

James R. Tresilian · Mark Mon-Williams

Getting the measure of vergence weight in nearness perception

Received: 2 July 1999 / Accepted: 24 December 1999 / Published online: 31 March 2000
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Abstract Combining multiple sources of information allows the human nervous system to construct an approximately Euclidean representation of near (personal) space. Within this space, binocular vergence is an important source of egocentric distance information. We investigated how the nervous system determines the significance (weight) accorded to vergence information when other (retinal) distance cues are present. We found that weight decreases with (1) increasing discrepancy between vergence information and other cues and (2) reduced vergence demand. The results also provided evidence that the nervous system represents vergence related distance information in units of nearness (the reciprocal of distance).

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

Introduction

Humans (and other primates) are extremely proficient in reaching to pick up objects. Such skilled behaviour is marked by an ability to correctly judge the distance to be reached before onset of movement. Prehensile behaviour occurs within a region (<1.5 m) generally reported as being approximately Euclidean in nature (see Cutting 1997 for a review of the empirical evidence) and described as ‘personal’ space (Cutting 1997). In order to achieve an Euclidean representation of this space, people integrate multiple sources of information or ‘cues’ (Cutting 1997; Brunswick 1952; Landy et al. 1995). A number of cues potentially contribute to the representation of distance

(Cutting 1997), but this paper is restricted to considering ocular vergence. Since at least the time of Descartes it has been appreciated that observers could obtain an estimate of the distance of a binocularly fixated point from knowledge of vergence angle. Some recent studies have explored the use of binocular vergence in distance perception (see Tresilian et al. 1999; Mon-Williams and Tresilian 1999). The results of these studies have indicated that binocular vergence is a valuable source of egocentric distance information. Nonetheless, little progress has been made in documenting how vergence is integrated with other cues to provide the Euclidean representation required for skilled interaction with objects in personal space.

Many studies have reported that cue integration is equivalent to computation of the weighted mean of participating cues (Landy et al. 1995; Bruno and Cutting 1988; Doshier et al. 1986; Young et al. 1993) – only at threshold have significant exceptions been found (Bradshaw and Rogers 1996). Thus, weighted average computation is a well established model of cue combination (Landy et al. 1995; Howard and Rogers 1995). The model requires that: (1) each cue is associated with a multiplicative scale factor or weight (the sum of the weights being one) and (2) cues are represented in a common unit so that they can be added together in a meaningful manner (Landy et al. 1995). We investigated the role of two factors hypothesised as major contributors to the determination of cue weight: (1) the cue’s intrinsic reliability, which is related to such factors as its signal to noise ratio (Massarro 1988; Young 1971; Von Holst 1973). Previous work suggests that the reliability of vergence information decreases with increasing egocentric distance – implying a constant level of additive noise or a constant uncertainty in the measure of vergence angle (Cutting 1997; Collett et al. 1991). (2) The degree to which the cue conflicts with information provided by other available cues – its discrepancy (Landy et al. 1995; Maloney and Landy 1989).

To investigate the role of fixation distance and discrepancy, vergence was manipulated with ophthalmic prisms. In order to unequivocally interpret the prismatic

J.R. Tresilian
Human Movement Studies, University of Queensland,
St. Lucia, Queensland 4072, Australia

M. Mon-Williams (✉)
School of Psychology, University of St. Andrews,
St. Andrews, Fife KY16 9JU, Scotland
e-mail: mon@st-andrews.ac.uk
Tel: +44 1334 462074, Fax: +44 1334 463042

effect, it is necessary to consider the units in which vergence and discrepancy information are represented by the nervous system for the purpose of determining cue weight (otherwise it is not clear as to whether cue discrepancy is being held constant or varying when viewing targets at different distances through a fixed power prism). Two possible alternatives for the type of unit suggest themselves. First, actual distance units might be used. Second, since vergence is essentially an angular quantity it could be represented in angular or reciprocal distance units. We refer to the angular or reciprocal distance units generically as *nearness* units (Gårding et al. 1995; Koenderink and van Doorn 1976). Let the estimate of fixation distance provided by vergence (vergence specified distance) be denoted D_v and the estimate of a fixated object's distance provided by other cues be denoted D_c . The discrepancy of the vergence estimate from the estimate provided by the other cues is equal to $|D_c - D_v|$ in distance units and $|(1/D_c) - (1/D_v)|$ in nearness units. It should be noted that angular and nearness units are virtually equivalent in the reported experiment (they only become significantly different when the small angle approximation breaks down). A number of models implicitly assume that angular units are used in distance perception (e.g. Gårding et al. 1995), but the issue of what units are used in weighting different cues requires empirical investigation. Notably, our particular concern is not with the units of combination, per se, but in the units used in weighting different cues for the purpose of combination. The level at which such weighting occurs is not clear a priori and thus the issue rests upon empirical study.

Formally, we hypothesised that vergence weighting ($0 \leq w \leq 1$) would decrease as either discrepancy (δ) or the fixation distance specified by vergence (D_v) increased and thus $w = f(\delta, D_v)$ where f is a monotonically decreasing function in each argument. We investigated two specific questions about the dependency of vergence weighting on D_v and δ : first, is the dependency (f) linear or non-linear? Second, do δ and D_v act additively or do they interact? In order to examine the first question, we formulated a linear model meeting the requirement that f is monotonically decreasing:

$$w = a - b\delta - cD_v \quad (1)$$

where $a, b, c \geq 0$ are parameters, constant for a given set of conditions. Note that both δ and D_v are bounded: vergence has a physiological near limit (ca. 10 cm) and a far limit (the eyes are effectively parallel for fixation $\geq 3-6$ m). The discrepancy of vergence from other cues is also bounded in the context of our experiment and almost certainly in the experience of the nervous system. These facts make a linear model a plausible one for the nervous system to use in determining vergence weighting.

In order to test this model empirically it is necessary to vary discrepancy (δ) and fixation distance (D_v) independently and observe the effect on a measure of vergence weight. Figure 1, upper, shows the weight plotted

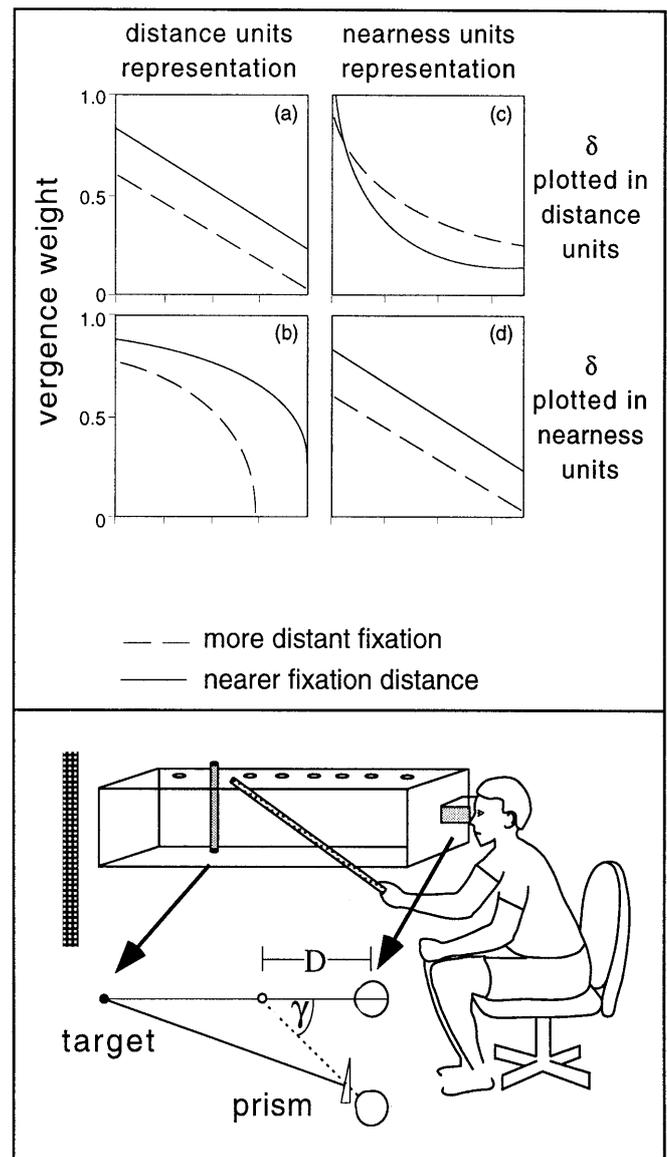


Fig. 1 Upper Schematic qualitative behaviour of vergence weighting as a function of discrepancy predicted by the linear model ($0 < \text{vergence discrepancy} < 80$ cm; $10 \text{ cm} < \text{fixation distance} < 1$ m). The curves are characteristic of Eq. 1 for values of the free parameters within the required range ($0 < w < 1$). Panels *a* and *c* plot the weights derived from the models in units of distance. Panels *b* and *d* plot the model derived weights in units of nearness. The left panels (*a*, *b*) show model behaviour when discrepancy is represented (by the system) in distance units; *c* and *d* show model behaviour when discrepancy is represented in nearness units. Lower Schematic of the experimental apparatus. Participants indicated perceived distance by placing the tip of an unseen stick so as to be equidistant with the target. The diagram also illustrates the geometry of binocular viewing. Vergence angle (γ) decreases as fixation distance (D_v) increases. For small values vergence angle is almost exactly equal to the reciprocal distance (N) scaled by the interocular distance (I), i.e. $\gamma \approx IN$. When D_v is 22 cm, the error is less than 0.5° . The vergence angle required to fixate a target at distance D_v can be manipulated by placing a prism in front of one eye as shown

as a function of δ for two different values of D_v within the range $0.1 < D_v < 1.0$ m (Eq. 1). These plots match the values and range of D_v used within the actual experiment. If the units in which discrepancy is represented by the (nervous) system match the units in which discrepancy is plotted, then plots of Eq. 1 are straight lines (Fig. 1, upper, a,d). If the plotting and representation units do not match, then the lines are curvilinear (Fig. 1, upper, b,c). It is important to note an interesting feature of the model. If discrepancy is represented in nearness units but distance units are used for plotting, then the curve for the nearer fixation distance falls below that of the larger fixation distance over a wide range of discrepancies. This is an important qualitative feature for identifying the units of representation since it is only predicted for nearness units. We report an experiment designed to investigate these issues by varying δ and D_v independently and observing the effect on an empirical estimate of vergence weighting.

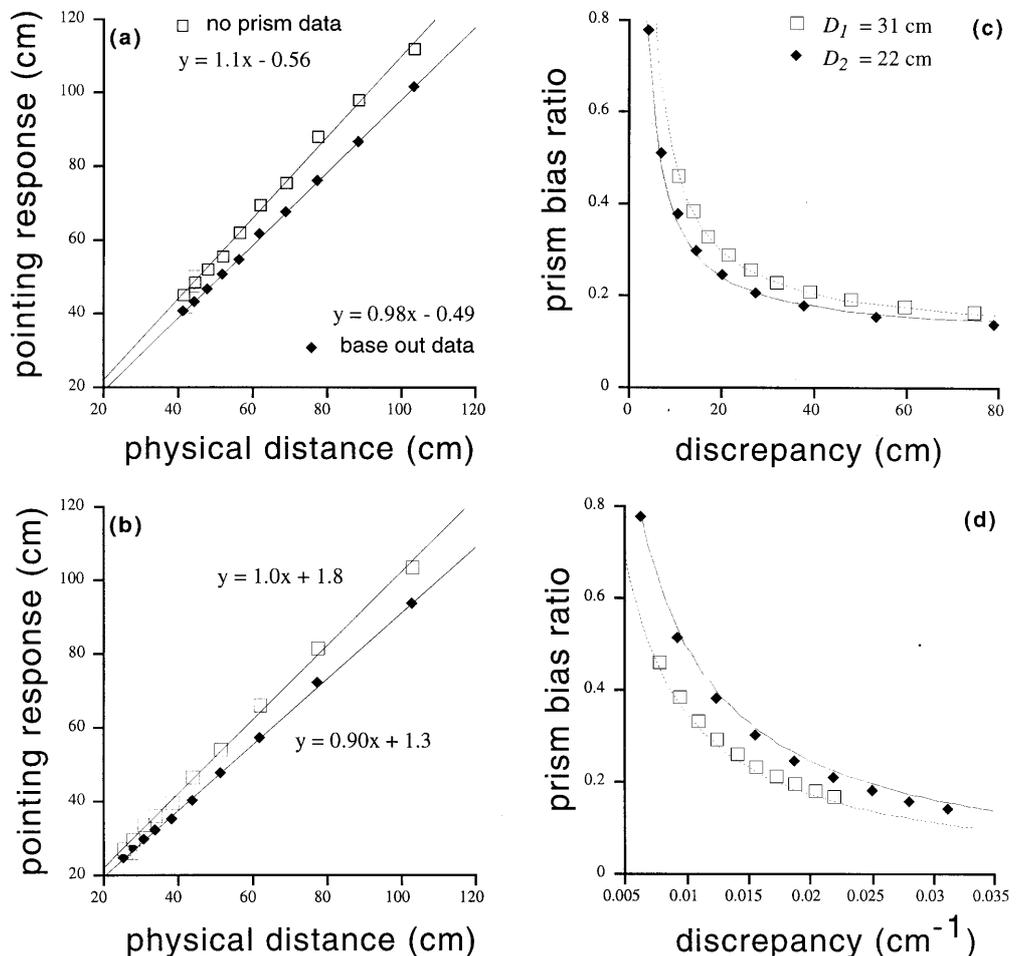
Materials and methods

Twelve undergraduates (aged 18–21 years, six females) participated in the experiment. Participants binocularly viewed targets through an aperture (9×4 cm) in front of a viewing box (dimensions = 130 cm deep × 65 cm wide × 21 cm high). A moulded plas-

tic restraint reduced head movements and occluded peripheral vision. The constraint minimised motion parallax but did not remove this source of information. The restraint contained trial frames (diameter 3 cm) into which an ophthalmic prism could be placed. The prisms were designed to minimise unwanted optical aberrations: they were reduced aperture trial lenses which had no refractive power but had a curved front and rear surface (equal to +6.00 D and -6.00 D). This type of prism is known as a meniscus plano prism. Apertures in the top of the box allowed targets to be aligned with the axis of the right eye (primary position). The viewing environment was well illuminated (ca. 500 lux) but sparse – all of the surfaces were painted matt black. Painting the surfaces reduced the visible texture of the viewing environment but did not remove it – texture and linear perspective information were thus available. The box had its far end open so that a vertical disparity gradient (approx. 30°) was available as a distance cue. A homogeneous textured surface was placed 15 cm from the end of the box and the target was viewed against this background. The participants fixated the targets through the prism so that the target was foveated by both the right and left eyes. In these circumstances, prisms do not change retinal image disparities but they do alter the vergence information used to interpret the disparities. It should be noted, therefore, that the background surface was carefully positioned in order to ensure that monocular cues regarding the background surface were not combined with horizontal retinal image disparity cues. We previously have observed unexpected distortions of visual space when this condition is not met (see Tresilian and Mon-Williams 1999). A target of constant size was used so the participants had access to distance information from learned target size.

The experimental task was to position the tip of an unseen stick (96×1.6-cm circular dowel tapered to a 2-mm tip) at the perceived distance of the target (Fig. 1, lower). The stick was held

Fig. 2 *Left panels* Perceived distance data averaged across participants, plotted as a function of target distance: **a** 31-cm condition (D_1); **b** 22-cm condition (D_2). *Error bars* show standard deviation between participants. *Straight lines* are least squares fits to the data using linear regression ($r^2 \geq 0.99$ in every case). Equations for each fit are shown (y = perceived distance, x = target distance). *Right panels* Mean results expressed as the prism bias ratio and plotted as a function of discrepancy in distance units (**c**) and nearness units (**d**) for D_1 and D_2 . *The curves* show the best-fitting two-parameter model represented by Eq. 4 – see text for details



with the right hand and participants were free to grasp it wherever they chose. The target was a 0.7-cm-diameter dowel that extended from the bottom to the top of the box. The prismatic power was systematically increased with target distance so that vergence specified distance (D_v) was always constant when viewing through the prism. The participants were randomly allocated to one of two groups. In the first group, D_v was maintained at 31 cm (D_1) whilst in the second group D_v was maintained at 22 cm (D_2). In the first group the prism systematically increased from 5Δ for the closest target (42 cm) to 14Δ for the furthest target (ca. 104 cm) in 1Δ steps – this resulted in ten target positions between 42 and 104 cm. In the second group the prism systematically increased from 2Δ (the angular shift induced by a prism dioptre, 1Δ , is atan 0.01) for the closest target (ca. 25 cm) to 20Δ for the furthest target (ca. 104 cm) in 2Δ steps – this resulted in ten target positions between 25 and 104 cm. The observers pointed to each target 5 times when viewing through a prism and 5 times without a prism (i.e. a total of 100 trials) with the order of presentation randomised for each participant. 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).

Landy et al. (1995) developed a definition for an empirical measure of cue weight based on the weighted averaging model. The measure relies on changing one cue whilst holding several others constant. For distance perception, the weight is the change in perceived distance expressed as a proportion of the change in that cue (vergence discrepancy in the current experiment). The change is the difference between the perceived distance of a target with vergence discrepant and with vergence concordant (no prism). Thus, the ratio (perceived distance difference)/(vergence discrepancy) is an empirical measure of vergence weighting conforming to Landy et al.'s (1995) definition. We refer to this measure as the ‘‘prism bias ratio’’ (PBR, Tresilian et al. 1999) and calculate it for each individual participant as follows. For each target position, the perceived distance for a given prism induced discrepancy was subtracted from the perceived distance with no discrepancy. This difference was then divided by the difference between the target's physical distance and the vergence specified target distance (D_v) with the prism in place. D_v was calculated in the following manner: let the vergence demand of the target without prism be γ_1 and the vergence demand of the target with prism be γ_2 and Δ the prismatic displacement. Then, if the prism increases vergence demand, $\gamma_2 = \gamma_1 + \arctan \Delta$. The vergence specified distance, D_v , can be calculated as:

$$D_v = I \cot \gamma_2 \quad (2)$$

where I is the interpupillary distance. This measure of PBR requires that the participants show reasonably accurate pointing – this requirement was met under the experimental conditions.

Results

Testing the linear model

Figure 2a,b shows the group mean pointing response as a function of target distance. The plots show that the perceived distance of the target was a linear function of its actual distance. The effect of the prism was always in the predicted direction: the target appeared nearer than it did in the absence of the prism. In order to evaluate the linear model, the data were replotted in the form of Fig. 1, upper, using the PBR as a measure of vergence weighting. When the effect of the prism is small, the PBR becomes sensitive to response variability. In order to circumvent this problem we used the linear regressions shown in Fig. 2a,b to calculate the effect of the prism for

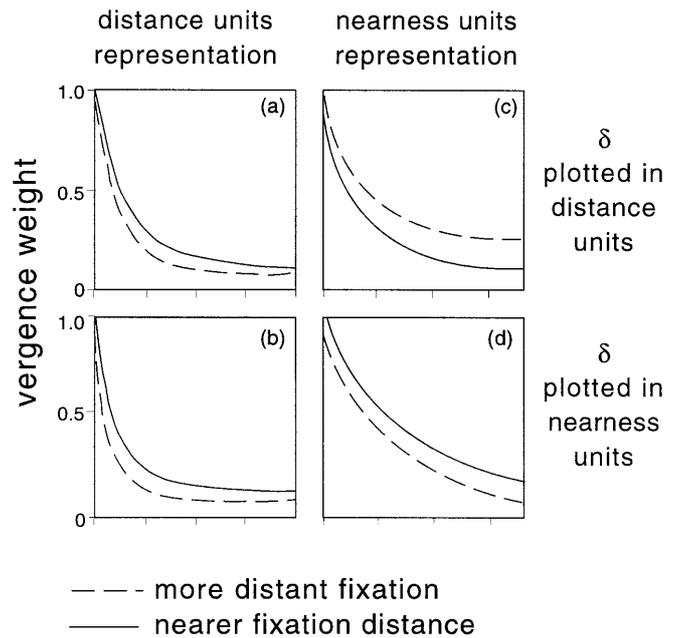


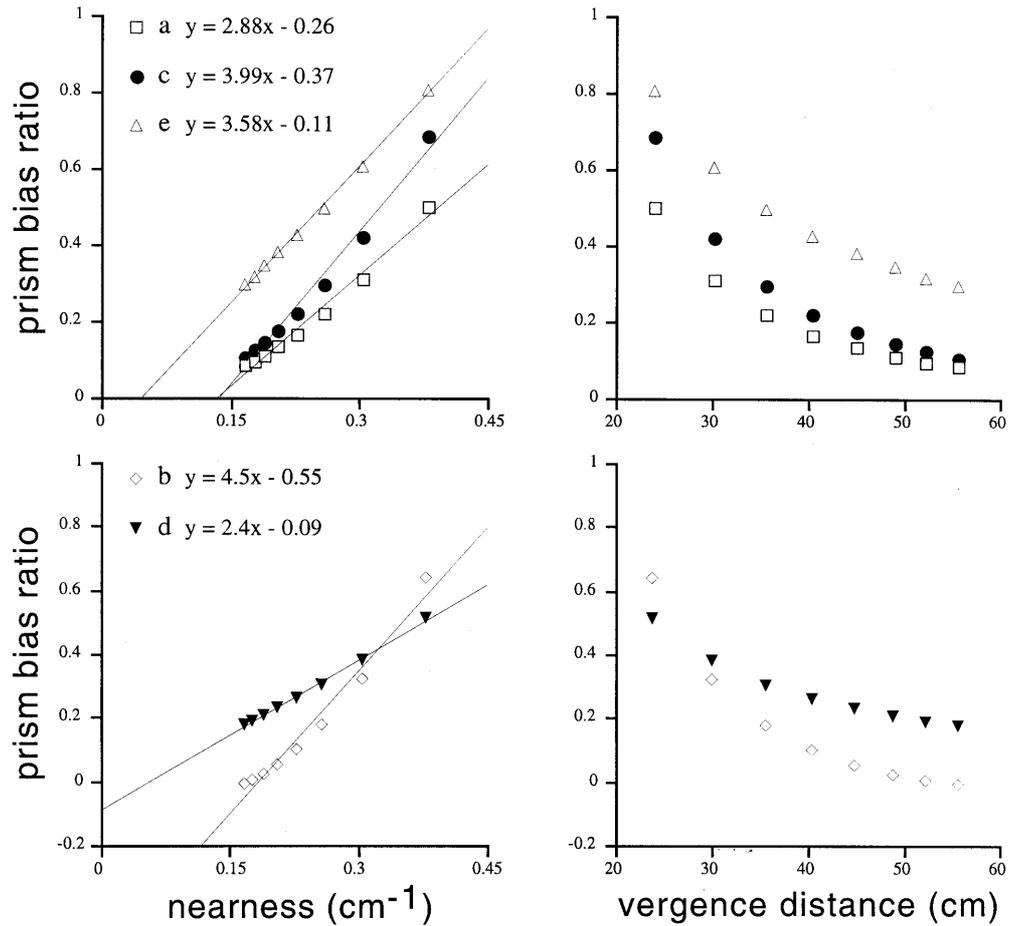
Fig. 3 Schematic qualitative behaviour of vergence weighting as a function of discrepancy predicted by Eqs. 3–6 in the text. Format is the same as Fig. 1, upper: the upper panels (a,c) plot the weights derived from the models in units of distance. The lower panels (b,d) plot the model derived weights in units of nearness. a and b show model behaviour when discrepancy is represented (by the system) in distance units; c and d show model behaviour when discrepancy is represented in nearness units

each target position; these regressions gave extremely good fits to the data ($r^2 \geq 0.99$). Since the PBR changes with discrepancy for fixed vergence angle (Fig. 2c,d), the data clearly show that discrepancy influences vergence weighting independently of fixation distance. Figure 2c,d can be compared with the qualitative predictions of the linear model shown in Fig. 1, upper. It is clear that the results do not agree with the form shown and thus we can exclude the linear model.

Testing non-linear models

We investigated further the form of the non-linear dependency of the PBR by formulating a series of simple non-linear models. We chose the simplest models in the sense that they were monotonically decreasing in D_v and δ , had no more than three parameters and involved no complex functional dependencies. Two types of model were considered: (i) those in which vergence weighting is inversely proportional to both δ and D_v and (ii) those in which vergence weighting is inversely proportional to δ but directly proportional to D_v . It is important to note that the model-fitting exercise is an empirical enterprise – as there is no theory about cue weight determination it is impossible to derive models from a theoretical base. The models are, however, motivated by both the form of the data and parsimony. The following possible models were considered (in each case $m_i, n_i, p_i \geq 0$ are the param-

Fig. 4 Mean results from the base-out prism data of Tresilian et al. (1999) expressed as the prism-bias ratio and plotted as a function of target nearness (*left*) and vergence specified distance (*right*). Straight lines are fits to the data from each condition using linear regression ($r^2 > 0.97$ in each case). Symbols denote the stimulus conditions as shown in the key. The different conditions were: *a* target size information in a rich cue environment, *b* no target size information in a rich environment, *c* target size information in a reduced cue environment, *d* no target size information in a reduced cue environment, *e* target size information in darkness



eters). First, a model of type (i) without interaction between δ and D_v :

$$w = [m_1 + n_1 \delta]^{-1} + p_1 / D_v \tag{3}$$

Second, a model of type (i) with interaction:

$$w = [m_2 + D_v(n_2 + p_2 \delta)]^{-1} \tag{4}$$

Third, a model of type (ii) without interaction:

$$w = [m_3 + n_3 \delta]^{-1} - p_3 D_v \tag{5}$$

Finally a model of type (ii) with interaction:

$$w = (m_4 - n_4 D_v) [p_4 + \delta]^{-1} \tag{6}$$

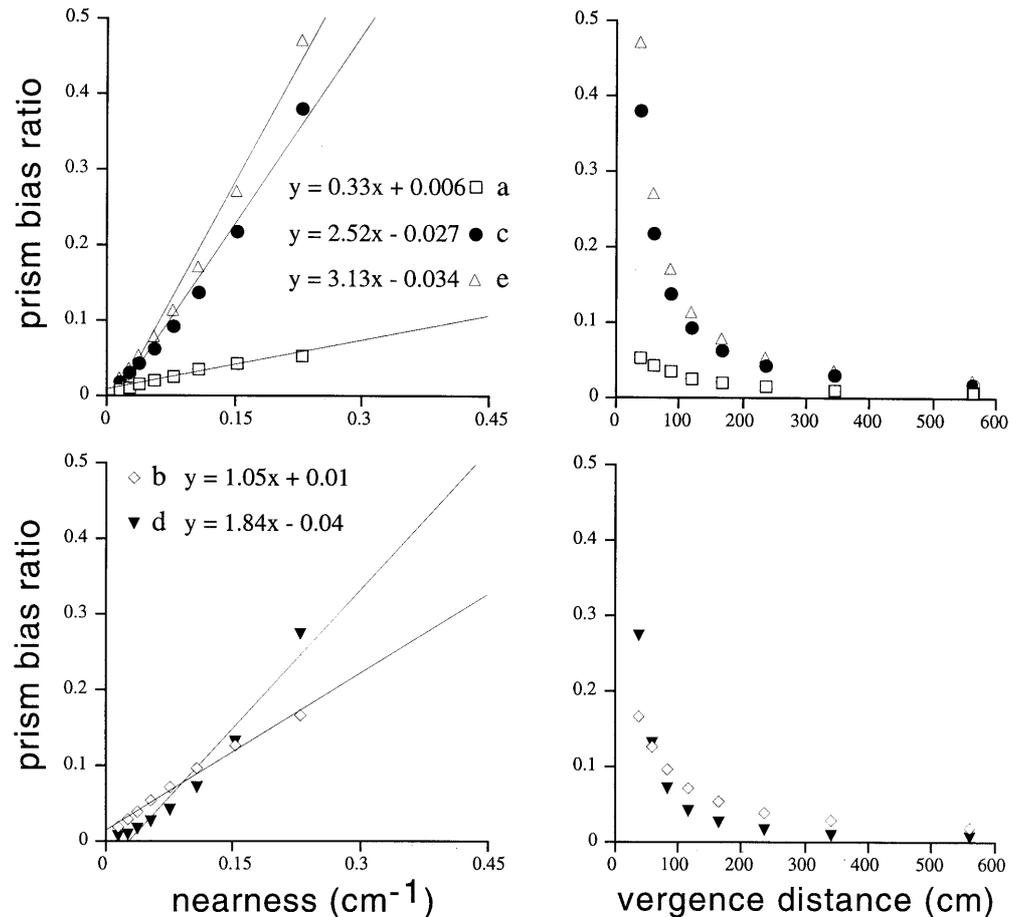
Qualitatively, these types of model all display a similar pattern of behaviour (Fig. 3). When discrepancy is represented in nearness units and the plotting units fail to match, the curve for the nearer fixation distance lies beneath the curve for the more distant fixation distance (Fig. 3c). When the plotting units match, the expected ordering of the curves is observed (Fig. 3d). This effect is also observed in the linear model (Fig. 1, upper, c,d). The PBR data show exactly this feature: when plotted as a function of discrepancy expressed in distance units, the data points for D_1 all lie above those for D_2 (Fig. 2c). When the same data are plotted as a function of discrepancy in nearness units, the data points for D_1 lie beneath those for D_2 (Fig. 2d). This pattern in the results is thus

evidence that the nervous system represents discrepancy in nearness units.

All the non-linear models can reproduce the qualitative pattern of the data. Moreover, models of type (i) cannot be distinguished from type (ii) quantitatively – we were able to produce similarly accurate fits with models of either type. We attempted to determine which of them best describes observed performance in two stages. First we used results reported in an earlier paper (Tresilian et al. 1999) to determine which type of model was more appropriate. Second, we evaluated the ability of the model favoured in the first stage to quantitatively fit the data shown in Fig. 2c,d.

In the experiment reported by Tresilian et al. (1999), participants pointed at targets placed at eight different distances between 30 and 100 cm looking through a fixed power prism oriented nasally or temporally under five viewing conditions (Figs. 4, 5). If discrepancy is represented in nearness units, the use of a fixed power prism implies that δ was held constant (in angular units) as D_v varied. In this case, variations in the PBR would be due to changes in D_v . Furthermore, if vergence weighting varies in inverse proportion to D_v , the PBR should be a linear function of D_v expressed in nearness units but a non-linear (reciprocal) function in distance units. To assess this prediction we replotted the PBR data. Figures 4 and 5 show the data (obtained from the linear regression

Fig. 5 Mean results from the base-in prism data of Tresilian et al. (1999) expressed as the prism-bias ratio and plotted as a function of target nearness (*left*) and vergence specified distance (*right*). See legend to Fig. 4



equations of Tresilian et al. 1999) expressed in terms of nearness (left) and distance (right), separated into plots for prism oriented temporally (Fig. 4) and nasally (Fig. 5). The plots are approximately linear in units of nearness but non-linear in units of distance. The only indication of non-linearity in the 'nearness' plots is where some of the lines show signs of a 'toe' region as they approach very low values of the PBR. These results suggest that a model of type (i) is appropriate. We therefore fit models of type (i) to the data shown in Fig. 2 using non-linear least squares regression. Both sets of data (D_1 and D_2) were fit simultaneously to find the single set of parameters that minimised the squared error for the complete data set. We compared the quantitative fits provided by Eqs. 3 and 4 to determine whether there was evidence for an interaction between D_v and δ . The mean squared error for the fit of the model defined by Eq. 3 was 0.007. It was found that even the one-parameter model, $[p_2 D \delta]^{-1}$, formed when m_2 and n_2 in Eq. 4 are set to zero, gave a better fit to the data than a three-parameter model defined by Eq. 3: mean squared error for the one-parameter model was an order of magnitude smaller (being less than 0.0007). A two-parameter version which included n_2 improved the fit, giving a mean squared error of less than 0.0002 (Fig. 2c,d). These results suggest that D_v and δ interact in the determination of vergence weighting.

An interesting feature of the data replotted from Tresilian et al. (1999) is that the temporal prism data (Fig. 4) are different from the nasal prism data (Fig. 5). These differences may be explained by the direction of the prism induced discrepancy – temporal prism causes vergence to provide a distance estimate which is closer than the other information whilst nasal prism causes an estimate which is further. It seems reasonable to suggest that the nervous system decreases the weighting attached to vergence when it provides a further estimate than other available cues because of the decreased reliability associated with increasing fixation distance.

Discussion

In the interpretation of our findings we assume: (1) the weighted averaging hypothesis for cue combination; (2) the prism bias ratio (PBR) is a measure of vergence weighting directly proportional to the actual weighting; and (3) the only stimulus related variables influencing the PBR are vergence specified fixation distance (D_v) and discrepancy (δ). With these assumptions, the data may be interpreted as demonstrating three things. First, increased δ causes a non-linear decrease in vergence weight, with the relationship being accurately described as reciprocal. Second, δ and D_v codetermine vergence

weight and interact. Third, the nervous system represents distance information in nearness units – at least for the purpose of determining cue weight.

The three assumptions we have made are likely to be only approximately true. Assumption (1): the weighted averaging hypothesis should be viewed as an approximate, empirical description of the combination process. Assumption (2): the PBR is only a measure of vergence weight if (1) is accurate and is an unstable measure of weight for small discrepancies. Assumption (3): vergence discrepancy was increased in the experiment by increasing actual target distance. As the reliability of some retinal cues may decrease with increasing distance, the reliability of some retinal information may also have varied in the experiment. Within the weighted averaging model framework, this covariation will lead to the PBR overestimating the true vergence weight. The model assumes that the nervous system associates a scalar quantity, c , with each cue. This quantity reflects the confidence placed in that cue (Massarro 1988; Young 1971). A weight is then computed as the normalised confidence, i.e. for some number, n , of cues, the weight of the i th cue being given by $c_i/(c_1+c_2+\dots+c_n)$:

$$w_i = \frac{1}{(\sum c_o / c_i) + 1} \quad (7)$$

where $\sum c_o$ is the sum of the confidences associated with all cues except the i th. Let w_i be the vergence weight: if the reliability of other cues decreases as discrepancy increases, then $\sum c_o$ will decrease as c_i decreases. This means that $(\sum c_o / c_i)$ will be smaller and vergence weight larger than if $\sum c_o$ remained constant. Indeed, if the decrease in $\sum c_o$ exactly matched the decrease in c_i , then vergence weight would remain constant with increasing discrepancy. The fact that the PBR decreased with increasing discrepancy can be interpreted as meaning that the decrease in c_i is greater than any accompanying decrease in $\sum c_o$.

Even if all three assumptions are false and the concept of vergence weight has no referent within the nervous system, it is still possible to conclude that the contribution of vergence to nearness perception is codetermined by D_v and δ and that these factors interact. Precise interpretation of the interaction is complicated even in weighted average type models because of the way weights are determined by ‘confidences’ (Eq. 7). This means that an interaction between two factors may result from: (1) direct interaction in determining confidence for a particular cue and (2) the confidence associated with one or more of the other cues being indirectly influenced. Whilst the vergence discrepancy should affect only the confidence attached to the vergence cue, it is possible that fixation distance influenced the confidence in other cues. Nevertheless, the two experimental fixation distances were only 9 cm apart and we know of no evidence to suggest that the confidence in retinal cues would be influenced by such a small interval. We suggest, therefore, that fixation distance and discrepancy

may interact directly in the determination of vergence weight.

In summary, we suggest that vergence weighting is determined by vergence specified fixation distance and discrepancy and that these quantities are represented by the nervous system in nearness units. It follows that Fig. 3a shows a non-linear decrease in vergence weighting associated with increasing discrepancy, whereas Figs. 4 and 5 show a linear decrease in weighting associated with decreasing fixation nearness. There was evidence for an interaction between discrepancy and fixation. These results are the first to have demonstrated that the weighting given to a cue decreases systematically with that cue’s discrepancy and that the nervous system uses nearness units when determining the weight given to a distance cue.

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