Vision Research 125 (2016) 1–11

Contents lists available at ScienceDirect

Vision Research

journal homepage: www.elsevier.com/locate/visres

Size and distance are perceived independently in an optical tunnel: Evidence for direct perception

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ARTICLE INFO

Article history:
Received 9 July 2015
Received in revised form 29 April 2016
Accepted 30 April 2016
Available online 25 May 2016

Keywords:
Perceived size
Size-distance invariance
Mediation model
Direct model
Optical tunnel

ABSTRACT

The historical but questionable size-distance invariance hypothesis (SDIH) features computation over geometric, oculomotor, and binocular cues and the coupling of percepts—perceived size, S', is mediated by perceived distance, D'. A contemporary non-mediational hypothesis holds that S' and D' are specific to distinct optical variables. We report two experiments with an optical tunnel, an arrangement of alternating black and white concentric rings, that allows systematic manipulation of the optic array at a point of observation while controlling a variety of size and depth cues. Participants viewed targets of different sizes at different distances monocularly, reporting S' and D' via magnitude production. In Experiment 1, the target was either placed in a continuous tunnel (extending 164 cm) or in a tunnel that truncated at the target's location. Experiment 2 included a third tunnel, one that was truncated with a flat depiction of the posterior surface structure that would have been visible in the continuous tunnel. In both experiments, S' decreased with D but D' was unaffected by S. Partial correlation analyses showed that the relationship between S' and D' was not significant when the contributions of other variables were removed. Importantly, S' and D' were affected differently by manipulations of the optical tunnel's continuity while computationally obvious visual cues were controlled. These outcomes suggest that D' is not a mediator of S'. Rather S' and D' are independently determined with correlated but different optical bases, results that support the direct model.

1. Introduction

Visually perceiving the sizes of objects near and far is an everyday occurrence. Even though the visual angle subtended by an object at the point of observation shrinks as physical distance increases, perceived size of the object remains approximately the same (Gruber, 1954). Regarding this phenomenon of size constancy, how perceived size and perceived distance relate, has been a recurring question in the psychology of visual perception (e.g., Epstein, Park, & Casey, 1961; Kaufman et al., 2006).

At the phenomenal level, a classical but still prevalent explanation of the relation is that: "A retinal projection or visual angle of given size determines a unique ratio of apparent size to apparent distance" (Epstein et al., 1961, p. 491; Kilpatrick & Ittelson, 1953, p.224). The geometric relation between physical size and distance also holds in perception for small values of θ, where S' is perceived size, D' is perceived distance, and θ is the visual angle (Kilpatrick & Ittelson, 1953). That is

$$S'/D' = \theta \qquad (1)$$

Thus, when the visual angle is held constant, the perceived size of an object is proportional to its perceived distance in a unique way. We will refer to Eq. (1) as the geometric size-distance invariance hypothesis (SDIH).

Discordant empirical findings, however, have questioned the validity of geometric SDIH. Of particular significance is the observation of a size-distance paradox (e.g., Epstein & Landauer, 1969; Gruber, 1954; Higashiyama, 1979; Jenkin & Hyman, 1959): perceived size and perceived distance can change in directions opposite to that predicted by geometric SDIH. Either an underestimation of size co-occurs with an overestimation of distance or an overestimation of size co-occurs with an underestimation of distance. In other studies, even though perceived size and distance changed in the direction predicted by geometric SDIH, the degrees of change deviated substantially from the geometric expectations (e.g., Baird & Biersdorf, 1967; Vogel & Teghtsoonian, 1972; see Sedgwick, 1986 for a review). Brenner and van Damme (1999), more recently, also found that "indicated distance" manually reported by their participants as perceived distance was clearly different from "size distance" calculated using visual angle for

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http://dx.doi.org/10.1016/j.visres.2016.04.007
0042-6989/

reported perceived size. In short, geometric SDIH fails to accommodate the relation between perceived size and perceived distance (see also Gogel, Wist, & Harker, 1963; Higashiyama & Kitano, 1991; Higashiyama & Shimono, 2004; Vogel & Teghtsoonian, 1972).

The basic conception of SDIH, however, can be salvaged.[1] Gogel (1971) reanalyzed Epstein and Landauer's (1969) evidence for the size-distance paradox and showed that it could be accounted for by a general form of SDIH (see also Higashiyama & Shimono, 1994; Oyama, 1974) formulated as a power function with a scale factor K and an exponent n:

$$S'/D' = K\theta^n \tag{2}$$

This generalization is consistent as well with the conclusion by Brenner and van Damme (1999) that the measure of distance determining perceived distance also determines perceived size to some extent.

1.1. Mediation model, direct model

Higashiyama and Adachi (2006) and Higashiyama and Shimono (1994, 2004) have labeled the two contrasting theoretical models for addressing perception of size at a distance—that commonly associated with Helmholtz (1867/1910/1962) and that commonly associated with Gibson (1950, 1966, 1979/1986)—as the mediation model and the direct model, respectively.

1.1.1. Mediation model

The mediation model interprets the empirical results as a dependence of perceived size on perceived distance and visual angle (e.g., Epstein, 1973, 1982; Gogel, 1973a, 1973b; Kaufman et al., 2006; Rock, 1975, 1984). Assuming that visual angle is immediately usable as a proximal datum, perceived size can be determined algorithmically by combining the visual angle with perceived distance or by "taking distance into account" (Epstein, 1973, 1982; Higashiyama & Shimono, 2004). That is, perceived distance mediates perceived size. Its commonplace expression is geometric SDIH. For the mediation model, however, the failure of geometric SDIH and the fitting of general SDIH (Eq. (2)) with varied values of scale factor and exponent in various studies (e.g., Epstein & Landauer, 1969; Gogel, 1971; Higashiyama & Adachi, 2006; Higashiyama & Shimono, 1994, 2004; Vogel & Teghtsoonian, 1972) can be attributed to different computational operations for particular conditions of viewing. In other words, different visual cues can be used in different ways (e.g., cue weighting) for computing perceived size from perceived distance, as well as, computing perceived distance itself in particular situations (e.g., Brenner & van Damme, 1999; Landy, Maloney, Johnston, & Young, 1995). In sum, in the mediation model, perceived size is determined by perceived distance and other relevant visual cues.

1.1.2. Direct model

The direct model, in contrast, takes size perception and distance perception as independent (Haber & Levin, 2001; Sedgwick, 1973); perceived size does not depend on perceived distance via an internal mechanism. If SDIH or similar mediational model appears to hold, it is only because relevant dimensions of optical stimulation can coincide for both size and distance perceptions (cf. Gruber, 1954). As Epstein and Landauer (1969, p. 272) suggest "Both size estimates and distance estimates are directly determined by relative visual angle ... in neither case does one judgment depend on the other judgment," a conclusion affirmed by Oyama (1974). For Brenner and van Damme (1999), inconsistencies of perceived size and perceived distance would be the case if the two kinds of perceiving depended on different visual cues. The direct model, however, stands in contrast to the foregoing perspectives. It rejects the description of the environment in terms of the Euclidean notions of angle, size and distance as the basis for the perception of environmental layout. For the direct model, S' and D' are tied to different specifying variables ("higher-order invariants") available in the ambient optic array (cf., Gibson, 1966, 1979/1986; Lee, 1980; Mace, 2002; Warren, 2006).

The ambient optic array at a point of observation is structured light of different intensities in different directions that is lawfully generated by the environmental surface layout and, perforce, specific to that layout (Gibson, 1961, 1966, 1979/1986). As the point of observation moves, the nested hierarchy of optical solid angles lawfully transforms leaving invariant optical relations specifying the propertied relational structure of the environmental layout relative to the new points of observation. These invariant optical relations are distinct from each other, but still correlated with each other, on the basis of their lawful relationships to the environmental structure.

In sum, in the direct model, it is assumed that S' and D' are influenced directly by those exogenous higher-order variables; S' and D' are not causally related. The inconsistent previous findings in which general SDIH (Eq. (2)) does not fit with unique values of scale factor and exponent might be due to the different but correlated optical bases for S' and D' underlying particular conditions of viewing.

1.1.3. Debate on the relationship between S' and D'

Whether S' and D' are dependent or independent is still controversial: The inconsistent fitting of general SDIH is interpretable by either model, mediation or direct. One limitation that prevents drawing a definitive conclusion is that different conditions of viewing in various studies are not compatible with each other. Systematically comparable conditions of viewing should shed light on the independence of S' and D'. If general SDIH varies only for computationally obvious variables such as visual angle and visual cues (e.g., depth cues), then the mediation model will be favored. The variations will be attributable to the existence of putative cue-based computational algorithms (i.e., cue combination) using those computational variables as well as D'. But if conventional visual cues are held constant and general SDIH still varies for computationally non-obvious variables—variables that are relevant to structural properties of environmental surface layout (Gibson, 1979/1986; Meng & Sedgwick, 2001, 2002)—then the direct model will be preferred. The variations will be ascribable to different higher-order invariants specifying the metric properties of the environmental layout—namely, S and D—that are defined over both obvious and non-obvious variables. Thus, an apparatus for systematically controlling the conditions of viewing is needed to manipulate, or control for, those variables.

1.2. The optical tunnel

In the present study, an optical tunnel (Gibson, Purdy, & Lawrence, 1955) was constructed (see Section 2.1.2 for details) to investigate the above question empirically. The optical tunnel is a device for systematically controlling optical structure of potential relevance to perceptions of object size and object distance. Given that objects in the environment are nested or embedded within larger-scale environmental entities, the corresponding optical structure for an observer can be conceived as a nested hierarchy of angular extents (see Gibson, 1979/1986). The optical tunnel is

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[1] Kaufman et al. (2006) supported SDIH based on measures of discrimination for size and depth. From the finding that the precision of size discrimination decreased with perceived distance in the same way as but uniformly poorer than that of depth discrimination, they argued perceived size would be proportionally related to perceptual distance with posterior mental steps.