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Some recent studies on the extraretinal contribution to distance perception

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Abstract. Some recent studies on the extraretinal contribution to distance perception are reviewed. These experiments demonstrate that vergence can provide reliable information for judgments on the distance of proximal targets in the absence of all other cues. We argue that, although vergence is an unreliable cue at large fixation distances and is subject to a strong contraction bias when studied in isolation, these facts do not imply a minor role for vergence in near-space perception. When additional depth and distance cues are added, the contribution of vergence information becomes more complicated. We present results which indicate that the different cues to depth and distance are combined in a manner that can result in unexpected distortions of visual space. A simple heuristic model which can produce the observed distortions is outlined.

1 Introduction

Many human behaviours involve reaching forward and picking up objects. Skilled action is marked by an ability to correctly judge the distance and direction to be reached before the onset of the movement. If we are to make progress in understanding manual positioning it is necessary to consider what perceptual information is available to allow for the accurate estimation of egocentric distance and direction. This paper is concerned with the question of how a person might obtain the body-referenced distance information required to interact with (stationary) objects of interest.

Potential sources of distance information are present in the retinal image(s) but the majority of such information is of an ordinal or relative nature. Such information cannot, on its own, allow for judgments on where an object is located and is therefore insufficient for the control of actions which require such information. If there is sufficient relative information to allow judgments on where visible things are relative to each other (eg object X is 20% further away than object Y) then knowledge of the actual egocentric distance to one object can allow for the determination of the distance to all other visible objects. We will discuss the use of the two potential extraretinal sources of such egocentric distance information: the vergence angle of the eyes and the state of accommodation. Both of these sources can, in principle, provide information about the distance of a fixated object from the visual egocentre. This information could be used to scale the relative information from retinal images or to directly control a manual interaction with a fixated object.

1.1 *Vergence as a distance cue*

Figure 1 illustrates the relationship between distance and binocular parallax (γ), the angle made between two lines drawn between the optical centres of both eyes and the target point. Binocular parallax depends upon the radial distance (D) of the target point from the eyes (see figure 1a, which shows the geometry of symmetrical binocular fixation). Binocular fixation of a target means that the vergence angle of the eyes will be approximately equal to

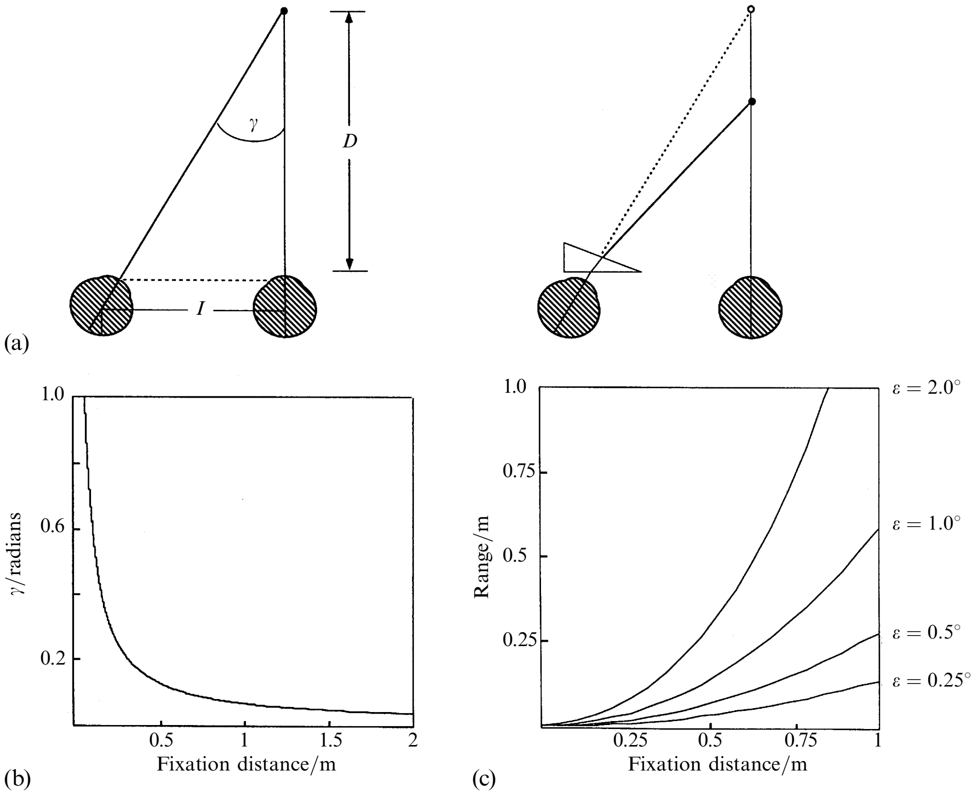

Figure 1. Relationships between binocular parallax (γ) and target distance. (a) Symmetrical binocular geometry of target fixation. (b) Binocular parallax plotted as a function of target distance for the symmetrical binocular geometry shown in (a) and an interpupillary distance (I) of 6.5 cm [this is a plot of equation (1) in the text]. (c) The range of the distance estimate resulting from a range of 2ε in the binocular-parallax estimate plotted as a function of target distance for four values of ε as indicated.

the binocular parallax of the target. Since (at least) the time of Descartes it has been appreciated that human observers could obtain an estimate of the distance of a binocularly fixated point from knowledge of the vergence angle. Only relatively recently, however, has it been conclusively established that a vergence-related signal contributes to perceived distance (for reviews see Foley 1980; Howard and Rogers 1995).

It is important to recognise that vergence is only of limited utility as a fixation-distance cue because it is bounded by the physiological limits of near fixation (about 10 cm) and effective optical infinity when the eyes are parallel (for fixation distances greater than about 6 m). Within these bounds the information provided by vergence drops off as fixation distance increases and is probably effectively absent at distances much closer than 6 m. This decrease in information content can be appreciated from inspection of figures 1b and 1c. Figure 1b is a plot of the relationship between binocular parallax and radial distance (D) for symmetrical fixation:

$$\gamma = 2\arctan\left(\frac{I}{2D}\right), \tag{1}$$

where the interocular separation (I) is assumed to be 6.5 cm. From figure 1b it can be seen that any sensory error in the measurement of vergence angle will yield an increasing error in the corresponding estimate of distance as the distance to the fixation target increases. This can be further illustrated as follows: suppose that the vergence-derived sensory estimate, $\hat{\gamma}_0$, of a binocular parallax is prone to error such that it lies within the range $\gamma_0 \pm \varepsilon$. Equation (1) implies that the corresponding range for the distance estimate ($\hat{D}_0$) derived from the sensory estimate $\hat{\gamma}_0$ will be

$$I\cot(\gamma_0 + \varepsilon) \leqslant \hat{D}_0 \leqslant I\cot(\gamma_0 - \varepsilon)\,. \qquad (2)$$

Thus, if we consider sensed binocular parallax as the input and distance as the output then a range of size 2ε in the input translates into a range of $I[\cot(\gamma_0 - \varepsilon) - \cot(\gamma_0 + \varepsilon)]$ in the output. The range of the output (distance estimate) is plotted as a function of fixation distance for various values of ε in figure 1c and clearly shows an accelerating increase in the range with increasing fixation distance. This means that vergence angle is much less sensitive to distance variations at large fixation distances and so provides decreasing information as fixation distance increases.

Although the precision of sensory estimates of vergence angle has not been investigated to date, it is clear that vergence is only a good distance cue for relatively close fixation distances (probably not much greater than 2 m or so). Within such a range it has been well established that vergence can contribute to the perception of distance in reduced-visual-cue conditions [Foley (1980) provides a comprehensive review]. In addition, vergence information has been shown to be involved in interpreting horizontal binocular disparities to provide information about the distances of nonfixated objects (see Foley 1980; Rogers and Bradshaw 1995). In normal ('full cue') viewing conditions there are other sources of information about distance such as known size and vertical disparities in addition to vergence. This then raises the issue of how vergence contributes to distance perception when other information about distance is available. It has been suggested that vergence does not contribute to visual space perception when retinal information is sufficient to determine distances (eg Turvey and Solomon 1984) but little is actually known about the role of vergence in distance perception in multiple-cue environments (but see Rogers and Bradshaw 1995).

1.2 *Accommodation as a distance cue*

The role of accommodation in distance perception is very unclear: whilst the bulk of the early literature suggests that it does not contribute to perceived distance, methodological problems preclude any firm conclusions (Fisher and Ciuffreda 1988). A recent study which controlled for most of the methodological problems of earlier experiments gave a mixed result: a minority of participants (about 25%) showed a strong correlation between the perceived distance of a target (average of four trials) and the average accommodative response on those trials (Fisher and Ciuffreda 1988). This result indicates that some people are able to use information about their accommodative state to gauge target distance. On the other hand, Fisher and Ciuffreda's result does not actually establish the usefulness of accommodation as a distance cue since the accommodative response does not precisely covary with target distance; average cited values of the depth of focus of the accommodation system are in the range between $\pm 0.13D$ (Kotulak and Schor 1986) and $\pm 0.36D$ (Mordi 1991). If, for illustrative purposes, we take the mean of these two figures, accommodation on a target at 50 cm could be associated with a distance in the range 44.54 cm to 59.98 cm. This range increases rapidly with fixation distance in a similar fashion to vergence (figure 1c). It should also be noted that vergence and accommodation are cross coupled so that accommodation may influence distance perception indirectly via its effect on vergence.

1.3 *Experimental manipulations*

In summary, it has been well established that a signal from the vergence eye-movement system contributes towards distance perception in reduced cue environments. Unfortunately, however, the contribution of vergence to distance perception in more structured visual environments is not well understood. In contrast to the contribution of vergence, the role played by accommodation in distance perception has not been established. In this paper we review a series of simple experiments that we have recently conducted to investigate the influence of vergence and accommodation on proximal-distance perception in minimal visual environments.

2 Methods

All of the experiments that we report used a similar methodology. The basic paradigm employed a pointing response as a measure of perceived distance: participants were required to position an unseen finger at the same distance as a visual target.

2.1 *General methods*

Although the pointing task we employed needed little explanation to the participants (the task appeared to be self-evident) it was nevertheless necessary to ensure that the finger was not laterally displaced from the target by more than a few centimetres. The reasons for this are as follows: positioning the finger on, or close to, a visual target is a common everyday task and so is readily interpretable by a participant. If the finger is required to be positioned some lateral distance from the target then it is not clear what the participant's interpretation of 'at the same distance' will be. For example, one interpretation is that it means in the same frontoparallel plane as the target in which case the known distortions of the perceptual frontoparallel plane (see Foley 1980) would have to be taken into account. Another possible interpretation is that the finger should be positioned at the same radial distance from some coordinate origin such as the visual egocentre or a shoulder-centred coordinate system (Flanders and Soechting 1990). Clearly, a person's interpretation of what 'same distance' means will determine the distance pointed. It is therefore impossible to know whether or not distance has been accurately perceived in the absence of knowledge about what a person is actually doing when positioning the finger.

We studied the accuracy of normal pointing accuracy using a specially designed viewing box (Tresilian and Mon-Williams 1999). The viewing box was rectangular (60 cm long by 20 cm wide by 20 cm high) and its internal surfaces were smooth and painted matt black except at the far end where a thin (0.5 mm) sheet of white translucent Perspex was located, behind which a 10 W bulb was placed. The Perspex sheet was 53 cm (±0.5 cm) from the centres of rotation of the observers' eyes. The bulb produced a homogeneous illumination from the end of the box (approximately 250 lx) and provided a matt white screen against which targets could be easily seen. Observers viewed targets through an aperture in front of the box (10 cm × 5 cm). A moulded plastic restraint mounted in front of the aperture provided some support for the observer's head, completely occluded peripheral vision, allowed the observers to position themselves correctly with respect to the box, and acted as a light shield. The head restraint had a binocular occluder which meant that participants could position themselves within the apparatus before viewing presented targets. The restraint ensured that head movements were minimised during performance of the pointing tasks. The participants' angular field of view was further restricted by a pair of trial frames (diameter 3 cm) into which ophthalmic prisms could be placed. The experimental task was to position the unseen index finger of the right hand so that its tip was placed on the outside of the viewing box at the judged distance of the target light.

Positional accuracy was measured with an Optotrak 3-D optoelectronic movement-recording system. This system measures the 3-D position of small infrared-light-emitting diodes (IREDs); it was factory precalibrated to a static resolution of IRED position less than 0.2 mm. The system recorded the distance between an IRED placed on the distal end of the index fingernail and reference IREDs placed on the box. It was then possible to calculate the judged egocentric distance and compare this with the target distance.

The configuration allowed measurement of the error to within 3 mm. On each trial the system recorded the positions of the IREDs for 0.5 s at a sampling rate of 60 Hz. The position of each IRED was computed as the mean of the samples over the collection period. The pointing response was taken as the mean of either four (experiments 2.3 and 2.5) or five (experiments 2.2, 2.4, and 2.6) separate trials (trials were always presented in a random order with the constraint that the same target position could not occur more than twice consecutively).

2.2 *Pointing in full cue conditions*

For the reasons given in section 2.1 we believe that the best indicator of perceived distance is a pointing response directed to the immediate vicinity of the target. Somewhat surprisingly, such a response has seldom been used in studies of distance perception and it was therefore necessary to quantify the accuracy with which people could point to a visual target under open-loop conditions. Six participants were asked to point to targets consisting of a single solid-black mirror-symmetric Snellen letter (H, T, X, or Y) printed onto a clear plastic slide approximately equal in size to the cross section of the viewing box (Tresilian and Mon-Williams 1999). Targets were printed on the slide in a position such that they were aligned with the axis of the right eye when the eye was in the primary position. The slides could be placed through slots cut into the top of the box at nine different distances. All nine slots were used when assessing pointing accuracy in full cue conditions and the step size between each slide position corresponded to 0.5 metre angles (the metre angle is approximately equivalent to the reciprocal of distance).

2.3 *Pointing when vergence is the sole indicator of distance*

The second issue we addressed was the relationship between perceived distance and vergence-specified distance when no other sources of distance information were available. In order to quantify this relationship we conducted an experiment which involved six participants pointing at a very small point source of light located inside the viewing box in complete darkness. The light was placed directly in line with the right eye so that there was no information on target distance when the left eye was covered. We then quantified the ability of the six participants to point at the light when vergence information was available. Vergence demand was manipulated by placing different powers of prism either base in (increasing vergence-specified distance) or base out (decreasing vergence-specified distance) in front of the left eye. The advantage of this arrangement was that the fixated target was in a constant location and had an identical appearance throughout the whole experiment. The prism powers used resulted in fourteen different vergence-specified distances between 20 and 60 cm.

2.4 *Pointing when accommodation is the sole indicator of distance*

The next issue we addressed was the relationship between accommodation and perceived distance. Six participants (who did not participate in any of the other experiments) took part. A control experiment was first conducted to ensure that these participants pointed accurately at the targets in the full cue conditions (the same methods were used as those described in section 2.2). As in the control study, the experimental task was to point at a series of targets when accommodation was the only available cue to distance. In order to ensure that no other distance cues were present, participants viewed the targets through an occluder with a 6 mm square opening in front of the right eye. When the occluder was in position the observer could only see the target letter against the white background. Disparity-driven vergence and retinal cues were thereby removed as potential sources of distance information. The targets were all carefully positioned along the viewing axis of the right eye so that monocular vergence cues were also eliminated. Particular care was taken to ensure that the targets (letters) served as adequate accommodative stimuli and were sufficiently small for an accommodative response to be necessary for their identification (participants were asked to verbally report the presented letter). Letters placed at different distances subtended approximately (but not exactly) the same visual angle (10.5 min of arc) so as to remove any size cues to distance: size variations were uncorrelated with distance variations. We also arranged that the targets at the different distances were different letters. This arrangement ensured that there was no conflict between size and accommodation: if the target were always the same letter then the approximately constant size might suggest that the distance had not changed and so conflict with any information from accommodation.

2.5 *Binocular pointing with two dots of light*

We explored how well six participants (the same participants took part in experiments 2.3 and 2.5) could localise a fixated and a nonfixated target located inside the viewing box when these two targets were dots of lights presented in complete darkness (ie in the absence of any other cues to distance). In the experiment, a single red point-light source was located at 33 cm whilst three green point-light sources were positioned at 20 cm, 25 cm, and 50 cm. All of the lights (which, apart from the colour, appeared identical) were placed in line with the visual axis of the right eye but were vertically separated from one another. The red light was always illuminated together with one of the green lights. We again used ophthalmic prisms in order to alter the vergence-specified distance of the fixated target. The presentation order for the green lights was randomised. Participants were always given a number of practice trials followed by experimental trials without a prism in place prior to the prism trials. The participants were asked to point at the red (fixated) dot of light and then to point at the green (nonfixated) dot.

2.6 *Pointing in somewhat reduced cue conditions*

The final issue we addressed was the role of vergence in conditions where the information on target distance is reduced but, nevertheless, there are some distance cues present. In this experiment only five target positions were used: the targets (letters) were placed through slots in the viewing box at 16.6, 20, 25, 33.3, and 50 cm (± 0.5 cm) from the observers' eyes. It is important to note that the target size at each distance was set so that its vertical angular subtense was approximately 10.5 min of arc at the observer's eye (there was some variation equal to less than 2 min of arc in the angular size of the target but this was not correlated with distance). We tested the effect of manipulating vergence-specified distance in this more structured visual environment by again using ophthalmic prisms. The experiment was conducted on the same six participants who took part in the study reported within section 2.2. In condition A, a 5Δ prism (Δ is the angle whose tangent is 0.01) was placed with its base towards the nose ('base in'), in condition B the prism was placed base out. The triangulation account of distance perception (where known interpupillary distance and vergence angle allow for the estimation of egocentric distance) predicts that the apparent target distance should decrease with prism placed base out and increase with prism placed base in.

3 Results

3.1 *Performance in full cue conditions*

It may be seen from figure 2 that the participants were accurate at the pointing task we employed. These results agree with those from a number of other studies (eg Mon-Williams et al 1997; van Beers et al 1996; von Hofsten and Rosblad 1988; Wann 1991). In contrast, a couple of studies (Foley 1977; Foley and Held 1972) have found far less accurate pointing responses (median errors of 25 cm). The reason for the poor accuracy found by Foley is not clear. The important point for this paper is that our results suggest that pointing may be usefully employed as an index of perceived distance.

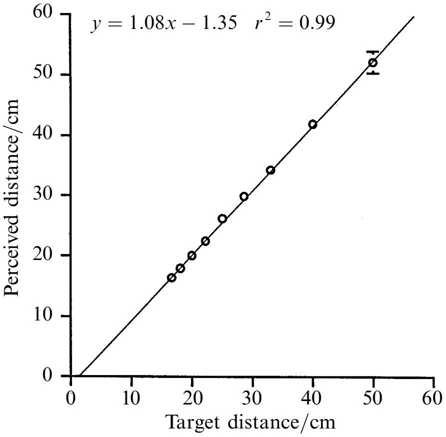

Figure 2. Pointing performance in full cue conditions. The figure shows the data across six participants with target distance plotted along the ordinate axis and perceived distance along the abscissa. Standard error bars are shown unless smaller than the plot symbol.

3.2 *Performance when vergence is the sole indicator of distance*

The results of this experiment are shown in figure 3. All participants showed a strong relationship between perceived distance (as judged from their pointing response) and the vergence-specified distance (calculated from trigonometry by using the interpupillary distance). The mean variable error for any target position was always less than 2 cm (suggesting that participants consistently located the target in the same position).

These results suggest that observers can reliably locate the distance of a target on the basis of a signal from vergence but that the space in which the binocularly viewed targets are perceived is contracted. These results are described by the 'specific distance tendency' (SDT) of Gogel (1978; Gogel and Tietz 1973) which refers to the tendency of observers to locate isolated targets in some intermediate and contracted range when viewing in the absence of contextual cues.

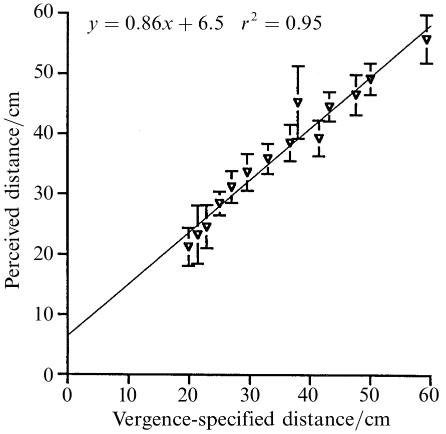

Figure 3. Pointing performance across six participants when vergence was the only cue to distance (fourteen vergence-specified locations were used). The perceived location of the target has been regressed on vergence-specified distance. Standard error bars are shown.

3.3 *Performance when accommodation is the sole indicator of distance*

The control study established that the participants could accurately carry out an open-loop pointing task (the results were similar to those reported within section 3.1). The results of the experiment that explored the relationship between accommodation and perceived distance were essentially the same as those of Fisher and Ciuffreda (1988): two of the six participants (33%) showed a strong relationship between mean pointing response and actual target distance ($r^2 > 0.6$), two participants showed a weaker relationship ($0.3 < r^2 < 0.6$), and two showed little or no relationship. These results confirm part of Fisher and Ciuffreda's conclusion: accommodation can bias perceived distance in some people. Analysis of individual trial performance suggests, however, that this conclusion needs considerable qualification. Figure 4a shows the mean pointing response plotted as a function of dioptric distance (ie a plotting scheme corresponding to that used by Fisher and Ciuffreda) for one of the two participants who showed a strong relationship between these two variables. Figure 4b shows the responses from the individual trials plotted as a function of actual target distance in millimetres. It is clear from the figure that, although the mean response might be taken as evidence for accommodation being used as a distance cue, the individual trial data tell a rather different story. For the two observers who showed the strongest relationship between mean pointing response and target distance, the pointing error (distance between finger and target position) had a range of 39.5 cm and 40.5 cm (as compared with 6.25 cm and 7.1 cm respectively in a full cue control condition). When one considers that the range of possible target distances was only 24 cm, it is clear that accommodation is providing no metric distance information and responses were largely unrelated to the actual distance of the target (figure 4).

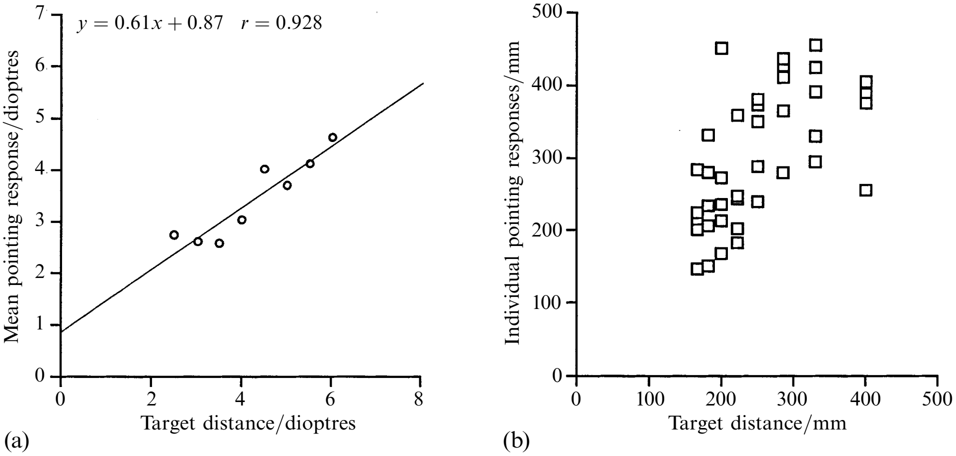

Figure 4. Pointing performance when accommodation is the only cue to distance. (a) Perceived distance in dioptres is plotted as a function of dioptric target distance for the participant who showed the highest level of performance. Each data point represents the mean of five trials. This method of data presentation is the same as that used by Fisher and Ciuffreda (1988). (b) Perceived distance plotted as a function of target distance for the same observer. Each trial is shown rather than the mean of the trials and absolute distance is plotted in mm rather than dioptric position.

Further scrutiny of the individual trial data revealed that the observers who showed a correlation between response and target distance were able to determine whether a target presented on a particular trial (trial k) was nearer or further away than the target presented on the previous trial ($k - 1$) but were unable to determine where the target actually was.

3.4 *Binocular performance with two dots of light*

The notable finding from the experiment with two point-light sources was that the nonfixated target was always seen at the same location regardless of vergence angle (ie the ophthalmic prism had no effect on the perceived distance of the nonfixated dot). This result was not what we would have expected had vergence angle been used to scale the horizontal disparities: this would have resulted in changes in the perceived distance of the nonfixated dot as vergence changed. Figure 5a shows the relationship between the perceived position of the nonfixated point before and after a prism was present. It may be seen that the relationship is almost identical: the presence of a prism did not alter the perceived location of the nonfixated point. This finding may be contrasted with the perceived location of the fixated point (figure 5b). It will be noted that the perceived location of the fixated point is affected by the presence of the prism but that the relationship is dramatically altered by the presence of a second dot of light (compare with figure 3).

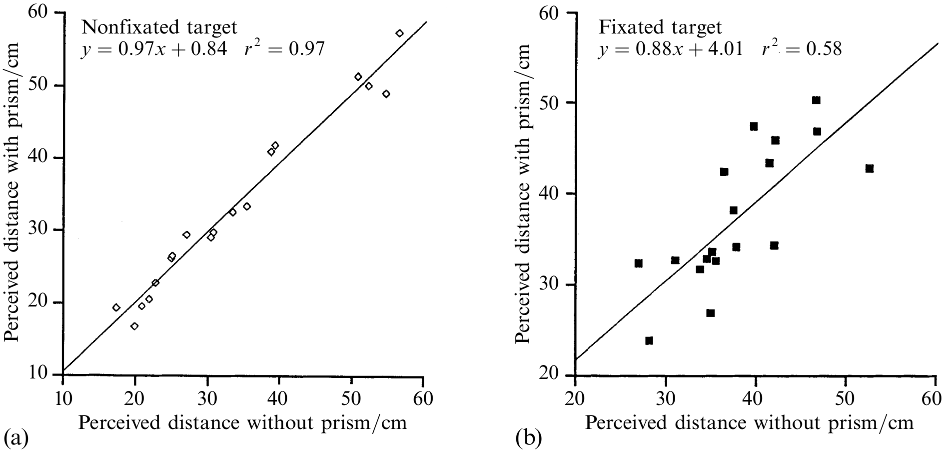

Figure 5. Pointing performance when two dots of light are the only stimuli. (a) The perceived location of the nonfixated target light before and after a prism is introduced for six participants. The perceived location of the nonfixated point without prism has been regressed on the location of the fixated point with prism. The perceived distance of the nonfixated point varies across the participants: the responses themselves are remarkably similar before and after the introduction of the prism. (b) The perceived location of the fixated target light before and after a prism is introduced for all participants. The perceived location of the fixated point without prism has been regressed on the location of the fixated point with prism. In common with the nonfixated point, the perceived distance of the fixated target varies across participants. It is notable that the relationship between perceived location before and after the introduction of the prism is much weaker than for the nonfixated target.

3.5 *Performance in somewhat reduced cue conditions*

The results of the experiment conducted in a somewhat reduced cue environment were unexpected. The prism altered the pointing response (demonstrating that a signal from vergence was being used when determining target distance) but a consistent illusion of perceived distance was obtained in the viewing box: egocentric target distance was judged to be significantly greater regardless of prism orientation or target distance (figure 6). The overshoot was larger in condition A (8.07 cm) than in condition B (5.7 cm) and this difference was statistically reliable. This phenomenon (overshooting target distance when binocular parallax is increased or decreased) has subsequently proved to be remarkably robust across and between participants.

4 Discussion

We have presented data (figure 2) which suggest that manual pointing responses can provide a useful indicator of perceived distance (see also Bingham and Pagano 1998). We have used such responses to determine the relationship between vergence-specified distance and perceived distance in the absence of any other cues. Our data clearly indicate that binocular parallax is capable of providing reliable information for the perception of egocentric distance. On the other hand, near objects appear a little further away than they actually are whilst distant objects appear closer. Thus, participants' distance estimates ($\hat{D}$) are directly proportional to the actual distance:

$$\hat{D} = mD + c, \qquad 0.4 < m < 1, \quad c > 0, \tag{3}$$

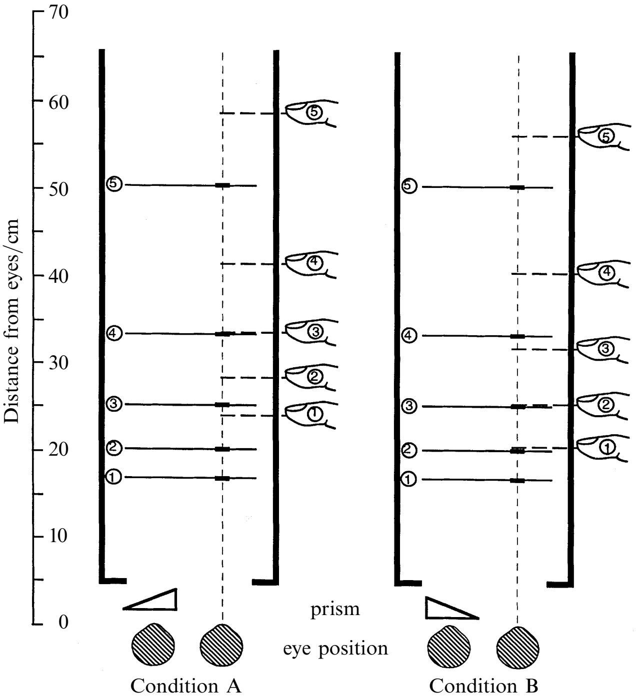

Figure 6. Experimental apparatus and results from the experiments where vergence was manipulated in the somewhat reduced cue conditions. Within the box, the numbered solid line represents actual target position and the dotted line indicates mean judged target location. The six participants *always* overshot target position in condition A (prism base in) and B (prism base out). No statistically reliable relationship exists between the amount of overshoot and target position.

where m and c are constants for a particular individual performing a particular distance-estimation task. In our experiments, m and c were generally found to lie in the ranges $0.5 < m < 0.9$ and $5 < c < 20$ cm. The line described by equation (3) will cross the line $\hat{D} = D$ at some point (D_s). Thus, equation (3) suggests a contraction of perceived space around the point D_s with points closer than D_s to the observer appearing further away (tending towards D_s) and points further away than D_s appearing closer (again tending towards D_s). This kind of observation led Gogel (1969; Gogel and Tietz 1973) to refer to observations described by a relationship such as equation (3) as displaying an SDT where D_s is the specific distance to which other distances tend. Gogel actually reified D_s into an internal (psychological) variable in order to explain the observed tendency and remarked that it depends upon an observer's "behavioural preference for a distance of a general magnitude" (Gogel 1969, page 1091). Various suggestions have been made concerning what this internal variable might be: for example, Owens and Leibowitz (1976) suggested that it was the resting state of vergence in the absence of visual stimulation (dark vergence).

For the case of the SDT observed when vergence is the major egocentric distance cue, it seems rather contrived to base an explanation on the psychological (or physiological) reification of the 'crossing' distance, D_s. It seems more likely that the SDT is an example of what Poulton (1989, pages 178–181) refers to as a "contraction bias": a general tendency to bias responses towards the centre of the range of possible responses in an experiment. The action of a contraction bias in a distance-estimation experiment would result in responses to near and far targets being biased towards the centre of the range and thus being perceived as further or nearer respectively than the actual distance of the target (ie an SDT would be observed). The question then arises as to why the SDT is only observed in reduced cue conditions if it simply reflects a general contraction bias. It seems plausible to suggest that such biases only have significant effects under conditions of uncertainty. When there is insufficient information to be confident of where the target actually is, a contraction bias will tend to maximise the average accuracy of responses. Thus, the more uncertain the experimental conditions then the bigger the effect of the contraction bias. Such a notion suggests that the form of the SDT should be somewhat dependent on the range of targets presented, open to 'cognitive' influences (eg knowledge of the viewing environment), not just found when vergence is the only distance cue but observed in all limited cue environments (eg when size is the only available cue) and show considerable individual variation. An examination of extant studies confirms that these expectations are met (eg Gogel 1969; Tresilian et al 1999).

A general tendency to bias responses towards the range mean is sufficient to explain the SDT observed in reduced cue environments. It is possible, however, that another factor may be contributing towards the distance underestimation found for objects beyond D_s when vergence is the sole distance cue. If vergence is used alone as a distance cue, nothing can be further away than about 6 m or nearer than about 10 cm (outside these bounds there is no distance information, see section 1.1). Within these bounds, the nervous system must be inverting the relationship described by equation (1) (see figure 1b) to determine fixation distance from vergence-angle information. In order for the nervous system to carry out this operation, it must obtain information about the relationship itself—presumably using a process which associates different states of vergence with distance information obtained from other sources. As noted earlier in section 1.1, sensory noise leads to an increase in distance indeterminacy as fixation distance increases. It follows that a small range of vergence states is associated with a large distance range for larger fixation distances [equation (1), figure 1c]. These observations are suggestive: vergence information shrinks space into the range 0.1 to 6 m and, within that range, information content drops off with distance. One further observation may be the key to understanding why the nervous system inverts the angle–distance relationship [equation (1)] in a way which leads to the underestimation of distant objects as described by equation (3). First, if one refers back to equations (1) and (2), a small, symmetrical error range in the vergence-derived binocular-parallax information ($\gamma_0 \pm \varepsilon$) translates into a large range [equation (2)] in the distance estimate. The latter range is asymmetrical about the distance, D_0, corresponding to the binocular parallax, γ_0:

$$D_0 - I\cot(\gamma_0 + \varepsilon) < I\cot(\gamma_0 - \varepsilon) - D_0 \,.$$

This asymmetry is small for near fixations but becomes very large as fixation distance increases. This means that, on average, vergence for more distant fixation will tend to lead to an overestimate of distance. In an attempt to compensate for this, the system could incorporate an underestimation bias for more distant targets. This idea is necessarily speculative but it can be seen that the physiological limitations of vergence may contribute (together with a tendency to systematically bias uncertain magnitude judgments in the direction of the mean) towards the so-called 'SDT'.

Another study which used an open-loop pointing task to assess the contribution of vergence to distance perception gave rather different results from those we have reported (Swenson 1932). In Swenson's study, participants had to point 120 times at three targets (25 cm, 30 cm, or 40 cm) when vergence was the only information available on target distance. Swenson found that the mean pointing response across participants was 24.8 cm, 29.88 cm, and 39.81 cm respectively with a mean variable error (standard deviation) of 1.65 cm. Swenson's results lend support for the notion that vergence can provide reliable distance information but his data lack the SDT. It is known that 'blocking' trials can prevent the appearance of a contraction bias in experimental data (Poulton 1989).

In Swenson's experiments, participants pointed at a single target repeatedly with different targets shown on different days. Swenson's data thus support our contention that vergence can provide accurate distance information and that the SDT should only be manifest in situations where observers are asked to make a series of judgments in conditions of uncertainty.

In contrast to the vergence data, our results suggest that accommodation provided no information that could tell observers where to put their fingers so as to be equidistant with a target (metric distance information). Accommodation was, however, able to provide information about the depth order of sequentially presented targets (ordinal depth information). The ordinal information it did provide was imperfect—the two best participants made the correct ordinal response on about 80% of trials. This contrasts with visually available ordinal cues (such as occlusion) which will normally be 100% reliable; this makes it highly unlikely that accommodation could ever provide useful information for visual space perception. Most importantly, accommodation cannot apparently provide the information necessary for establishing a distance metric for near visual space.

The role of vergence in distance perception becomes more complicated when other information is available. We found that the simple addition of another (nonfixated) dot of light dramatically altered participants' behaviour when pointing at a fixated point light. In this situation, participants judged the nonfixated target to be at the same distance despite changes to the binocular parallax of the fixated target. This result was unexpected because a signal from binocular parallax is required to interpret the available disparity information as a specific distance. Let us suppose, however, that vergence angle was initially used to interpret the horizontally disparate images of the nonfixated point but, after a number of practice trials in which the prism was not present, the nervous system no longer used this extraretinal signal and relied on retinal information regarding the horizontal separation of the disparate images. This explanation suggests that the nervous system learned to associate a particular retinal separation of the diplopic images with a particular egocentric distance. If this explanation were correct then practice trials would be essential for the consistent localisation of the nonfixated target after the addition of the prism. We have conducted additional experiments and discovered that practice trials with no prism are indeed necessary for the consistent localisation of the nonfixated target: if the practice trials are removed then participants locate the nonfixated target on the basis of a signal from the binocular parallax of the fixated object. Notably an SDT was observed in the data collected without the practice trials; this is consistent with previous findings of contraction biases from stereoscopic disparities (Foley 1980; Johnston 1991; neither Johnston nor Foley interpreted their findings in terms of contraction biases) and lends support for the idea that the SDT is not particular to vergence-based estimates of distance. In summary, these results show that extraretinal information is used for distance perception within reduced cue conditions but that perception is also influenced by learning—in particular the memory of the association between the retinal image and distance.

The constant and approximately veridical localisation of the nonfixated target (figure 5a) means that the contribution of vergence to the perception of the distance of this point was negligible. On the other hand, the perceived distance of the fixated point (figure 5b) depended on the vergence angle but the relationship was not as clear-cut as that found when only the fixation point was visible. This suggests that information on the nonfixated target was contributing to the perception of the fixation distance. Thus, memory of the position of the nonfixated point contributed (with vergence) to the perception of fixation distance—but vergence hardly contributed at all to the perception of the distance to the nonfixated point. This behaviour is consistent with our account of the results of the experiment in the somewhat reduced cue conditions

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(sections 2.6 – 3.5) in which the amount of visual information was further increased. In this experiment, a consistent illusion of perceived distance was obtained where egocentric target distance was judged to be significantly greater regardless of whether binocular parallax was increased or decreased (figure 6).

To understand this illusion we formulated a simple heuristic model (Tresilian and Mon-Williams 1999) based upon the premise that individuals use many sources of distance information to obtain a self-consistent representation of 3-D space (see Bruno and Cutting 1988; Brunswick 1952). Particular cues are likely to be ambiguous or unreliable in isolation; a suitable combination can, however, yield a veridical and accurate representation of space (see Grossberg 1994; Massaro 1988). The heuristic model assumes that there are three interacting sources of information: the vergence angle of the eyes, horizontal disparities from the box end, and monocular cues providing information about box-end distance. We propose that these cues interact as follows.

(a) The sensory estimate of the convergence angle (γ') provides an estimate (D'_v) of target distance (D):

$$D'_\mathrm{v} = I \cot \gamma' . \tag{4}$$

(b) Relative horizontal disparity, $R(\approx dI/D^2)$, provides information about the distance, d, between the target letter and the end of the viewing box. Combined with information about target distance and interpupillary distance I, disparity can provide an estimate (d') of d,

$$d' = D'^2_\mathrm{v} R/I = D'^2_\mathrm{v} d/D^2 . \tag{5}$$

Substituting for D'_v from equation (5):

$$d' = d(I \cot \gamma'/D)^2 . \tag{6}$$

(c) Consistent (prism-independent) monocular cues and vertical binocular disparities could, in principle, provide a reasonably accurate estimate of the distance of the box end from the eye (E). This information, combined with the disparity-derived information about d [equation (6)], can provide an estimate (D'_ER) of the target distance: $D'_\mathrm{ER} = E' - d'$, hence

$$D'_\mathrm{ER} = E' - d(I \cot \gamma'/D)^2 . \tag{7}$$

(d) The two sources of information about target distance provided by equations (4) and (7) can be combined by a weighted averaging process (Anderson 1981; Bruno and Cutting 1988; Massaro 1988) to give an overall estimate of target distance:

$$D'_\mathrm{p} = w_1 (D'_\mathrm{v}) + w_2 (D'_\mathrm{ER}) , \tag{8}$$

where w_1 and w_2 are weighting factors. Such a weighted averaging requires that the weights sum to 1 (eg Mulligan and Shaw 1980). Weights of this kind are often treated as factors which reflect the 'confidence' that the nervous system attaches to different sources of information (eg Young 1971; see also Massaro 1988; Welch and Warren 1980). If the confidence associated with D'_v is c_1 and that associated with D'_ER is c_2 then the relative confidences, $c_1/(c_1+c_2)$ and $c_2/(c_1+c_2)$, sum to 1 and the weights (w_1, w_2) can be made equal to these (see Tresilian 1994). This scheme means that the weights are constrained to lie in the interval [0, 1].

This model is an heuristic simplification but it does explain the consistent overestimation of distance with both base-in and base-out prism. It also explains why the fixated target was seen to be in different places in the experiment with two dots of light that we described (figure 5). In the experiment with two dots of light, participants had access to fairly accurate information about the location of the unfixated point as indexed by their pointing responses. When estimating the location of the fixated point, participants appeared to use a combination of the information derived from the unfixated point and that obtained from vergence-angle information—as the heuristic model just outlined supposes. It will be noted that the model makes certain predictions regarding pointing responses as a function of the viewing environment. If the premises of the model are correct, then moving the end of the viewing box should alter where participants locate the targets. We have tested this in a series of experiments. The results of these experiments have supported our prediction: bringing the box end closer or increasing the box length by a metre results in the illusion disappearing and participants underpointing when binocular parallax specifies a closer distance (Tresilian and Mon-Williams 1999; Tresilian et al 1999).

In summary, 'absolute' distance information is required to provide a body-referenced distance metric for visual space. Both retinal cues and extraretinal cues can, in principle, provide this necessary information: this paper has been concerned with the potential contribution of the two extraretinal cues to distance perception. The results of our experiments clearly show that accommodation cannot be a source of the required distance information. Moreover, although in certain conditions accommodation may influence depth perception it seems highly unlikely that it does so in everyday situations (since it appears to provide only coarse ordinal information—possibly via the accommodative – vergence crosslink). In contrast, it is well established that vergence is a distance cue for near visual space. Our own experiments have shown that vergence can be used to reliably locate the distance of targets up to at least arm's length although such judgments are prone to a contraction bias. When additional depth and distance cues are added, the contribution of vergence information quickly becomes complicated. Our results indicate that the different cues to depth and distance are combined to provide a coherent percept of space and that this combination is not a simple linear averaging of the available cues (see also Rogers and Bradshaw 1995; Tresilian et al 1999). The combination process appears to be a complex one which can result in unexpected distortions of visual space, such that the distances of some visible points and objects can be perceived accurately whereas others, within the same scene, are perceived as closer or further away than they actually are.

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