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RESEARCH ARTICLE

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The role of size and binocular information in guiding reaching: insights from virtual reality and visual form agnosia III (of III)

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Abstract Reaching out to grasp an object requires information about the size of the object and the distance between the object and the body. We used a virtual reality system with a control population and a patient with visual form agnosia (DF) in order to explore the use of binocular information and size cues in prehension. The experiments consisted of a perceptual matching task in addition to a prehension task. In the prehension task, control participants modified their reach distance in response to step changes in vergence in the absence of any clear reference for relative disparity. Their reach distance was unaffected by equivalent step changes in size, even though they used this information to modify grasp and showed a size bias in a distance matching task. Notably, DF showed the same pattern of results as the controls but was far more sensitive to step changes in vergence. This finding complements previous research suggesting that DF relies predominantly on vergence information when gauging target distance. The results from the perceptual matching tasks confirmed previous findings suggesting that DF is unable to make use of size information for perceptual matching, including distance comparisons. These data are discussed with regard to the properties of the pathways subserving the two visual cortical processing streams.

Keywords Prehension · Binocular · Vergence · Distance perception · Visual form agnosia · Human

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Introduction

Reaching out to grasp an object requires information on the distance of the object from the body. Distance information is required for two different questions regarding the object. First, it is necessary to know the distance of the object so that the hand can be moved to the correct location. Second, it is necessary to know the size of the object so that the hand can achieve the appropriate grasp aperture. In order to know the size of an unfamiliar object, however, it is necessary to judge how far the object is from the body, as perceived size is a function of perceived distance (Emmert 1881). Emmert's law underlies size constancy whereby an object appears the same size when it moves closer or further from the observer despite increases or decreases (respectively) in its retinal image size. The relationship between size and distance is further complicated because the size of an object (e.g. a familiar cup) can also provide information about the object's distance. Jeannerod (1988, 1994) proposed the term "semantic" for the use of information that relies upon object recognition (object constancy) in contrast to the "pragmatic" use of size information in modifying grasp aperture. This distinction maps onto the dissociation between perceptual judgements and vision for action (Milner and Goodale 1995), where perceptual judgements are associated with processing along the ventral occipitotemporal route and vision for action is processed via the dorsal pathway. We have recently provided evidence that an intact occipitotemporal processing pathway is necessary for the semantic processing of size information when making distance judgments (Mon-Williams et al. 2001a). The evidence was based on an experiment involving a patient with visual form agnosia (DF). DF can be regarded, to a first approximation, as functioning with an isolated dorsal stream (Milner and Goodale 1995). DF does not show the normal advantage of size information when making distance judgements (Mon-Williams et al. 2001a) despite being able to adjust her grip aperture when grasping an object (Goodale et al. 1991) indicating that pragmatic size information is available to the dorsal-stream cortex.

It is accepted widely that different visuomotor channels control the transport and grasp phases of prehension movements (Jeannerod 1988 but cf. Smeets and Brenner 1999). [Smeets and Brenner (1999) have provided an alternative account to the "two channels" hypothesis of how prehension movements are organised. Nonetheless, their account still relies at some stage on the extraction of information regarding the distance to be reached and the properties of the object to be grasped. The issues discussed within this manuscript are therefore apposite regardless of the actual manner in which the motor commands are formulated.] The purpose of this study was to explore the extent to which both channels rely on a common input signal regarding an object's distance. If we assume that the visuomotor task of pointing serves as an index of the distance information used to control the reach component of prehension, then the findings from patient DF raise an interesting paradox. It is established that changes in size (looming) can produce rapid defensive responses in animals (e.g. Sun et al. 1992) and that size change may be combined with binocular information when humans make judgements about time-to-contact (Heuer 1993; Rushton and Wann 1999). Thus, size change appears to be a primary source of information for the control of action. It seems curious that retinal size can provide a primary source of information when a ball is approaching the hand but may be ignored when the hand is moved to a target (e.g. a ball). One essential difference between the two tasks is that in judging immediacy (ball approaching hand), the essential parameter is changing size (looming), which must be scaled by instantaneous size ($[d\theta/dt]/\theta$) to provide a temporal metric. In the case of judging immediacy there is no requirement to recover object properties, in fact the appeal of the τ model (Lee 1976) was that the temporal estimate was completely independent of distal properties. In this respect the use of $d\theta/dt$ is highly pragmatic and $[d\theta/dt]/\theta$ provides a direct sensorimotor link rather than implicating any semantic mediation. The paradox arises in the task of the hand reaching to a ball. If we accept that semantic size information does not inform the transport component of rapid reaching in patient DF, then does a *change* in size serve to modify transport (e.g. by specifying object approach)? The research on looming would suggest that size change provides pragmatic, temporal information, but the recovery of a distance metric would seem to require a more semantic solution – if the nervous system has registered the retinal size (θ_1) of an object at a particular distance (Z_1) then a subsequent change in retinal image size (θ_2) can indicate the new position of the object ($Z_2=Z_1\tan[\theta_1]/\tan[\theta_2]$). This estimate relies on the assumption that θ_1 and θ_2 are projections of the same object and that the object has not changed in actual size (e.g. the assumption of object constancy). Hence, although size change may present a strong phenomenological effect and a temporal metric, its use in spatially guided action would seem to require semantic support. We decided to explore the impact of step changes in size in the absence of sustained looming on the reaching responses of control participants and participant DF (for whom it may be assumed the semantic route has been lost).

We also used an equivalent paradigm to explore how reaching is affected by step changes in binocular information. It has been established that binocular information contributes to the programming of prehensile movement (Servos and Goodale 1994). In an extension of this work, Mon-Williams and Dijkerman (1999) showed that vergence information is used in the programming of prehension. In contrast to this general finding, however, Erkelens and Collewijn (1985) have provided evidence that smooth changes in target vergence do not produce a sensation of motion in depth unless they are accompanied by changes in relative disparity. We used a virtual reality system in order to implement a perturbation technique for an exploration of these issues. The advantage of a virtual reality (VR) display is that it provides complete control over the information available within a viewing environment. VR systems thus allow precise perturbations of the information content of a display. In the current experiment, we were interested in how reach distance and grasp aperture would be affected by: (i) a step change in vergence (ii) a step change in relative disparity (iii) a step change in object size. We were also interested in the extent to which a perceptual matching task is affected by vergence information or semantic size cues.

In order to study the role of vergence or size as a distance cue, we created a textured stereoscopic sphere in a dark environment so that distance was specified by vergence. A second condition placed a textured wall behind the sphere, so that although vergence was required to recover absolute distance, any perturbation in distance was specified by a change in relative disparity. We also manipulated the physical size of the sphere in order to study the use of size information in the control of prehension and the influence of size in a perceptual matching task. In the following description we use the term "physical size" to refer to the scale specified by the display parameters for the virtual object (e.g. virtual actual size) and use the term "retinal size" for the projected size of that object.

Materials and methods

We tested the use of size information and binocular information using two different paradigms: in the first paradigm (Action) the participants had to reach out and grasp a "virtual ball". The virtual ball was a computer generated stereoscopic sphere. In the second paradigm (Perception), two separate spheres were generated by the computer. The two spheres were not visible simultaneously. Participants could switch between a target sphere and an adjustable sphere by pressing the space bar. The participants were asked to scale the adjustable sphere so that it was either at the same distance *or* was the same size as the target sphere. The adjustments were made by pressing the vertical arrows on a computer keyboard. The participants were allowed to take as long as they wanted, make as many adjustments as required, and switch between views as often as they desired.

The stereoscopic display was created using SimulEyes field-sequential shutter glasses (Stereographics, USA). All of the displays were presented on a 17” colour monitor of 1024×768 pixels with an 80 Hz display refresh rate. Fusion of the two disparate images created by the glasses resulted in the sphere having a vergence specified distance of 40 cm from the observer (10 cm in front of the monitor). The sphere was located at eye height in the prehension and perceptual matching studies. All of the participants were able to fuse the two images and all reported that the sphere produced a vivid impression of a 3D ball hanging some distance in front of them.

In both conditions there were two viewing backgrounds. In the first presentation block, the sphere was presented on an otherwise dark background. In the second presentation block (run immediately after the first block of trials), a textured background of a brick wall was present on the computer monitor. The textured background greatly enhanced the phenomenological appearance of the sphere (as reported by all participants including DF). None of the participants had any difficulty in understanding or following the task procedures in either condition.

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 causes 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 addition, five unpaid female participants were recruited for the experiment. All of the participants were academic staff (faculty members 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.

Procedure

Participants sat with their head in a rest (consisting of a chin rest and a forehead rest). The computer screen was located at 50 cm from their eyes (±0.5 cm) and their seated eye height was 90 cm. In the first paradigm (A), participants always began a trial with the thumb and index finger of their right hand placed on the starting position located on the space bar of the computer keyboard (the starting position was located 15 cm from the edge of the table and 40 cm from the screen). The starting position and the centre of the virtual object were located along the participant’s midline. We asked participants to make quick, accurate and natural reaches with their right hand, grasping the virtual object with their thumb and index finger along the vertical axis of the sphere. The participants were given a small number of practice trials before the experiment began. Although most of the participants reported that the task “felt strange”, they all understood the task and carried it out appropriately (as indexed by the kinematics of their reaching movements). The participants carried out the task in a completely darkened room so that only the virtual sphere was visible but the ambient illumination from the computer monitor made it possible for the participants to see their hand at the end of the reaching movement.

Reaching tasks

In the reaching condition (A), the participants grasped the sphere in one of four viewing conditions: (Ai) control condition where the sphere stayed a constant size (7 cm) and position 40 cm in front of the participant (Aii) the sphere jumped 10 cm towards the participants with a corresponding increase in retinal size; (Aiii) the sphere increased 33% in size but stayed in the same position; (Aiv) the sphere jumped 10 cm towards the participants but was scaled down in size such that it stayed the same retinal size. The shifts in distance and size occurred as soon as the participants began their movement (i.e. as soon as the pressure on the shift bar was released). The experiment began with a block of ten control trials followed by a random presentation of ten trials of conditions (i) to (iv), resulting in a total of 50 trials per background condition.

Three infra red 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. We were interested in two variables: (i) the distance reached and (ii) the size of the grasp aperture. In addition, we also examined the following five kinematic variables in order to ensure that the participants (especially DF) were showing normal prehensile behaviour: (1) movement duration, (2) peak velocity, (3) time to peak velocity, (4) maximum grip aperture, (5) time to maximum grip aperture.

Matching tasks

The matching condition (P) always followed two blocks (no texture followed by texture) of the reaching (A) trials. There were four matching tasks in total.

Distance matching

The first two tasks required the participants to match the *distance* of the adjustable and target sphere when: (Pi) the spheres were the same size and (Pii) the spheres were different sizes. In conditions (Pi) and (Pii), the retinal image size followed the normal viewing geometry and increased and decreased in line with the adjustments made to distance. It is important to note that the adjustable sphere always started in front of the target sphere (which started at a variety of distances) and thus the participants had to move the sphere towards the screen in order to match the distance. In task Pi, this could be achieved using vergence or by matching retinal size. In task Pii, the adjustable sphere was scaled in size so that it presented a similar retinal size (θ_2) from its forward position to that of the target sphere (θ_1). This was directly equivalent to the perturbations in the reaching tasks. If participants used a strategy based on perceived size to carry out task Pi then in task Pii, they should show a bias to set the adjustable sphere too close to themselves ($Z_2=Z_1\tan[\theta_1]/\tan[\theta_2]$ – see Introduction) as the adjustable sphere started closer to the observer. If DF is unable to use semantic size information she should show the same responses in condition Pi and Pii, i.e. based on binocular information only.

Size matching

The second two tasks required the participants to match the “graspable size” of the adjustable sphere. These instructions were intended to encourage subjects to imagine themselves grasping the sphere when making their judgements. In task Piii the spheres were at the same (vergence specified) distance whereas in Piv the spheres were at different distances. The control participants should find condition Piii very straightforward as the task can be performed using either the semantic or retinal matching of size information. Task Piv attempts to tap a core component of the action system – the use of distance and retinal size information to scale actual graspable size. We predicted that this would be more difficult for the control participants than simple size matching of the type required in task Piii. We further predicted that DF would find task Piii difficult if she was unable to use semantic size information. Her performance in task Piv was of interest because although she has displayed difficulty with previous matching tasks, the visual processing required in Piv would seem to be a pre-requisite of reaching to grasp an object and in that sense is pragmatic. The perceptual matching task was run in the same order for all the participants so that they all completed Pi followed by Pii, Piii and then finished with Piv. In common with the prehension experiment, the second experiment was run in two blocks with the first block having no background and the second block having a textured background.

Results

The presence or absence of the textured background had a large effect on the phenomenological appearance of the sphere. Despite these reported differences, the presence of the textured background had no effect in either paradigm (A) or (P) for any of the control participants or for DF (*t*-tests, $P>0.05$). We collapsed these data together, therefore, when comparing across conditions. We will consider the results from the two conditions (reaching response and matching task) separately.

Reaching response

Table 1 provides the kinematic variables recorded during the experiment. It can be seen from the presented variables that all of the participants (including DF) showed normal reaching and grasping responses. Inspection of the movement trajectories suggested that participants were programming movements that were either the same or at least closely approximated those movements made when reaching for real objects. The actual reach distance was around 43 cm in the non-perturbed condition. The movement times are slightly slower than those found previously for a similar movement trajectory (Mon-Williams et al. 2001b) in the control participants but comparable for patient DF. It seems reasonable to suggest that one effect of using a virtual ball was to increase the uncertainty associated with the prehension movement. It has been shown previously that increasing uncertainty causes participants to slow down their movements. Notably, the experiment conducted by Mon-Williams et al. (2001b) used a perturbation paradigm that had a large effect on DF but minimal impact on a control population. The use of a virtual reality system may have caused the control group to show comparable tentative movements to those already in evidence in DF's reaching. Figure 1 shows the two variables of interest to this study (reach distance and grip aperture). It can be seen that the general pattern of results for the control task was the same for DF and the control participants. The notable difference between DF and the controls in the perturbation tasks was the sensitivity to shifts in vergence specified distance. In task Aii, where the ball jumped forward, both the controls and DF decreased their reach distance. The decrease was far greater in DF (9.2 cm), however, than control mean (2.19 cm). The computer generated shift in vergence specified distance was 10 cm, giving an empirical estimate of the percentage weighting attached to dynamic shifts in vergence, approximately 22% for the controls and 92% for DF. We have reported previously (Mon-Williams et al. 2001b) that DF relies predominantly on vergence information for the programming of prehension when reaching for objects at eye height. The current findings provide evidence in favour of this notion.

In line with their under-compensated changes in reach distance, the controls showed an increase in grasp aperture (i.e. they showed a failure of distance scaling for grasp aperture). In contrast, DF showed no change in her grasp aperture, indicating that her increased sensitivity to changes in vergence specified distance provided her with accurate grasp information under the experimental conditions. In task Aiii, where the ball jumped in size, neither the controls nor DF showed any change in reach distance (as compared to the control condition) but both showed an increase in grasp aperture. This finding confirms previous reports of DF being able to use pragmatic size information to control grasping (Goodale et al. 1991). In condition Aiv, where the sphere jumped 10 cm

Table 1 Summary kinematic data from the reaching study. The *top row* indicates the condition and the *left column* identifies the kinematic variable. The plain digits located at the top of the box show the control data with the standard deviation shown in parentheses. DF's data are given underneath the control data in *bold*

	Ai	Aii	Aiii	Aiv
Movement duration (ms)	999.39 (177.67) **1112.2**	1000.53 (207.14) **1083**	995.26 (195.93) **1139.2**	1015.14 (234.72) **1034.2**
Peak velocity (mm/s)	825.76 (130.48) **778.75**	796.89 (154.76) **618.95**	819.96 (155.06) **750.15**	784.24 (169.18) **622.9**
Time to peak velocity (ms)	376.58 (74.72) **448.03**	376.34 (93.42) **407.4**	384.1 (91.63) **458.15**	372.89 (85.92) **408.75**
Maximum grip aperture (mm)	74.26 (67.23) **66.31**	81.93 (65.92) **65.27**	84.30 (94.14) **70.1**	68.93 (43.17) **60.34**
Time to maximum grip aperture (ms)	809.67 (157.51) **948.03**	842.19 (206.60) **912.4**	861.25 (197.51) **1022.65**	805.85 (272.72) **837.75**

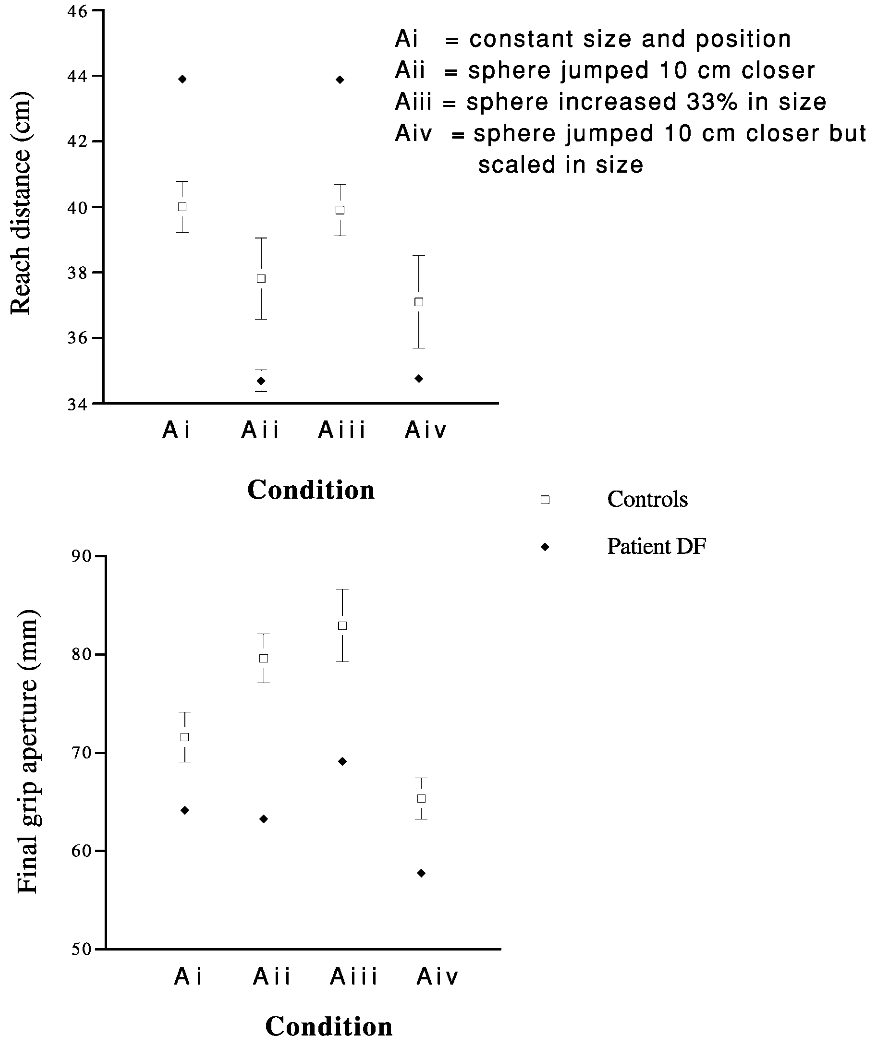

Fig. 1 Results from reaching condition. The *upper graph* shows the distance reached in cm (the sphere was located 40 cm from the participants' eyes). The control data are indicated by the squares and DF's data is shown by the *filled diamonds*. Standard error bars are shown unless these are smaller than the symbol size (note that the control data shows inter-participant variability whereas DF's data indicate intra-participant variability). The *lower graph* uses the same symbols and variability bars as the upper graph to show the data regarding the final grip aperture in mm

towards the participants but was scaled down to present the same retinal size, both the controls and DF showed a modification of hand transport and reached to the same location as condition Aii. They showed a corresponding decrease in grasp aperture.

In the conditions where the ball increased or decreased in size, the observed change in grasp aperture was less than would be predicted from the physical change for both DF and the controls. This observation is most readily explained by the presence of a contraction bias, which is a general tendency to bias responses to the mean of the range (Poulton 1989). Nonetheless, the changes in the sphere size or location did predict whether grasp aperture would increase or decrease relative to the control condition.

Matching task

The matching task had two forms, either matching the distance of the spheres or matching the size of the spheres. Figure 2 shows a compensation index, which is the proportional scaling applied in the matching task, where a value of 1.0 indicates perfect adjustment of the sphere to the target size or distance, respectively. A value less than 1.0 indicates under-compensation. Figure 2, upper panel, shows that when the task was to match the distance of spheres of the same size (Pi) the control participants had a bias towards placing the adjustable sphere slightly farther away than the target distance (compensation 1.19; 0.94 cm overshoot). DF displayed a slight amplification of this bias (compensation 1.35; 1.55 cm overshoot). When the task was to match the distance of the different sized spheres (Pii) the bias in control participants was reversed and they placed the adjustable sphere closer to them than the target distance (compensation 0.85; 0.65 cm undershoot). This confirms a size effect in the judgement of distance by controls. This effect was not evident for DF who displayed precisely the same accuracy for different sized spheres (compensation 1.31). The mean performance of DF varied from her control performance by only 0.15 cm, whereas controls produced an offset of 0.9 cm in favour of equalising size when matching distance. In this respect it seems that control participants find it difficult to ignore size information when the task is to match distance, whereas DF seems to be isolated from this source of bias.

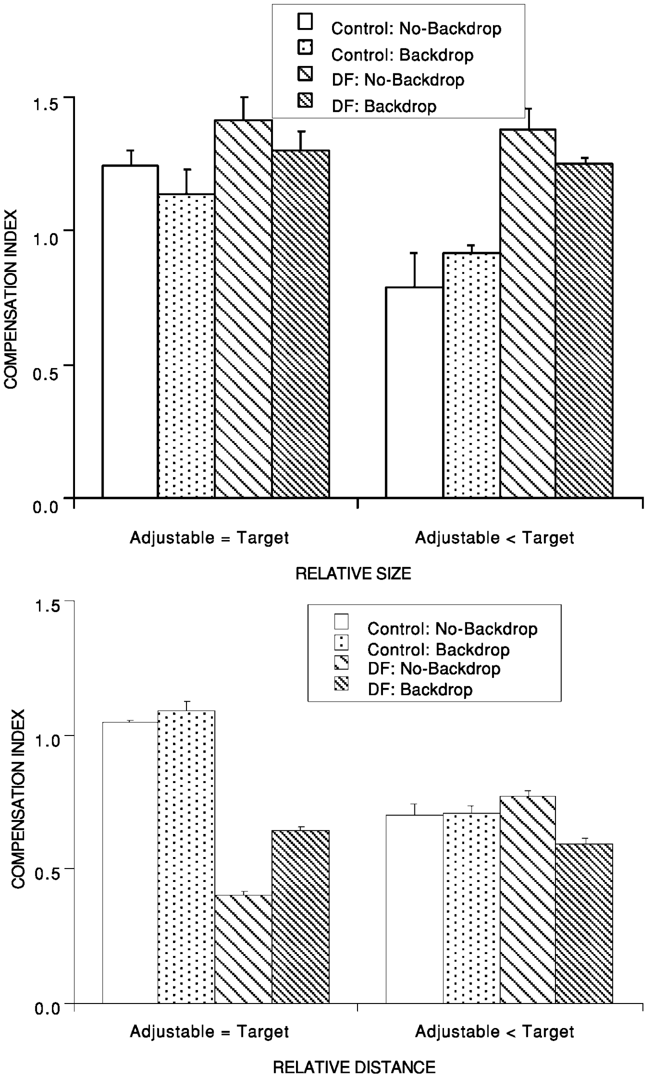

Fig. 2 Accuracy of distance or size matching in controls and DF. Compensation index indicates the degree of adjustment relative to a perfect match. CI<1.0 indicates an under-compensation; CI>1.0 indicates an over adjustment. The presence of a backdrop provides a reference to relative disparity to supplement vergence information. *Upper graph* shows the accuracy of distance matching when the size of the spheres was the same or different. *Lower graph* shows the accuracy of size matching when the distance of the spheres from the observer was the same or different. Error bars indicate the standard error across participants for controls and across trials for DF

In the size matching task (Fig. 2, lower panel), the control participants were extremely accurate in Piii when adjusting the size of the spheres that were placed at the same distance (compensation 1.07, 0.14 cm undersized). DF appeared to be unable to complete the size matching task (compensation 0.52, 0.95 cm oversized) despite the task requiring a "simple" monocular comparison. When participants were required to scale size with respect to specified distance (task Piv) to match actual graspable size, then controls displayed a slight bias towards under scaling the closer (and initially smaller) sphere (compensation 0.7). DF, however, improved her performance when she had to use binocular scaling (compensation 0.68) and displayed accuracy equivalent to the controls. The fact that DF performed task Piv as well as controls but is markedly poorer on task Pii rules out a simple attentional explanation. The size matching results do reflect two reciprocal trends; simple "monocular" size matching is very accurate for controls but they undercompensate if they need to scale retinal size with binocular distance information, whereas DF is very poor at monocular size matching but improves slightly if she is required to scale size with binocular distance information.

Discussion

These experiments explored the specification of distance for reaching towards graspable objects presented in free-space rather than constrained to a table top. They demonstrate that step shifts in vergence can cause changes in reach distance (tasks Aii and Aiv) in both controls and participant DF. This stands in contrast to step changes in retinal size which did not produce an illusion of motion in depth (tasks Aiii). The effect of a step shift in vergence specified distance (VSD) caused a far smaller effect in controls than that predicted from the viewing geometry and VSD would appear to have something close to a 20% weighting. A shift in size might have been expected to produce a change in distance estimation because known size is a powerful cue to distance perception (Mon-Williams and Tresilian 1999; Tresilian and Mon-Williams 1999; Tresilian et al. 1999). This type of perceptual bias was evident in the distance matching paradigm (Pii), but not during reaching to a target that jumped in size (task Aiii). These results suggest that in control participants, rapid reaching is not affected by the type of semantic information that comes into play for slower perceptual judgements.. As expected from previous studies (see Goodale et al. 1991; Mon-Williams et al. 2001a) DF was impervious to the influence of changes in size in either reaching or perceptual matching tasks. It was clear, however, that DF was considerably more sensitive to step changes in binocular distance information (90% weighting) and a perceptual task that required the use of binocular distance information improved her performance in a size matching task. It is possible that DF has learned to rely more heavily on vergence information because of her inability to use a range of other distance cues (see Marotta et al. 1997, Mon-Williams et al. 2001b).

This general pattern of results is in line with the distinction drawn between visual perceptual judgements and the information used in vision for action (Milner and Goodale 1995). The observation that the reach transport component is influenced by step changes in binocular distance information but encapsulated from equivalent step changes in size is of particular note. Although looming (smoothly changing size) is a paradigm example of a "direct" source of information that can inform action

(Lee 1976), our results illuminate the subtlety of the semantic/pragmatic distinction. Smooth, sustained changes in size (looming) can provide an estimate of immediacy for a ball approaching a hand independent of the processing of any distal properties. There is evidence of neurones that respond selectively to this type of information (Wang and Frost 1992; Sun and Frost 1998) and changing size is directly coupled to action, even in the infant (Ball and Tronick 1971; Bertenthal et al. 1997). There is little doubt that looming is an example of "pragmatic", action-linked visual information. In our experiments there was a change in size ($\theta_1 \rightarrow \theta_2$), but because the change was within a single screen refresh there was no period of looming ($d\theta/dt=0$). Hence, looming clearly provides information to the action stream but step changes in size apparently do not. In contrast it is clear that an instantaneous shift in binocular angular subtense *is* sufficient to alter reaching amplitude in the absence of sustained binocular motion. This is especially the case for participant DF. The distinction between semantic and pragmatic processing should be whether or not the visual specification can provide direct visual information that can guide that category of action. It cannot be the case that size information is always semantic – there is little room for semantics in catching a speeding cricket ball. If the action is to reach to a place of interception, however, changing size per se is not pragmatic information regarding reach distance, even though it is taken into account for the pragmatic modification of grasp size.

We obtained identical results when the shift in binocular angular subtense produced a step change in vergence as when a background provided an associated step change in relative disparity. This is superficially at odds with previous reports suggesting that motion in depth judgements are unaffected by changes in vergence. Erkelens and Collewijn (1985) reported that if participants binocularly viewed a target while vergence angle continually varied in a sinusoidal fashion, none of the participants reported seeing the target moving in depth or changing in size. A percept of motion in depth was nevertheless reported if relative disparities were available. The results of Erkelens and Collewijn (1985) are somewhat difficult to interpret, however, as the stimulus conditions created a significant cue conflict between vergence (which signalled that the target was moving in depth) and the absence of any looming which is recognised as a powerful cue to motion-in-depth (Regan and Beverley 1978). Thus, Erkelens and Collewijn's finding may demonstrate only that if looming is placed in conflict with vergence then, in a perceptual evaluation, participants weight the size and looming cues more heavily than extra-retinal vergence information. Our results support the role of vergence and vergence change in on-line modification of reaching in depth and suggest that it is equivalent to that of relative disparity.

The effects discussed above were amplified in our patient with visual form agnosia, where there is good evidence that information regarding metrical object properties is no longer available to the perceptual system. DF was sensitive to vergence specified distance to an abnormally high degree, and was also able to use size changes to modify her grasping response; yet she seemed immune from any semantic influences of size information. The question remains as to whether DF can catch a speeding cricket ball through the pragmatic use of changing size, or whether she would depend exclusively on binocular changes.

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