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RESEARCH ARTICLE

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Vertical gaze angle: absolute height-in-scene information for the programming of prehension

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Abstract One possible source of information regarding the distance of a fixated target is provided by the height of the object within the visual scene. It is accepted that this cue can provide ordinal information, but generally it has been assumed that the nervous system cannot extract "absolute" information from height-in-scene. In order to use height-in-scene, the nervous system would need to be sensitive to ocular position with respect to the head and to head orientation with respect to the shoulders (i.e. vertical gaze angle or VGA). We used a perturbation technique to establish whether the nervous system uses vertical gaze angle as a distance cue. Vertical gaze angle was perturbed using ophthalmic prisms with the base oriented either up or down. In experiment 1, participants were required to carry out an open-loop pointing task whilst wearing: (1) no prisms; (2) a base-up prism; or (3) a base-down prism. In experiment 2, the participants reached to grasp an object under closed-loop viewing conditions whilst wearing: (1) no prisms; (2) a base-up prism; or (3) a base-down prism. Experiment 1 and 2 provided clear evidence that the human nervous system uses vertical gaze angle as a distance cue. It was found that the weighting attached to VGA decreased with increasing target distance. The weighting attached to VGA was also affected by the discrepancy between the height of the target, as specified by all other distance cues, and the height indicated by the initial estimate of the position of the supporting surface. We conclude by considering the use of height-in-scene information in the perception of surface slant and highlight some of the complexities that must be involved in the computation of environmental layout.

Keywords Prehension · Distance perception · Motor programming · Visual cues · Height-in-scene · Human

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Introduction

Artists, philosophers and scientists have been interested in distance perception for many centuries (Cutting and Vishton 1995). Cutting and Vishton (1995) have suggested that "the most curious fact about psychological approaches to the study of layout is that its history is little more than a plenum of lists". Cutting and Vishton are referring here to the various lists of distance cues (e.g. vergence, vertical disparity etc.) provided in almost every introductory textbook on psychology or physiology. In the perceptual literature, it is customary to reserve the term "distance" for egocentric judgements, whilst the term depth is used to describe an object's dimension along the line of sight. This paper is concerned with *how* just one of those distance cues – height in the visual scene – is used. It has been recognised for a long time (since at least the time of Euclid) that the vertical position of objects within the visual scene provides useful distance information. Moreover, most commentators recognise that height-in-scene can provide good ordinal information regarding distance (many introductory textbooks provide figures that illustrate this point). It is widely accepted, however, that height-in-scene cannot provide absolute distance information (e.g. Cutting and Vishton 1995). There is no evidence against the notion that height-in-scene can provide absolute distance, but it is generally held that the assumptions required to obtain absolute information are too strong. Cutting and Vishton have suggested that four assumptions are required for the use of height-in-scene as a distance cue: (1) opacity of the ground plane; (2) each object has its base on the surface of support because of gravity; (3) the observer's eye is at a known distance above the surface of support; and (4) that the surface of support is generally planar and orthogonal to gravity. We would suggest that an additional assumption is required for extracting absolute information from height-in-scene: (5) the nervous system has knowledge of ocular position with respect to the head and to head orientation with respect to the shoulders (i.e. vertical gaze angle). Cutting and Vishton (1995, p. 87) suggest that the numerical order of these assumptions follows "acceptance, if not plausibility" and state that "we feel that Assumptions (1) and (2) are the only ones generally valid" (the first two assumptions mean that height-in-scene can provide ordinal information). There is little evidence against Cutting and Vishton's suggestion, but the results of a study by Marotta and Goodale (1998) hint at the idea that height-in-scene might be able to provide absolute distance information. Marotta and Goodale studied prehensile movements and found that participants carrying out the task with only one eye open made "fewer on-line adjustments when the elevation of the target object in the visual scene could be used to help program the required movements". Moreover, some recent studies have indicated a role for eye-height (EH) in visual perception. Size information can be scaled by EH if object height is specified relative to the horizon (Sedgwick 1973) – either the visible horizon or the "implicit horizon" as specified by texture gradients or optic flow fields (Wraga 1999a). A number of studies have provided evidence that EH is used when judging the size of target objects (Warren and Whang 1987; Bertamini et al. 1998; Wraga 1999a, 1999b). Nonetheless, there is no clear evidence against the generally held position that height-in-scene does not provide absolute distance information.

A recent observation caused us to question the received position regarding absolute information from height-in-scene. Our observation concerned a patient with visual form agnosia, patient DF. Patient DF relies predominantly on vergence information when gauging target distance in an open-loop pointing task (Mon-Williams et al. 2000). This finding suggested that the programming of prehension might be severely disrupted if DF viewed target objects whilst vergence angle was perturbed. We found, however, that this prediction was erroneous – DF is able to program reasonably accurate movements to objects located on a tabletop despite perturbation of vergence angle. A second experiment showed that placing target objects at eye height whilst manipulating vergence angle caused DF to move her hand to the wrong position. Notably, the evidence for DF's reliance on vergence distance information was obtained in a task where the targets were at eye height.

This observation indicated that the human nervous system can extract absolute distance information from height-in-scene. Figure 1 illustrates how the nervous system could extract absolute distance information – we will refer to the source of absolute information from height-in-scene as "vertical gaze angle" (VGA) in order to differentiate this cue from the ordinal and relative information available from the retinal image alone. From Fig. 1, three facts emerge: first, if the height of the eye above a planar supporting surface orthogonal to gravity is known, then VGA provides a potentially accurate cue to a target's egocentric distance (Fig. 1, upper panel). Second, the relationship between VGA and distance is nonlinear (Fig. 1, middle panel), with small changes in VGA being related to large changes in egocentric distance for far objects and vice-versa for proximal targets. This aspect of the viewing geometry is important for understanding our experimental results, and we will return to this point in the discussion. Third, height-in-scene can provide relative distance information (information on the relative distance between objects resting on the supporting surface) if viewing distance (D) and eye height (H) are known (Fig. 1, lower panal) – in the same manner that horizontal retinal image disparities can provide relative information if interpupillary distance and fixation distance are known.

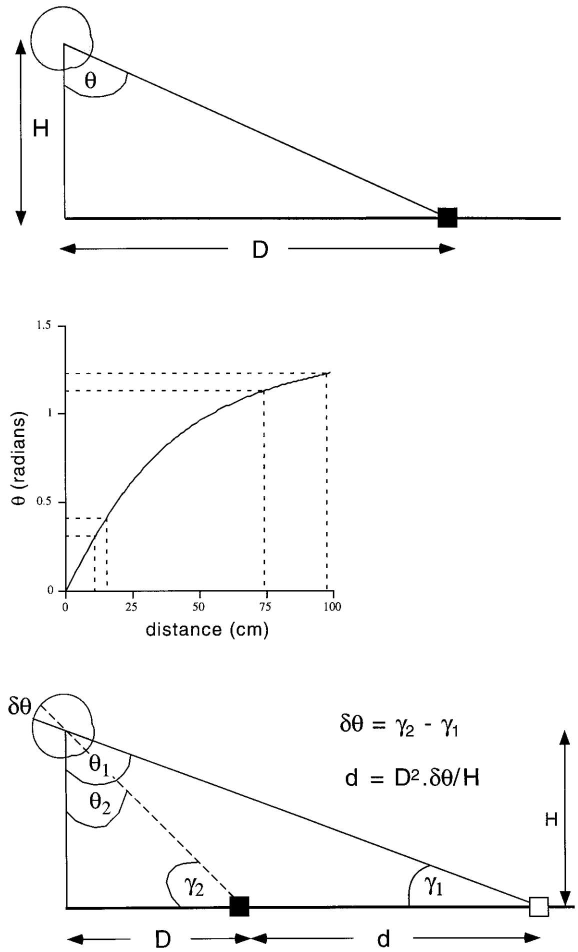

Fig. 1 *Upper panel* Planar geometry of vertical gaze angle when a target object (*black box*) resting on a planar supporting surface orthogonal to gravity is fixated. It can be seen that θ can provide an estimate of distance (*D*) if eye-height (*H*) is known. *Middle panel* The relationship between vertical gaze angle (θ) and fixation distance (D) for the geometry shown in the upper panel. The relationship has been calculated assuming an eye-height of 35 cm above the surface (the actual value of H used in the experiments). The *dotted lines* indicate a constant level of noise in the measurement of θ. It can be seen that the range of possible target distances is much greater for a given level of noise when fixation is further away. *Lower panel* Planar geometry of vertical gaze angle, demonstrating that the depth (*d*) between a fixated target (*black box*) and a non-fixated target (*white box*) is given by the angular vertical discrepancy ($\delta\theta$) on the retina if distance (D) and eye height (H) are known

We explored whether the nervous system uses vertical gaze angle as an absolute distance cue by using a perturbation technique. We perturbed vertical gaze angle by using vertically oriented ophthalmic prisms. These prisms caused a change in gaze angle, but did not affect the retinal cues to distance. In the first experiment, we explored the use of vertical gaze angle in an open-loop pointing task. In the second experiment, we studied the use of vertical gaze angle for the programming of prehension under closed-loop conditions.

Material and methods

Participants

In the first experiment, 50 unpaid volunteer undergraduates from the School of Psychology were recruited as part of their second-year methodology course. For the second experiment, another eight unpaid undergraduate participants were recruited from the School of Psychology. All participants were naive to the purpose of the experiment, and none had any history of neurological or ophthalmological abnormalities.

Experiment 1

Participants sat at a thin (2 cm) matte brown surface, 100 cm wide and 125 cm deep (the surface acted as a table top with a rigid top surface, but a cork underside that allowed pins to be easily positioned). The experimental task was to reach under the surface and to position the tip of a pin directly underneath a target (a 5 mm circle) located on the top of the surface. The targets were placed at one of three distances (20, 30 or 40 cm from the starting point) along the participant's midline. The eye was 35 cm above the table, resulting in the targets being 40.3, 46.1 or 53.2 cm from the nodal point of the eye (±0.5 cm). Participants always began a trial with the thumb and index finger of their right hand placed at the starting position (on the edge of the surface directly underneath the eye). We were interested in exploring the role of vertical gaze angle under normal viewing conditions, so the viewing environment was fairly rich with cues to distance. The viewing environment was well illuminated and the sides of the table were visible – texture and linear perspective information were thus available. The participants had a wide field of view and, thus, a vertical disparity gradient was potentially available as a distance cue (see Mayhew and Longuet-Higgins 1982).

The participants viewed the targets in one of three viewing conditions: (1) normal binocular viewing; (2) wearing 12-Δ prism base-up; or (3) wearing 12-Δ prism base-down (1 prism dioptre, Δ = the angle whose tangent is 0.01). If VGA is used as a distance cue, then the base-up prism should cause an under-estimation of target distance whilst the base-down should cause an over-estimation. If the participants had used VGA alone to determine target distance, then the prisms should have caused them to locate the targets (physically located at 20 cm, 30 cm and 40 cm from the front edge of the table) at 14.8 cm, 23.2 cm and 31.5 cm when wearing the base-up prism and at 26.0 cm, 38.1 cm and 51.2 cm when wearing the base-down prism. The different viewing conditions were created with three separate pairs of spectacles (the spectacle frames were a standard size and were identical). The participants completed a session in one sitting (approximately 20 min) with the spectacles changed from trial to trial in a randomised order (each participant receiving one of six possible randomised orders). Participants carried out five trials in each condition, resulting in a total of 45 points (three viewing conditions × three target distances). Participants performed the task as follows: they closed their eyes, the experimenter fitted the appropriate pair of spectacles, the participant leant forward, opened their eyes, binocularly fixated the target object, reached under the table and inserted the pin, closed their eyes and leaned back. The distance of the pin from the target was measured using a standard millimetre rule. Accuracy was approximately ±0.5 mm.

Experiment 2

Participants sat with their head in a head rest (consisting of a chin rest and a bar against which they leant their forehead) at a matte white table, 100 cm wide and 55 cm deep. The experimental task was to reach forward and grasp an object placed at one of three distances (20, 30 or 40 cm from the starting point). The eye was 35 cm above the table, resulting in the targets being 49.5, 57.0 or 65.2 cm from the nodal point of the eye (±0.5 cm). Participants always began a trial with the thumb and index finger of their right hand placed on the starting position (15 cm from the edge of the table). The starting position and the centre of the object were located along the participant's midline. We asked participants to make quick, accurate and natural reaches with their right hand, grasping (but not lifting) each object with their thumb and index finger along the long axis of the object, which was always perpendicular to the body midline. The participants were given a small number of practice trials before the experiment began. Three different objects were used in the experiment. The blocks were painted different colours (maroon, grey and yellow) and were presented in a randomised order (a different randomised order for each participant). All of the blocks were 2 cm high and 3 cm deep. Two of the blocks were 5 cm long and the other was 4 cm long. We were interested in exploring the role of vertical gaze angle in standard viewing conditions, so the viewing environment was fairly rich with cues to distance (as in the first experiment).

The participants grasped the objects in one of three viewing conditions: (1) normal binocular viewing; (2) wearing 12-Δ prism base-up; (3) wearing 12-Δ prism base-down. The different viewing conditions were created with the three separate pairs of spectacles, as described for experiment 1. Participants carried out eight trials in each condition, resulting in a total of 72 reaches (three viewing conditions × three target distances). Participants performed the task as follows: they closed their eyes, the experimenter fitted the appropriate pair of spectacles, the participant leant forward to position him/herself in the headrest, opened their eyes, binocularly fixated the target object, reached forward to grasp the object, closed their eyes and leant back.

Three infrared-emitting diodes (IREDs) were placed on the participant's reaching limb (styloid process of radius, distal phalanx of the index finger and thumb). Positions of the IREDs were recorded by an Optotrak movement-recording system factory pre-calibrated to a static positional resolution of better than 0.2 mm at 100 Hz (dynamic resolution was not significantly different from this). Data were stored in computer memory for subsequent off-line analyses. The data were filtered using a 10-Hz Butterworth dual-pass filter and analysed using customised software (see Jakobson and Goodale 1991 for details). The following seven kinematic variables were examined: (1) movement duration, (2) peak velocity, (3) peak acceleration, (4) time to peak velocity, (5) time to peak acceleration, (6) movement time after the point of peak velocity (the time to peak velocity subtracted from the movement time), (7) normalised time spent decelerating (movement time after the point of peak velocity divided by the movement time).

The rationale for the experiment was as follows: if participants are using VGA in prehension, then the base-down prism should cause the programming of a reaching movement suitable for an object further than the actual physical position. In contrast, the base-up prism should cause the opposite effect (i.e. participants should begin to reach as if the object were closer). It is known that participants scale the velocity of prehensile movement with the amplitude of the reach (see Jeannerod 1988) – this means that lower peak velocities and accelerations together with proportionately longer deceleration phases should be observed with the base-up prism than with the base-down prism. Nonetheless, participants should still be able to carry out the prehension task under visually closed-loop conditions (as they can correct any errors under visual guidance at the end of the movement). The longer deceleration phase with the base-up prism is predicted because most adjustments occur in this low-velocity portion of the movement (Soechting 1984; Fisk and Goodale 1988). In other words, the hand is accelerated rapidly to peak velocity and then decelerates under on-line visual feedback to the target. If the hand is initially programmed to land short of the target, then the duration of the lower-velocity portion of the movement will need to be increased – thereby increasing the deceleration phase and the movement duration. In contrast, if the hand is initially programmed to land beyond the target, then the nervous system will need to use on-line visual feedback to implement rapid deceleration of the hand, resulting in relatively less time spent in the deceleration phase. Previous findings (Mon-Williams and Dijkerman 1999) suggest that such adjustments cause only modest increases in total movement duration.

Results

Experiment 1

Figure 2 shows the pointing response for the three different viewing conditions. It will be noted that the pointing was accurate when no prism was present. It is clear that the base-up prism caused participants to undershoot target position, whilst the base-down prism had the opposite effect. We estimated the weighting attached to VGA as a cue to the perceived distance of the target (see Tresilian et al. 1999; Tresilian and Mon-Williams 2000). This weighting is estimated as the change in perceived distance as a ratio of the change in that cue under VGA discrepant (with prism) and VGA concordant (no prism) conditions. 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 VGA-specified target distance (D_v) with the prism in place. D_v was calculated in the following manner: let the VGA of the target without prism be γ_1 and VGA of the target with prism be γ_2 and Δ the prismatic displacement. Then, if the prism *decreases* VGA distance, $\gamma_2=\gamma_1+\arctan \Delta$. The VGA-specified distance, D_v, can be calculated as:

$$D_v = H \cot \gamma_2 \qquad (2)$$

where H is eye height. This measure of weighting requires that the participants show reasonably accurate pointing (±2 cm). If the pointing were inaccurate, then it would not be possible to establish the change in perceived distance created by the prism. In fact, the requirement for accurate pointing was met under the experimental conditions. Figure 3 shows the VGA weighting plotted as a function of target distance. Two aspects of the results will be noted: first, the weighting falls with increasing distance and second, the base-down prism has an higher weighting than the base-up prism. This aspect of the results is considered in the discussion section.

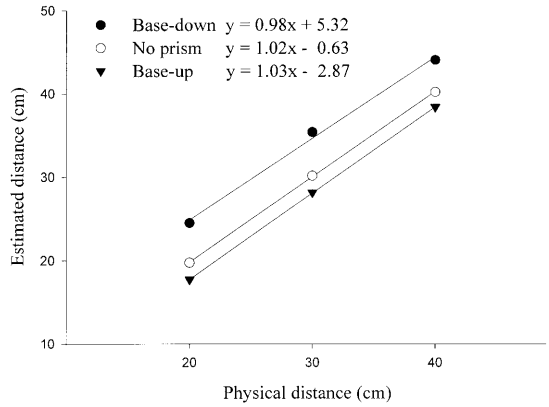

Fig. 2 Estimated distance (pointing response) in cm plotted against physical distance in cm. It can be seen that participants pointed accurately to the target under normal viewing conditions, but overpointed when the base-down prism was worn and undershot when the base-up prism was worn. Standard error bars were smaller than the symbol size. *Straight lines* are least-squares fits to the data using linear regression analysis. The equations for each fit are shown (*y* estimated distance, *x* target distance; all r^2=0.99)

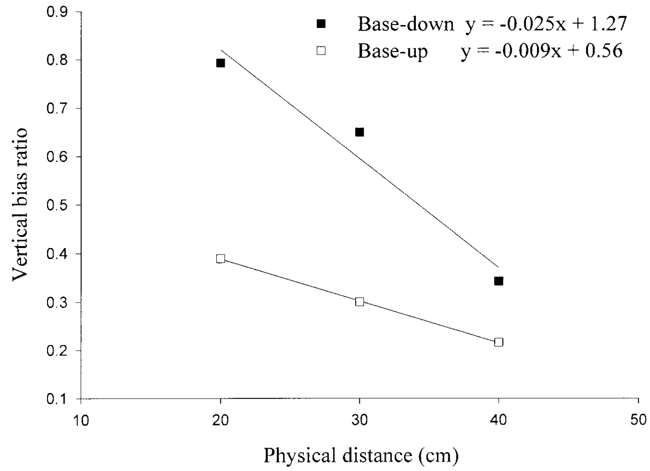

Fig. 3 Empirical estimate of weighting attached to vertical gaze angle (vertical bias ratio) plotted against physical distance. It can be seen that the weighting decreased as target distance increased, and that the weighting attached to the base-down prism was higher than that attached to the base-up. See text for details on the calculation of the vertical bias ratio. *Straight lines* are least-squares fits to the data using linear regression analysis. The equations for each fit are shown (*y* vertical bias ratio, *x* target distance; both r^2=0.96)

Experiment 2

Table 1 provides the mean values of each of the seven dependent kinematic variables for the participants. The mean values for the dependent variables from participants were entered into separate 3×3 (viewing condition × object distance) repeated-measures analysis of variance, with alpha set at 0.05. A main effect of viewing condition was found for all of the seven variables, apart from time to peak velocity. A main effect of distance was found for all of the variables. Only one interaction between target distance and viewing condition was found

Table 1 Summary table of the effect of viewing condition on the seven kinematic variables measured. The values are the means of the three object distances. The *F* value is provided for all the statistically reliable (*P*<0.05) main effects (*NR* not reliable), together with the results of the planned contrasts carried out between the base-down and base-up prisms

	No prism	Base-down	Base-up	*F* value (2, 5)	Base-up vs. Base-down
Movement time	631.66	686.37	721.18	20.55	*P*<0.05
Deceleration time	358.60	407.79	452.59	24.96	*P*<0.05
Normalised deceleration time	56.1%	59.0%	62.4%	24.53	*P*<0.05
Peak acceleration	565.75	620.80	484.09	18.25	*P*<0.05
Peak velocity	996.97	1091.17	903.01	23.00	*P*<0.05
Time to peak acceleration	406.68	422.36	390.49	9.15	*P*<0.05
Time to peak velocity	273.07	278.58	268.59	NR	–

and that was for peak velocity – we are unable to interpret this interaction.

The issue of interest for this experiment was whether the perturbation of VGA would affect prehension in the predicted manner. In the methods section, we hypothesised that, if VGA were used in prehension, then lower peak velocities and accelerations together with proportionately longer deceleration phases should be observed with the base-up prism than with the base-down prism. Examination of Table 1 shows that the prism had the effect predicted from the premise that VGA is used in the programming of prehension. In order to formally test between the effects of the base-up and base-down prism, we carried out planned contrasts for the variables in which a main effect was observed – all of the differences between the base-up and base-down prisms were statistically reliable (see Table 1, last column).

Discussion

Experiments 1 and 2 provide evidence that the nervous system uses vertical gaze angle (VGA) as a distance cue. In the first experiment, it was found that vertical prisms affected the perceived distance of the target: prisms orientated base-up caused participants to undershoot target position whilst prisms orientated base-down caused participants to overshoot target position. Likewise, in experiment 2, the vertical prisms caused predictable changes in prehension. The rationale for the second experiment was as follows: if participants are using VGA in prehension, then the base-down prism should cause the programming of a reaching movement suitable for an object further than the actual physical position. In contrast, base-up prisms should cause the opposite effect (i.e. participants should begin to reach as if the object were closer). The results showed exactly this pattern with the kinematic variables following the predictions made in the methods section.

There were two interesting features of the data found in experiment 1. First, the weighting attached to VGA fell with increasing fixation distance. Second, the weighting attached to VGA was higher when the prisms were oriented base-down than when oriented base-up. In order to understand these experimental results, it is necessary to consider how the nervous system uses distance cues. In multiple-cue environments, it has been established that the perceptual contribution of a cue depends upon the “confidence” that the nervous system attaches to the information: the greater the confidence, then the larger a cue’s relative contribution or “weight” (Von Holst 1973; Massaro 1988; Landy et al. 1995). Weighted averaging schemes such as the *modified weak fusion* scheme of Landy et al. (1995) hypothesise that there are two major factors which determine cue weight: (1) the cue’s intrinsic reliability, which is related to such factors as its signal to noise ratio (Young 1971; Von Holst 1973; Massaro 1988); and (2) the degree to which the cue conflicts with information provided by other available information – its discrepancy (Maloney and Landy 1989; Landy et al. 1995). In addition, the contribution of any given cue will tend to decrease as the number of other contributing cues increases (Landy et al. 1995). These predictions have received empirical support (e.g. Rogers and Bradshaw 1995; Tresilian et al. 1999; Tresilian and Mon-Williams 2000).

Figure 1 (middle) shows that distance estimates from VGA will become noisier as fixation distance increases – under the assumption that there is a constant level of additive noise or a constant uncertainty in the measure of VGA. This suggests that the contribution of VGA to distance estimates should decrease as target distance increases in multiple-cue environments. This prediction is based on the established principle that the noisier a cue is then the lower the confidence placed in it (see, e.g. Massaro 1988; Landy et al. 1995; Tresilian and Mon-Williams 2000). The data show exactly this pattern (Fig. 3), demonstrating that the weighting attached to VGA decreases as the signal-to-noise ratio drops off. The signal to noise ratio cannot, however, explain why the base-down prism had a higher weighting than the base-up prism. In fact, the signal-to-noise ratio would give rise to the opposite result – the base-down prism causes the VGA to specify a further distance than the base-up prism. This raises the question of what other factor might be determining the weighting attached to the VGA? One possibility is that the base-down prism caused less discrepancy with all the other distance cues (D_A) than the base-up prism. For example, it has been shown that the weighting attached to vergence decreases as the cue becomes increasingly discrepant with other distance information (Tresilian and Mon-Williams 2000). Calculation shows, however, that the discrepancy between the VGA and D_A is actually higher when the prism is oriented with its base down. Nonetheless, the base-up prism does produce a greater discrepancy with

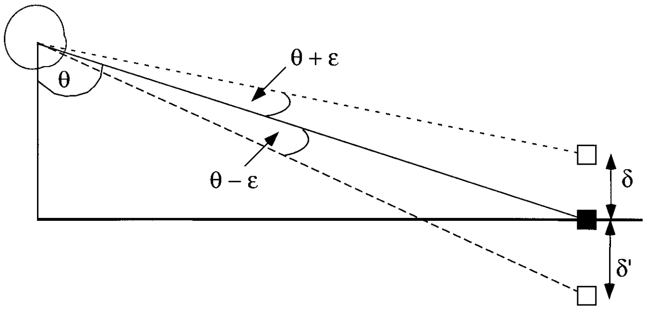

Fig. 4 Planar geometry of vertical gaze angle (VGA) when the VGA is shifted with a prism of constant power. The *black box* indicates the fixated target, whilst the *white box* shows specified target position when viewing through a prism of constant power (ε). It can be seen that shifting VGA upwards with a base-down prism causes a smaller discrepancy (δ) than the discrepancy (δ') created when shifting VGA downwards with a base-up prism. Discrepancy in this situation refers to the difference between the height of the target, as specified by the distance cues, and the height indicated by the initial estimate of the supporting surface's position

regard to another source of information – the initial estimate of the ground plane position. Figure 4 demonstrates that the discrepancy (δ) between the height of the target, as specified by the distance cues, and the height indicated by the initial estimate of the position of the supporting surface is greater when the prism is oriented base-up than when it is oriented base-down. Our findings suggest that the nervous system is sensitive to this discrepancy and decreases the weighting attached to VGA as this discrepancy increases. The current experiments do not address questions regarding the dependency of VGA weighting on fixation distance and δ: is the dependency linear or non-linear; do δ and fixation distance act additively or do they interact? Moreover, the current experiments do not address the issue of whether discrepancy between VGA and D_A also co-determines the weighting. Nonetheless, our results do show that the nervous system uses VGA as a distance cue, with the weighting attached to the cue altering as a function of both fixation distance and δ.

Our findings raise the question of how the nervous system judges eye height above the surface of support (note that, in the introduction, we highlighted a number of studies providing evidence that eye-height is used when judging the size of target objects: Warren and Whang 1987; Bertamini et al. 1998; Wraga 1999a, 1999b). It is possible that the system uses visual information to judge eye height above the supporting surface. Alternatively, kinaesthetic information regarding the position of an effector resting on the supporting surface (e.g. the hand on a table top or the feet on the ground plane) might be used by itself or in combination with visual cues to indicate eye height. Another issue raised is whether our findings indicate that the system "assumes that the surface of support is generally planar and orthogonal to gravity" (the fourth assumption of Cutting and Vishton 1995, p. 87). We suggest that the nervous system need not assume that supporting surfaces are planar and orthogonal (an unreasonable assumption, as pointed out by Cutting and Vishton 1995), but can (and we suggest, does) determine the orientation of the supporting surface on the basis of retinal information (possibly supplemented by kinaesthetic information from an effector resting on the surface). In support of this idea, it has been established that the nervous system can use perspective cues to estimate slant with good reliability (e.g. Banks and Bachus 1998). Finally, our findings indicate that the system has access to reliable information on ocular position with respect to the head and head orientation with respect to the shoulders. We note that such information is anyway a prerequisite in object localisation for the purpose of skilled movement (e.g. Berthoz 1985).

One interesting phenomenon noted when wearing the vertical prisms was that a flat ground plane appeared to either slope upwards (when the prisms were oriented down) or downwards (when the prisms were oriented up). This observation could not be explained by any optical distortions introduced by the prisms (the aberrations associated with the prisms have the potential to introduce curvature distortion, but would not result in the percept of a flat, slanted plane). In order to understand this phenomenon it is necessary to consider target localisation: the visual position of the target is specified by a vector whose direction is given by gaze angle, but whose magnitude is not specified uniquely. There are two estimates regarding the length of the vector: one estimate is provided by D_A and the other, independent, estimate is provided by VGA. We have seen that perceived target distance is a weighted average of these two estimates – meaning that the target location is described by a vector whose direction is given by gaze angle, but whose magnitude lies between the two distance estimates. It will be noted that such a distance estimate produces a conflict between other estimates of the viewing environment – either the system must have misestimated eye height and/or misestimated the slope of the supporting surface. We have suggested that the system uses perspective cues to determine the slope of a supporting surface for the purpose of using VGA as a distance cue. This idea is, however, an oversimplification as it ignores the possibility that height-in-scene information might itself be used to provide an estimate of slope. Inspection of Fig. 1 (lower panel) shows that points lying along the supporting surface will produce a vertical gradient of $\delta\theta$ on the retinae. Such a gradient can be used to provide an estimation of surface slant (the angle between the surface normal and VGA) if the system has information on gaze direction and fixation distance (see Banks and Bachus 1998). Notably, the vertical prisms change estimates of both gaze direction and fixation distance and, thus, have the potential to alter the perceived slope of the supporting surface. The shifts in both gaze direction and fixation distance created by the base-down prism would predict the slope rotating upwards, and the shifts created by the base-up prism would predict a downwards change in slope. The fact that the prisms cause the ground plane to shift in such a fashion suggests that height-in-scene information must be contributing to the estimation of slope (at some level). Such an estimate of slope might be combined with perspective cues on slant, which could then feed back into the computation of target distance. This computation of target distance might, in turn, feed back into the estimate of slope. This process could continue until a consistent interpretation of the physical dimensions of the target and viewing environment was produced.

A consideration of the results reported in this experiment thus suggests that the use of height-in-scene information is likely to be rather complicated. Nevertheless, the data reported in this paper provide unambiguous evidence that the nervous system extracts absolute distance information from vertical gaze angle. We have provided the simplest possible explanation for our findings, but we suspect that it will be some time before a full understanding of the results is possible.

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