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Ordinal depth information from accommodation?

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The ability to judge egocentric distance was assessed in two groups of six observers using a manual pointing task. The purpose of the study was to determine the extent to which blur-driven accommodation can provide information on target distance in the absence of any retinal cues to distance. Observers were extremely accurate when carrying out the pointing task in a 'full-cue' condition. In contrast, observers were extremely poor at carrying out the task when accommodation was the only distance cue available. Responses on individual trials bore little relationship to the actual target distance in any of the observers. On the other hand, accommodation weakly biased the mean responses in some observers. This bias appears to be due to the observers' effective use of accommodation to determine whether the target presented in one trial was nearer or further away than the target presented in the previous trial. Accommodation therefore appears to provide ordinal information, although the distance signal may actually arise from accommodation-driven vergence. The poverty of accommodation as a source of metric information was highlighted in a second group of observers who all demonstrated a strong bias when perceiving distance in the presence of an initially ambiguous retinal cue. It is concluded that accommodation can act as a source of ordinal distance information in the absence of other cues to distance but the contribution of accommodation to normal distance perception in full-cue conditions is questioned.

1. Introduction

Information regarding an object's egocentric distance is available through a number of retinal and extraretinal cues. Extraretinal cues include the vergence angle of the eyes and the degree of accommodation. It is well established that vergence angle can provide metric information on target distance to human observers (Foley 1980, Mon-Williams and Tresilian 1999, Tresilian and Mon-Williams 1999) but the role of accommodation in distance perception is controversial. It has long been suggested that accommodation might be a source of distance information for human observers (Berkeley 1910 [1709]) and it has been shown that accommodation is a major distance cue for some animals (e.g. the chameleon; Ott and Schaeffel 1995). On the other hand, a body of early work investigating whether accommodation plays a role

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in human distance perception is in general agreement that accommodation plays little or no role. More recently, however, Fisher and Ciuffreda (1988) comprehensively reviewed previous research and argued that these studies were ambiguous, as they either failed to provide targets constituting adequate accommodative stimuli (Kunnapas 1968, Crannel and Peters 1970, Foley 1977), had confounds in experimental design (Wallach and Norris 1963) or placed accommodation in conflict with vergence (Grant 1942, von Holst 1973 [1969]). As Fisher and Ciuffreda (1988) point out, experiments that place accommodation in conflict with vergence are confounded due to the synergistic coupling of accommodation and vergence (accommodation drives vergence and vice versa).

Fisher and Ciuffreda (1988) concluded that the question of whether accommodation information plays a role in human distance perception was unanswered. They designed an experiment that avoided the problems associated with earlier work in order to provide a definitive answer. Fisher and Ciuffreda found that although most observers showed either a small or negligible ability to use accommodation information, a significant minority (25%) demonstrated a reliable relationship between accommodative response and the mean pointing response to targets at different distances. The implication was that the distance at which this minority of participants were accommodating determined in large part the distance at which they perceived the target. Since Fisher and Cuiffreda reported a good relationship between the accommodative response and target distance in all participants, it appeared that the accommodative response was providing a minority with quite good information about the actual distance of the target. Fisher and Cuiffreda (1988: 609) concluded that 'accommodation can indeed serve as a source of distance information, particularly for some individuals'. It appears, therefore, that the question of accommodation's role in human distance perception has been answered: it can be used as a distance cue but, in the group of people for whom it would be most useful (non-presbyopes), not all can use it effectively. On the other hand, the result does not actually establish the accuracy of accommodation as a distance cue in reduced cue conditions since the accommodative response does not precisely covary with target distance. Unfortunately, Fisher and Cuiffreda did not provide any indication of the variability of the individuals' pointing responses. In the absence of these data it is not possible to conclude that accommodation provides metric information on target distance—in §4 it is shown that averaging responses can provide a misleading picture of the information available from ordinal distance cues. The purpose of this paper is to report experiments that replicate Fisher and Cuiffreda's results and yet lead to a quite different conclusion.

2. Method

In order to explore the relationship between accommodation and perceived distance the authors employed an open-loop pointing task, which involved observers pointing an unseen finger to a series of seen targets. Particular care was taken to ensure that the targets (letters) served as adequate accommodative stimuli and that the observers were skilful in carrying out the actual pointing task. It was arranged that the targets placed at different distances were different letters. This arrangement ensured that there was no conflict between size and accommodation: if the targets were always the same letter then the constant size might suggest that the distance had not changed and so conflict with any information from accommodation. The sizes of the letter targets were made so that they subtended slightly different visual angles uncorrelated with their distance (see below).

2.1. *Observers and apparatus*
Twelve visually normal asymptomatic observers ranging in age from 19 to 32 years (mean age= 21 years) were recruited from a group of undergraduate and research staff at the Department of Human Movement Studies. No observers were paid, with the research staff volunteering and the undergraduate students participating in a laboratory class. All of the observers were emmetropic with no ophthalmic abnormalities or history of ocular problems. Six of the observers were randomly allocated to the first group and the other six to the second group. The experimental apparatus is shown in figure 1.

The apparatus consisted of a wooden rectangular box ($55 \times 20 \times 20$ cm) with an aperture (12×7 cm) at one end. The box was internally illuminated by a masked bulb at its far end. A thin sheet of white translucent perspex acted as a filter creating a constant ambient illumination (350 lux) within the box and providing a matt white screen against which targets could be easily displayed. The walls and floor of the box were painted matt black. The top of the box had nine thin slots to allow for the precise positioning of colourless transparent slides (15×15 cm). The slides each displayed a well-defined solid black Snellen letter (93% contrast) designed to provide an excellent accommodative stimulus. The three letters chosen as targets were X, Y and T. These letters are of equal legibility and have the advantage of being symmetrical around their mid-line (McGraw and Winn 1993). The letters provided high-contrast targets that stimulated the fovea and met the spatial frequency criteria for accurate accommodation (Charman and Tucker 1977, Owens 1980, Ciuffreda and Hokoda 1983). If changes in letter size are completely removed and the target is always the same (e.g. always the letter X) then a conflict between size and

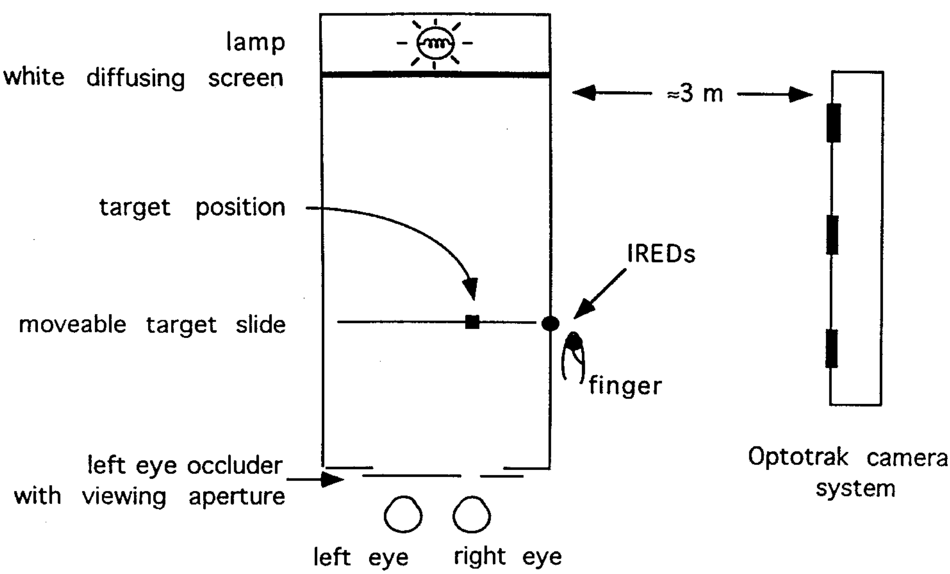

Figure 1. A schematic representation of the experimental apparatus.

accommodative cues is introduced. It is necessary to avoid this conflict but also to ensure that size changes are either absent altogether or unrelated to distance changes. In order to avoid this confounding, different target letters (X, Y and T) were used. These letters were of different sizes resulting in approximately the same angle of subtense at the observer's eye (10.5 arcmin was chosen to ensure that a precise accommodative response was elicited) and unpredictable small variations in size (2 arcmin) at the different distances. Observers were informed of this arrangement and it was emphasized that the size of the target would not be an indicator of egocentric distance. Nine slides were used to assess pointing accuracy. The slots for the respective slides were positioned in 0.5 D steps over a range from 2D to 6D (it is easiest to describe the accommodation stimuli in terms of dioptres (D): these are the reciprocal of distance in metres so that 1 D corresponds to 100 cm, 2 D corresponds to 50 cm, etc.).

Observers viewed the slides through the aperture in front of the box. A moulded plastic restraint mounted in front of the aperture provided some support for the observer's head and allowed observers to align themselves correctly with regard to the box. The restraint also meant that head movements were minimized in the viewing conditions. It was not possible to measure the actual accommodation response within the box. It seems reasonable to suggest, however, that measuring the accuracy of the accommodative response was not necessary for the following reasons. First, the targets met the criteria for providing an excellent accommodative stimulus. Second, the range of the target presentation was within the linear range where equality between accommodative stimulus and response exists (Morgan 1944, Heath 1956, Ciuffreda *et al.* 1984). Third, previous experiments (Fisher and Ciuffreda 1988) have shown that the accommodative response is accurate under the conditions employed here. Fourth, if the accommodation response of an observer was inaccurate (in spite of the factors just outlined) it would bring into question the extent to which such an inaccurate motor response is capable of providing a consistently good source of distance information. Finally, the presented results are in complete agreement with those of a study that did measure accommodation in very similar experimental conditions (Fisher and Ciuffreda 1988).

In order to measure pointing accuracy, an Optotrak 3-D optoelectronic movement recording system was used. This system measures the 3-D position of small infra-red light emitting diodes (IREDs); it was factory pre-calibrated and had a static positional resolution of within 0.2 mm. An IRED was placed on the fingernail of the observer's right hand (all observers were right-handed) and another was located next to the target slide (figure 1). The Optotrak system recorded the position of the finger and the slide for a 0.5 s period after the observers indicated that their finger was correctly positioned (positions of the IREDs were computed as the mean of the sampled positions over the 0.5 s period; sampling rate was 60 Hz). The data were stored in computer memory for later analysis. A software routine provided both absolute position and the distance between the IREDs (the error).

2.2. *Procedure for Experiment 1*

Observers were positioned within the apparatus with the ambient room illumination turned down. In Experiment 1, nine slides were presented in a randomized order and the observer pointed at each slide five times. This procedure supplied an assessment of normal pointing accuracy but also allowed observers to develop the skill of carrying out the open loop pointing task. The changes in step size were also randomized. In the first condition observers were able to see the whole of the slide and the inside of the box using both eyes (the 'full-cue' condition). They were instructed to point at the target displayed on the slide within the box. Observers slid their fingers along the outside of the box until they felt that they had accurately localized the target's position. Following this first condition, an occluder was placed within the viewing aperture. The occluder covered the majority of the aperture apart from a 6 mm square opening through which the right eye could view (the size of this opening ensured that the accommodative loop stayed closed: Gray *et al*. 1993). When the occluder was in position the observer could only see the target letter against the white background. Disparity-driven vergence and visual cues were thereby removed as potential sources of distance information. The targets were all carefully positioned along the viewing axis of the right eye so that monocular vergence cues were also eliminated. This arrangement was also necessary to ensure that the observers' pointing responses were not biased by any changes in cyclopean direction caused by vergence occurring via the accommodative vergence cross-link (Mon-Williams and Tresilian 1999). With the occluder in place, observers were again asked to point to each target five times in the nine randomized positions. In between pointing at each slide, the observer shut their eyes and moved their finger back to a predetermined starting position. This ensured that no temporal visual cues were available and controlled for proprioceptive drift (Wann and Ibrahim 1992). It was emphasized to the observers that the target letter had to be in focus before they pointed (this occasionally took several seconds in the accommodation only condition).

2.3. *Procedure for Experiment 2*

The protocol for the second experiment was essentially identical to the first apart from two factors. First, in the 'full-cue' condition, observers only pointed three times at the target letter. Although this still allowed for an assessment of pointing accuracy it decreased the potential for any training effect to occur. Second, in the 'reduced-cue' condition, only a single slide was used for all of the nine possible positions. This slide used a 1 mm letter as a target but observers were not informed about the size. Presentation order was still randomized and observers pointed five times at each target location. This procedure meant that accommodation was still available but that observers had the potential to use changes in relative size (the target subtended an angle ranging between 20.6 arcmin at 16.66 cm and 8.6 arcmin at 40 cm). It should be noted that the potential visual cue was initially ambiguous and required a learning process (although any strategy might be implicitly rather than explicitly adopted).

3. Results

The data were initially examined in terms of the pointing error in millimetres. Examination of the data revealed a problem with the data from the furthest (50 cm) target. When the variability of the data was examined it was found to be more variable than all other target positions for eight of the observers and less variable for the other four. The greater variability of the data for the majority of participants may be explained by a range effect. It transpired (on *post hoc* questioning) that the individuals who demonstrated a lower variability had adopted a strategy of adopting a consistent arm position whenever they saw what they considered to be the furthest target. In view of these confoundings it was decided to exclude these data from further analysis. It should be noted that this step favours finding a role for accommodation in distance perception as accommodation decreases inversely with distance.

Following the initial data examination, it was ensured that all observers were accurate at carrying out the pointing task in the full-cue condition. Target position was plotted against finger position in distance (as opposed to dioptres) and a linear function was fitted to the data. All of the observers were found to be accurate at carrying out the task in the full vision condition. The mean signed error was 1.49 cm (SE= 0.18 cm) and the mean unsigned error was 2.36 cm (SE= 0.15 cm) across observers. A linear function fitted to the grouped data showed a significant positive correlation between target position and finger position (r^2= 1.00) with a slope of 1.08 and an intercept of −2.36. These data agree well with previous findings (Von Hofsten and Rosblad 1988, van Beers *et al*. 1996, Mon-Williams *et al*. 1997, Tresilian and Mon-Williams 1999).

Having established that observers were able to carry out the task in the full-cue condition, the data were plotted for the experimental conditions. As the interest was in comparing the present data with those of Fisher and Ciuffreda (1988), their method of data analysis was followed. The target position was plotted against the mean finger position in dioptres and a linear function fitted to the data. As individual differences are of interest to this study, each observer's data were plotted separately rather than observers being grouped together. Figure 2 illustrates the data from the observers in Experiment 1 and figure 3 illustrates the data from Experiment 2.

If the observers were using accommodation to provide metric information about target distance then the pointing responses on individual trials should be metrically related to the target distance on those trials for each observer. Only two observers showed a reasonable gain for the mean response vs. target distance relationship (figure 2) in Experiment 1 and so only these observers are sensible candidates for metrical use of accommodation information. Figure 4 shows the raw response data for these observers plotted against the actual distance of the target.

Examination of the raw data in figure 4 indicates that the responses do not support the conclusion that accommodation is providing metric distance information: the observers were almost never within 2 cm of the target on any individual trial and the unsigned range of error was 39.47 cm for Observer 1 (as compared to 6.25 cm in the full-cue condition) and 40.49 cm for Observer 2 (7.12 cm in the full-cue condition). When it is considered that the range of possible target distances was 24 cm, it is clear that accommodation is providing no functionally useful metric distance information for these observers. The responses were unrelated to the actual distance of the target.

The question of whether accommodation might be providing ordinal distance information on a trial by trial basis was next examined. If ordinal information of this type were available, observers would be able to determine whether a target present on a particular trial (trial k) was nearer or further away than the target presented on the previous trial (trial k−1) but would be quite unable to determine where the target actually was. This was examined by determining whether the responses on trials k were in the appropriate direction with respect to responses on the immediately preceding trial (k−1): if the target were further away on trial k than on k−1 then observers should point further on trial k than they did on k−1. All trials, including those excluded in the initial analyses because of a range effect, were examined. The results of this analysis were conclusive: observers pointed in the appropriate direction on the majority of trials (table 1). These results demonstrate that most observers were able to correctly determine whether a given target was nearer or further away than the previously presented target. It should be noted that the observers who showed the higher gains when linear regression analyses were conducted on their mean data (reported above, figure 2), showed the better ability to use ordinal information.

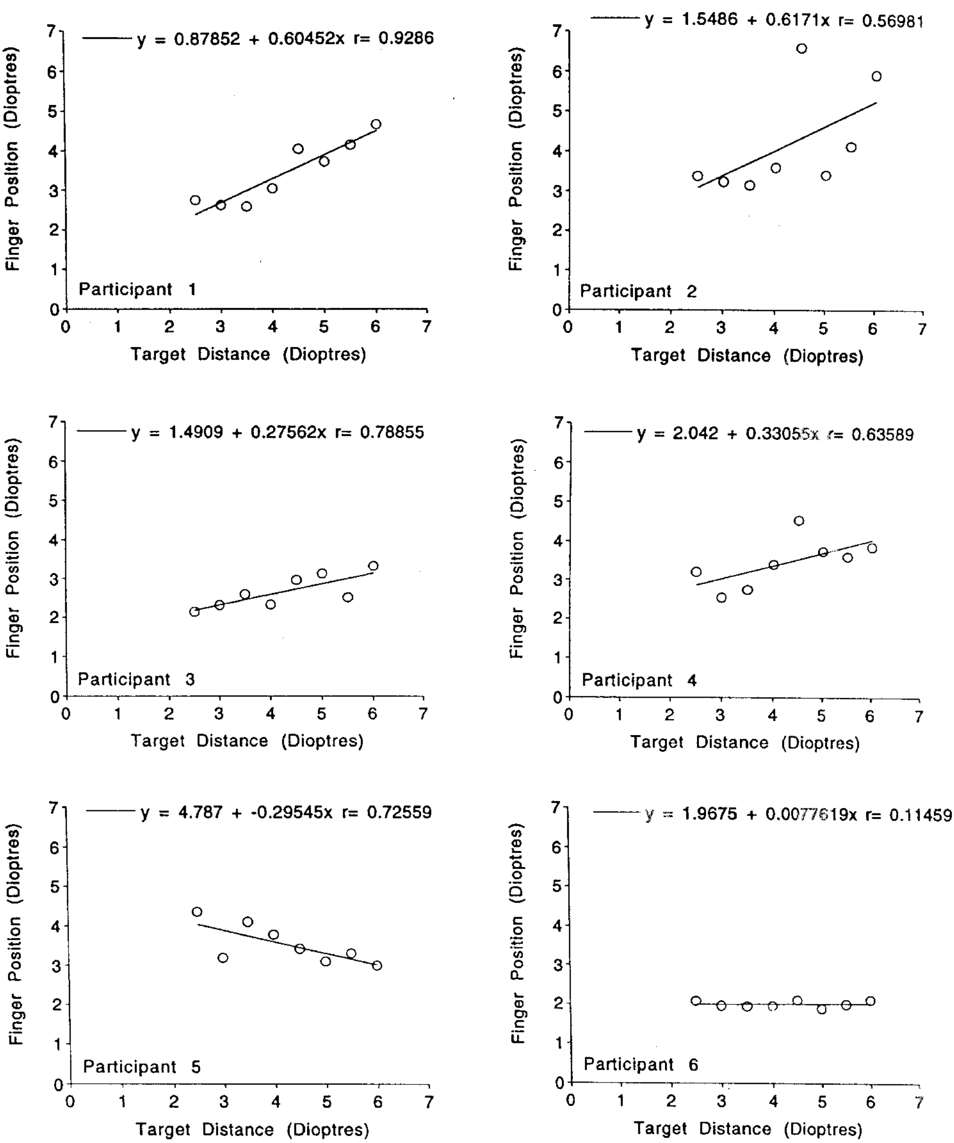

Figure 2. Finger position in dioptres plotted as a function of dioptric target distance for individual observers in Experiment 1. The solid line and equation represents the linear function fitted to the data. Each data point represents the mean of five trials.

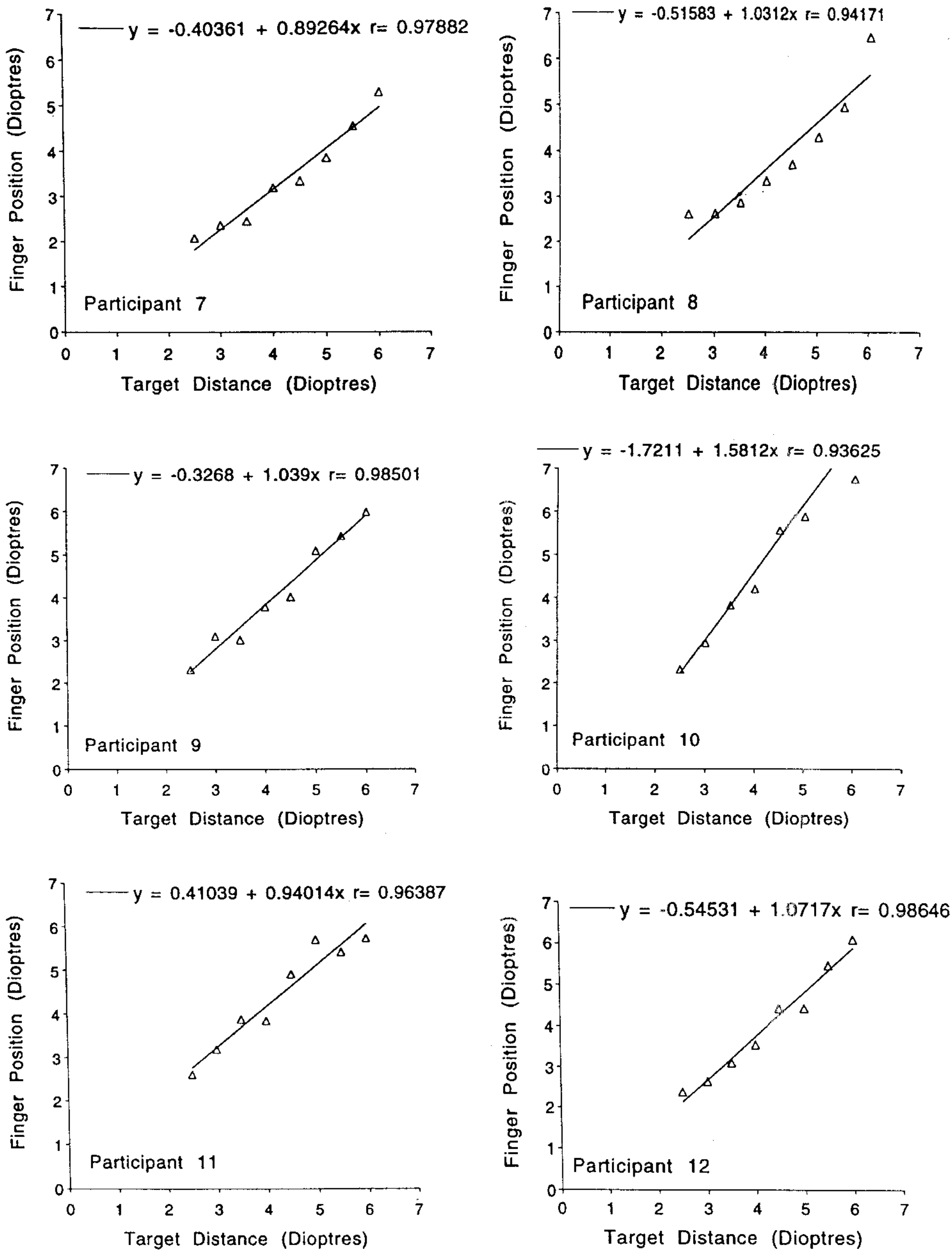

Figure 3. Finger position in dioptres plotted as a function of dioptric target distance for individual observers in Experiment 2. The solid line and equation represents the linear function fitted to the data. Each data point represents the mean of five trials.

4. Discussion

When averaged (either over observers or over the trials for individual observers) the data from the current experiment are very similar to those presented by Fisher and Ciuffreda (1988). The data showed a gain for the relationship between stimulus

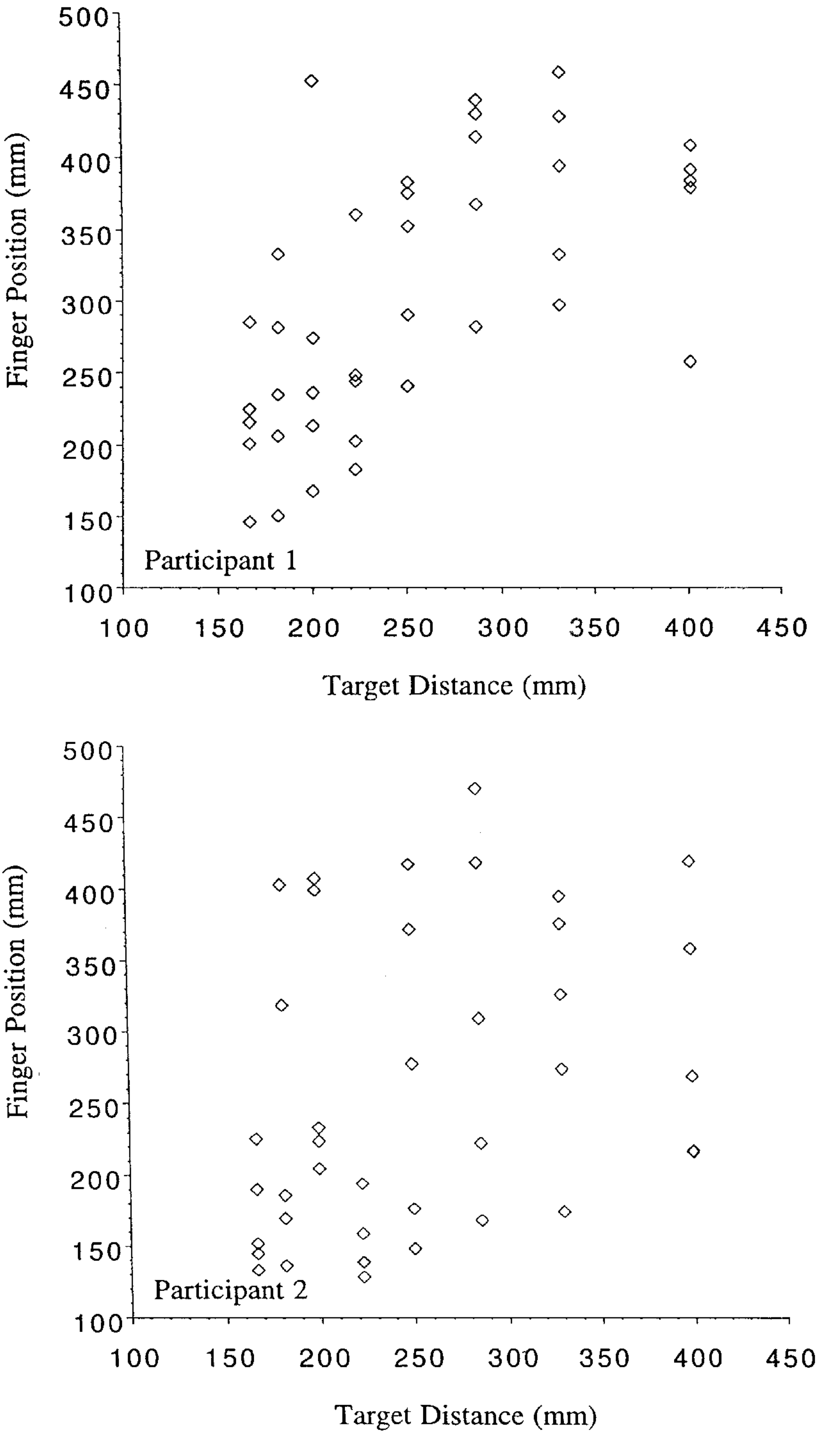

Figure 4. Finger position plotted as a function of target distance for Observer 1 and Observer 2 in Experiment 1. Each trial is shown rather than the mean of the trials and absolute distance is plotted in mm rather than dioptric position. These data may be compared to the means plotted in the top two graphs of figure 2.

Table 1. The results of the analysis on ordinal judgements of distance. The first column indicates the participant, the second column provides the linear (least squares fit) regression and correlation coefficient (to the nearest two decimal places) for the mean pointing response and the third column indicates the percentage of trials in which the observer pointed in the correct direction from the previous trial (to the nearest 0.5%)

Participant	Linear function of mean data	Trials in correct direction (%)
Observer 1	0.61x+ 0.89 r= 0.93	86.5% of trials
Observer 2	0.62x+ 1.55 r= 0.57	78% of trials
Observer 3	0.28x+ 1.49 r= 0.79	79% of trials
Observer 4	0.33x+ 2.04 r= 0.64	75.5% of trials
Observer 5	– 0.30x+ 4.79 r= 0.73	33.5% of trials
Observer 6	0.01x+ 1.97 r= 0.12	47% of trials

distance and perceived distance of around 60% for Observers 1 and 2, a weaker gain of about 30% for Observers 3 and 4 and negligible gains for Observers 5 (negative gain) and 6 (positive gain). These results compare well with those of Fisher and Ciuffreda who found that 4 of their 16 observers had a gain of around 60%, another 4 had a gain of around 30% and the remaining 8 had small positive or small negative gains. Averaging, however, can give a very misleading picture as demonstrated by the data from individual observers shown in figure 4. The individual trial data from each observer clearly showed that the judged distance bore little relationship to the actual distance of the target on any given trial. Further analysis, however, showed that, for most observers, the sequence of responses was ordered in distance in close correspondence to the distance ordering of the targets in the trial sequence. These results strongly suggest that if accommodation is used in distance perception its role is not to provide metric distance information but merely ordinal information. That is, accommodation does not inform about how far away a target is (the pointing response on any given trial bore little or no relationship to actual target distance), rather it informs about whether or not the target seen on one trial is closer or further than that seen on the last trial. This ordinal information is not used effectively by all individuals but most were able to use it at least 75% of the time. Note that use of ordinal information does not necessarily lead to a strong relationship (gain >0.5) between perceived and actual distance on the average. Such a relationship may emerge, but equally it may not. These data indicate that if the ordinal information is being used successfully on more than 75% of trials, there is about an equal chance of a gain greater than 0.5. These results provide an alternative explanation for the data of Fisher and Ciuffreda (1988)—the reasonable relationship that they reported between accommodation and mean pointing response for 25% of their participants was due to the observers using ordinal information on target distance (Fisher and Ciuffreda did not provide any information on the variability of the pointing responses and there is therefore no evidence to support the contention that accommodation provides metric distance information).

The observation that accommodation can provide individuals with ordinal distance information does not mean that accommodation contributes to distance perception when other distance cues are available. Indeed, the exact opposite is likely to be the case. This experiment has only demonstrated the availability of ordinal information from accommodation in a very reduced visual environment (where no retinal information for distance existed). If accommodation can only provide ordinal distance information then it would be unlikely to play a role in the localization of an object under normal viewing conditions as this requires metric distance information. Moreover, there are various neurophysiological limitations of the accommodation system that drastically reduce the reliability of any available information on focusing distance (Atchison *et al*. 1997). It is clear that even for the 'best' observer (Observer 1) the ordinal information available via accommodation is not completely reliable as the responses were only ordered correctly 86.5% of the time. It is hard to imagine a less reliable ordinal distance cue. This argues against accommodative information being combined with other cues when these are available (Bruno and Cutting 1988, Massarro 1988) since combination of a reliable cue with an unreliable one results in degraded performance relative to that obtained using the reliable cue in isolation (Green and Swets 1966).

The results and analyses of the present study therefore reconcile the existing literature on accommodation as a cue to distance: accommodation provides no metric distance information—explaining why so many investigators (albeit with confounds in their experimental designs) have failed to find evidence that accommodation provides metric distance information—but accommodation does provide ordinal information to some observers explaining why Fisher and Ciuffreda (1988) found a relationship between mean pointing response and accommodation in some of their non-presbyopic participants.

Experiment 2 shows that when just one additional static monocular visual cue to distance is provided, performance improves dramatically. In Experiment 2 the conditions were identical to those of Experiment 1 except that the visual angle subtended by the target letter varied in a predictable way with slide position (the same target was used in every position). Observers, however, did not know the absolute size of the target letter a priori and were therefore required to learn the relationship between the object's size and its distance. Nevertheless, the gain of the relationship between actual target position and pointing response was extremely high for all observers. The observers were less accurate (mean unsigned error was 4.37 cm, SE= 0.23) than in the full-cue condition, but all were notably better than the best two observers from Experiment 1.

The ability of accommodation to provide ordinal information may actually depend upon vergence rather than accommodation *per se*. As accommodation drives vergence (via the accommodative vergence cross-link), it is possible that the visual system is using the vergence signal resulting from the accommodative response as a cue to distance. Vergence is known to be an egocentric distance cue, especially in the absence of retinal information (Foley 1980, Mon-Williams and Tresilian 1999, Tresilian and Mon-Williams 1999). Hollins (1976) has previously argued that accommodative micropsia (a reduction in perceived target size following accommodation) is due to vergence rather than accommodation. Hollins' argument was based upon the observation that when accommodation was briefly altered with vergence held constant, perceived distance did not change whereas briefly altering vergence with accommodation held constant changed the perception of target distance. This observation is not definitive as the presence of a constant vergence signal may have overridden any distance signal from the accommodation system. This observation does show, however, that the change in perceived distance (which causes the change in perceived size) is primarily due to the cross-linked vergence response. This observation strongly suggests that the ordinal information from accommodation is obtained from changes in accommodative vergence.

The cross-linking of vergence and accommodation means that distance perception can be indirectly influenced by accommodation. In fact, Swenson (1932) has shown that dissociating accommodation from vergence causes a bias in distance perception in the direction of the accommodative level (i.e. if fixation distance is closer than the accommodative level then distance judgements will be biased away from fixation distance and vice versa). This finding is predicted from the oculo-motor response to sustained conflicts between accommodation and vergence—in situations of conflict the system shifts the resting position of the extra-ocular musculature. It has been established that such low level shifts in muscle innervation will cause predictable changes in perceived distance (Shebilske *et al*. 1983). This conclusion has implications for the design of virtual reality systems where accommodation and vergence are dissociated and low level shifts in muscle innervation are known to occur (Mon-Williams *et al*. 1993). If a virtual reality system is organized so that the accommodative demand is beyond the fixation distance, the eyes will show a convergent shift in resting position and targets will be perceived as further than their actual location. If the situation is reversed so that fixation distance is further than the accommodative level then the eyes will show a divergent shift in resting position and targets will be perceived as closer than their actual location. Furthermore, it is known that a vergence signal is used to interpret horizontal image disparities (Bradshaw *et al*. 1996) so that shifts in muscle innervation will also impact upon the distance and depth information contained within the display's horizontal disparities. It may be seen that the motoric action of accommodation can have a large influence on distance and depth perception despite the fact that accommodation does not directly contribute a signal to the distance percept. It follows that the motoric action of accommodation must be considered when building binocular virtual reality systems if the system is designed to provide veridical perceptual information (i.e. in 'virtual surgery' or teleoperation).

In conclusion, there appears to be little support for the notion that accommodation provides useful distance information. The empirical results support the view that accommodation does not allow for adequate metric determination of egocentric distance. The results suggest instead that accommodation (probably via accommodative vergence) may enable some individuals to make reliable ordinal distance judgements some of the time in the absence of other cues. Ordinal judgements in full-cue environments are easy to make and seldom, if ever, erroneous except in artificially contrived situations. The normal salience of optical information for ordinal judgements means that accommodation is almost certain to play no direct role in distance perception under normal viewing conditions for human observers. None the less, the neural cross-linking of accommodation and vergence means that accommodative level can influence distance perception indirectly and must therefore be considered as a factor in conditions (e.g. stereoscopes or binocular virtual reality systems) where accommodation and vergence are in conflict.

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