Exp Brain Res (2000) 133:407–413
Digital Object Identifier (DOI) 10.1007/s002210000410

RESEARCH NOTE

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Vergence provides veridical depth perception from horizontal retinal image disparities

Received: 5 July 2000 / Accepted: 22 March 2000 / Published online: 16 May 2000

Abstract One useful source of depth information available to the human nervous system is present in the horizontal disparities that exist between the two retinal images (stereoscopic depth). The relationship between horizontal disparity and depth varies with viewing distance so that an interpreting signal is required if disparities are to yield useful information. One potentially useful interpreting signal is available from ocular vergence. A number of studies have concluded, however, that a vergence signal does not provide veridical stereoscopic depth. All of these studies required observers to make a range of judgements under conditions of uncertainty (often using random dot stimuli) and we suggest that the lack of veridicality arose because of a contraction bias: a general tendency to bias judgements towards the centre of the range of possible responses. We re-examined the role of ocular vergence in the maintenance of stereoscopic depth constancy for real three-dimensional objects. Our results question the conclusions reached by previous studies and suggest that vergence can provide a veridical interpretation of stereoscopic depth. Our results indicate that horizontal retinal image disparities are not interpreted by a 'higher order' signal (i.e. the 'perceived distance' of the fixation point). The results of the experiment have significant implications for models of depth processing from disparity.

Key words Binocular · Vergence · Depth perception · Cue weight · Human

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Introduction

The human nervous system requires visual information on the orientation, size and shape of objects within the environment. In order to determine an object's shape, the nervous system must determine the depth of the object (the distance between the closest and furthest egocentric point). It can be readily established that the system is able to extract depth information under monocular viewing and thus the monocular retinal image must supply the system with depth information (Servos and Goodale 1994). Nonetheless, binocular viewing provides the nervous system with extra information about an object's depth. The additional binocular information arises from horizontal image disparities (the differences between the retinal images of the laterally separated right and left eye). It has been argued that the nervous system is not concerned with obtaining metric distance information from retinal disparities (Gårding et al. 1995; Johnston 1991) but it seems improbable that this information would be neglected by a system which "never misses a good trick" (Morgan 1989). Nevertheless, extracting metric information from disparity presents a problem to the nervous system because knowledge of fixation distance (D) is required if the binocular depth of an object is to remain constant with viewing distance (the retinal images of an object become more similar as distance increases). The following equation relates interpupillary distance (I) and horizontal disparity (H) to depth (d):

$$d=D^2H/I \qquad (1)$$

demonstrating that information about fixation distance (D) is needed if disparities are to yield veridical measures of 3D structure. There are several candidate signals that could allow 'depth constancy' from disparities: these include higher order estimates of fixation distance and lower order signals of either a retinal or an extraretinal nature (Johnston 1991; Rogers and Bradshaw 1993; Foley 1980; van Damme and Brenner 1997). Vertical disparities provide one source of retinal information for the interpretation of horizontal disparities (see Bishop

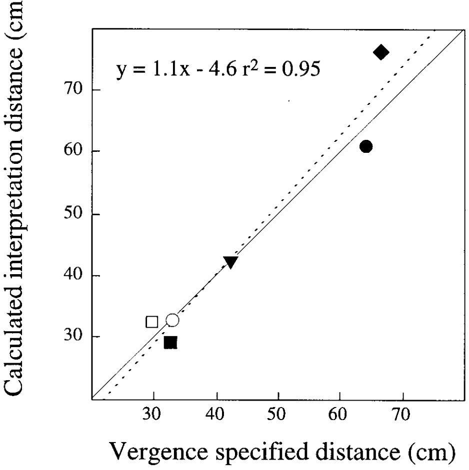
1989), but this paper is concerned with the use of an extraretinal signal. The convergence angle of the eyes is one possible source of extraretinal information for the interpretation of horizontal disparities. If the direction of a binocular fixated target is not too eccentric (neither «0° nor »0°), then vergence angle provides a potentially accurate cue to a target's egocentric radial distance. It has been claimed that vergence can provide complete depth constancy (Ritter 1977), but the evidence is ambiguous because the data were obtained with a disparity matching task (Johnston 1991). Moreover, a number of studies have shown only partial depth constancy from a vergence signal (von Helmholtz 1925; Gogel 1960; Foley 1980; Johnston 1991; Rogers and Bradshaw 1993; Cumming et al. 1991; Bradshaw et al. 1996).

The finding of incomplete stereoscopic depth constancy is generally regarded as a "puzzling teleological question" (Johnston 1991, p. 1359). Collett et al. (1991, p. 751) provided the following summary: "the stereoscopic system calibrates disparities perfectly on the basis of the distance information it receives from vergence, but strangely the vergence system does not supply a veridical estimate of distance". These findings are not merely a phenomenological curiosity – they have important implications for theoretical models of stereopsis (see Erkelens and van Ee 1998; Gårding et al. 1995). The apparent failure of vergence to provide an accurate signal has also been reported for judgements of distance. It has long been reported that physical space is contracted when distance is specified by vergence alone (see von Helmholtz 1925; Foley 1980). This contraction of physical space has become known as the 'specific distance tendency' (SDT, Gogel and Tietz 1973).

We have argued, however, that the SDT is a classic example of a "contraction bias" in distance judgements. A contraction bias describes a general tendency to bias judgements towards the centre of the range of possible responses under conditions of uncertainty (Poulton 1981). Contraction biases have been reported under a wide range of experimental conditions (Poulton 1981) and we have suggested that distance judgements are no exception to this general rule. In support of this idea, we have demonstrated that: (a) the specific distance tendency systematically decreases with the addition of additional distance cues and (b) the SDT occurs when size is the only distance cue (Tresilian et al. 1999). From this perspective, reduced cue situations which introduce uncertainty should result in contraction biases for distance or depth estimates (Fig. 1b). In particular, a range of depth estimates regarding random dot stereograms (where all depth information except disparity has been removed) would be expected to be contracted. Indeed, all of the studies which have reported inaccurate depth judgements have found that depth is overestimated at near presentations, is underestimated at far presentations but is approximately veridical in the centre of the range (Fig. 1b).

We therefore suggest that finding a contraction bias should not be taken as evidence for a failure of depth

(a) Physical object



(b) Stereogram

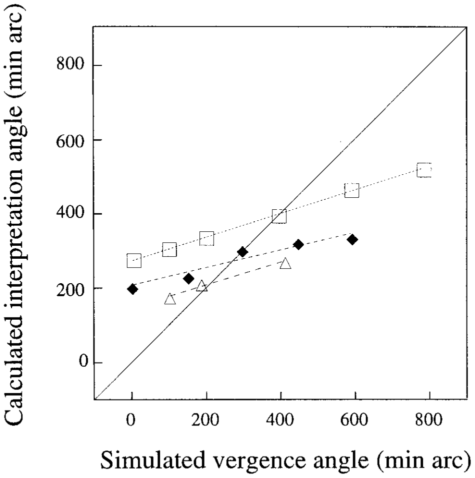


Fig. 1 **a** Vergence specified distance plotted against calculated interpretation distance in studies which measured depth perception when perceived fixation distance was dissociated from vergence specified distance. Each datum point has been calculated from the data presented in 6 separate studies involving 295 participants (including the present study). Symbols indicate the studies from which the data were taken as follows: □ Wallach and Karsh 1963b, ■ Wallach and Karsh 1963a, ○ Fisher and Ebenholtz 1986, ● Wallach et al. 1963, ◆ Wallach and Zuckerman 1963, ▼ the present study. *The solid diagonal line* indicates 1:1 correspondence. *The dashed line* shows the least squares linear fit to the data with the equation showing the relationship between vergence specified distance (y) and calculated interpretation distance (x). These data show that vergence can allow for good depth constancy (explaining 95% of the variance). **b** Replotted data from studies which used random dot stereograms to study depth constancy from vergence: □ data from Bradshaw et al. (1996, Fig. 5d), △ data from Johnston (1991, Fig. 7, EBJ), ◆ data from Cumming et al. (1991</refcite, Fig. 2, BCG). These data are classic examples of 'contraction biases': a general tendency to bias judgements towards the centre of the range of possible responses under conditions of uncertainty

constancy from vergence but should be expected as a predictable response to reduced and uncertain visual cue conditions. In support of this idea, Glennerster et al. (1994) have shown that nearly perfect metric depth constancy is obtained under full-cue conditions (where higher confidence would be predicted). In a series of later studies, Glennerster et al. (1996) showed that depth constancy depends upon the ‘task used to measure it’ and speculated that the stereoscopic system might consist of two representations – a non-metric representation and a metric representation. Indeed, Gårding et al. (1995) have provided a two-stage model of stereoscopic processing that produces two such representations. Erkelens and van Ee (1998) have gone on to suggest that the metric representation is achieved by the disparities being interpreted with a higher-order signal (the perceived distance of the target). It will be noted that this explanation is at odds with our interpretation of the results – we suggest that the disparities are interpreted veridically with the lower order vergence signal but that the responses are prone to a contraction bias. If we are correct, caution is required in interpreting the results of previous studies using very reduced cue situations (including random dot stereograms). A similar conclusion was reached by Frisby et al. (1996) following a series of experiments exploring the stereo representation of real objects. Frisby et al. (1996, p. 153) suggested that: “it is particularly hazardous to found proposals on the nature of the representations computed by human vision (e.g. metric versus affine) on the basis of data from monitor displays. Our experiments strongly suggest that when length judgements of natural discrete objects (twigs) are required under (quasi-)natural viewing then stereo can be used to support good representations of metric scene structure”.

In summary, it is unclear whether or not the system can use a vergence signal to interpret horizontal retinal image disparities veridically or whether it depends upon a higher order signal (perceived distance). In order to explore this issue it is necessary to dissociate the vergence specified distance (D_v) of a physical target from its perceived distance (D_p) and ensure that a contraction bias does not occur. Poulton (1981) has suggested that contraction biases may be removed by the use of a ‘block’ design (where a single judgement is made) and by increasing the confidence of participants in their judgements. We identified five existing studies which measured depth perception in a block design using real objects under conditions where D_v was dissociated from D_p. It should be noted that only one of these studies (Wallach and Zuckerman 1963) was actually concerned with the question of depth constancy. We explored the issue further in a simple experiment which used an ophthalmic prism to perturb D_v whilst leaving all other distance cues unaltered. In an environment that has a number of different cues to distance this has the affect of dissociating D_v from D_p as the vergence cue is given a relatively low weighting (Tresilian et al. 1999).

Materials and methods

Reanalysis

In the experiments we reanalysed (Wallach and Karsh 1963a, 1963b; Fisher and Ebenholtz 1986; Wallach et al. 1963; Wallach and Zuckerman 1963), participants viewed a skeletal (wire frame) pyramid through a ‘telestereoscope’. Telestereoscopes increase horizontal disparities via mirrors which optically increase interpupillary distance (von Helmholtz 1925). Enlarging interpupillary distance (I) increases the convergence required to fixate a proximal target (Judge and Miles 1985), but the mirrors were orientated in the experiments we consider so that vergence demand was equal to that required with normal I. This arrangement is equivalent to viewing increased retinal disparities in the presence of a prism with its base orientated towards the nose. All of the studies used open-loop kinaesthetic judgements as an index of perceived depth (i.e. disparity matching was not a potential strategy). None of the studies included participants who did not show telestereoscopic depth enhancement (approx. 50% of those initially screened) and we only considered data reported for initial judgements (to avoid effects of adaptation or memory). These criteria resulted in depth judgements from 286 participants of normal visual status who participated in 14 separate experiments with 5 different vergence specified distances. We analysed these data in the following manner: Eq. 1 can be rearranged to calculate horizontal disparity (H) from known I, D and d. Multiplying H by the appropriate scaling factor $(\Delta I+I)/I$ yields the disparity (H_T) created by the telestereoscope. Equation 1 can be further rearranged to provide the *interpretation distance* (D_i) from the perceived depth (d_P), the enlarged interpupillary distance (I_T) and the increased disparities (H_T). D_i can then be compared with the vergence specified distance (which in these experiments is equal to the target’s physical distance but not its perceived distance).

Experiment

Forty-five undergraduate students (18 males and 27 females, age range 17–27 years) participated in the experiment for course credit. Participants were naive as to the purpose of the experiment. All participants were screened (Bausch and Lomb “Vision Tester”) to ensure they had normal eyesight and stereoscopic vision. The experiment was approved by the University of Queensland’s Biological and Social Science ethical review committee. Participants viewed a skeletal pyramid whose 4-cm base was 30 cm from the observer with the apex 38 cm along the midline, through an aperture (9×4 cm) in front of a rectangular viewing box (65 cm wide by 21 cm high). The pyramid was constructed from copper wire (ca. 0.1 cm diameter). We chose the pyramid shape rather than a cube as pilot work had indicated that cubes are rather poor at eliciting telestereoscopic enhancement. The problem with using a cube is that monocular cues can specify that the object is a cube in which case its depth must equal its extent in the frontoparallel plane (this problem does not occur with a pyramid). Notably, a majority of the earlier studies with telestereoscopes had also used a pyramid (although no reasons were given for this choice). The internal surfaces of the box were smooth and white with a translucent screen located at the far end providing a matt white surface of homogeneous illumination (approx. 250 lux) against which the pyramid could be easily seen. 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 ophthalmic lenses could be placed. Participants fixated the base of the pyramid and positioned the tip of the unseen right index finger outside the box at the perceived distance of the base and the apex (5 times in a randomised order). We monitored horizontal eye position in both eyes to ensure that participants could maintain fixation on the front of the pyramid whilst pointing. Eye position was measured by comparing diffuse infrared light from the nasal and temporal limbi (*ASL* Eye Tracker

Model 210; Bedford, MA). The eye movement sensor's two output channels had bandwidths of 180 Hz and noise in the system was equivalent to approximately 30 min of arc. The eye movement sensors were adjusted so that the sensors were centred in the vertical and horizontal planes.

Three viewing conditions were used: (a) monocular, (b) binocular with no prism, (c) binocular through ophthalmic lenses and 6Δ prism equally split between the eyes (prism dioptre; 1Δ=arctan 0.01) orientated base towards the nose. The prism increased the vergence specified distance and the lenses ensured there was no accommodative conflict. Participants (n=15) were randomly allocated to one of three groups with each group participating in just one viewing condition to circumvent memory effects. The mean positional pointing accuracy was measured for 0.5 s at a sampling rate of 60 Hz using an Optotrak 3D optoelectronic movement recording system (accurate to within 0.2 mm).

Results

Figure 1a illustrates the results of the reanalysis and shows that: (a) good depth constancy was present between 32.5 and 66.5 cm; (b) the signal used for disparity interpretation was approximately equal to D_v and not D_p. The weakest relationship between the vergence specified distance and the calculated interpretation distance was found for the study in which vergence specified distance was equal to 66.5 cm. The weaker relationship is likely to be due to the decreased signal to noise ratio for smaller vergence angles (Mon-Williams and Tresilian 1999).

We confirmed the result of the reanalysis in a simple experiment where participants pointed at a skeletal pyramid under three viewing conditions: (a) monocular, (b) binocular with no prism, and (c) binocular through ophthalmic prisms (Fig. 2). ANOVA showed a reliable difference between viewing conditions [$F_{(2,42)}$=17.106, P<0.01] but this effect was confined to differences between prismatic and non-prismatic viewing [Scheffe F-test: (a) vs (c)=11.447, (b) vs (c)=14.076] with no reliable differences between (a) and (b) [Scheffe F-test=0.136]. Dunn's planned comparisons (Keppel 1982) between binocular conditions (b) and (c) indicated that the prism reliably caused: (a) the base to be seen at a greater distance (t_{14}=3.315, P<0.01) and (b) the pyramid to be perceived as extended in depth (t_{14}=3.315, P<0.01). Inspection of individual data from the prismatic condition revealed six participants who did not show depth enhancement (depth judgements inside the 99% confidence interval for the binocular no prism data). For the nine participants who showed depth enhancement, we calculated the *interpretation distance* (D_i, see "Materials and methods") and conducted tests of difference (Dunn's planned comparisons) and equivalence (Rogers et al. 1993; equivalence interval set at 1.5 cm) between: (a) D_i and D_v (calculated for individual interpupillary distances) and (b) D_i and D_p (taken from an individual's mean pointing response to the base of the prism). The tests of difference and equivalence agreed: D_i and D_p were reliably different (t_8=5.23, P<0.0008) and not equivalent (P>0.2) whilst D_i and D_v were not reliably different (t_8=1.33, P>0.2) and were equivalent (P<0.05). The results indicate that a signal from vergence was used to interpret disparity information and that the depth was correct for the vergence signal (i.e. vergence can allow depth constancy).

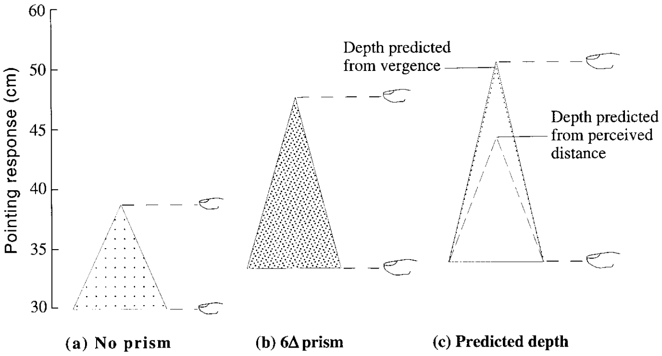


Fig. 2 **a** The perceived and actual properties of a skeletal pyramid were in close agreement when viewed with no prism present; **b** viewing through a prism reliably caused the fixation distance (base of the pyramid) to be seen as further away (by 3.9 cm) and the pyramid to be perceived as extended in depth (by 7.9 cm); **c** the extension in depth (*solid line*) was reliably predicted by the vergence specified distance (*dotted line*) but not by the perceived fixation distance (*dashed line*) for the nine observers who saw the pyramid extended in depth when viewing through the prism. The width of the finger shows the variability (standard error) across the group for the pointing response. It can be seen that increasing vergence specified distance causes a predictable overshoot in the pointing response (which we take as an index of perceived distance). The perceived distance of the fixation point does not, however, account for the interpretation of the horizontal disparities whereas the vergence specified distance does account for the perceived depth of the target

Discussion

These data clearly demonstrate that the nervous system can use a vergence signal to interpret the horizontal disparity field with good depth constancy. Furthermore, the data show that the system uses the lower order signal provided by vergence in preference to a higher order signal (the perceived distance of the object). These behavioural data support recent neurophysiological studies showing that vergence is involved in stereoscopic depth perception (Trotter et al. 1992; Trotter 1995). The data therefore suggest that previous findings of incomplete depth constancy from vergence are due to the presence of contraction biases. This conclusion is consistent with models of depth processing that emphasise cue reliability (Landy et al. 1995) and lend support to the contention that "it is important to understand what 'reality checks', if any, are present in early visual processing and to create precisely controllable stimuli that are sufficiently *veridical* to pass these checks" (Landy et al. 1995).

We have only considered the interpretation of disparity information under reduced cue conditions. One important source of information missing (deliberately) from our display was a significant vertical disparity gradient: vertical disparities can provide accurate fixation distance information if a wide enough field of view is available (Bradshaw et al. 1996). Banks and Bachus (1998) have provided evidence that vergence and vertical disparities are used to interpret horizontal disparity information in order to determine an object's slant. Rogers and Bradshaw (1995) have shown that the curvature of a stereoscopically defined surface is interpreted nearly perfectly when both vergence angle and an horizontal gradient of vertical disparities were in accordance. As the display size became larger so the weighting attached to vergence decreased and the weighting attached to vertical disparity increased. This makes good sense as vertical disparities only become reliable when a large enough gradient is available. If only vergence or vertical disparity information was available then the interpretation was incomplete – but the relative weighting attached to the separate information sources (when manipulated independently) added up to an almost perfect interpretation. In contrast, Rogers and Bradshaw (1995) found incomplete depth interpretation from either vergence or vertical disparity. According to our explanation, the incomplete interpretation was due to the presence of a contraction bias. The *pattern* of the results was identical, however, to those reported above for curvature – strongly suggesting that vergence and vertical disparities are used together to interpret depth from horizontal disparity with the weighting attached to either altering according to signal availability.

It is likely that the perception of an object's depth normally depends upon a variety of additional factors including memory from previous exposure to the object and 'monocular' visual information about the object's shape (e.g. texture). Johnston et al. (1993) have established previously that stereopsis and texture are combined in a weighted averaging scheme to provide information about an object's depth. We removed most monocular information by using an unfamiliar skeletal figure in which monocular shape cues were ambiguous with respect to depth. We have complimentary data that suggest monocular visual information and memory play a role in normal depth perception – perceived and physical depth are closer if a skeletal cube is used (if monocular cues specify that the object is a cube then its depth must equal its extent in the frontoparallel plane), a solid target is shown or if participants have previously seen the target. Moreover, even a skeletal pyramid provides sufficient monocular information for 50% of a research population to veridically judge its properties despite stereoscopic depth enhancement (Wallach and Karsh 1963a, 1963b; Fisher and Ebenholtz 1986; Wallach et al. 1963; Wallach and Zuckerman 1963) – either the weighting attached to stereopsis dropped to a very low level or the stereo information was effectively 'vetoed' by the monocular cues (see Landy et al. 1995).

It is interesting to note that interpreting disparities with vergence allows the nervous system to calibrate itself. If vergence is used to interpret disparity then small biases in the vergence system (artificially created by a prism or naturally caused by neuromuscular change) will result in the stereoscopic shape of a physical object altering when fixation is changed between the front and the rear of the object. These changes in perceived shape would produce an error signal which could be used to recalibrate the relationship between vergence and disparity. Indeed, the vergence system would require such an adaptive mechanism to ensure accurate feedforward responses in the face of long-term physiological or environmental challenge. A recalibration process of this sort may explain the findings of previous studies (Wallach and Karsh 1963a, 1963b; Fisher and Ebenholtz 1986; Wallach et al. 1963; Wallach and Zuckerman 1963) reporting perceptual adaptation in response to telestereoscopes: these studies created a nonconstant vergence bias by adjusting the telestereoscopes' mirrors to decrease fusional demands. This would explain why the perceptual adaptation occurs in the absence of any oculomotor change and yet is not found when changes in fixation are prevented by making participants view through a pinhole (Fisher and Ebenholtz 1986).

The starting point for this study was the paper by Servos et al. (1992) showing that binocular information is used in the programming of prehensile movements. Evidence also exists to show that vergence plays an important role in the programming of the transport phase of the movement (Mon-Williams and Dijkerman 1999). The current study shows that binocular information may also play a role in the grasping component of the prehensile movement (where the hand is shaped to the dimensions of the object). This conclusion is consistent with the findings of Servos and Goodale (1994) and Jackson et al. (1997) showing that binocular depth cues are particularly important at the end point of the movement when "greater precision is required such as in conditions of selective reaching" (Jackson et al. 1997, p. 140). Our findings are also in broad agreement with a range of neuropsychological studies showing the importance of binocular information for the control of grip aperture in patients with impaired object-recognition abilities (Dijkerman et al. 1996; Jackson and Husain 1996; Marotta et al. 1997). It is widely accepted that different visuomotor channels (located within the dorsal stream of visual processing) control the transport and grasp phases of prehension movements (Jeannerod 1988). It may be concluded, therefore, that vergence contributes in two distinct ways to prehension – vergence serves the visuomotor channel concerned with transporting the hand whilst also contributing an interpreting signal to the channel concerned with shaping the hand. In other words, vergence contributes with a number of other cues to provide information on an object's distance whilst combining with vertical disparity to provide a signal for the interpretation of stereoscopic information on the object's shape. We have recently found that a patient with visual form agnosia (DF) is insensitive to 'monocular' depth and distance cues and relies predominantly on vergence information when judging distance, and on disparity information when judging an object's depth

(Mon-Williams et al., unpublished data submitted for publication). DF has a lesion deafferenting the object-recognition systems in inferior temporal cortex (James and Goodale, unpublished data) so these results suggest that: (a) retinal disparities are carried in the dorsal stream and (b) the dorsal stream has access to a signal from extraretinal vergence. It appears, therefore, that horizontal retinal image disparities are interpreted using information (vertical disparities and vergence) available to the dorsal pathway with no input from the ventral stream (where we assume that 'monocular' depth and distance cues are processed). Such an arrangement makes good sense and explains why DF shows such good prehensile skills under binocular viewing conditions but why she experiences profound problems with one eye closed (Marotta et al. 1999).

In summary, vergence can provide veridical depth perception from stereo information. The weight of empirical evidence suggests that in normal conditions stereoscopic depth constancy is achieved by a combined signal provided by vertical disparity and vergence with the weighting attached to either signal varying as a function of availability (Rogers and Bradshaw 1995). Furthermore, it seems likely that the available stereoscopic information is combined with monocular depth cues in some kind of weighted averaging scheme (Johnston et al. 1993) with the weighting attached to stereopsis decreasing as it becomes increasingly discrepant with the other available depth cues. Such a scheme is consistent with a wide body of data (see Landy et al. 1995) and would allow for the greatest possible precision in prehension for any given viewing conditions. Nonetheless, a weighted averaging scheme does not imply that disparities cannot be veridically interpreted from a vergence signal alone – our results stongly suggest that vergence does provide good depth constancy from horizontal retinal image disparities.

Acknowledgements We are grateful to Phil Servos for making useful comments on an earlier version of this manuscript.

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