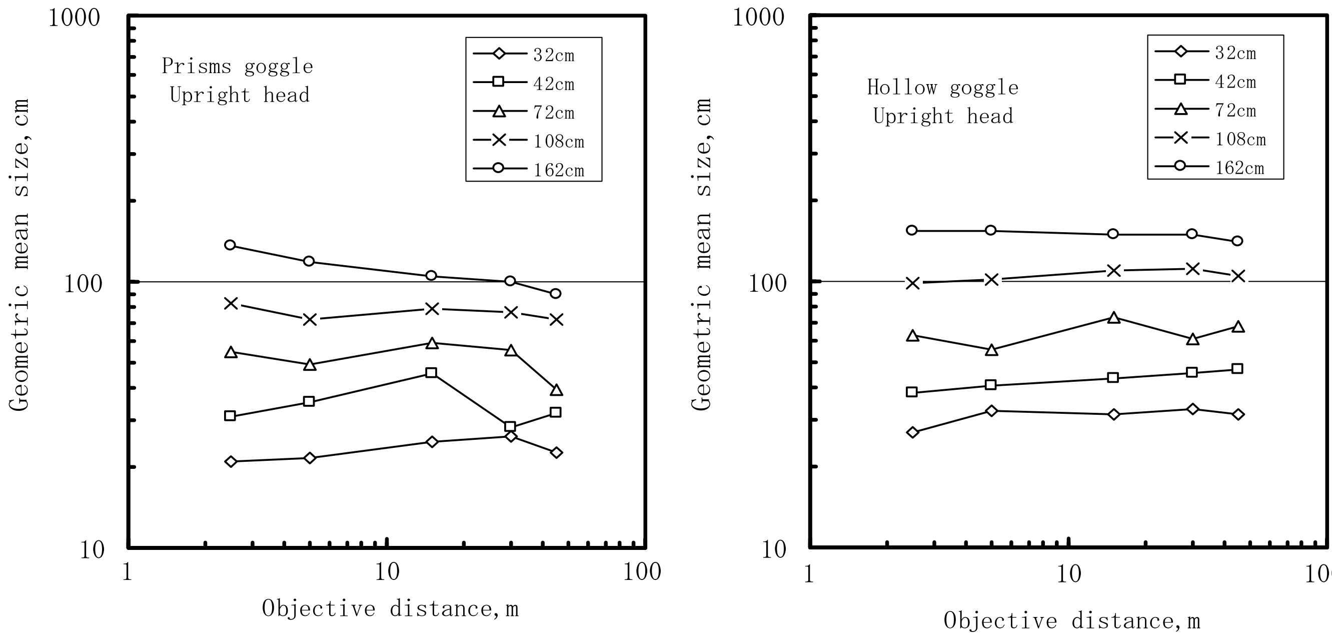

Fig. 3. Geometric mean size judgments (cm) as a function of objective distance (m), with the target size as the parameter. Left, prism-goggle viewing with the upright head. Right, hollow-goggle viewing with the upside-down head.

Fig. 4 shows the mean distance judgments for prism- (left panel) and hollow-goggle viewing (right panel). A three-way (goggle × size × distance) repeated-measure ANOVA showed that the main effect of distance was significant, $F(1,\ 28) = 565.4$, $p < 0.001$, and the main effect of size was significant, $F(4,\ 112) = 10.2$. $p < 0.001$. Clearly, it is suggested that: (1) mean perceived distance increased with increasing viewing distance and (2) mean perceived distance for the smallest target (i.e., 32 cm) was generally larger than that for the largest target (i.e., 162 cm), while mean perceived distances for the other targets were generally between the extremes.

We fitted a power function to the distance judgments for each target. Table 2 shows the results. Note that the exponents of the power function were essentially identical in the prism and the hollow condition (∼1.0), but the scale factors of the power function for the prism goggles were somewhat larger than those for the hollow goggles. This means that mean perceived distance of the targets observed with the prism goggles was larger than those observed with the hollow goggles.

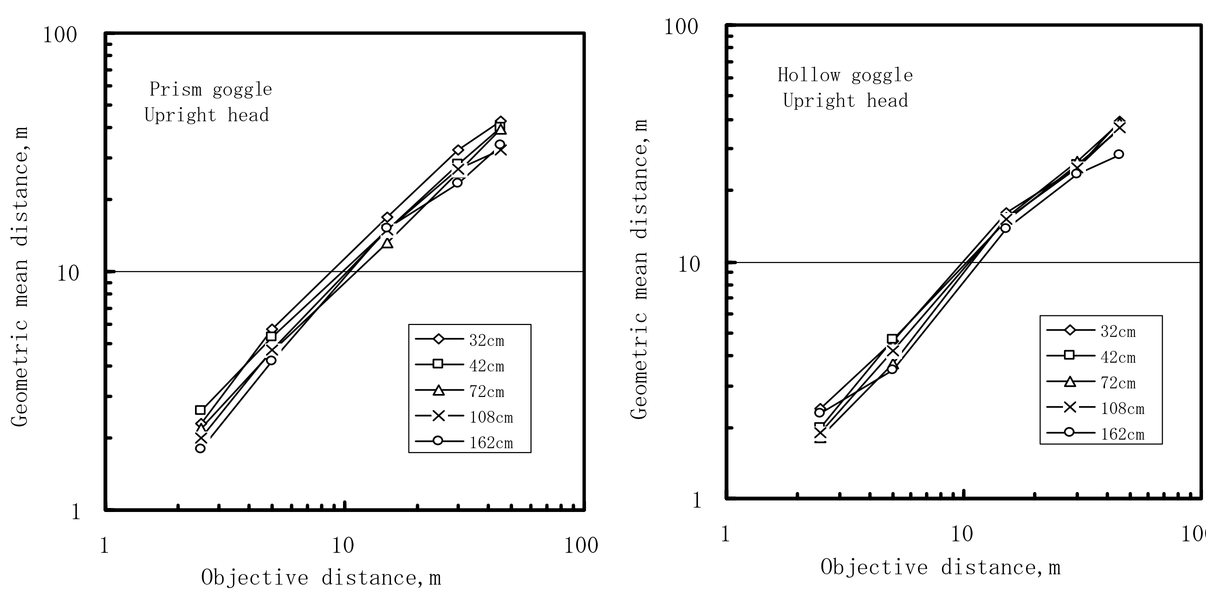

Fig. 4. Geometric mean distance judgments (m) as a function of objective distance (m), with the target size as the parameter. Left, prism-goggle viewing with the upright head. Right, hollow-goggle viewing with the upright head.

Table 2
Exponents, scale factors and r^2 of power functions fitted to the distance judgments obtained through prism or hollow goggles with the head upright

Target size (cm)	Prism goggles (r^2)	Hollow goggles (r^2)
32	$y = 1.02\ x^{1.01}$ (0.99)	$y = 1.01\ x^{0.97}$ (0.99)
42	$y = 1.13\ x^{0.94}$ (1.00)	$y = 0.88\ x^{0.99}$ (0.99)
72	$y = 0.91\ x^{0.99}$ (1.00)	$y = 0.69\ x^{1.08}$ (0.99)
108	$y = 0.91\ x^{0.98}$ (0.99)	$y = 0.79\ x^{1.03}$ (0.99)
162	$y = 0.79\ x^{1.01}$ (0.99)	$y = 0.93\ x^{0.93}$ (0.98)
Mean	$y = 0.95\ x^{0.99}$	$y = 0.86\ x^{1.00}$

x, objective distance; y, judged distance; r^2, coefficient of determination.

3.3. Comparison 3

Fig. 5 shows the mean size judgments for prism-goggle viewing with the head upside down (left panel) and for hollow-goggle viewing with the belly on the ground (right panel). A three-way (head × size × distance) repeated-measure ANOVA was performed. The main effect of size was significant, $F(4, 114) = 399.6$, $p < 0.001$, indicating that the size judgments increased with increasing target size.

The main effect of distance was significant, $F(4, 112) = 12.9$, $p < 0.001$, and the head × distance interaction was significant, $F(4, 112) = 3.0$, $p < 0.05$. These results suggested that, in prism-goggle viewing with the head upside down, the mean size judgments decreased more steeply as a function of viewing distance, compared with hollow-goggle viewing with the belly on the ground (see Fig. 5).

Fig. 6 shows the mean distance judgments for prism-goggle viewing with the head upside down (left panel) and for hollow-goggle viewing with the belly on the ground (right panel). A power function was fitted to the distance judgments for each target (see Table 3). Note that the exponents of the power functions for the upside-down head condition were consistently smaller than those for the upright head condition, but the scale factors for the upside-down head condition were consistently larger than those for the upright head condition. These results are similar to the results of Comparison 1.

We also performed a three-way (head × size × distance) repeated-measure ANOVA on distance judgments. The main effect of distance was significant, $F(4, 112) = 691.9$, $p < 0.001$ and the head × distance interaction was significant, $F(4, 112) = 3.0$, $p < 0.05$. This suggested that, in prism-goggle viewing with the head upside down, the mean distance judgments increased less rapidly than in hollow-goggle viewing with the belly on the ground. As is indicated in Table 3, the mean exponent of the power function for prism-goggle viewing with the head upside down was 0.89, while the mean exponent of the power function for hollow-goggle viewing with the belly on the ground was 1.01. The head × distance × size interaction was also significant, $F(16, 448) = 1.8$, $p < 0.05$. This seems to mean that the head × distance interaction, just mentioned, was limited to the small targets. As suggested in Table 3, the differences in exponents between the head conditions were 0.15, 0.17, 0.11, 0.13, and 0.08 for targets of 32, 42, 72, 108, and 162 cm, respectively.

The head × size interaction was significant, $F(4, 112) = 7.6$, $p < 0.01$. The interpretation of this interaction is depicted in Fig. 7, where the mean distance judgment is represented as a function of target size, with the head and the distance as the parameters. For small targets, the mean distance judgments for prism-goggle viewing with the head upside down were equal or larger than those for hollow-goggle viewing with the head upright, whereas for

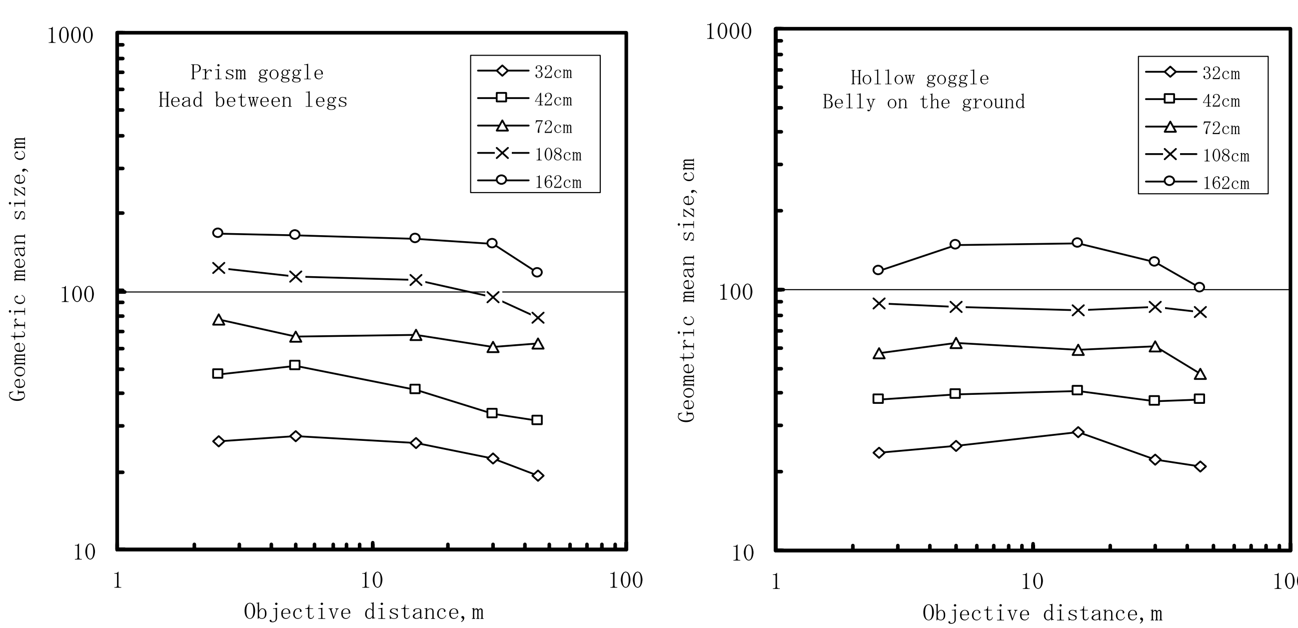

Fig. 5. Geometric mean size judgments (cm) as a function of objective distance (m), with the target size as the parameter. Left, prism-goggle viewing with the upside-down head. Right, hollow-goggle viewing with the belly on the ground.

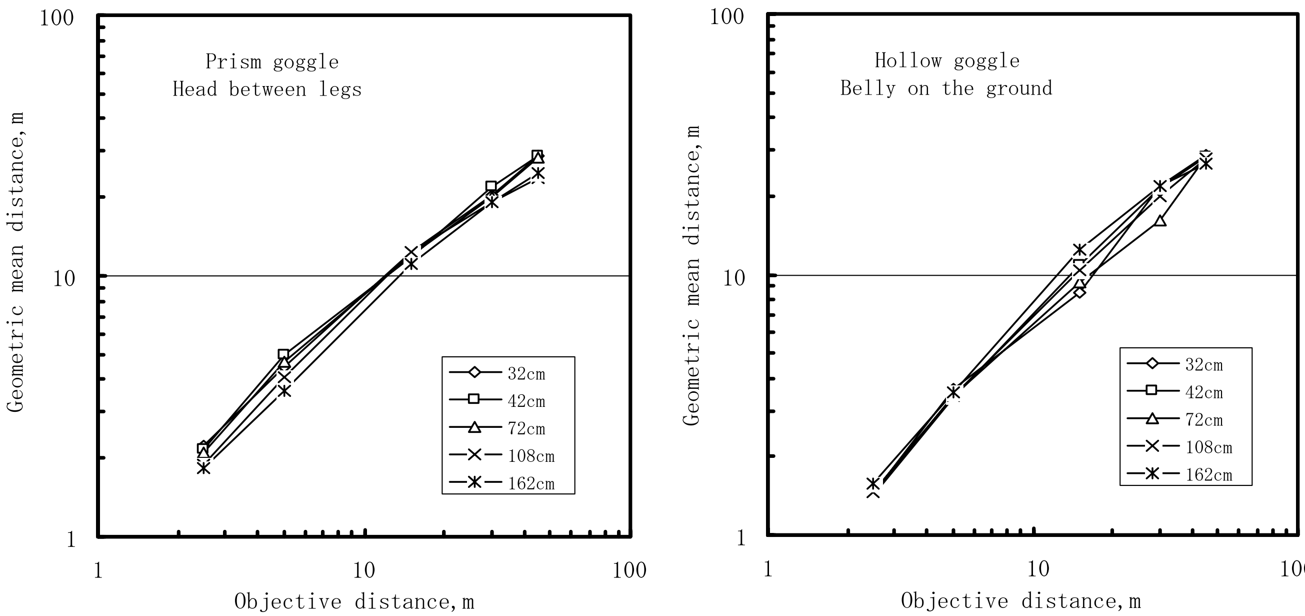

Fig. 6. Geometric mean distance judgments (m) as a function of objective distance (m), with the target size as the parameter. Left, prism-goggle viewing with the upside-down head. Right, hollow-goggle viewing with the belly on the ground.

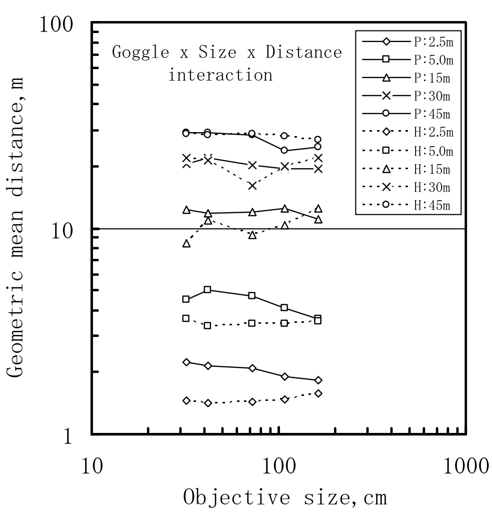

Fig. 7. Geometric mean distance judgments (m) as a function of objective distance (m), with the goggle–distance combination as the parameter (P, prism; H, hollow).

Table 3
Exponents, scale factors and r^2 of power functions fitted to the distance judgments obtained through prism goggles with the head upside down or through hollow goggles with the head upright on the ground

Target size (cm)	Prism goggles with head upside down (r^2)	Hollow goggles with head upright (r^2)
32	$y = 1.05\ x^{0.87}$ (1.00)	$y = 0.61\ x^{1.02}$ (0.99)
42	$y = 1.06\ x^{0.88}$ (0.99)	$y = 0.59\ x^{1.05}$ (1.00)
72	$y = 1.03\ x^{0.88}$ (0.99)	$y = 0.63\ x^{0.99}$ (0.99)
108	$y = 0.94\ x^{0.88}$ (0.99)	$y = 0.63\ x^{1.01}$ (1.00)
162	$y = 0.82\ x^{0.92}$ (0.99)	$y = 0.69\ x^{1.00}$ (0.99)
Mean	$y = 0.98\ x^{0.89}$	$y = 0.63\ x^{1.01}$

x, objective distance; y, judged distance; r^2, coefficient of determination.

large targets, the mean distance judgments for prism-goggle viewing with the head upside down was equal or smaller than those for hollow-goggle viewing with the belly on the ground. This means that the effect of relative size on perceived distance (Epstein & Landauer, 1969; Gogel, 1964, 1969; Higashiyama, 1977, 1979; Landauer & Epstein, 1969) was enhanced in prism-goggle viewing with the head upside down, compared to hollow-goggle viewing with the belly on the ground.

The size × distance interaction was significant, $F(16, 448) = 2.5$, $p < 0.01$. Fig. 7 helps to interpret this interaction. For a viewing distance of 2.5 or 5.0 m, the mean distance judgment generally decreased with increasing target size, but for a distance of 15 m or more, it was almost constant, regardless of target size. Thus, the effect of relative size on perceived distance was limited to targets close to the observers, but for distant targets, its effect was reduced.

3.4. Variability of judgments

To examine variability of verbal size and distance judgments, we calculated a standard deviation (SD) for each of the 25 size-distance combinations under each comparison. Fig. 8 shows the results. The three left panels show the SDs of size judgments and the three right panels show the SDs of distance judgments. The top, middle, and bottom panels represent the results of Comparisons 1, 2, and 3, respectively. In each panel, SDs for the experimental condition are plotted against those for the control condition.

Fig. 8 suggests that: (1) variability of size or distance judgments increased with increasing physical counterpart, (2) variability of the experimental size judgments was larger than that of the control size judgments in all comparisons,

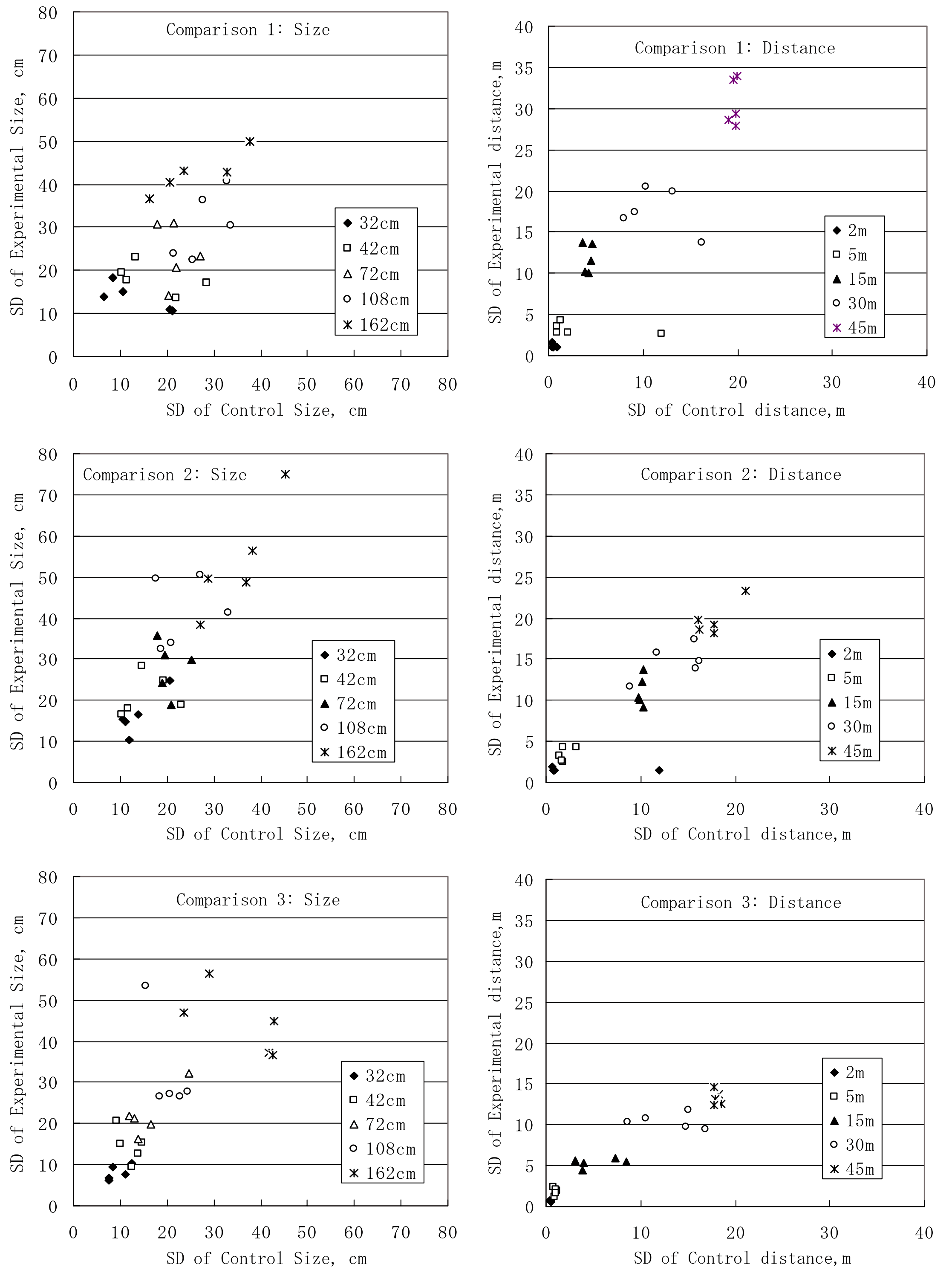

Fig. 8. Scatter diagrams of standard deviation between the experimental condition and the control condition. The left panels are for size judgments with the target size as the parameter, and the right panels for distance judgments with the viewing distance as the parameter. The upper, middle, and bottom panels are for Comparisons 1, 2, and 3, respectively.

and (3) variability of the experimental distance judgments was larger than that of the control distance judgments in Comparisons 1 and 2, but the reverse held in Comparison 3: the variability of the experimental condition was larger than that of the control condition.

These results imply that the variable errors of size and distance judgments were smaller when the observers viewed targets with the head upright and were larger when the observers viewed them from between their legs. But, the results for Comparisons 2 and 3 were somewhat complicated. When only the retinal image was inverted while keeping the head upright or when only the body was inverted while keeping the retinal image upright, the variable errors of judged size were larger than those of the control size, but the variable errors of judged distance were equal to or smaller than those of the control distance.

3.5. Size–distance invariance

To examine the relationship between size judgment, distance judgment, and visual angle in each condition, the ratio of size judgment to distance judgment (S'/D') is represented, as a function of visual angle on log–log coordinates, in Fig. 9. The top, middle, and bottom panels of Fig. 9 show the 50 size–distance ratios for Comparison 1, 2, and 3, respectively. The 25 data points for each condition were fitted by a power function:

$$S'/D' = k\theta^n, \tag{1}$$

where θ is the visual angle in rad, and k and n are constants (Higashiyama & Shimono, 1994, 2004). Table 4 shows the values of k and n, estimated by least-square criteria.

From Fig. 9 and Table 4, it is clear that the power function approximately fits to S'/D', but the exponent and the scale factor varied to a considerable degree, depending on the experimental situation. The exponent ranged from 1.00 to 1.11, and the scale factor ranged from 0.90 to 1.45.

Fig. 9 and Table 4 are used to examine the size–distance invariance hypothesis (SDIH). If the SDIH holds exactly, the S'/D' for a constant visual angle would be the same in all conditions of this study. However, for Comparison 1 (top panel), the S'/D' in the inverted head condition was consistently smaller than that in the upright head condition. Similarly, for Comparison 2 (middle panel), the S'/D' in the prism goggle condition was consistently smaller than in the hollow goggle condition. These results challenge the SDIH. Yet, for Comparison 3 (bottom panel), where prism-goggle viewing with the head upside down was compared with hollow-goggle viewing with the belly on the ground, the two functions were almost the same, supporting the size–distance invariance hypothesis. So, we may conclude that the SDIH is formulated as Eq. (1), but the constants in Eq. (1) depend on experimental conditions, including both visual and proprioceptive conditions. This is consistent with the results of perceived size and perceived distance of objects that were observed through different mediums. Higashiyama and Shimono (2004) obtained the S'/D' for the targets that were observed in plane and convex mirrors. For a given visual angle, the S'/D' for convex mirrors was larger than that for the plane mirror. Ross and Nawaz (2003) compared validity of SDIH in air and in water and found that the SDIH held better in water and it did not hold precisely in air.

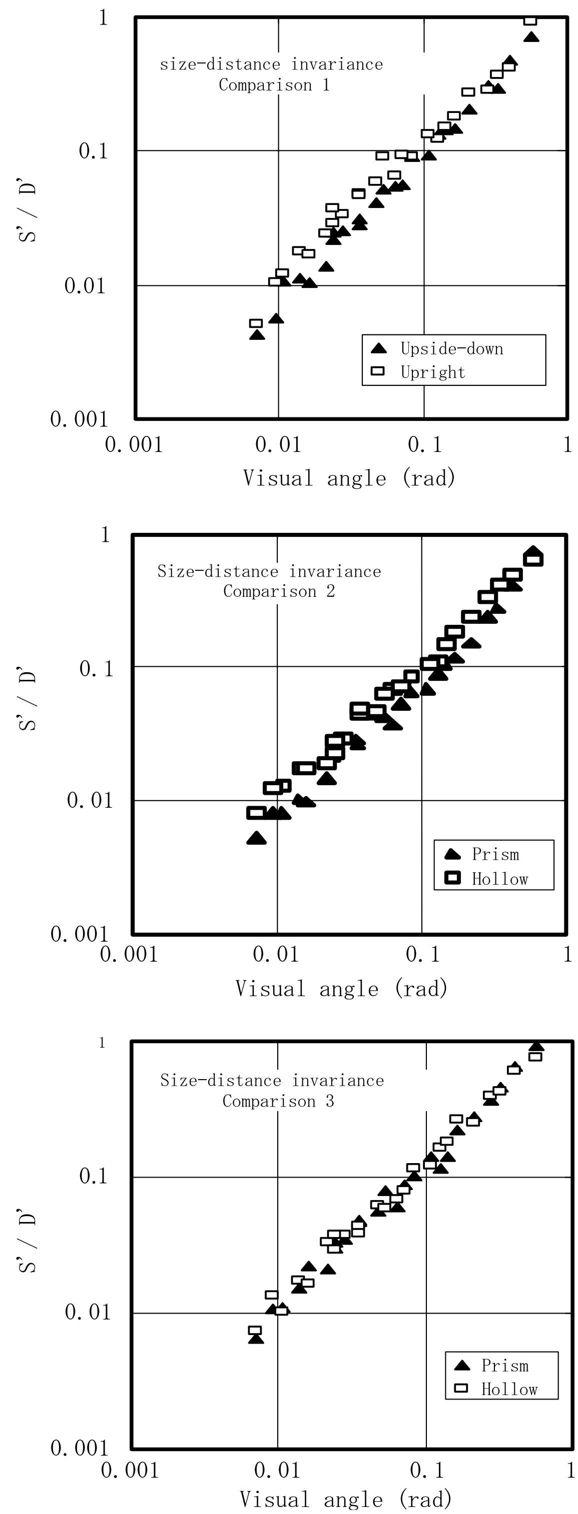

Fig. 9. S'/D' as a function of visual angle (rad), with the goggle or head condition as the parameter.

3.6. Path analysis

To compare the apparent-distance and direct-perception models by means of path analysis, all data in this study were run on the AMOS program. For either model, the independent or exogenous variables were objective size,

Table 4
A power function fitted to S'/D' as a function of visual angle (in rad) in each of the six conditions

Visual condition	Head condition	Power function (r^2)
Natural viewing	Upside down	$S'/D' = 1.21\theta^{1.11}$ (.99)
Natural viewing	Upright	$S'/D' = 1.24\theta^{1.02}$ (.98)
Prism goggles	Upright	$S'/D' = 0.90\theta^{1.04}$ (.98)
Hollow goggles	Upright	$S'/D' = 1.13\theta^{1.00}$ (.99)
Prism goggles	Upside down	$S'/D' = 1.45\theta^{1.06}$ (.99)
Hollow goggles	Upright head with lying on the belly	$S'/D' = 1.39\theta^{1.04}$ (.99)

objective distance, visual angle, body orientation, and retinal image orientation; dependent variables were perceived size and perceived distance. Since objective size, objective distance, visual angle, perceived size, and perceived distance are metric variables, these variables were all converted to logarithmic scores. Since body and retinal-image orientations are nominal variables, '1' was arbitrarily assigned to the upright posture or normal retinal image, and '0' was assigned to the upside-down posture or inverted retinal image.

There were three assumptions among the variables in this analysis. First, visual angle is correlated with objective size or objective distance, because a relation, $S = D \tan\theta$, holds among objective size, objective distance, and visual angle. Second, body orientation is independent of objective size, objective distance, or visual angle, and retinal-image orientation is also independent of objective size, objective distance, or visual angle, and body orientation is independent of retinal image orientation. Third, perceived size or perceived distance is connected with a residual error, which reflects both unexplained variance and measurement error.

As was mentioned earlier, the apparent distance model assumes that perceived size is affected by both visual angle and perceived distance, and perceived distance is affected by objective distance, body orientation, and retinal-image orientation. Fig. 10 represents the apparent distance model that was assumed in path analysis. This model and all research data were entered into the AMOS program and the path coefficients (i.e., standardized regression coefficients or beta weights) were obtained. The path coefficients thus obtained are shown in Fig. 10 as the effect of an arrow-nocked variable on an arrow-headed variable, controlling other prior variables; the asterisks attached to several coefficients represent the significance of 1% by z tests (Note that several path coefficients were larger than unity in this analysis. If exogenous variables are independent of each other ($r = 0$), all path coefficients have to be within a range of +1.0 and −1.0. But, if there are correlations among the exogenous variables, as a case of the present model, some path coefficients may be larger than +1.0 or smaller than −1.0). At the upper right of each of boxes, representing perceived size and perceived distance, the multiple correlation coefficient is shown, which is based on independent variable and prior variables connected by arrows to the dependent variable. Although there are probably 20 or more tests to explain how well this model fits the data (e.g., Hu & Bentler, 1998), we made use of three of the tests provided by the AMOS program, and obtained goodness-of-fit index (GFI) of 0.80, adjusted GFI (AGFI) of 0.61, and Akaike information criterion (AIC) of 213.44. It is said that the more the GFI approaches unity, the better the fit of the model to data, and, in particular, a model that produces a GFI of 0.90 or more should be satisfactory. AGFI and AIC are used to compare models with respect to goodness of fit: the larger the AGIF, the better the model; inversely, the smaller the AIC, the better the model.

The direct perception model assumes that each of the five exogenous variables affects both perceived size and perceived distance, but there is no causal relationship between perceived size and perceived distance. Fig. 11 represents the results for the direct perception model. The GFI of 0.91, AGFI of 0.71, and AIC of 91.80 were obtained. Clearly,

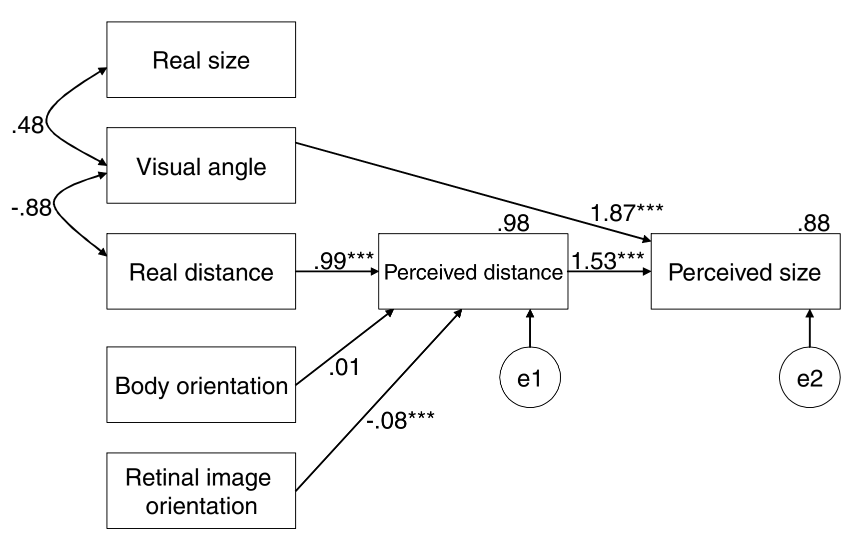

Fig. 10. The apparent distance model and the results of path analysis.

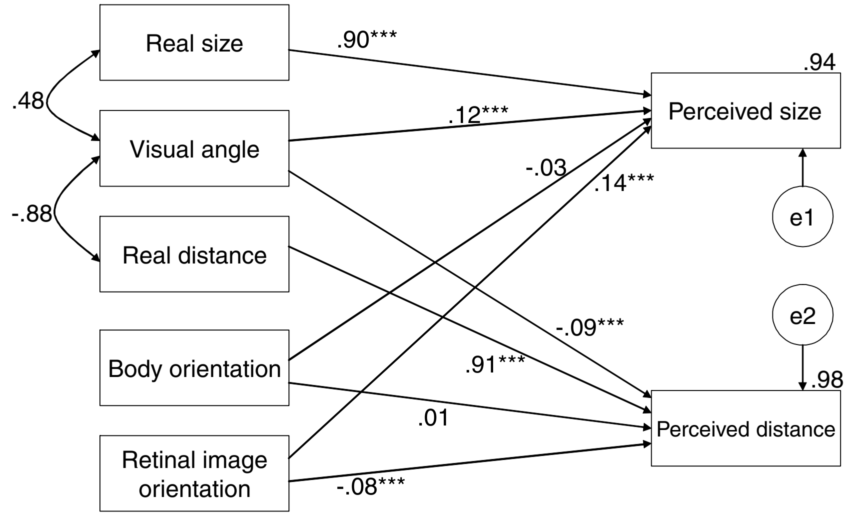

Fig. 11. The direct perception model and the results of path analysis.

the GFI value obtained shows that the direct perception model fitted the data satisfactorily. Note that the AGFI for the direct perception model was larger than that for the apparent distance model, whereas the AIC for the direct perception model was smaller than for the apparent distance model. These imply that the direct perception model provided a better fit to the data than the apparent distance model.

One notes that body orientation did not significantly contribute to size or distance judgments in either model, although the effect of body orientation was significant in the results of ANOVA performed on the data. There are two possible explanations for these seemingly conflicting outcomes. First, path analysis differs from ANOVA, so that path analysis and ANOVA did not produce the same outcomes. In ANOVA, sources of variances are separately evaluated relative to their error terms, whereas in path analysis, path coefficients are determined so as to give the best goodness-of-fit to a model as a whole. Second, more important, either apparent-distance or direct-perception model we have considered is not a model that suitably reflects the network of size-and-distance processing. To contrast the apparent-distance and direct-perception models clearly, we had to represent these models as simply as possible, as illustrated in Figs. 10 and 11. So, if we constructed a better model than the present models, it would show a significant effect of body orientation.

3.7. Partial correlation analysis

Table 5 shows the partial correlation between physical variable, S,D, or θ, and perceptual variable, S' or D', and the partial correlation between S' and D'. In obtaining each partial correlation, it is assumed that the effects of the three other variables were controlled. Since there was a unique pattern of partial correlations for each condition, it is difficult to summarize the outcome succinctly. However, several general tendencies were found in Table 5. First, the partial correlation between perceived size and perceived distance, $r(S', D')$, was not significant in five of the six conditions and was significant only for prism-goggle viewing with the head upside down. Second, when the observers wore the prism goggles or bent their heads downward, the partial correlation between physical size and perceived

Table 5
Partial correlations between physical variables (S, D, and θ) and perceptual variable (S' and D')

Visual/head conditions	Natural viewing/ upside down	Natural viewing/ upright	Prism goggles/ upright	Hollow goggles/ upright	Prism goggles/ upside down	Hollow goggles/ upright[a]
$r(S, S')$	0.063	0.137	0.425*	0.411*	0.264	−0.103
$r(S, D')$	−0.392	−0.163	−0.487*	0.010	−0.487*	−0.190
$r(D, S')$	0.003	0.190	−0.307	−0.189	−0.160	0.227
$r(D, D')$	0.486*	0.470	0.617**	0.070	0.559**	0.342
$r(\theta, S')$	0.106	0.130	−0.308	−0.134	−0.016	0.290
$r(\theta, D')$	0.315	0.229	0.467*	−0.126	0.351	0.147
$r(S', D')$	0.338	−0.269	0.144	0.320	0.525**	0.216

Each correlation was obtained when the effects of the other three variables are kept constant.
[a] Lying on belly.
* $p < 0.05$.
** $p < 0.01$.

distance, $r(S, D')$, and the partial correlation between physical distance and perceived distance, $r(D, D')$, were mostly significant (five of six cases). Third, when the observers stood erect and saw targets with naked eyes or with the hollow goggles, the partial correlations examined mostly failed to be significant (20 of 21 cases).

4. Discussion

4.1. Visual or proprioceptive?

An important finding of this study was that, when targets were viewed from between the legs with the head bent forwardly, the perceived size decreased as the viewing distance increased (i.e., underconstancy of size), and the perceived distance increased less rapidly, compared to the usual standing condition (i.e., contraction of distance). These results agree with Helmholtz's description, mentioned in Section 1.

More interestingly, underconstancy of size and the contraction of the scale for distance were not obtained in the inverted retinal-image condition with the head upright, but were obtained in the inverted head condition with the retinal image upright. This suggests that the proprioceptive body state affects both perceived size and perceived distance, and bending the body from the normal upright position directly lowers the degree of size constancy and compresses growth of perceived distance. This result does not support Helmholtz's account, which is based on inappropriateness of visual information.

How can one explain the fact that a change of body orientation is accompanied by a change of perceived size and perceived distance? It is assumed that in the course of development of visual space perception, visual space perception may have been conditioned to proprioceptive body state. Since a person began walking, he or she has seen objects mainly with the head and trunk being upright, and the upright body position has worked as a framework of our visual space perception. In other words, the ability of seeing objects accurately has been formed, contingent on the body being upright, so that size and distance perception is most sensitive to the upright body position. This means that size constancy mostly prevails for the upright body and deteriorates according to unusual orientations of the body. It can be assumed that a similar connection holds between perceived distance and body orientation. In the upright body position, we have learned to achieve accurate distance perception. However, with the body bent forwardly, the usual proprioceptive body state that we are familiar with is so disturbed that the function of the visual–proprioceptive system is lowered, resulting in less discrimination of distance.

4.2. Size and distance judgments in the normal conditions

Figs. 1, 3, and 5 show that size judgments were accurate under normal conditions, where both the head and retinal image are upright. These results agree with the results of Teghtsoonian and Teghtsoonian (1970) and Teghtsoonian and Beckwith (1978).

Tables 1–3 indicate that the exponents of the power function, fitted to the distance judgments, were close to 1.0 when the head and retinal image were upright. This result agrees with the results of our previous studies, in which perceived distance were judged for objects on the ocean (Higashiyama & Shimono, 1994) and in playgrounds (Higashiyama & Shimono, 2004). It is thus readily concluded that the judged distance is proportional to the objective distance under the natural environment. In contrast, the scale factors of the power function in this study were less than 1.0, even under normal conditions; they were 0.80, 0.86, and 0.63 for Comparisons 1, 2, and 3, respectively. Considering the values of exponent and scale factor together, it is suggested that reported distances averaged about 76% of its objective distance. This result supports the study of Foley, Ribeiro Filho, and Da Silva (2004), who found a reduction of perceived egocentric distance in an open field.

In short, although both perceived size and perceived distance are visual extents, perceived size is judged accurately relative to familiar physical units, such as meters or centimeters, but perceived distance is judged shorter than its true distance. This outcome agrees with the results of Higashiyama (1996); Higashiyama and Ueyama (1988); and Toye (1986).

4.3. Direct or mediational?

The results of path analyses favored the direct perception model, rather than the apparent distance model. This implies that there was no causal relationship between perceived size and perceived distance. A similar conclusion was obtained by partial correlation analysis, in which the partial correlation between perceived size and perceived distance, $r(S', D')$, was not significant in five of the six conditions in this study.

According to the path coefficients obtained for the direct perception model, the size judgments were affected overwhelmingly by objective size. This means that as objective size increases, judged size increases, presumably by responding to the higher-order variables (e.g., relation of a target to the background) that lead to veridical size perception. Size judgments were also affected mildly by visual angle. This means that the visual angle per se, without combining with perceived distance, is available to experience of perceived size (Rock & McDermott, 1964). Similarly, the distance judgments were affected overwhelmingly by objective distance. This means that as objective distance increases, the judged distance increases by responding to the higher-order variables (e.g., texture gradient), which lead to veridical distance perception. Distance judgments were also affected mildly by visual angle. This means that, even in the informative condition of viewing, distance is perceived to be larger for the target of smaller visual angle (Epstein & Landauer, 1969; Gogel, 1964, 1969; Higashiyama, 1977, 1979; Landauer & Epstein, 1969).

We maintain that the causal relationship between perceived size and perceived distance depends on the experimental situation (e.g., Norman, 1980). The results of the present and our previous studies, in which partial correlation analysis was applied to assess the network of size and distance perception, have suggested that, in an informative condition of viewing (Higashiyama & Shimono, 1994), perceived size is independent of perceived distance, whereas in a reduced condition of viewing (i.e., Higashiyama, 1983; for monocular viewing in total darkness, and Higashiyama & Shimono, 2004; for convex-mirror viewing, where virtual size and virtual distance of targets are extremely shrunken), perceived size depends on perceived distance. It seems that the visual system needs a cognitive or mediational manipulation to judge size and distance in a reduced condition of viewing, but in an informative condition of viewing, the visual system is able to produce perceived size and perceived distance by responding directly to the abundant optical and physiological variables.

4.4. Physiological correlates

The proprioceptive theory assumes that the function of visual space perception is conditioned to tactile and proprioceptive state of the body. Recent studies of physiology and neuroscience (e.g., Ganong, 2003; Klatzky, Lederman, & Reed, 1987; Zangaladze, Epstein, Grafton, & Sathian, 1999) have indicated that tactile and proprioceptive information interacts with visual information at the posterior parietal cortex. Tactile information, produced at Pacini capsules and others in the skin, is projected to the primary somatosensory area S1 in the postcentral gyrus, and proprioceptive information, yielded at specific receptors in joints and ligaments, is projected to the cerebellum and also to the postcentral gyrus. The information from S1 or the related areas in the postcentral gyrus is then sent to the posterior parietal cortex and is mixed with visual information that is sent out through the dorsal pathway of visual processing. It is thus suggested that the posterior parietal cortex is an important site for haptic-visual interactions.

Typical haptic-visual interactions are visually guided actions or eye-and-hand coordinating actions (e.g., reaching out and answering a phone, picking up a coffee cup, or shaking a colleague's hand when he or she comes into the room). If we are about to take these actions, we have to compute absolute distance and absolute size of the visual objects to relate them to the hand of our body that provides an egocentric frame of reference (Goodale & Milner, 2004). Thus, visual perception of absolute distance and absolute size may be related to neural activity at the posterior parietal cortex, where tactile/proprioceptive information is mixed with visual information.

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