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Distance perception within near visual space

Alain Viguier, Gilles Clément, Yves Trotter
Centre de Recherche Cerveau et Cognition, UMR 5549 CNRS/UPS, Faculté de Médecine de Rangueil,
133 Route de Narbonne, 31062 Toulouse Cedex, France; e-mail: gclement@cerco.ups-tlse.fr
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Abstract. We investigated the perception of distance of visual targets with constant size and luminance presented between 20 and 120 cm from subjects' eyes. When retinal disparity cues were present, the subjects could reproduce very accurately the distance of a seen reference in this area. When only extraretinal information was available, distance perception was still correct for distances of 40 cm or less. However, distances beyond 60 cm were underestimated. When forced to evaluate the distance between a reference and themselves, eg when evaluating the absolute distance or half the distance or twice the distance of a reference, subjects used an egocentric plane of reference located on average 10.4 cm in front of their eyes. Measurements of binocular eye movements indicated a clear relationship between vergence angle and target distance. The egocentric plane of reference at 10.4 cm also corresponds to the maximum achievable vergence. These results suggest that ocular convergence can be used as a reliable cue for distance within the arm's reaching space.

1 Introduction

Before reaching for an object, an observer must evaluate its shape, particularly its thickness, and its position relative to the other objects in the near space. It is also necessary to estimate its distance relative to the observer. The estimation of the exact position of an object in the perspective of a motor act then requires both stereoscopic and distance cues. Stereopsis can give information about an object's absolute distance only through its distance relative to other objects for which the absolute distance is known. Perceived size, brightness, texture, motion parallax, and retinal vertical disparity are other potential cues which can also be used for absolute-distance perception (Bishop 1989).

The perception of distance of an isolated object cannot be performed on the basis of retinal disparity alone, since the image of this object can be projected at the same retinal location in both eyes (most often on the fovea) irrespective of its absolute distance. In this case, it is necessary to combine retinal information with information about ocular convergence (from motor efference or sensory feedback) and/or the related state of accommodation (Gogel 1961). Ocular convergence provides direct and unambiguous information on the absolute distance of an object, as each distance corresponds to a unique convergence angle (Richard and Miller 1969).

The convergence signal is relatively weak beyond about 2 m. Previous studies have shown that the magnitude of perceived distances is usually erroneous for targets at these distances (see Collewijn and Erkelens 1990, for review) with a systematic tendency to underestimate the objective distance range (Gogel 1961; Gogel and Tietz 1973; Foley 1977; Morrison and Whiteside 1984).

Surprisingly few studies have dealt with the relation between vergence and perception of distances below 1 m (Swenson 1932; Grant 1942; Foley and Held 1972; Foley 1978; Brenner and van Damme 1998; Mon-Williams and Tresilian 1999). Distance perception of the objects in such a space, corresponding roughly to arm's length, is of fundamental importance for accurate reaching. Although some authors have clearly shown that the estimation of short distances is related to ocular vergence (von Hofsten 1976; Foley 1980; Tresilian et al 1999), the results were variable across studies, probably owing to the different methods used for eliminating additional cues to distance. Furthermore, the dissociation between ocular vergence and disparity is especially hard to establish, since eye movements have not been recorded in most psychophysical studies on the role of vergence in the perception of distance (Collewijn and Erkelens 1990).

In the present study, we examined the relationship between vergence and distance perception when subjects looked at actual targets at distances ranging from 20 to 80 cm. In order to dissociate between ocular vergence and retinal disparity, tests were performed with and without a seen reference. We also explored the importance of the subjective egocentric reference for measuring distance by asking the subjects to make half-distance or double-distance settings and oral evaluation of target distance. Binocular eye movements were measured in order to check that accurate binocular fixation was achieved during the test.

2 Methods

2.1 *Subjects and apparatus*

Twelve subjects aged 27 to 56 years (mean: 32.8 years) were used in this study; all had normal or corrected-to-normal visual acuity. The experiment was undertaken with the understanding and written consent of each subject.

The subjects were sitting upright with chin and forehead supported in an adjustable rest. The reference targets consisted of six red light-emitting diodes covered by a flat diffusing surface. All diodes were placed in the sagittal plane, on a horizontal line passing through the centre of interpupillary distance at eye level (figure 1). They were presented one at a time, at a distance of 20, 30, 40, 60, 80, or 120 cm from the subject's cornea. A circular aperture on the front of the diode was arranged to form a circular dot with a diameter of 0.57 deg for the observer, eg 2 mm in diameter at 20 cm, 3 mm at 30 cm, etc. The luminance of each diode was empirically adjusted so that the reference target appeared the same for the observer whatever its distance. The naïve subjects were not shown the experimental layout of targets in the lit room prior to performing the experiment.

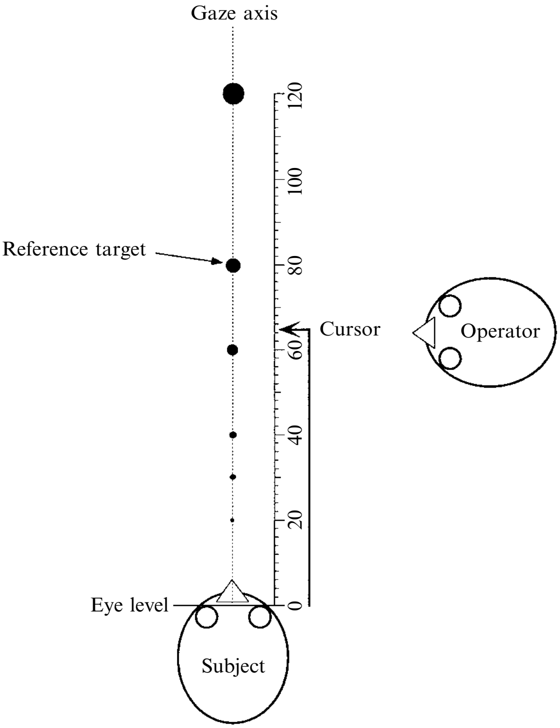

Figure 1. Schematic representation of the apparatus.

The subject could move a cursor along a horizontal line, 4 cm to the right of the horizontal line supporting the references, by means of a hand-held crank. The cursor consisted of a yellow-emitting diode arranged to form a 0.45 cm × 0.1 cm rectangle. The variations in size and eccentricity of the cursor as it changed distance were intentional as they provided clear distance cues to the subjects. The distance between the cursor and the subject's cornea was measured for each trial with an accuracy of 0.1 cm. Between each trial the cursor was brought back by the operator to a position at about 8 cm from the eyes. Five subjects were also tested with an initial position of the cursor at 80 cm from the eyes. No statistical differences in the results were observed between the two methods, indicating that the initial position of the cursor had no effect on target distance estimation.

During the experiment, in four subjects both the right and left eyes were recorded in near infrared (750 – 820 nm) with two video cameras (NTSC, 60 Hz) through reflection in dichroic mirrors (ISCAN Inc, Cambridge, MA). The eye movements were calibrated at the beginning of the test by having the subject fixate a centre target at eye level at a distance of 4 m and four other targets ±5 deg apart in the horizontal and vertical planes. The eye images were analysed off-line to reconstruct the centre of the pupil with a precision of 0.03 deg (Sung and Reschke 1997). Vergence was calculated as the difference between the horizontal positions of the two eyes (Fajardo et al 1998). Zero values of ocular vergence corresponded to fixation of the centre target at optical infinity during calibration.

2.2 *Experimental protocol*

The experiment, conducted in complete darkness in a totally lightproof experimental room, included five tasks:

(a) Equal distance with a seen reference: the subjects were asked to align the cursor with a seen reference at all the tested distances, in order to check that they had normal stereoscopic acuity.

(b) Equal distance without a seen reference: the reference and the cursor were never visible at the same time. The reference (at 20, 30, 40, 60, or 80 cm) was presented for 5 s, then switched off for 5 s before the cursor was switched on. Foley (1976) has shown that the vergence tended to go to a rest level when the subject was in darkness after fixating a near target. Accordingly, we used a 5 s period of complete darkness after presenting the reference to ensure that the retinal disparities which might result from looking successively at the reference and the cursor would not be used to evaluate its distance. The task was to set the cursor to the same distance as the previously seen reference.

(c) Half distance with a seen reference: both the reference (at 30, 40, 60, 80, and 120 cm) and the cursor were presented simultaneously. The subjects had to set the cursor to half the distance between themselves and the seen reference. Retinal disparity cues were present during this task, but the subjects were forced to evaluate the distance between the reference and their subjective egocentric reference.

(d) Double distance with a seen reference: both the reference (at 20, 30, and 40 cm) and the cursor were presented simultaneously. The subjects' task was to set the cursor to twice the distance between themselves and the seen reference.

(e) Oral evaluation: the references (at 20, 30, 40, 60, and 80 cm) were presented in a random order. The subjects' task was to make ballpark estimates of the distance between themselves and the seen reference in centimetres. They did not know in advance the range of possible distances. Retinal disparity cues were absent during this task.

For the first and the last task, each reference target was presented twice in a random order. This small number of trials was judged sufficient since the settings and oral evaluations in these tasks were highly reproducible for each subject. The other three tasks were performed sequentially in blocks of 40 trials, with each reference presented 8 times in a random order. Standard deviations were calculated on overall data. In all tasks, the subjects were free to take as long as they wished to make their settings with the cursor or oral evaluations.

3 Results

The perceived distance as a function of the actual distance during the five tasks is shown in figure 2. The equal-distance settings were very close to the seen reference for all distances. However, when the subjects attempted to replicate the distance of a previously seen reference (figure 2a) the results were different between near distances (20, 30, and 40 cm) and farther distances (60 and 80 cm). For near distances, the settings were very accurate, whereas for references placed at 60 and 80 cm, the distances were underestimated by 10.3 and 24.1 cm, respectively, with a large variability among trials. The perceived half distance was clearly overestimated by all subjects for the first three references, whereas it was underestimated by some subjects when the reference was placed at 80 cm (figure 2b). The perceived half distance of a reference placed at 120 cm was generally underestimated. The perceived double distance of references placed at 20, 30, and 40 cm was underestimated (figure 2c). When asked to estimate in centimetres the distance of seen references, all subjects also underestimated these distances (figure 2d).

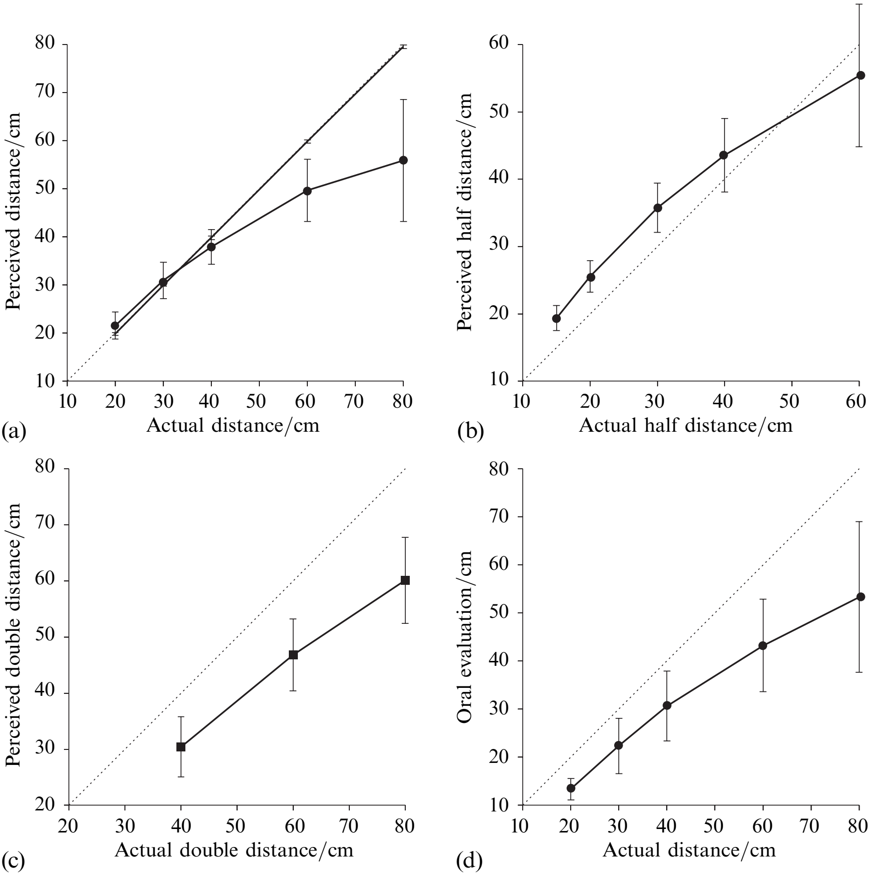

Figure 2. (a) Equal-distance settings with (diagonal solid line, mean ± SD of 2 trials for twelve subjects) and without (filled symbols, mean ± SD of 8 trials for twelve subjects) a seen reference. (b) Half-distance settings (mean ± SD of 8 trials for twelve subjects). (c) Double-distance settings (mean ± SD of 8 trials for twelve subjects). (d) Oral evaluation (mean ± SD of 2 trials for twelve subjects).

For the reference targets placed at 30, 40, and 60 cm, corresponding to actual half distances of 15, 20, and 30 cm, the measured overestimation of the perceived half distance was constant, with a mean value of 5.2 ± 2.7 cm for 288 trials. Such constant overestimation of the near distances is striking, since the errors in setting the distances in this range were found to be minimal in the first two tasks. However, this discrepancy can be explained if we assume that the subjects did not estimate the half distance of the references relative to the frontal plane passing through their eyes, but to a frontal plane located 10.4 cm (ie 2×5.2 cm) in front of their eyes. An example is illustrated in figure 3. When a reference is placed 40 cm from the subjects' eyes, the subjects put the cursor on average 25.5 cm from their eyes. This value can be interpreted as an overestimation of the perceived half distance. However, if the egocentric reference used by the subjects for evaluating the actual distance between themselves and the target is located 10.4 cm in front of their eyes, then the reported half distance is exactly midway between this egocentric reference and the target reference.

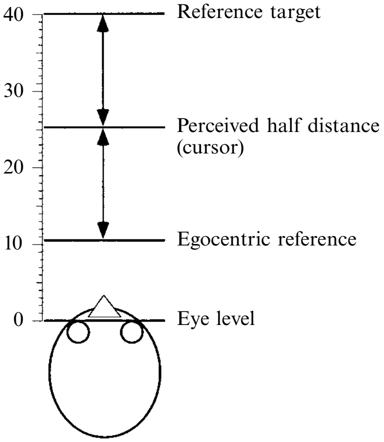

Figure 3. Schematic illustration of why a constant overestimation in the half-distance setting of a target reference when measured from the eye level corresponds in fact to the veridical half-distance setting when measured from a plane located 10.4 cm in front of the eyes.

This could also explain why the oral evaluations and the double distances were underestimated. Since all subjects showed no errors in judging distances ranging from 20 to 40 cm, it is likely that they estimated correctly the half distances and double distances in this range as well. Accordingly, in figure 4a, the distance settings by the subjects have been plotted relative to the distances of the references measured from an egocentric plane of reference located 10.4 cm in front of the subjects' eyes. The corrected half-distance and double-distance settings and the oral evaluations are plotted relative to the expected half distances, double distances, and absolute distances if the subjects used an egocentric plane of reference located 10.4 cm in front of their eyes, respectively. For example, the expected half distance of a reference located 40 cm from the eyes is now $\frac{1}{2}(40 - 10.4) + 10.4 = 25.2$ cm in front of the eyes. On average, the subjects actually perceived this half distance at 25.5 cm, which is very close to 25.2 cm. Plotted this way, the set target distances are the same in the four tasks. In figure 4b, the error in the perceived distance has been calculated as the difference between the corrected subjects' settings and the perfect correspondence. For all tasks, the error in perceiving distances up to 50 cm in front of the eyes remained below 4 cm. Above this distance, the error increased markedly with the distance.

The eye movements were recorded in four subjects during these tasks. Figure 5 shows two representative vergence eye movements from unreferenced settings at distances of 30 and 80 cm. In both examples, the subject started to look at the reference targets with an absolute convergence angle of about 11° and 4°, respectively. When the reference disappeared, eye convergence tended to decrease, especially when the reference

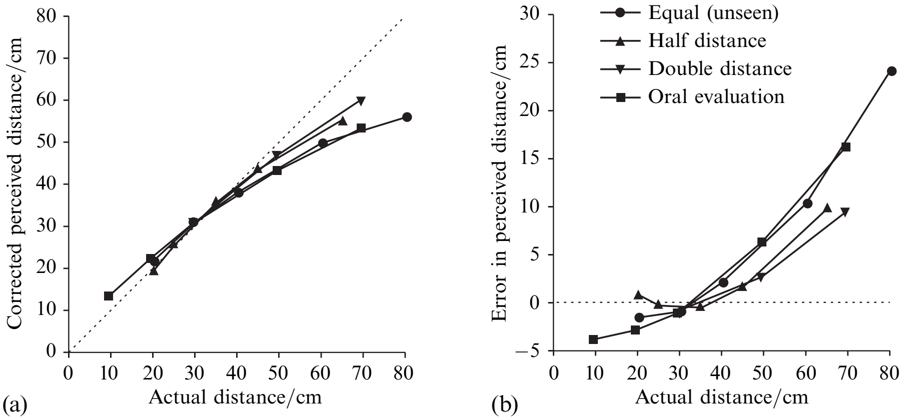

Figure 4. (a) Same results as in figure 2. The actual distances in the half-distance and double-distance and the oral-evaluation tasks are the expected settings when an egocentric plane of reference located 10.4 cm in front of the subjects' eyes is used: the expected half distances of references placed at 30, 40, 60, 80, and 120 cm are 20.2, 25.2, 35.2, 45.2, and 65.2 cm, respectively; the expected double distances of references placed at 20, 30, and 40 cm are 29.6, 49.6, and 69.6 cm, respectively. (b) Error in the corrected perceived distance in all four tasks, measured as the difference between the distance settings and the actual distances. The responses in all tasks are very similar, with a small error in judging distances below 50 cm, and a larger error, which increases with distance, for distances above 50 cm.

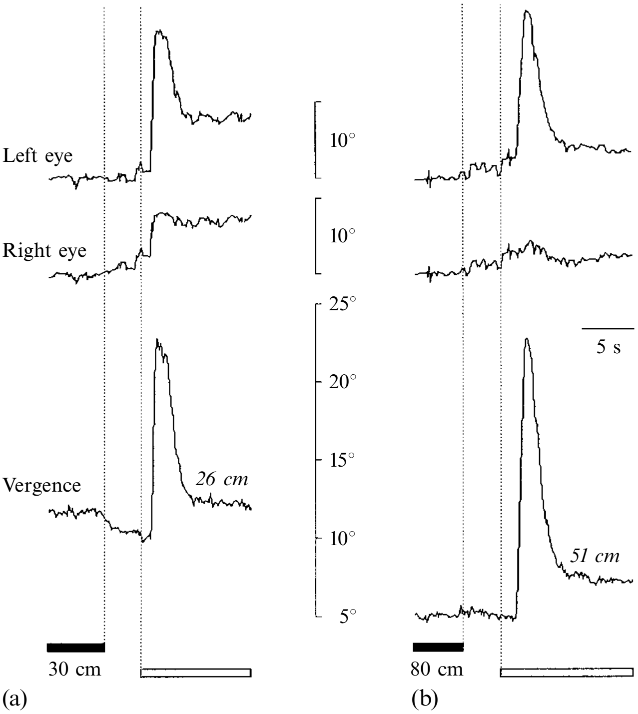

Figure 5. Examples of left and right eye movements and corresponding vergence angle (left eye − right eye) in one subject when evaluating the distance of references placed (a) 30 cm and (b) 80 cm from eye level. The filled bar indicates the period during which the reference was presented. The open bar indicates the period during which the cursor was presented. Upward deflection of the eye traces indicates movement to the right. The eyes converged quickly to the cursor when it was switched on, and followed its displacement until set to the desired position (perceived distances in these examples are indicated in italics). Displacements of the left eye are larger than those of the right eye because the cursor is slightly to the right of the right eye.

was at a distance shorter than 60 cm. Then the eyes quickly converged on the cursor, whose original position for each trial was systematically located about 8 cm from the eyes. The eyes diverged as the cursor was moved to the set distance. In these examples, the end vergence angle was about 12.5° for setting the cursor 26 cm from the eyes (figure 5a) and about 7° for a cursor setting at 51 cm (figure 5b).

The eye vergence angle (mean of a 3 s interval) was measured in the four subjects as a function of reference distance and/or cursor position (figure 6). As expected the vergence angle was found to be inversely proportional to the distance. It is interesting to note that the same relationship between vergence angle (a) and actual distance (d) in our subjects would have been obtained by a theoretical evaluation of symmetric vergence angle with the formula $a = 57.3b/d$ (see Collewijn and Erkelens 1990, pages 214–215) with an interpupillary distance (b) equal to 61 mm (subjects' mean).

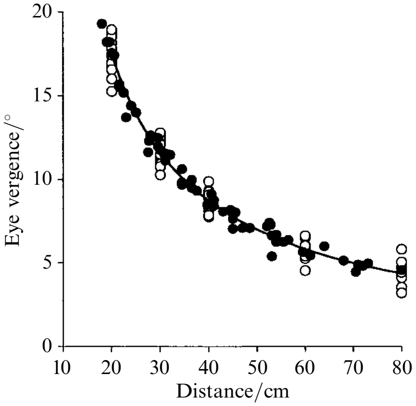

Figure 6. Relationship between the vergence angle and the distance during the equal-distance alignment task with four subjects. Each dot represents the mean vergence angle during a 3 s interval of visual fixation in one subject. Vergence angles were measured during fixation of the references at 20, 30, 40, 60, and 80 cm (open symbols) and during fixation of the cursor in the absence of reference (filled symbols). There was a clear relationship between vergence angle and target distance in both conditions. Interindividual differences in vergence angle are due to different interpupillary distances among subjects.

In addition, little interindividual difference in vergence was observed in the four subjects tested. Based on these results, the perceived distance settings obtained in all twelve subjects from figure 4a were converted into eye vergence and expressed as a function of actual distance in vergence angles rather than in centimetres (figure 7). There was a clear linear relationship between the vergence angle and the actual distance for distance settings in each task. The linear regression fit value for these angular data was slightly better than for the metric distance data shown in figure 4a (0.96 versus 0.89).

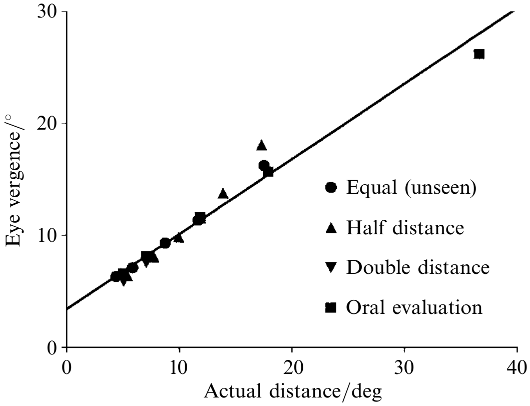

Figure 7. Settings of equal distance (without a seen reference), half distance, and double distance, and oral evaluations given as vergence angle (the vergence required to fixate the cursor's final position) as a function of the vergence angle required to fixate the reference. Conversion from settings or actual distances to vergence angles in the twelve subjects was based on the actual measurements of vergence angle in four subjects. The diagonal line represents a linear regression curve fitted to the data ($R^2 > 0.96$).

4 Discussion

The goal of the alignment tasks used in this study was to eliminate the retinal disparity cues: one way was to set the cursor to the same distance as the reference in the absence of the reference; another way was to set the cursor to half or twice the distance of the reference, so that the cursor and the reference were far from each other. The main result was that distance settings were nearly the same in all tasks, with a good evaluation for distances up to 40 cm. The distance range where good evaluation was made corresponds to the range where vergence (and accommodation) varies steeply as a function of distance.

Prior to this study, very few psychophysical studies had been devoted to the estimation of relatively short distances. Although it was observed that, when only extraretinal cues are available, the estimation of absolute distance below 50 cm is possible (Swenson 1932; Foley and Held 1972; Komoda and Ono 1974; Mon-Williams and Tresilian 1999), the accuracy of the distance estimates was found to vary among studies. Swenson (1932) and Komoda and Ono (1974), using an apparatus similar to ours, reported accurate distance estimates in the range 25 – 40 cm. In Grant's (1942) study, subjects using monocular vision were able to report target distances of 25, 33, and 50 cm in the correct order, but with erroneous values. A large overestimation of absolute distances of 15 – 36 cm was obtained by Foley and Held (1972) who used a virtual point target of which only the visual parallax was varied. Overestimation of absolute distance was also reported by Morrison and Whiteside (1984) for virtual distances of 0.5 – 4.0 m. On the other hand, an underestimation of absolute distance is generally observed for distances ranging from 3.5 – 10.0 m (Foley 1991; Sinai et al 1998).

Collewijn and Erkelens (1990, page 219) stated that "the best isolation of vergence was reached in experiments using real stimuli in large rooms [...] when successive stimuli are presented with a sufficient time interval and a sufficient duration to eliminate any existing absolute disparities". In agreement with this statement, we used real stimuli placed at real distances in front of the subject in a dark room and a 5 s dark period was introduced after the presentation of the reference targets. In contrast to previous studies which used virtual targets at varied virtual distances (Foley and Held 1972; Morrison and Whiteside 1984), in our apparatus the perceived distances in the absence of retinal cues were close to veridical.

The accuracy in distance perception is not a linear function of actual distances, since subjects are very accurate for reproducing distances below 50 cm but they underestimate distances above 50 cm. From actual measurements of vergence we found a linear relationship between the perceived distance and the actual distance of targets when these distances were expressed in eye vergence angles. This result by no means proves that distance perception is directly derived from the state of convergence. It suggests that, in conditions where only extraretinal cues are available for judging distances, the subjects are likely to use convergence cues for estimating absolute distances. It is possible that our subjects also used accommodation as a distance cue. However, the results of studies on the role of accommodation in distance perception are inconclusive (Wallach and Floor 1971; Fisher and Ciuffreda 1988). Only a minority of subjects (about 25%) showed a strong correlation between the perceived distance of a target and their accommodative response, and, when present, individual trial data revealed that perceived distance was largely unrelated to the actual target distance (Mon-Williams and Tresilian 1999). Nevertheless, vergence and accommodation are cross-coupled so that accommodation may also influence distance perception indirectly via its effect on vergence (Kenyon et al 1978).

It is interesting to note that the near space where vergence signals are more effective as a distance cue and where distance perception is very accurate corresponds roughly to arm's length. The perception of three-dimensional space must be very accurate within manual reaching distance for a good motor coordination (Paillard 1991). The use of convergence cues is particularly relevant within this near space as about 90% of the vergence range is used for distances less than 1 m (see figure 6). In normal conditions, both retinal disparity and vergence eye movements presumably participate in the specification of target location relative to the hand. In fact, it has been shown that manual reaching behaviour develops in infants at the same time as binocular convergence (von Hofsten 1977). From a physiological point of view, the distance of fixation and vergence angle have been shown in behaving monkeys to strongly influence the neural activity of primary visual cortex neurons, thus controlling the expression of disparity selectivity. This retinal and extraretinal interaction would participate in the neural coding of absolute distance (Trotter et al 1992, 1996).

When a subject is instructed to align the cursor with a previously seen reference target (equal distance task), the absolute distance of the reference or the cursor relative to him/her is not important. The task is an alignment task, and the error is simply the difference between the cursor's final position and the reference. On the other hand, when a subject is instructed to place the cursor at half or twice the distance between himself/herself and the reference or to give an oral evaluation, an absolute distance has to be estimated. This latter task requires a body-egocentric reference system. Our results suggest that the subjects used an egocentric frontal plane of reference located on average 10.4 cm in front of their eyes. Mon-Williams and Tresilian (1999) also found a change in the egocentric distance reference of about 8 cm when subjects manually pointed at targets through prisms which set targets at specified distances ranging from 15 to 60 cm. Two out of the three subjects of Brenner and van Damme's study (1998), when presented with a seen reference at 1 m, also reported an overestimation in half-distance settings and an underestimation of double-distance settings, which could be explained by an egocentric distance reference placed in front of their eyes. At the distance of 10.4 cm the angle of vergence is of the order of 36°, ie close to the maximum achievable by most subjects. The body-egocentric reference used for estimating absolute distance when only extraretinal cues are available might therefore be related with the punctum proximum, below which vision is blurred and double (Bennett and Francis 1962).

In conclusion, in agreement with previous studies (von Hofsten 1976; Foley 1980; Brenner and van Damme 1998; Mon-Williams and Tresilian 1999; Tresilian et al 1999) the results of our experiment indicate that vergence can be used to reliably evaluate target distance. This is particularly effective in the near visual space corresponding to arm's length.

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