Research Article

ASSOCIATION FOR PSYCHOLOGICAL SCIENCE

Psychological Science
21(5) 667–675

DOI: 10.1177/0956797610367753
http://pss.sagepub.com
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Observer Movement and Size Constancy

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Abstract

It is commonly assumed that size constancy—invariance of perceived size of objects as they change retinal size because of changes in distance—depends solely on retinal stimulation and vergence, but on no other action-related signals. Distance to an object can change through displacement of either the observer or the object. The common assumption predicts that the two types of displacement should lead to the same degree of size constancy. We measured size constancy while observers viewed stationary stimuli at different distances. Changes in distance between trials were either actively produced by the observer or generated by real or simulated object displacement, with retinal stimulation held constant across the movement conditions. Responses were always closer to perfect constancy for observer than for object movement. Thus, size constancy is enhanced by information from observer displacement, and, more generally, processes thought to be purely perceptual may have unexpected components related to action.

Keywords

size perception, action, constancy, vision

Received 5/18/09; Revision accepted 8/30/09

The perceived size of an object can be based on its retinal (or *proximal*) size or on an inferred physical (or *distal*) size. The phenomenon known as size constancy has been defined as "the tendency for objects to appear much the same size over a wide range of distances in spite of the changes of the retinal images associated with distance of the object" (Gregory, 1963, p. 679). Given that most retinal size changes are due to changes in distance between the observer and the object, rather than to changes in the physical size of the object, size constancy can be considered as the extraction of an invariant, physical (distal) object size. However, distance changes can be due to the observer's movement in a stationary environment, the object's movement while the observer is stationary, or a combination of these two factors. Although *subject movement* and *object movement* can result in identical relative geometric changes—namely, changes in the distance between subject and object—and therefore in identical changes in the retinal image, the two types of movement are very different physiologically and psychologically, as well as in terms of practical consequences for the subject. However, most studies of size constancy have assumed, explicitly or implicitly, the equivalence of size constancy in subject and object movement. In other words, size constancy has been assumed to follow from the interpretation of retinal data (and ocular vergence). The goal of the experiments that we present here was to test this assumption.

There are indeed valid reasons for thinking that size constancy might be stronger in the case of observer movement than in the case of object movement. It has long been known that size constancy depends on the presence and quality of information about absolute distance, being stronger when more depth cues are provided (Biersdorf, Ohwaki, & Kozil, 1963; Heinemann, Tulving, & Nachmias, 1959; Holway & Boring, 1941). If the observer compares the distal size of an object at two different distances, and the intermediate movement is carried out by the observer, rather than by the object, extraretinal self-motion cues could provide additional information about distance change, and this additional depth information could in turn strengthen size constancy. To make use of this information, however, the visual system must make the assumption that objects tend to remain stationary, in an observer-independent reference frame, while observers move. If such an assumption is not made, then self-motion information is useless in predicting absolute distance, for the object could move independently by any amount during observer movement. There is mounting evidence that a stationarity assumption does play an important role in the interpretation of optic flow (Colas, Droulez, Wexler, & Bessière, 2007; Naji & Freeman, 2004; Wexler, Lamouret, & Droulez, 2001; Wexler, Panerai, Lamouret, & Droulez, 2001). Moreover, the

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stationarity assumption has been shown to be effective even in the absence of visual landmarks, and this indicates that extraretinal information contributes to optic flow processing, and thus, potentially, to size constancy (Wexler, Lamouret, & Droulez, 2001; Wexler, Panerai, et al., 2001).

In the three experiments reported here, subjects judged the distal size of static stimuli whose size and absolute distance varied independently between trials (a similar technique was used by McKee & Welch, 1992). Distance variations were carried out when stimuli were not visible. In the subject-movement (SM) condition, these variations were due to the observer's own forward and backward head movement (measured and guided by a motion tracker); in the object-movement (OM) condition, equivalent changes in object position (either simulated or real) were implemented while the subject sat still (see Fig. 1). Thus, the projections of the stimuli on the retina were the same in the two conditions, with the only difference being the observer's movement. Note that we use the term *movement* to refer to changes in the distance of stimuli; there was no significant movement, either of the observer or of the stimulus, during stimulus presentation. In the three experiments, the absolute distance was conveyed through different depth cues. In the first experiment, the depth cue was binocular disparity, whereas in the second and third experiments, it was vergence. Distance variations were produced by the observer's movement or by simulated equivalent object movement. After briefly seeing the stimulus, the subject characterized its distal size as being "small" or "large," compared with an implicit standard (McKee & Welch, 1992; Morgan, Watamaniuk, & McKee, 2000). The dependence of response patterns on the independent variables of size and distance allowed us to calculate the degree of size constancy in each condition.

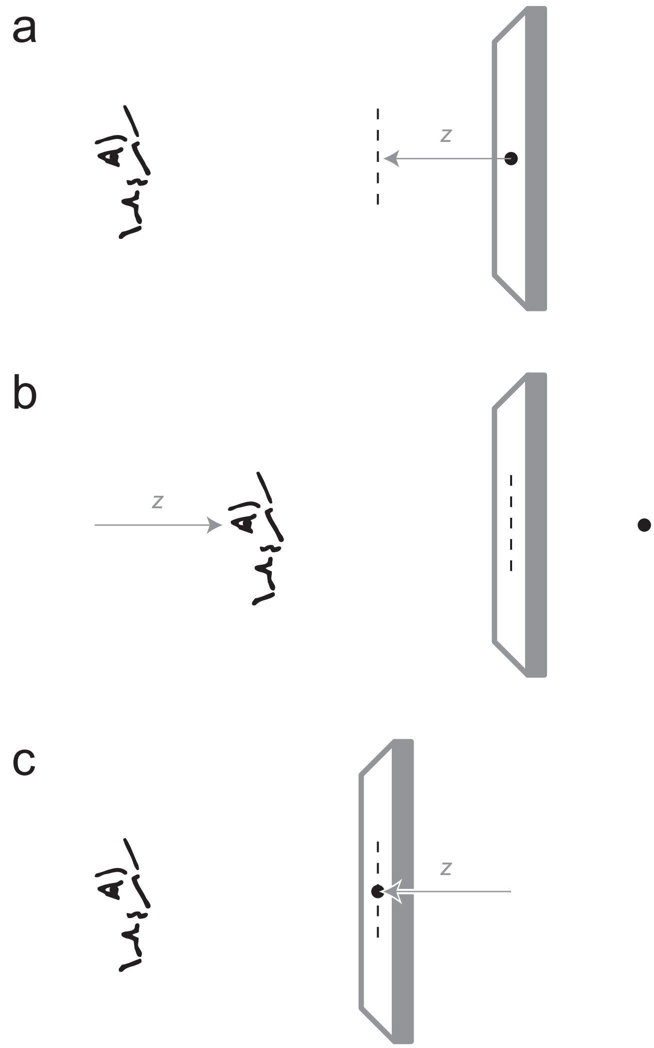

Fig. 1. Schematic illustration of the main conditions. In the object-movement (OM) condition of Experiment 1 (a), the subject remained approximately still. The fixation point was always at the same distance from the subject, and the stimulus was simulated (by stereoscopy) to be at a distance *z* from the fixation point. The OM condition in Experiment 2 was similar, except that the fixation point was in the same depth plane as the stimulus. In the subject-movement (SM) condition of Experiment 1 (b), the subject performed movements in depth equal and opposite to those of the object in the OM condition. Relative to the subject, all stimuli were at the same depth as in the OM condition. The SM conditions of Experiments 2 and 3 were similar, but the fixation point was in the same plane as the stimulus. In the OM condition of Experiment 3 (c), the subject remained still while the monitor moved on a robotic platform in order to present stimuli at different depths.

Experimental Method

Stimuli

The stimuli were static objects displayed on a monitor during one frame. They were composed of the two horizontal sides of a square, of a given simulated distal size and absolute distance. In Experiments 1 and 2, the distal size varied in six equal steps, either from 2.8 to 3.2 cm or from 2.6 to 3.4 cm, depending on the subject's acuity as determined in a pretest. The two lines, drawn in red, had a thickness of 0.1 cm. The fixation point, whose projection was always in the center of the square, was a red disk of the same diameter as the line thickness. The simulated or real distance between the subject and the stimulus varied as well. In Experiments 1 and 2, this distance was ±5, ±10, or ±15 cm around a central value of 57.3 cm. In Experiment 3, all lengths and distances were doubled. In Experiments 1 and 2, the center of the stimulus was always directly opposite the point halfway between the subject's eyes; in Experiment 3, the center of the stimulus was randomly chosen on each trial to project within a square that had a length of 2 cm and was centered on the center of the monitor. The simulated distance between subject and fixation point was 57.3 cm in Experiment 1; in Experiments 2 and 3, the fixation point was in the same depth plane as the stimulus.

Apparatus

In Experiments 1 and 2, stimuli were displayed on a CRT monitor (size: 36 × 27 cm, resolution: 1024 × 768, vertical refresh rate: 60 Hz); in Experiment 3, they were displayed on an LCD monitor (size: 30 × 23 cm, resolution: 1024 × 768, refresh rate: 60 Hz). In Experiments 1 and 2, depth was simulated using shutter glasses (CrystalEyes 2, Stereographics, Boulder, CO), which cut the vertical spatial resolution by a factor of 2. In Experiment 3, the monitor was mounted on a mobile robotic platform (Robulab 80, Robosoft, Bidart, France), and stimuli were presented at different real depths. The observer's head movement and eye position were measured with an optical motion tracker (LaserBird, Ascension, Burlington, VT), with the sensor worn on a lightweight helmet that held it fixed to the head. Experiments 1 and 2 and the dark condition of Experiment 3 were performed in near darkness (although we cannot exclude the possibility that the edges of the monitor were faintly visible because of stray light). In the light condition of Experiment 3, normal indoor illumination was used.

Procedure

The subject's task was to judge whether the distal vertical size of the stimulus was smaller or larger than an implicit standard—the method of single stimuli (Morgan et al., 2000). During the instructions, the subject's attention was drawn to the difference between proximal and distal sizes. The absolute distance could change in three different ways: In the OM condition, subjects remained still while stimuli appeared in different simulated (Experiments 1 and 2) or real (Experiment 3) depth planes; in the SM condition, subjects positioned themselves at different distances from the monitor while stimuli appeared in the monitor plane; and in the no-movement condition, subjects remained still and stimuli always appeared in the plane of the immobile monitor.

Each trial began with the appearance of a fixation point. During this phase, the subject had to place his or her head at an appropriate distance from the monitor. In Experiments 1 and 2, this distance was 57.3 cm in the no-movement and OM conditions and 57.3 ± 5, ± 10, or ± 15 cm (with tolerance of 1 cm) in the SM condition. In Experiment 3, all lengths were doubled. If the subject was outside this range, he or she was guided to move closer to or farther from the monitor by auditory cues. In the plane parallel to the monitor, the subject's position had to be no more than 10 cm from the point opposite the center of the monitor. Finally, the subject's head had to move no faster than 1 cm/s. The fixation and positioning phase lasted until all these conditions were met (but for at least 1 s).

Next, the main stimulus was presented for one monitor frame while the subject's head remained essentially immobile. After the disappearance of the stimulus, the subject reported his or her response using a mouse button.

There were six experimental sessions, each containing one movement condition, performed in the following order: no-movement, SM, OM, OM, SM, no-movement. Each session had 180 trials in a factorial design: Each combination of distal size (six sizes) and distance (six distances) was repeated 5 times in the SM and OM conditions. In the no-movement condition, each distal size was repeated 30 times. Trials were performed in random order. In Experiment 3, three sessions were performed in the dark condition, and three in the light condition. The light condition preceded the dark condition for half the subjects, and the other subjects performed the conditions in the opposite order. Before the first block of every new movement condition, subjects had a training block of 50 trials. The training trials differed from the experimental ones only in providing auditory feedback after every response; for the purposes of feedback, the "correct" answer was based on whether the object was larger or smaller than the median distal size.

Subjects had to reach a criterion of 75% correct responses in the no-movement training session. If they failed to reach this level, they performed a second training session. If they still failed to attain this level, the range of distal sizes was doubled.

Participants

All participants were naive as to the goals of the experiments. All had normal or corrected-to-normal vision and had a disparity threshold of at least 50 arc sec at 40 cm (Randot stereotest, Stereo Optical Co., Chicago, IL). Eight volunteers took part in Experiment 1. Four volunteers, 3 of whom had participated in Experiment 1, took part in Experiment 2. Six different volunteers took part in Experiment 3.

Data analysis

We scaled the independent variables (distal size and distance) to run from –1 (corresponding to the minimum) to +1 (maximum), in order to compare different subjects and different experiments. We assumed that perceived size is a linear combination of distal size and distance. This makes sense for our particular stimuli: In the case of perfect size constancy, the linear combination would equal distal size alone. Our stimuli were chosen so as to decorrelate angular and distal size (see Stimuli paragraph and Fig. 2a): For each distal size, exactly half the stimuli (the ones closest to the subject) had angular size above the median, and therefore angular size was correlated only to distance. Therefore, in the case of responses based on angular size alone, the linear combination would equal distance alone. Furthermore, we also assumed that the "larger" and "smaller" responses were equal to the perceived size filtered through a logistic function.

We used maximum likelihood techniques (Wichman & Hill, 2001) to estimate the parameters of our model. The probability of replying "large" on any given trial was $1/\{1 + \exp[-(a\sigma + b\delta + c)]\}$, where σ is distal size and δ is distance. We assumed a uniform prior on the parameters and assumed independent trials.

The angle used to measure size constancy is θ, which is calculated as $\tan^{-1}a/b$; a value of 90° corresponds to perfect size constancy, and values in the range from 0° through 14° indicate responses based on angular size (for details, see the

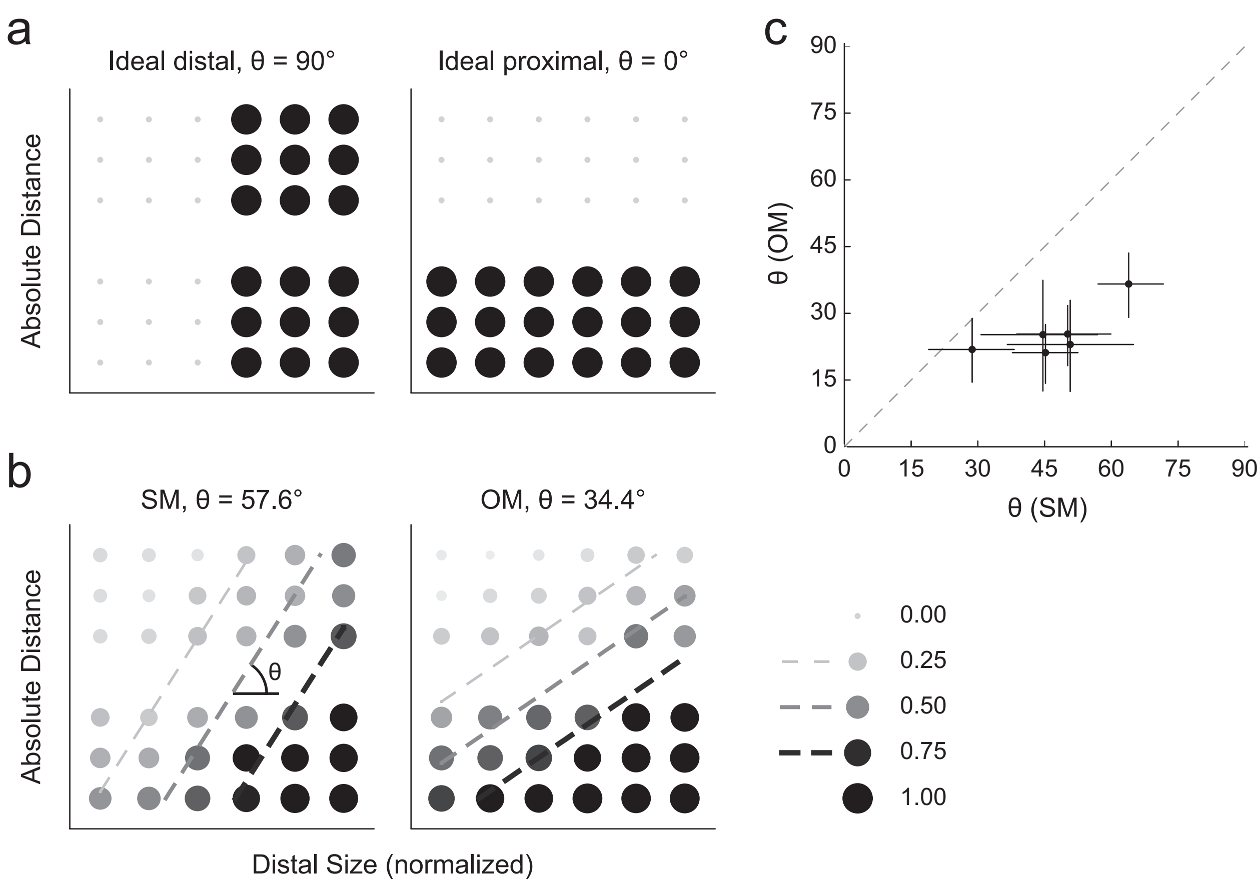

Fig. 2. Ideal responses and mean data in Experiment 1. In (a) and (b), each circle corresponds to a discrete combination of the independent variables: normalized distal size (*x*-axis) and absolute distance (*y*-axis). The absolute distance ran from 42.3 cm (57.3 – 15 cm) to 72.3 cm (57.3 + 15 cm), and distal size ran either from 2.8 to 3.2 cm (2.22° to 4.33°) or from 2.6 to 3.4 cm (2.06° to 4.60°), depending on the subject's acuity. Small and light circles represent "small" responses; large and dark circles represent "large" responses. The graphs in (a) show the ideal responses in the case of perfect size constancy (left) and the total absence of constancy (right), based on a simple model in which the subject compares either distal size or retinal size with its median, and always responds "small" if the value is below the median, and "large" if it is above. Stimulus parameters were carefully chosen to make the two patterns orthogonal. (See the Supplemental Material available online for further details.) The graphs in (b) present the mean responses of all subjects in the subject-movement (SM) and object-movement (OM) conditions. The dashed lines show the 25%, 50%, and 75% levels of a logistic fit to the data. The θ angle is the orientation of these subjective-equality lines and is a measure of size constancy: The closer θ comes to 90°, the greater the degree of constancy. The scatter plot (c) presents the value of θ in the SM condition (*x*-axis) and OM condition (*y*-axis) for individual subjects, along with 95% confidence intervals.

Supplemental Material available online). The width of the logistic function is given by w, calculated as $\ln 3/(a^2 + b^2)^{1/2}$. We removed all data from subjects for whom the value of w was greater than 1 in any condition (2 subjects in Experiment 1 and 1 in Experiment 2). To compare values of θ for different conditions within single subjects, we used a bootstrap technique with 1,000 resamples (Efron & Tibshirani, 1994).

Results

Experiment 1

Figure 2a shows the ideal response patterns that would be observed if responses in Experiment 1 were based on distal size (i.e., perfect size constancy) or on proximal, or retinal, size (i.e., total absence of constancy). To maximize the contrast between constant and nonconstant responses, we chose values for the size and distance parameters that would make the two ideal response patterns orthogonal or nearly so (see the Supplemental Material available online). In other words, size and distance values were chosen so that for every distal size, half of the conditions had retinal size below the median, and half had retinal size above the median. Therefore, if a subject's responses were based entirely on comparison with the median retinal size, there was no correlation whatsoever with responses based on distal size.

Figure 2b shows combined data for all subjects and reveals that responses in the SM condition were closer to constancy than responses in the OM condition. We calculated the degree of constancy for each subject in each of the two conditions by fitting a logistic surface to size and distance variables, using a maximum likelihood procedure. For each subject and each condition, we calculated θ, the orientation of the lines of subjective equality, in the size-distance plane. The θ measure is analogous to the Brunswik and Thouless ratios of constancy (see, e.g., Hershenson, 1998), in that it interpolates between total lack of constancy (θ between 0° and 14°; see the Supplemental Material) and perfect size constancy (θ = 90°). Figure 2c shows individual subject's values of θ in the OM and SM conditions, along with 95% confidence intervals (calculated using a bootstrap). In all subjects, θ in the SM condition was both greater than θ in the OM condition and closer to perfect constancy (90°); bootstrap tests showed that the between-condition difference in θ was individually significant in 5 subjects. A between-subjects test (two-sided *t* test) on individual values of θ showed that constancy was significantly greater in the SM condition than in the OM condition, $t(5) = 6.76$, $p = .001$. All subjects exhibited underconstancy (i.e., θ < 90°) in both the conditions in this experiment, with bootstrap tests showing that for every subject, θ was significantly less than 90° in both the SM and the OM conditions.

We have thus shown a clear effect of observer movement on size constancy. Given that the retinal stimulus was the same in the SM and OM conditions, we have shown that extraretinal information arising from observer movement enhances size constancy.

Experiment 2

In Experiment 1, the main cue to distance—other than observer movement—was binocular disparity. We wanted to test whether the effect of observer movement would generalize to a case in which depth variations are perceived through ocular vergence only. We therefore carried out a second experiment, in which the fixation point appeared in the same depth plane as the stimuli, and thus variations in depth were specified by variations in vergence.

Results of the second experiment are shown in Figure 3a (averaged over all subjects) and in Figure 3b (for individual subjects). As in the first experiment, responses in the SM condition were more constant than responses in OM condition. All 3 subjects had a significantly greater degree of constancy in the SM than in the OM condition ($\theta_{SM} > \theta_{OM}$), as shown by bootstrap tests. We found significant underconstancy (θ < 90°) in all subjects and in both conditions, except in the case of 1 subject who had significant overconstancy in the SM condition. Thus, even though vergence was the only visual depth cue, observer movement enhanced size constancy, as in the first experiment, in which depth was conveyed through binocular disparity.

Experiment 3

In the first two experiments, two spurious differences between the SM and OM conditions arose from the fact that depth changes were produced by real movement performed by the subject in the SM condition, whereas object movement was merely simulated using a stereoscopic display. First, each condition (SM, OM) of each experiment gave rise to a different kind of conflict between focus and vergence cues (including a lack of conflict in the SM condition of Experiment 2). Second, if subjects faintly perceived the edges of the stationary monitor in Experiments 1 and 2, they might have been able to make use of relative retinal size cues, which could provide an alternate explanation for the greater constancy observed in the SM condition. In order to control for these possible confounds, we carried out a third experiment that was similar to the first two, but in which we put the monitor on a mobile robot platform, so

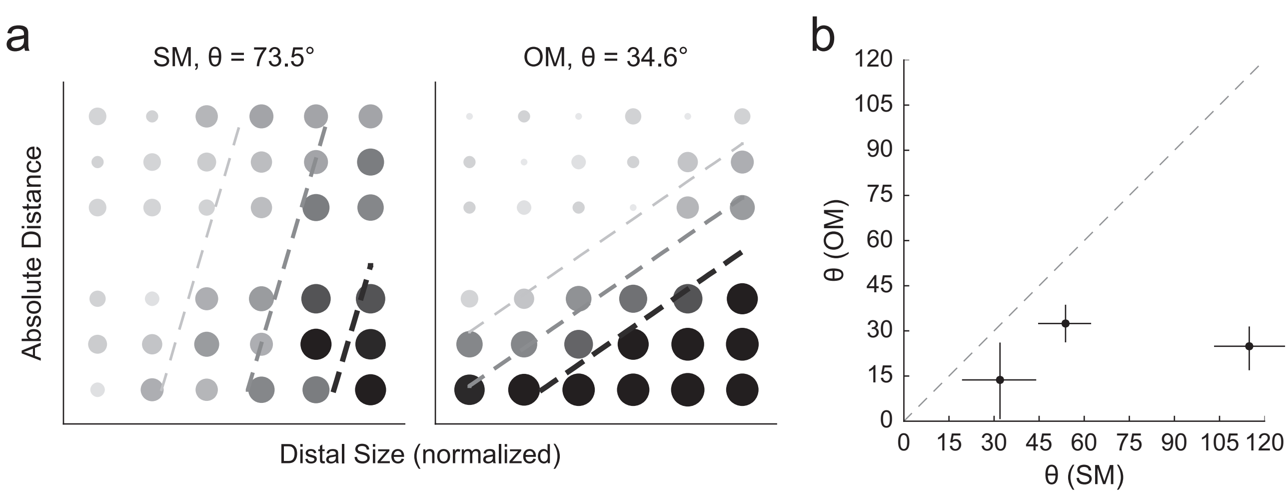

Fig. 3. Results from Experiment 2. The graphs in (a) present the mean responses of all subjects in the subject-movement (SM) and object-movement (OM) conditions. Each circle corresponds to a discrete combination of the independent variables: normalized distal size (*x*-axis) and absolute distance (*y*-axis). Small and light circles represent "small" responses; large and dark circles represent "large" responses. The dashed lines show the 25%, 50%, and 75% levels of a logistic fit to the data. The scatter plot (b) presents the value of θ, the measure of size constancy, in the SM condition (*x*-axis) and OM condition (*y*-axis) for individual subjects, along with 95% confidence intervals. See Figure 2 for further details.

that the stimuli were really presented at different depths in the OM condition, which eliminated all conflicts between focus and vergence cues. (Because of practical constraints in working with the robot, we had to double all lengths and distances in this experiment, keeping angular sizes the same as in the previous experiments.) If relative size cues or the complex pattern of cue conflicts were responsible for the differences between the SM and OM conditions in Experiments 1 and 2, these differences would disappear in Experiment 3.

Another goal of the third experiment was to test the robustness of the effect of observer movement on size constancy. In the first two experiments, depth cues were poor, so lower constancy in the OM condition could have simply been due to a relative lack of depth cues, including cues from observer movement. We therefore added a condition in which the lights of the experimental room were switched on, thereby tremendously increasing the total amount of absolute distance information available—in particular, adding pictorial depth cues, which are often dominant in depth perception. If the effect of observer movement on size constancy in Experiments 1 and 2 was an artifact of our impoverished stimuli, we would observe a smaller effect of movement type in the light than in the dark condition.

The results of Experiment 3 are shown in Figure 4a (average results) and Figure 4b (individual results). Unlike in Experiments 1 and 2, we frequently observed overconstancy, with θ being greater than 90° in 4 of the 6 subjects in the SM condition (significant overconstancy in 2 subjects), and in 5 of the 6 subjects in the OM condition (significant overconstancy in 4 subjects). We return to the possible reasons for overconstancy in the Discussion. However, performance was still closer to perfect size constancy in the SM condition (θ = 90°) than in the OM condition, as it was in the previous experiments. We also observed very similar patterns of responses in the two lighting conditions. Individually, 5 of the 6 subjects were closer to perfect constancy in the SM condition than in the OM condition, 4 of them significantly so (bootstrap test). We also performed an analysis of variance on the θ values with movement type (SM, OM) and lighting condition (dark, light) as independent variables. This analysis revealed an effect of movement type approaching significance, $F(1, 20) = 3.50$, $p = .08$), but no effect of lighting condition ($F = 0.10$), and no interaction between these two variables ($F = 0.04$).

Thus, we have shown that even compared with real object movement, observer movement leads to size judgments closer to perfect size constancy. Moreover, the effect of observer movement was as large in the light as in the dark condition, so we can conclude that this effect is not simply due to the poverty of visual cues to absolute distance in the dark: Even when a rich set of distance cues is available, observer movement improves size constancy. Additionally, if relative size cues with respect to the monitor edges had been responsible for greater size constancy in the SM than in the OM condition in Experiments 1 and 2, we would expect there to have been no difference between the two motion conditions in the dark condition of Experiment 3. Because there was an effect, we conclude that relative size cues do not account for the effects of observer movement.

Discussion

In three experiments, we found that size constancy is more robust when distance variations between observer and object are due to the observer's movement, rather than the object's. When we found underconstancy (Experiments 1 and 2), the underconstancy was more severe for object than for observer movement; the same pattern was found for overconstancy (Experiment 3). The difference between observer and object movement arose even though we equated the retinal stimulation in the two motion conditions. The effect was found for different depth cues: disparity, vergence, and pictorial cues. Therefore, contrary to the common notion that size constancy emerges as a result of retinal and vergence processing alone, extraretinal signals have an important role. These signals include proprioceptive feedback, efference copies of motor commands, and signals related to motor planning and the intentionality of action.

Why would size constancy depend on observer movement? We mentioned one possible reason in the introduction to this article. The visual system shows a preference for perceiving minimal motion from ambiguous stimuli, such as in apparent motion or the aperture problem (Ullman, 1979; Weiss, Simoncelli, & Adelson, 2002). A change in the size of an object on the retina is, without further information, ambiguous: It could be interpreted as a change in distance to a rigid object (size constancy) or as a change in the object's real size. Therefore, there is no overwhelming reason to prefer one interpretation over the other: The distance to objects often changes, but other objects change in actual size, or come in many sizes.

In an egocentric reference frame, the SM and OM conditions are identical. However, as already mentioned, in the case of the moving observer, the minimal-motion criterion has been shown to also apply in an observer-independent, or allocentric, reference frame (Wexler, Lamouret, & Droulez, 2001; Wexler, Panerai, et al., 2001). The allocentric minimal-motion criterion does distinguish between the SM and OM conditions. For subject motion, the allocentric minimal-motion criterion is maximized for a stationary object (in an allocentric reference frame)—one that changes distance with respect to the moving observer, and thus maximizes size constancy. For object motion, in contrast, both egocentric and allocentric minimal-motion criteria favor an unmoving object, cashing out retinal size change as real size change, and thus eliminating size constancy altogether. To the extent that other perceptual criteria are also operational, this effect could be partial, rather than all-or-nothing. This argument explains the difference in size constancy between the SM and OM conditions in Experiments 1 and 2, but not in Experiment 3, in which we found greater size overconstancy for object than for subject movement.

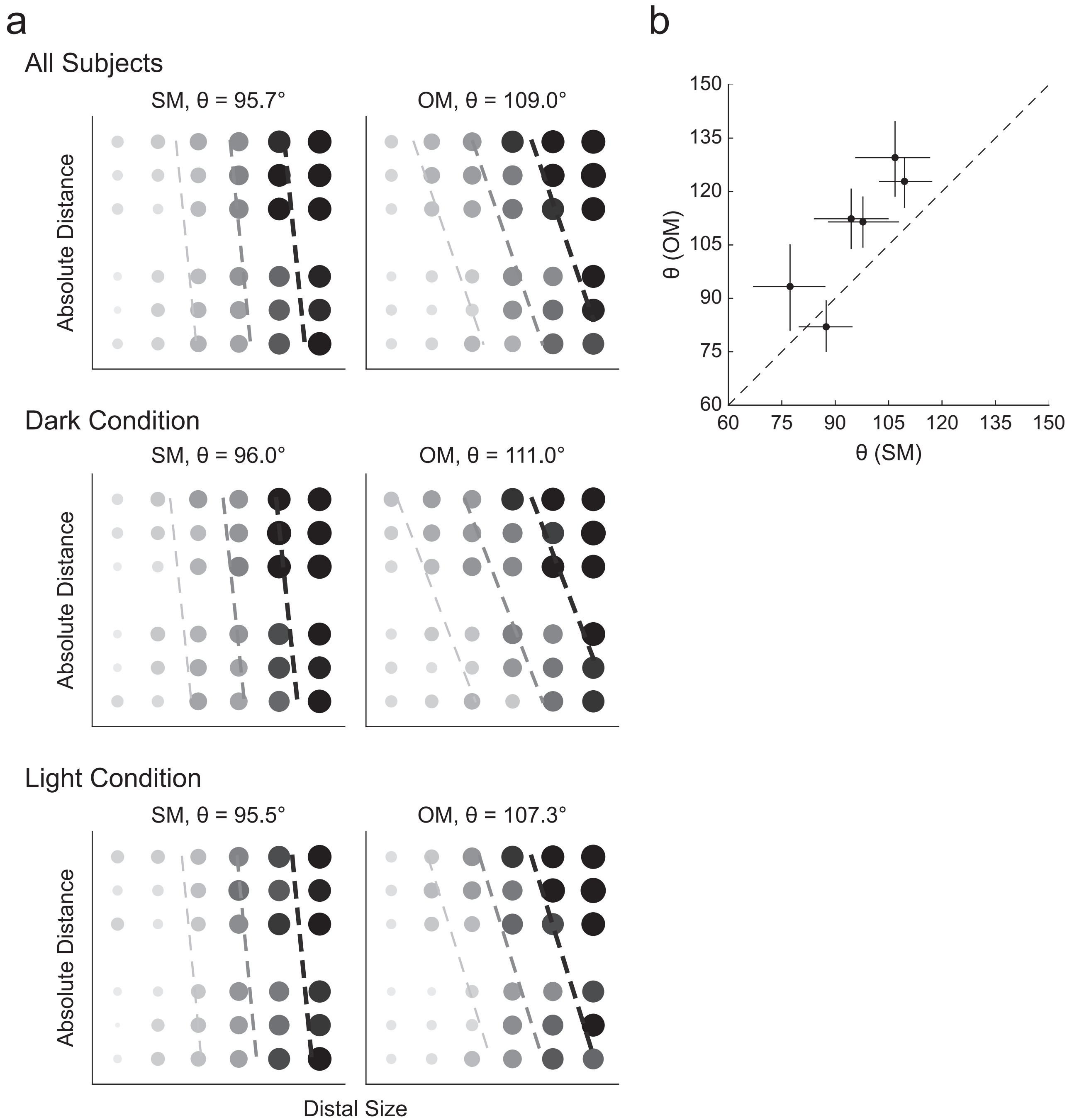

Fig. 4. Results from Experiment 3. The graphs in (a) present the mean responses of all subjects in the subject-movement (SM) and object-movement (OM) conditions, both overall and separately for the dark and light conditions. Each circle corresponds to a discrete combination of the independent variables: normalized distal size (*x*-axis) and absolute distance (*y*-axis). Small and light circles represent "small" responses; large and dark circles represent "large" responses. The dashed lines show the 25%, 50%, and 75% levels of a logistic fit to the data. The scatter plot (b) presents the value of θ, the measure of size constancy, in the SM condition (*x*-axis) and OM condition (*y*-axis) for individual subjects (dark and light conditions combined), along with 95% confidence intervals. See Figure 2 for further details.

Another explanation involves sensorimotor prediction mechanisms. For example, spatial constancy—the perception of the directions of objects and orientations of surfaces as unchanging despite eye movements leading to contrary sensory data (see Wurtz, 2008, for a recent review)—has been shown to be closely related to, and probably implemented by, mechanisms for anticipating the sensory consequences of upcoming eye movements (Wexler, 2005). Size constancy may arise in a similar way, except that in order to predict the consequences of, say, a given forward movement while looking at an object, one must also know the distal size of the object (or, equivalently, its distance): A small but nearby object will lead to a greater expansion on the retina than a large and faraway object subtending the same visual angle. Thus, distal size (and also distal shape) may arise as hidden parameters in sensorimotor anticipation mechanisms. Of course, being able to perceive distal size, and other visual constancies, has many and obvious benefits in everyday life; however, the preceding argument—admittedly speculative—shows how size and other constancies could have arisen as by-products of more primitive physiological mechanisms.

The necessity of distal size information for sensorimotor prediction might therefore be the reason that size constancy exists in the first place. If this is so, then it is no surprise that size constancy is more robust in observer movement than in object movement. Another way of changing the absolute distance to an object is to move it using one's hand. The sensorimotor model for size constancy predicts that size constancy will be more robust for manipulated objects than for those whose distance changes independently of the observer. Other studies have shown a link between manual action and the interpretation of ambiguous visual stimuli. The Taylor illusion (Carey & Allan, 1996; Mon-Williams, Tresilian, Plooy, Wann, & Broerse, 1997; Ramsay, Carey, & Jackson, 2007; Taylor, 1941), in which the perceived size of the afterimage of one's hand changes when the hand is moved in total darkness, provides an explicit example of how extraretinal information from hand movement can have an effect on size constancy. Another recent study has shown that hand movement information is available to the visual system in order to disambiguate optic flow (Umemura & Watanabe, 2009).

In addition to the main effect of movement type, we observed a surprising result: Subjects exhibited underconstancy in Experiments 1 and 2, but overconstancy in Experiment 3 (although in all three experiments, responses were closer to perfect constancy in the SM than in the OM condition). What differences between the experiments could have yielded this effect? One difference involved the varying, sometimes conflictual, combinations of vergence (Mon-Williams & Tresilian, 1999) and focus (Hoffman, Girshick, Akeley, & Banks, 2008) cues to distance. In Experiment 1, there was a disparity-blur conflict in the OM condition (subjects focused on the fixation point, which was at the same physical depth as the stimulus), whereas in the SM condition, there was also a decoupling between accommodation and vergence (because subjects converged on a fixation point at a different depth than the monitor). In Experiment 2, there were no conflicts in the SM condition, but there was an accommodation-vergence conflict in the OM condition (because subjects presumably accommodated to the monitor, while converging at a different depth). In Experiment 3, we used real depth movements, and therefore subjects had none of these conflicts. We did not observe significant differences between the orientations of subjective-equality lines in the SM conditions or the OM conditions of Experiments 1 and 2. Given that we systematically obtained underconstancy over the four conditions in Experiments 1 and 2, despite the varying combinations of cues and conflicts (including the absence of conflict), it seems unlikely that underconstancy was due to cue conflicts.

Another difference between the experiments is the distance scale: Distances were twice as large in Experiment 3 as in Experiments 1 and 2. This was the only difference between the SM conditions of Experiments 2 and 3, and nevertheless we observed a change from underconstancy to overconstancy. Thus, the change in the distance scale was probably the reason for overconstancy in Experiment 3.

Another reason for overconstancy in Experiment 3 may be related to the instructions regarding distal size. Previous studies of size constancy have observed overconstancy using full distance cues and instructions to base judgments on distal, or "real," size, rather than retinal size (Carlson, 1960; Gilinsky, 1955; Holway & Boring, 1941; Jenkin, 1957). Underconstancy in Experiments 1 and 2 might have been due to an imperfect understanding of the instructions, whereas the physical movement in the OM condition in Experiment 3 could have made the instructions clearer—possibly leading to overconstancy.

Acknowledgments

Emmanuelle Combe is now at the Laboratory for Adaptive Intelligence, RIKEN Brain Science Institute, Wako City, Saitama, Japan. We are grateful to Renault, SAS, and Andras Kemeny for their support of this work. We would like to thank Andrew Glennerster for useful discussions.

Declaration of Conflicting Interests

The authors declared that they had no conflicts of interest with respect to their authorship or the publication of this article.

Supplemental Material

Additional supporting information may be found at http://pss.sagepub.com/content/by/supplemental-data

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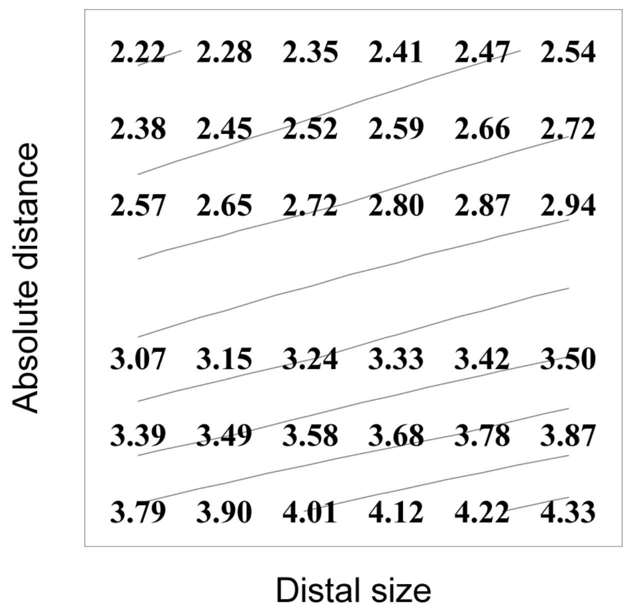
Supplementary material

Here we give additional information about our experimental design, and how we interpret different response patterns as different degrees of constancy.

The following figure shows the angular size (in degrees) of the 36 conditions in each of the three experiments, plotted as in Fig. 2a, with contours of constant angular size.



As can be seen in the figure, the 18 conditions in lower half all have angular size above the median, and the 18 conditions in the upper half have angular size below the median. Therefore, a subject who bases his or her responses on a zero-width logistic function of angular size centered on the median will have the reponse pattern shown in the right-hand side of Fig. 2a. In this sense, the value of θ corresponding to a total lack of constancy is 0°.

However, if the subject bases his or her answers on angular size but with a non-zero width logistic function, the lines of subjective equality will approach the contours shown above. In the limit of large width, we can simply fit a plane to the angular size function, in order to calculate the orientation of the corresponding lines of subjective equality. Doing this, we obtain an orientation of 14°.

Therefore, the sign of a total lack of size constancy in our data is a value of θ between 0° and 14°, depending on the width of the psychometric function. Perfect size constancy, on the other hand, always corresponds to $\theta = 90°$, regardless of width. If we assume that total lack of constacy corresponds to $\theta = 14°$ rather than 0°, this does not modify our conclusions, and indeed quantitatively increases the effects of observer movement.