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RESEARCH NOTE

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The size-distance paradox is a cognitive phenomenon

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Abstract The perceived size of a fixated object is known to be a function of the perceived fixation distance. The size-distance paradox has been posited as evidence that the perceived distance of a fixated object is, in turn, influenced by the object's perceived size. If this is correct then it challenges a widely accepted account (modified weak fusion) of how the nervous system combines multiple sources of information. We hypothesised that the influence of perceived size on the perception of distance is likely to be restricted to conscious perceptual judgements. If our hypothesis is correct then the size-distance paradox should not be observed when observers make action-based distance judgements. In line with this expectation we observed the size-distance paradox when participants made verbal reports on target distance but found no paradoxical judgements in a group who were asked to point at the target. We therefore suggest that the size-distance paradox should not be taken as evidence that perceived size feeds back into distance perception.

Introduction

When viewing similar targets that subtend the same visual angle at two different distances in reduced cue environments, observers have been reported as perceiving the closer target as smaller and further away than the farther target, which is perceived to be larger and closer (Epstein et al. 1961; Gogel 1978; Heinemann et al. 1959; Ono et al. 1974). This phenomenon has been referred to as the 'size-distance paradox' (Ono et al. 1974) for reasons detailed below.

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The change in perceived size is predictable from Emmert's law – Emmert (1881) demonstrated that the perceived size of an afterimage viewed against a surface depends upon the perceived distance to the surface. From this observation is derived Emmert's law: perceived size is a function of perceived distance. Emmert's law thus accounts for size constancy – objects do not appear to change size as they approach or recede from an observer because the nervous system uses information about the object's distance when determining size. In visually reduced cue situations a major cue to the distance of a binocularly viewed target is the vergence angle of the eyes (Foley 1980; Owens and Liebowitz 1980; von Hofsten 1976). It therefore follows from Emmert's law that increasing or decreasing vergence specified distance should lead to a respective increase and decrease in the perceived size of a target viewed in visually reduced cue environments. This expectation has been well established empirically (see Mon-Williams et al. 1998). The change in perceived size in the size-distance paradox is thus predicted by a size constancy mechanism mediated by an extraretinal signal from ocular vergence. In contrast, the change in perceived distance is paradoxical – if the target is appearing smaller when closer then the participants must have access to information that lets them judge the target as closer, yet they report that it appears further than the physically more distant target. This aspect of the size-distance paradox can be explained (in a post hoc fashion) by a two-stage mechanism in which the nervous system first uses an extraretinal signal to determine target distance for the perception of size and then uses that perceived size in the determination of the object's egocentric distance. This account explains the distance judgements because physical objects normally increase in egocentric distance when they decrease in size and vice versa. A number of investigators have proposed such a mechanism to explain the size-distance paradox (e.g. Ono et al. 1974; McCready 1965; Gogel and Sturm 1971; Higashiyama 1977, 1979) and some models of distance perception incorporate a two-stage process in which perceived distance is a weighted average of *pri-*

mary information from sources such as vergence and *secondary* information from perceived size (Higashiyama 1977, 1979). Although this account of the size-distance paradox appears to have a prima facie plausibility, it is difficult to reconcile with current accounts of distance perception as we will outline.

In normal circumstances the perception of distance relies on information from a number of different sources (or cues). Theoretical accounts of cue combination may be considered to fall on a continuum between the *weak* and the *strong* fusion accounts (see Landy et al. 1995). The weak fusion account suggests that each distance cue is considered in isolation and the cues are subsequently averaged to provide fixation distance whereas strong fusion supposes that the nervous system selects the interpretation providing the statistically most probable three-dimensional scene from the retinal images. In its pure form, weak fusion is an unrealistic account of cue combination (see Landy et al. 1995). In contrast, strong fusion is a plausible account but lacks any constraints and is therefore not falsifiable. A more useful framework for considering cue combination is the *modified weak fusion* (MWF) process proposed by Landy et al. (1995). In the MWF process one cue can promote another to allow it to provide information about absolute distance (some cues, such as horizontal retinal image disparity, can only provide relative depth information without an interpreting signal) but no other interactions are allowed. The modified weak fusion account is consistent with existing data on cue combination and provides a parsimonious summary of extant empirical studies. As Landy et al. (1995) note, however, "evidence of impermissible interactions would force one to reject the MWF hypothesis" in favour of strong fusion. The two-stage account of the size-distance paradox is incompatible with MWF – in the MWF hypothesis vergence can be used to interpret retinal image size but this could not feed back into the distance cue combination process. The size-distance paradox therefore serves as a useful test case for the process of cue combination as it seems to support an account based upon 'strong' rather than 'modified weak' fusion.

We suggest, however, that the size-distance paradox does not necessarily refute the MWF hypothesis. All the observations of the size-distance paradox have been made using verbal reports of ordinal distance relationships. It is known that there are two different processing streams in the primate cortical visual system: one stream appears to be involved in conscious perceptual judgements whilst the other is involved in controlling action (e.g. Bridgeman et al. 1979; Goodale et al. 1991). We suggest that the size-distance paradox may be cognitive in origin and reflect a bias for observers to rely on size cues when forced to make verbal judgements regarding the relative position of objects in reduced cue environments. If this suggestion is correct then the size-distance paradox should only be manifest when participants are forced to make cognitive judgements of distance (e.g. when verbally reporting distance). This study was designed to determine whether there is any evidence for the size-distance paradox when distance judgements are made with a pointing response.

Materials and methods

Twenty volunteers (12 males and 8 females, age range 18–49 years) consisting of student and staff members from the University of Queensland participated in the experiment. The participants were naive as to the purpose of the experiment and were given no practice. Participants viewed targets through an aperture (9×4 cm) in front of a rectangular viewing box (dimensions 130 cm long by 65 cm wide by 21 cm high). A moulded plastic restraint in front of the aperture minimised head movements, occluded peripheral vision and allowed the observers to correctly position themselves. The plastic constraint contained a pair of trial frames (diameter 3 cm) into which an ophthalmic prism could be placed. The target was a luminous piece of tubing (0.7 cm width × 3 cm length) and the box was light sealed with the room lights switched off to ensure that nothing was visible apart from the target. The room lights came on between trials to ensure that participants did not dark adapt. The target was directly in line with the right eye at a distance of 40 cm (±0.5 cm). The target was viewed through a prism placed in front of the left eye with its base orientated towards or away from the nose (see Fig. 1). Prism orientated base inwards increases the vergence specified distance whilst prism oriented base outwards decreases the vergence specified distance. The power of the prism was 3 Δ (prism dioptre; 1 Δ=arctan 0.01) resulting in a vergence specified distance of approximately 33.5 cm when the prism was orientated base outwards and approximately 49.6 cm when the prism was base inwards (the precise vergence specified distance depends upon the interpupillary distance – we have provided the vergence specified distance for the average interpupillary distance of our participants). The participants were randomly allocated to one of two groups who either provided verbal (group 1) or pointing (group 2) responses. The reason for using a between group design was to circumvent the responses from one set of measures biasing the other responses (this is a well-documented phenomenon described as *asymmetric transfer bias*; Poulton 1981). During the review process, an anonymous referee suggested that our strategy of using a between group design may have been unnecessarily cautious if "one is truly dealing with separate streams". The referee highlighted work (e.g. Carey et al. 1998) which suggests that verbal and action-based responses to target distances differ "not only when they are made within subject, but even when made within the same trial".

The experimental task for the first group was to make a forced choice verbal judgement on whether the target "*looks* closer or further than the preceding trial", following the protocol used by Ono et al. (1974). It should be noted that the term 'trial' was used in the instructions when describing a single presentation (with the actual experimental trial consisting of two presentations). Each trial consisted of the observer viewing the target through the prism orientated with its base towards or away from the nose. The observer was asked to memorise the distance of the target on the first presentation and then viewed the target through the prism orientated in the opposite direction. The time between presentations was between 5 and 10 s, during which time the participants had their eyes shut. The time between trials was approximately 10 s, during which time the participants were encouraged to look around the experimental laboratory. In ten trials the prism was initially orientated with its base inwards and in another ten trials the prism was initially orientated with its base outwards (i.e. there were 20 trials in total with each trial consisting of two presentations). The initial orientation of the prism was randomised across trials and between participants.

The experimental task for the second group was to position the tip of the unseen right finger outside the box so that it was equidistant with the target. Participants started each presentation with their hand resting in their lap and were allowed to take as long as they liked (and make as many corrections as they wanted) in order

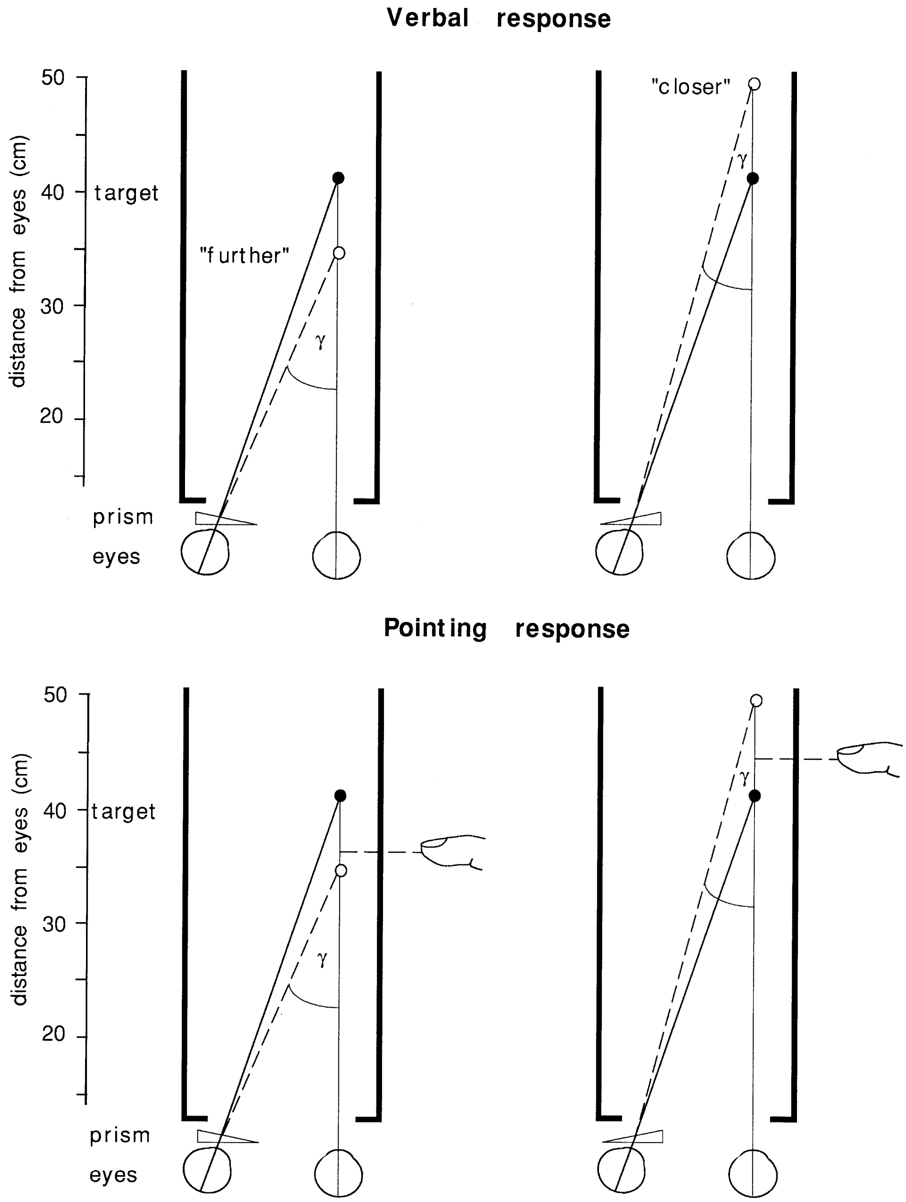

Fig. 1 Geometry of binocular viewing in the experimental apparatus. The vergence angle required to fixate the luminous target (*solid circle*) was manipulated by placing a prism in front of one eye as shown. Prism oriented with its base temporal decreases the vergence specified distance (*hollow circle, left column*); prism orientated with its base nasal increases the vergence specified distance (*hollow circle, right column*). *Upper* Participants were asked to verbally report whether the target appeared closer or further when the original orientation of the prism (through which they viewed the target) was reversed. Participants reliably reported that the target appeared closer when, paradoxically, the vergence specified distance increased and vice versa (see text for details). *Lower* Participants were asked to point at the target. All of the participants judged the target to be closer when vergence specified distance decreased and vice versa (i.e. there was no evidence of a size-distance paradox when a pointing response was made)

to produce the "most accurate response possible". The target was either viewed through the prism orientated with its base pointing towards the nose or with its base pointing outwards from the nose. The orientation of the prism was randomised across trials and between participants. The time between presentations was approximately 10 s during which time the participants were encouraged to look around the experimental laboratory and fixate their own hand (in order to prevent proprioceptive drift; Wann and Ibrahim 1992). The observers pointed at the target 10 times for each prism orientation. The mean positional pointing accuracy was measured for 0.5 s at a sampling rate of 60 Hz using an Optotrak 3-D optoelectronic movement recording system (accurate to within 0.2 mm).

Results

In the first group there was clear evidence for the existence of the size-distance paradox with eight of the ten participants reporting that the target appeared closer when the vergence specified distance was further and vice versa. Apart from one male, all of the participants were entirely consistent with their judgements so that they either always made 'paradoxical' judgements or never made paradoxical reports. One of the eight participants who normally made paradoxical judgements only made these paradoxical judgements on 16 of the 20 trials (80%). The percentage of paradoxical judgements made across the group was thus 78%, which agrees almost perfectly with Ono et al.'s report of an incidence of 79% across their participant group. The results from the second group were markedly different, with all of the participants making pointing responses in the correct ordinal direction on every trial (i.e. the size-distance paradox was never observed). The mean pointing response was 44.9 cm (SD 5.9 cm across participants) when the prism was orientated with its base inwards (increasing vergence specified distance) and 36.34 cm (SD 5.6 cm across participants) when the prism was orientated base outwards (Fig. 1). Fisher's exact probability test (Siegal and Castellan 1988) was used to determine whether the group differences were reliable (the chi-square test was unsuitable as one of the expected frequencies was smaller than five). Participants were placed in one of two categories (verbal report versus pointing) and classed according to whether the majority of their responses were in the correct ordinal direction or whether the majority of their responses were incorrect. A statistically reliable difference was found between the responses of the group who made verbal judgements and the action-based responses of the other group ($P<0.001$).

Discussion

The group of participants asked to verbally report ordinal distance relationships replicated the pattern previously found in studies of the size-distance paradox (e.g. Ono et al. 1974). Conversely, the group of participants asked to point to targets in identical stimulus conditions to the verbal report group showed no size-distance paradox: their responses were always in the direction predicted from the vergence demand.

Verbal reports of a target's distance are extremely variable and unreliable in very reduced cue environments where vergence is the only cue to distance (see, e.g. Gogel 1972; Turvey and Soloman 1984). Indeed, we have found that observers often state that they have "no idea" of a target's distance in such conditions (Mon-Williams and Tresilian 1998); Swenson (1932) reported a similar observation. These verbal responses contrast sharply with people's ability to point at targets under the same stimulus conditions: the standard deviation of the pointing response is in the order of only a few centimetres and the systematic error is much smaller than for verbal reports (e.g. Bingham and Pagano 1998; Mon-Williams and Tresilian 1998) sometimes as little as 1 or 2 cm (Swenson 1932). It thus appears that vergence-based distance information is available for the control of pointing movements and is a major determinant of such responses in reduced cue environments. This does not, however, appear to be the case for verbal reports, which are likely to involve a strong cognitive component which may serve to reduce the influence of sensory information on the final judgement. The verbal judgement task which has been used in studies of the size-distance paradox, and adopted here, has an obvious cognitive component. The observer has to remember where a previously presented stimulus target was perceived to be and judge whether or not the currently presented target looks to be nearer or further away. Since this judgement involves a memory component, it is not purely perceptual – despite the fact that observers were instructed to report what they "saw", rather than what they "thought" following the instructions used by Ono et al. (1974). It seems likely that under these conditions the observer judges the apparent size of the target to be the most significant piece of information as it is: (1) the most salient information when viewing a target in the complete absence of contextual cues, (2) easy to remember and (3) the easiest to compare between subsequent stimulus presentations.

These arguments can be readily interpreted within the two visual systems framework originally proposed by Bridgeman et al. (1979) and later refined by Goodale et al. (1991; Milner and Goodale 1995). Within this framework, the pointing responses would receive perceptual information from the 'motor visual system', the stream of visual processing subserving the guidance of movement and generally considered to be cognitively impenetrable (Pylyshyn 1998). Verbal judgements would be made on the basis of information available to the 'cognitive visual system', the stream of visual processing subserving conscious perceptual representation.

In the introduction to this article, we observed that the size-distance paradox presents a serious challenge to a widely accepted account of cue combination (modified weak fusion, MWF). The reason that the paradox challenges MWF is that it suggests complex interactions that are not permissible under the framework but which are consistent with strong fusion. The problem with strong fusion, from a scientific viewpoint, is that it is not falsifiable. Similarly, it is not possible to falsify the idea that the size-distance paradox occurs because of a two-stage mechanism in distance perception. Nonetheless, the results of the current experiment suggest that it is not necessary to resort to explaining the size-distance paradox in terms of strong fusion – an alternative explanation is that distance perception proceeds by combining cues in the manner of MWF but the percept that arises is used for controlling action and is cognitively impenetrable. In support of this conclusion we note that there is a large amount of empirical support for MWF (see Landy et al. 1995) and the presence of two visual systems (e.g. Bridgeman et al. 1979; Goodale et al. 1991). In contrast, the only evidence for the idea that perceived size influences the perception of distance is the size-distance paradox itself.

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