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RESEARCH ARTICLE

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Vertical gaze angle as a distance cue for programming reaching: insights from visual form agnosia II (of III)

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Abstract It has been shown that a patient with visual form agnosia (DF) relies predominantly on vergence information when gauging target distance in an open-loop pointing task. This finding suggested that the programming of prehension might be severely disrupted if DF viewed target objects through ophthalmic prisms. An initial experiment showed that this prediction was not upheld; DF was able to programme reasonably accurate movements to objects located on a tabletop despite large changes in vergence angle. A second experiment, however, showed that placing the target objects at eye height whilst manipulating vergence angle caused gross disruption to prehension, with DF mis-programming the reach component in a predictable manner. Notably, the evidence for DF's reliance on vergence distance information was obtained in a task where the targets were viewed at eye height. These experiments indicate that DF uses vertical gaze angle to gauge target distance in normal prehension and suggest that this extra-retinal cue may be a useful source of distance information for the human nervous system, especially where pictorial cues are impoverished.

Keywords Prehension · Binocular · Vergence · Distance perception · Human

Introduction

It has been long recognised that a number of distance cues might contribute to the programming of prehension. These cues can be classified as "retinal" or "extra-retinal" in origin. Only two extra-retinal signals have been considered as potential distance cues and these two candidate signals arise from the accommodation and vergence systems, respectively. The weight of empirical evidence suggests that accommodation does not provide a useful distance signal to the human nervous system (Mon-Williams and Tresilian 2000). In contrast, the evidence suggests that binocular vergence is a good source of distance information (Tresilian et al. 1999). Moreover, it has been established that binocular vergence contributes to the programming of prehension (Mon-Williams and Dijkerman 1999; see also Servos et al. 1992; Servos and Goodale 1994; Jackson et al. 1997). Mon-Williams and Dijkerman (1999) showed that perturbing vergence angle using ophthalmic prisms had a predictable effect on the programming of prehensile movement; longer movement duration and deceleration phases together with lower peak velocities and accelerations were observed when vergence specified a decrease in the egocentric distance to the target object (when the prism was orientated base-out). This finding can be explained in the following manner: participants rapidly accelerated their hand to peak velocity on the basis of target distance. Conversely, the peak velocity and acceleration were higher when the participants were wearing the base-in prism, as if they were programming a movement to a further target. When the base-in prism was worn, the participants programmed a movement that was too long, meaning that the nervous system had to increase the rate of deceleration resulting in a shorter deceleration phase. The base-in prism had little effect on movement duration when compared to the no-prism condition, indicating that the system was able to make spatial corrections during the deceleration phase despite the higher than normal rate of deceleration. When the base-out prism was worn, the participants programmed a movement that was too short, meaning that the nervous system had to increase the duration of the low velocity component of the movement. This resulted in an increase in the deceleration phase and an increase in total movement duration.

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A number of studies have shown that patients with specific brain lesions rely to an exceptional degree on binocular vision when carrying out prehensile movements (Dijkerman et al. 1996; Jackson and Husain 1996; Marotta et al. 1997). In particular, it has been shown that a patient (DF: Milner et al. 1991; Milner 1997) with visual form agnosia relied predominantly on binocular vergence when determining the distance of a target despite the presence of other (retinal) cues (Mon-Williams et al. 2001). It seems likely that DF's form of agnosia renders her unable to use "pictorial" cues from the retina to gauge distance, so that she consequently has to rely heavily on non-retinal cues. This finding was established using an open-loop pointing paradigm. DF pointed to targets at eye height within a viewing box whilst vergence angle was manipulated using ophthalmic prisms. The results of this study indicated that DF pointed to the position of the target as specified by vergence (i.e. she largely ignored the other available distance cues exploited by control participants). The current experiment explored DF's ability to reach out and grasp objects on a tabletop when vergence was manipulated using ophthalmic prisms (in a repeat of the paradigm of Mon-Williams and Dijkerman 1999). Remarkably, DF was now able to carry out the task reasonably well despite the erroneous distance information provided by vergence. However, a subsequent experiment showed that placing the targets at eye height caused DF once more to make predictable errors in the programming of the prehensile reach component. The results of these two experiments suggest that vertical gaze angle can provide useful information for the programming of reaching amplitude.

Materials and methods

Participants

A patient with visual form agnosia (patient DF) participated in the experiment. Patient DF experienced carbon monoxide poisoning in 1988 with subsequent structural MRI scanning revealing a dense bilateral lesion in lateral pre-striate cortex. DF was 45 years old at the time of the current experiment. A detailed report of the presenting features of DF's case is provided elsewhere (Milner et al. 1991). A preliminary study using functional MRI indicates that viewing drawings of familiar objects caused little or no activation in occipito-temporal lobe structures in DF, strongly indicating a disconnection of these areas from primary visual cortex (James and Goodale, personal communication). A comprehensive eye examination at the time of the current experiment revealed an absolute inferior field hemianopia (Henson VFA II) with some macular sparing in both eyes. DF was slightly presbyopic (add +1.25 DS) but was otherwise close to emmetropia (R. +0.25/–0.50×180; L. +0.25/–0.50×180) as assessed by an experienced retinoscopist. Ophthalmoscopy and tonometry revealed healthy eyes.

In the first experiment, we compared DF's performance with data collected from six control participants in a previous experiment conducted under identical conditions (Mon-Williams and Dijkerman 1999). For the second experiment, five unpaid participants were recruited. All of the participants were researchers (graduate students or post-doctoral staff) in the School of Psychology. All participants were naive to the purpose of the experiment and none had any history of neurological or ophthalmological abnormality.

Experiment 1

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 pick up an object placed at one of three distances (20, 30 or 40 cm from the starting point). The eye was maintained at 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. Following Servos et al. (1992), 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. The participants grasped the object front to back with the long axis of the object orthogonal to the body midline. The participants were given a small number of practice trials before the experiment began. Eight objects were used in an attempt to minimise memory effects. The size of the object (in the grasping plane) was not manipulated, as Servos et al. (1992) had established previously that there was no interaction between object size and viewing condition. The blocks were painted different colours 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. Four of the blocks were 5 cm long and the others were 6 cm long. We were interested in exploring the role of vergence in standard 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, and texture and linear perspective information were thus available. The headrest minimised motion parallax but did not totally remove this possible source of distance information. The participants had a wide field of view and therefore a vertical disparity gradient was potentially available as a distance cue despite the small size of the actual test objects (see Mayhew and Longuet-Higgins 1982). Fixation of the target produced an horizontal disparity gradient of the non-fixated parts of the viewing environment, potentially providing distance information (Tresilian and Mon-Williams 1999). A homogenous textured surface was placed behind the table and the target object was viewed against this background.

The participants grasped the objects in one of four viewing conditions: (i) normal binocular viewing; (ii) with the left eye covered; (iii) wearing 9 Δ prism base-in; (iv) wearing 9 Δ prism base-out (1 prism dioptre, Δ=angle whose tangent is 0.01). The different viewing conditions were created with four separate pairs of spectacles (the spectacle frames were a standard size and were identical). The first pair of spectacles consisted of plain lenses, the second pair consisted of a plain lens in front of the right eye with an occluder in front of the left. The prism spectacles had ophthalmic prisms glazed into the frames. The prismatic power was split between the eyes and the prisms were designed to minimise unwanted optical aberrations: they had no refractive power but had a curved front and rear surface (this type of prism is known as a meniscus plano prism). The participants completed a session in one sitting (approximately 1 h) with the spectacles changed from trial to trial in a randomised order (a different order was used for each participant). It has previously been established that this procedure circumvents any unwanted adaptation to the prisms (Mon-Williams and Tresilian 1999). Participants carried out eight reaches in each condition, resulting in a total of 96 reaches (four 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.

Experiment 2

The second experiment was identical to the first, apart from a new target object being located at eye height (35 cm above the table top). The target was 5 cm by 5 cm and 1 cm thick, orientated vertically with its thin edge pointing towards the participants. This arrangement meant that the participants had to grasp an object that was 1 cm wide and 5 cm high. The target was held by a mechanical stand positioned to the left of the target (so that it did not interfere with the movement of the right hand) and was positioned 35, 45 or 55 cm from the nodal point of the eye (±0.5 cm). The same starting position as experiment 1 was used for the thumb and index finger of the participant's right hand (15 cm from the edge of the table) resulting in three grasp distances of 40.31, 46.1 and 53.15 cm from the start point).

Measurements

Three infrared emitting diodes (IREDs) were placed on the participant's reaching hand (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 precalibrated 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 eight kinematic variables were examined: (1) movement duration, (2) peak velocity, (3) peak acceleration, (4) time to peak velocity, (5) time to peak acceleration, (6) maximum grip aperture, (7) movement time after the point of peak velocity (the time to peak velocity subtracted from the movement time), (8) normalised time spent decelerating (movement time after the point of peak velocity divided by the movement time). In addition, the terminal position of the hand was measured (i.e. the position of the hand at the end of the movement). In the first experiment, the terminal position was equal to the target position for the control participants and DF. In the second experiment, the control participants again terminated the movement with their hand at the target but DF undershot and overshot the target depending upon the glasses she was wearing (see Results).

Results

Experiment 1

Table 1 provides the mean values of each of the dependent variables for the control participants (normal text) and DF (bold). The data from the control participants have been reported previously (Mon-Williams and Dijkerman 1999). The notable finding from the current experiment was that DF showed the same pattern of results as the controls. Patient DF tended to move relatively slowly but her mean movement time fell within the 95% confidence intervals for the control participants. The mean values for the dependent variables from DF were entered into separate 4×3 (viewing condition× object distance) factorial analysis of variance with alpha set at 0.05. A main effect of viewing condition was found for four of the eight variables (movement time, peak velocity, time after peak velocity, normalised time after peak velocity). As in the control subjects, a main effect of distance was found for all of the variables apart from grip aperture. There were no interactions between target distance and viewing condition for any of the variables.

The prism thus affected DF's reaching in a manner consistent with the prism direction but she was able to carry out the prehension task despite the large disruption to vergence angle. This result was unexpected, because DF seemed largely unable to use any retinal distance cues (thus relying very heavily on ocular vergence) when scaling target distance during open-loop pointing. However, another difference between this and the previous experiment was that an additional non-retinal cue was available here, namely vertical gaze angle. We therefore retested DF's reaching in the second experiment where this cue was removed.

Table 1 Summary table of the effect of viewing condition on the eight kinematic variables for DF (upper values in *bold*) and the control participants (lower values in *plain text*) in experiment 1. The values are the means across the three object distances (there were no interactions between distance and viewing condition). In experiment 1, the targets were placed on a tabletop and thus allowed the use of vertical gaze angle as a distance cue

	Binocular	Monocular	Base-in	Base-out
Movement duration (ms)	**1003.04** 792.78	**946.29** 863.94	**928.83** 801.94	**1081.04** 859.69
Peak velocity (mm/s)	**753.0** 861.32	**730.41** 852.82	**754.79** 904.53	**684.79** 845.95
Time to peak velocity (ms)	**332.46** 271.20	**340.08** 273.84	**333.20** 266.39	**288.96** 269.12
Peak acceleration (dm/s^2)	**48.66** 48.93	**48.88** 49.02	**48.15** 52.87	**49.26** 49.12
Time to peak acceleration (ms)	**287.45** 120.15	**266.21** 118.56	**287.13** 116.03	**250.95** 86.63
Maximum grip aperture (mm)	**57.31** 62.87	**57.19** 65.48	**56.02** 64.70	**56.51** 63.94
Movement time after peak velocity (ms)	**670.58** 521.58	**606.21** 590.11	**595.63** 535.08	**746.5** 590.57
Normalised time after peak velocity (%)	**66.07** 64.62	**63.14** 67.32	**63.84** 65.63	**68.64** 67.45

Experiment 2

Placing the targets at eye height had no discernible qualitative effect on the control participants' reaching and grasping. In contrast, DF's prehension was qualitatively and quantitatively disrupted when compared to her performance in the first experiment. The base-in prism caused DF to overshoot the target by a large margin, whereas the base-out prism caused a large undershoot (the effect was large enough to be apparent when simply watching DF carry out the task). The monocular trials also caused a gross disruption to DF's reaching although there were no systematic overshoots or undershoots. The prism and monocular spectacles thus caused DF's hand to fall initially some distance from the target and required her to make corrective movements following the first movement phase. This disruption to viewing meant that DF failed to get her hand to the target on a number of trials (on these trials she would stop making corrective movements and report that she could not complete the task, see Table 2). This effect became increasingly frustrating for DF as the experiment proceeded (the effect did not decrease over trials). In contrast, DF always managed to grasp the target when she viewed binocularly in the absence of prism.

Table 2 Summary table of the effect of viewing condition on the terminal hand position for DF in experiment 2. Notably, DF always grasped the object in the first experiment regardless of viewing condition (as did the controls in both experiments) but consistently missed the target in the second experiment. The table indicates where the hand rested at the very end of the movement. The figures provided in the table describe the distance in the sagittal plane from the starting position. In experiment 2, the targets were placed at eye height and thus prevented the use of vertical gaze angle as a distance cue. It can be seen that patient DF moved her hand to the target under normal binocular conditions but generally failed to get her hand to the target when either vergence was manipulated (overshooting with base-in and undershooting with base-out) or removed (viewing monocularly)

Object distance	Base-out	Binocular	Base-in	MONOCULAR
20 cm	19.86 cm	20 cm	21.98 cm	20.87 cm
30 cm	26.99 cm	30 cm	32.11 cm	29.38 cm
40 cm	38.67 cm	40 cm	40.75 cm	37.48 cm

Table 3 provides the mean kinematic data from the second experiment for DF (bold) and the control participants (plain text). For the control participants, the mean values for the dependent variables were entered into separate 4×3 (viewing condition×object distance) repeated measures analyses of variance with Huynh-Feldt adjustments to the degrees of freedom and alpha set at 0.05. The same pattern of results was found in the second experiment as observed in the first, although this time a main effect was found for only two kinematic variables (peak velocity and peak acceleration), presumably because of the smaller number of control participants and the smaller interval between target distances. In common with the first experiment, a main effect of distance was found for all of the variables apart from grip aperture and again there were no interactions between target distance and viewing condition for any of the variables. DF's data were examined by entering her dependent variables into separate 4×3 (viewing condition×object distance) factorial analyses of variance with alpha set at 0.05. A main effect was found for all of the kinematic variables apart from maximum grip aperture.

It is not possible to compare directly the data from the first and second experiment as the reaching distance was different in the two experiments and because different control groups were used. Nonetheless, it is apparent that both the controls and DF show the same pattern of results, with the prismatic spectacles causing the predicted effects in both experiments. In the second experiment, both the controls and DF show shorter movement times with higher peak velocities, higher peak acceleration and

Table 3 Summary table of the effect of viewing condition on the eight kinematic variables for DF (upper values in *bold*) and the control participants (lower values in *plain text*) in experiment 2. The values are the means of the three object distances (there were no interactions between distance and viewing condition). In experiment 2, the targets were placed at eye height and thus prevented the use of vertical gaze angle as a distance cue

	Binocular	Monocular	Base-in	Base-out
Movement duration (ms)	**945.96** 665.02	**1153.3** 763.88	**952.48** 674.92	**1149.09** 707.78
Peak velocity (mm/s)	**1036.67** 1181.1	**1017.13** 1165.63	**1069.46** 1207.32	**984.0** 1164.6
Time to peak velocity (ms)	**282.83** 229.69	**294.5** 230.89	**285.96** 220.65	**294.5** 229.82
Peak acceleration (dm/s^2)	**49.12** 40.14	**53.12** 38.31	**51.93** 44.31	**49.86** 39.82
Time to peak acceleration (ms)	**255.63** 406.32	**265.85** 409.61	**286.93** 408.42	**233.2** 416.24
Maximum grip aperture (mm)	**63.89** 80.38	**67.03** 83.49	**65.47** 81.68	**63.55** 80.82
Movement time after peak velocity (ms)	**649.29** 439.03	**871.31** 537.09	**646.61** 443.72	**859.68** 483.83
Normalised time after peak velocity (%)	**68** 65	**75** 69.74	**67** 65.48	**75** 68.39

a decrease in time to peak velocity in the binocular condition. It is not clear why movement times were faster in the second experiment but these might reflect differences in the biomechanical demands of the two experimental configurations. Notably, DF maintained the higher velocities, peak acceleration and decrease in time to peak velocity when viewing was disrupted but the movement time was found to increase relative to the first experiment. These data are consistent with the finding that DF misprogrammed the distance of her reach in the second experiment (but not the first) and thus was required to make subsequent corrective movements. This effect can also be observed in the increased movement time and normalised movement time measured after the point of peak velocity.

Discussion

The first experiment established that DF shows the same pattern of behaviour as a control group when carrying out a prehension task under disrupted viewing conditions (i.e. when vergence angle was altered using ophthalmic prisms). This result was unexpected because previous research had indicated that due to her insensitivity to visual contextual cues, DF relied predominantly on vergence when computing target distance (Mon-Williams et al. 2001). We postulated (because we could not think of any other plausible factor) that DF might be using vertical gaze angle to compute target distance. The second experiment removed this potential source of information by positioning the target objects at eye height. The effect of this manipulation was to cause gross disruption to DF's prehensile movement. The disruption to prehension resulted in DF programming a movement to a position some distance from the target and frequently resulted in DF failing to contact the target despite subsequent corrective movements. We choose to interpret this result as indicating that patient DF uses vertical gaze angle as a distance cue when programming prehension movements. A reviewer raised the interesting possibility as to whether the differences between the experiments might be due to the different prehension trajectories required in the two experiments. The results from another experiment suggest that this is not the case; patient DF is able to programme normal movements to objects located at eye height (Wann et al. 2001). It should also be noted that DF was able to programme normal movements in the current experiment when vergence was not manipulated, suggesting that it was the perturbed information rather than the movement itself that caused a problem for DF.

Notably, we did not observe a main effect of the prism spectacles on grip aperture in either experiment for DF or the controls. There are two reasons why an effect on grip aperture might have been observed. First, it is known that perceived size is a function of perceived distance. If an object subtending a fixed visual angle is gauged as being closer then it is seen as smaller and vice versa. Second, the use of vergence to interpret the horizontal image disparities would result in a misperception of the object's properties. An increase in vergence specified distance would cause the disparities to specify the object as deeper and a decrease in vergence specified distance would cause the disparity specified depth to be shallower. It might be expected, therefore, that the base-in prism would cause a widening of the grip aperture and the base-out prism would cause a decrease in grasp aperture. We suggest that the lack of an effect on grip aperture is best explained by the fact that the size of the object in the grasping plane was always the same. This means that participants would have had continual kinaesthetic feedback on object size throughout the experiment, thus attenuating the effect of any visual alteration to the object's depth caused by the spectacles.

These results raise the question of how the nervous system can use vertical gaze angle to judge distance. Information on vertical gaze angle can be obtained from efference copy and afferent feedback (see Mon-Williams and Tresilian 1998). In order to use this information to compute target distance, it is necessary for the system to know the vertical distance between the eye and the hand, information that is presumably available from kinaesthetic sources. Knowledge of eye-hand distance and gaze angle allows the system to compute target distance via simple triangulation. The results with DF raise the issue of whether she has learned to use this information as part of a strategy to deal with the visual form agnosia or whether this distance cue is exploited more generally by individuals with an intact nervous system. We have recently conducted an experiment that provides evidence that the intact nervous system does use vertical gaze angle as a distance cue for the programming of prehension (Gardner and Mon-Williams 2001). In addition, a study by Marotta and Goodale (1998) hints at the idea that vertical gaze angle might be able to provide absolute distance information. Marotta and Goodale (1998, p. 465) studied prehensile movements and found that participants carrying out the task with only one eye open made "fewer on-line adjustments in the trajectory of the limb and the aperture of the fingers when the elevation of the target object in the visual scene could be used to help program the required movements".

Vertical gaze angle can also be used to judge the distance of objects located between 1.5 m and 30 m [an area that Cutting (1997) has referred to as action space]. If viewers are sensitive to their eye height (distance between their eye and the ground plane) then a standing observer can readily determine the distance of objects placed on the ground plane (assuming that the ground is relatively flat). A small pilot study demonstrated that DF showed normal performance in a task requiring her to fixate a target located in action space and then close her eyes and walk to the remembered location of that target. In conjunction with Dr. John Wann at the University of Reading, we have explored the information used to carry out this task in a control population. Our research indicates that adjusting vertical gaze angle using vertically orientated prisms causes predictable increases and decreases in judgements of distance in action space.

In summary, we have found that DF seems to rely on a signal from vertical gaze angle when programming prehensile movements to targets located on a tabletop. We found that removing this source of information (by placing objects at eye height), while manipulating vergence angle, caused a profound (qualitatively predictable) disruption to DF's reaching. These results suggest that vertical gaze angle can provide useful distance information to the human nervous system. We would expect that in tasks where healthy subjects are deprived of retinal distance cues (for example, perspective, occlusion), vertical gaze angle will begin to come into its own and that the use of eye-level targets may cause large disruptions as a function of horizontal prism orientation, just as we have observed in DF.

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