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Simultaneous hand tracking does not affect human vergence pursuit

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Abstract. In order to find out whether human vergence eye movements are influenced by simultaneous hand tracking movements, vergence was studied when sinusoidal (expressed in vergence angles) target movements were tracked. The target motion was externally generated and the target actually moved in depth. Tracking was done by the eyes alone or by the eyes and hand together, in both light and dark viewing conditions. Our data show that the target motion was tracked by the eyes with a short delay (on average 48 *ms*), independent of the tracking condition. This suggests that vergence modeling should include some predictive mechanism similar to that proposed for the smooth pursuit subsystem. Furthermore, in contrast to effects on smooth pursuit, simultaneous hand tracking movements did not influence vergence eye movements. From this, we argue that the balance between smooth pursuit and saccadic eye movements is adjustable and can be adapted to the requirements of different tasks.

Key words: Eye movement – Smooth pursuit – Vergence – Eye-hand coordination – Human

Introduction

Smooth pursuit eye movements are made in order to keep the image of a moving object of interest within the perifoveal area of high visual resolution in the human eye. At first, it was thought that smooth pursuit was evoked by retinal slip, which is caused by velocity differences between the eye and the image of the moving object on the retina (e.g., Young and Stark 1963). However, several studies on smooth pursuit have shown that, besides retinal information, extraretinal information is used to evoke smooth pursuit eye movements. Steinbach and Held (1968), for example, have shown that a person can more accurately track a target that is moved by himself than a target that is moved otherwise. Steinbach (1969) concluded that in such cases the oculomotor system has access to the efference (outflow) that produces the target movements. Other investigators have found that if a moving target was tracked simultaneously by the hand, the smooth pursuit eye movements were upgraded, i.e., they were larger than when the eyes tracked alone (Mather and Putchat 1983; Collewijn et al. 1985; Gauthier et al. 1988). In a previous study (Koken and Erkelens 1990, 1992) we have shown that simultaneous tracking with the hand of an externally generated target motion upgraded the smooth pursuit eye movements only if the target motion was not random, i.e. only if the target motion was periodic. As yet, a satisfactory explanation for the enhancement of smooth pursuit that occurs in the presence of simultaneous hand tracking movements has not yet been provided in either neurophysiological terms or even in terms of general usefulness.

As a first step towards an explanation for the improvement observed with simultaneous hand tracking, it could be asked whether such tracking enhances the performance of smooth eye movements in general. In other words, are vergence movements improved by hand tracking as well?

In this study we investigated horizontal vergence movements during tracking by the eyes alone and by the eyes and the hand together, in both light and dark conditions. We used a target which actually moved in depth and, therefore, did not only induce changes in disparity, but also in blur and target size. The use of such a target allowed us to make a direct comparison of our present results to those found in the literature. Finally, we discuss the implications for modeling the vergence and smooth pursuit systems.

Materials and methods

Subjects

Four subjects (three men and one woman) participated voluntarily in the experiments. They had visual acuities of 20/20 or better, with

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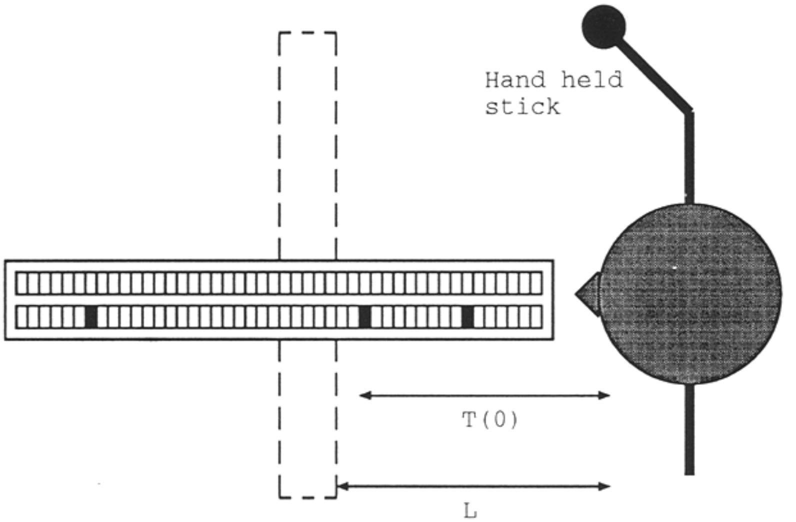

Fig. 1. Experimental setup as seen from above. During the calibration procedure the subject was seated behind two arrays of light-emitting diodes (LEDs) which were placed horizontally in the frontoparallel plane *(dashed lines)*. During the experiments the arrays were placed horizontally in the median plane *(continuous lines)*. The LED *(black rectangles)* in the *center* indicates the point of equilibrium of the sinusoidal target motion (expressed in vergence angles). The LEDs at the *left* and the *right* indicate the extreme target positions (which do not lie symmetrically around the equilibrium point). The distance L between the LED arrays and the cyclopic eye during the calibration procedure is around 50 cm. Finally, $T(0) = 40$ cm

(three subjects) or without (one subject) correction. None of them showed any manual, ocular, or oculomotor pathological condition. One subject (C.E.) was highly experienced in manual and oculotracking research and two subjects (W.D. and C.G.) had some experience. The other subject (J.D.) was participating in such experiments for the first time. Informed consent was obtained from all subjects prior to the study.

Apparatus

Horizontal and vertical movements of both eyes were measured with the use of induction coils mounted in scleral annuli in an a.c. magnetic field (S–3020; Skalar Medical) as first described by Robinson (1963) and modified and refined by Collewijn et al. (1975). The dynamic range of the recording system was from d.c. to 300 Hz (3 dB down), with a noise level of less than $\pm 10'$ and deviation from linearity less than 1% over a range of $\pm 25°$. Chin and forehead restraints were used to prevent head movements.

The apparatus used for the presentation of the target and for the recording of the hand movements was as described by van den Berg et al. (1987). Subjects were requested to hold a vertical handle in their right hand throughout the experiments. They could move this handle in a straight line along a horizontal rail over a distance of 55 cm. The handle was attached to a continuous and perforated metal belt running over two cog-wheels. The position of the handle was measured with a resolution of 0.01 cm by means of an optical shaft decoder attached to one of the cogwheels. A torque motor was attached to the same cogwheel. Strain gauges built into the handle were used to measure the forces exerted by the subject's hand on the handle. The force signal in or against the direction of movement was fed back to the torque motor in order to reduce the mechanical friction force to values below 1 N. The noise of the torque motor was of a very low level and did not contain any information about the target motion. The handle and the horizontal rail were placed parallel to the median plane throughout the experiments at a distance of about 40 cm from the subject, dependent on the subject's armlength (see Fig. 1). The handle could be moved horizontally and parallel to the median plane.

Two horizontal arrays of light-emitting diodes (LEDs) were positioned in front of the subject in the direction of the line of sight. The subject could view all LEDs separately. In the calibration procedure one array was horizontally placed 1 cm above the other in the frontoparallel plane at a distance of around 50 cm (see the dashed lines in Fig. 1), and in the experiments they were placed horizontally in the median plane, with the center of target motion at a distance of 40 cm from the subject (see the continuous lines in Fig. 1). The arrays consisted of 240 LEDs evenly spaced at 0.25 cm from each other. In each array only one LED was lit at a time. The lit LED (green) in one array indicated the target position and the lit LED (red) in the other array indicated the position of the vertical handle held by the subjects's right hand.

A microprocessor was used for stimulus generation and data acquisition. Positions of the vertical handle and of both eyes were digitized on-line at a frequency of 512 Hz with a resolution for the position of the eyes of 3.5′. The sampling period lasted 8 s and started 8 s after the onset of stimulus motion in order to avoid transient effects. Between trials the data were transferred to a minicomputer system where it was stored on disk for off-line analysis.

Procedure

The experiments were carried out in a normally lit room, which contained many visual objects, and in the dark (i.e., the room was darkened and the hand/arm were not visible). The subject was seated on a chair throughout the experimental sessions, which were limited to 45 min.

The vertical position of the handle was adjusted until the subject indicated that the handle could be moved comfortably without causing fatigue. The sensitivity of the eye movement recorder was also adjusted at the start of each experimental session, as were the polarity and offset of the eye position signals. Before each experiment a calibration target containing ten successive, equally spaced fixation marks was presented horizontally in the frontoparallel plane and the positions of the eyes were recorded while the subject fixated these marks monocularly. A calibration target presented vertically in the frontoparallel plane was not necessary as the amplifications of the horizontal and vertical eye signals were set equal. The offset of the vertical eye signals was acquired by averaging the vertical eye positions obtained from the horizontal calibration procedure.

We changed target vergence sinusoidally in order to allow a direct comparison with results in the literature. Target vergence as a function of time was defined as $\theta(t) = 2\arctan(d/T(t))$, where d is the distance between the nose and the center of rotation of the eye, and $T(t)$ is the distance of the target to the cyclopic eye at time t. In the present experiments, target vergence $\theta(t)$ was restricted to sinusoidal functions: $\theta(t) = A\sin(2\pi ft) + \theta(0)$, where A is the amplitude (degrees), f is the frequency (Hertz), and $\theta(0)$ is target vergence at $t = 0$ (about 9.1°). With this constraint $T(t)$ was computed. Note that T itself is not a sinusoidal function and that its extremes do not lie symetrically around the equilibrium point $T(0)$ of the target motion, as is indicated by the marked LEDs in Fig. 1.

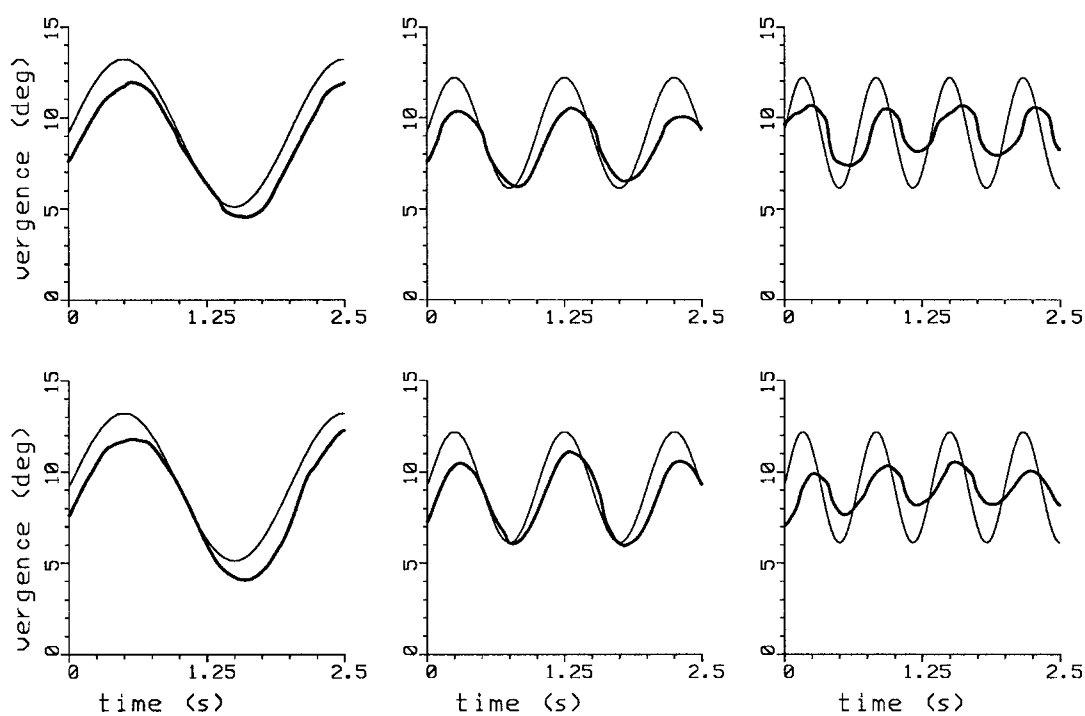

Fig. 2. Typical examples of horizontal vergence position signals of the target *(thin line)* and the eyes when subject W.D. tracked in the light *(thick line)*. All signals are expressed in vergence angles. The target frequency was 0.5 Hz and the amplitude was 4° *(left panel)*, 1 Hz and 3° *(middle panel)*, and 1.5 Hz and 3° *(right panel)*, respectively. Tracking with the eyes alone is shown in the *upper panel*, tracking with the eyes and hand together is shown in the *lower panel*

Target's movements, expressed in vergence angles, had frequencies of 0.5, 1.0, or 1.5 Hz and amplitudes of 2.0, 3.0, or 4.0°.

Each experiment consisted of pairs of trials in which the tracking conditions were different: the target was tracked by the eyes alone; the target was tracked by the eyes and the right hand together. Within a session each experiment was run twice, and was carried out in both light and dark conditions.

Data analysis

In the off-line analysis the vergence eye positions, the hand positions, and the target positions were calculated and expressed in angular displacements relative to the head. The velocity signals of these position signals were computed by means of a two-point differentiation, after filtering with a second-order digital Butterworth filter (cutoff frequencies were 20 Hz; Ackroyd 1973). Separation of the smooth (vergence) component from the horizontal eye movements was based upon the detection and removal of saccades in the velocity signal of each eye. Saccades were detected by using a velocity and an acceleration (deceleration) threshold in combination with a minimum and maximum duration. Subsequently, saccades were removed and replaced by the average velocity of the pursuit component just prior to and after the saccades. A fast Fourier transform was applied to all velocity signals. The gain (ratio of peak-to-peak amplitudes) and phase (lag or lead) between the fundamental components of all movements with respect to the target movement were then computed by means of auto- and cross-power spectral densities. In addition, the maximum of the cross-correlation function (degree of similarity of shape) was calculated from the eye velocity signals and hand velocity signals relative to the target velocity signals (Steel and Torrie 1981). Gain values (which describe the amplitude of a specific frequency component of the tracking signals), maxima of the cross-correlation functions (which describe the shape of the tracking signals) and phase values were arranged, for all subjects separately, according to the tracking conditions and the light and dark viewing conditions.

Results

Figure 2 shows typical examples of recorded tracking. Target movements with a low frequency of 0.5 Hz were accurately pursued by all subjects in the light and the dark. Vergence pursuit was asymmetrical for frequencies of 1 Hz and 1.5 Hz, i.e. smaller angles of target vergence were pursued better than larger ones. As a consequence, target vergence and ocular vergence did not oscillate about the same angle; for the eyes the center of oscillation was shifted toward a smaller vergence angle than that of the target. The highest velocities of smooth vergence were found for a target frequency of 1 Hz and a target amplitude of 4°. These vergence velocities were about 20°/s for all subjects. In the light condition, higher velocity peaks (up to 70°/s) of short duration (about 50 ms) were observed when the subjects made diverging eye movements. These velocity peaks were associated with saccades of unequal amplitude in the two eyes. When the subjects made diverging eye movements in the dark, lower peak velocities of up to just 40°/s were found. Vergence velocity peaks associated with saccades were found to be low (or absent) when the subjects made converging eye movements. Amplitudes of vertical saccades were up to 4°, depending on the target amplitude and frequency. Saccades were removed from the eye

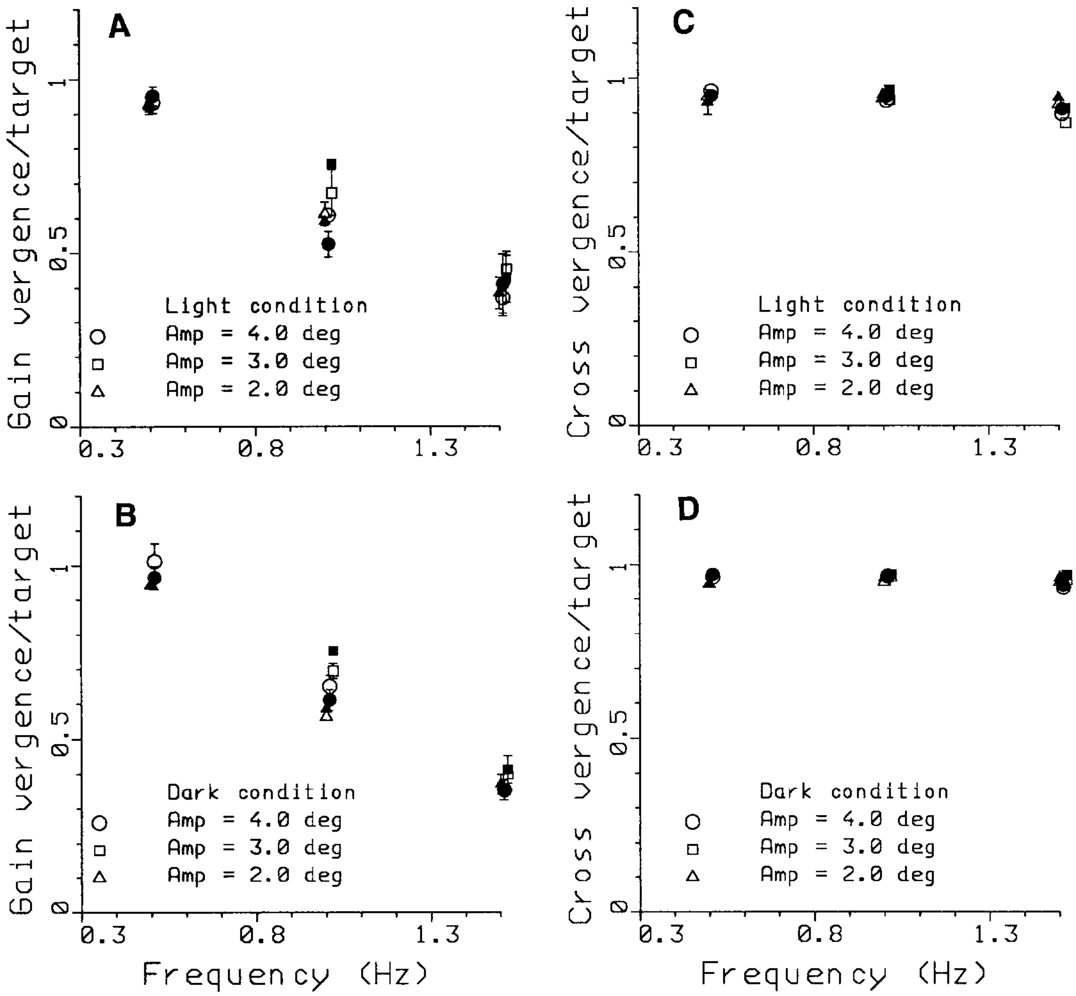

Fig. 3. **A** The gain of the vergence eye movements versus target frequency when subject W.D. tracked in the light with the eyes alone *(open symbols)* and with the eyes and hand together *(filled symbols)*. Different symbols refer to different target amplitudes, as indicated. **B** As **A** but in the dark condition. **C** Maximum of the cross-correlation functions versus target frequency when subject W.D. tracked in the light. **D** As **C** but in the dark condition

tracking signal and only the smooth vergence component was studied.

Tracking performance of the eyes

Gains and maxima of the cross-correlation functions

For vergence, gains and maxima of the cross-correlation functions were consistent within but not between subjects; therefore, means and standard deviations were computed only within subjects. Figure 3A–D shows gain and maxima of the cross-correlation functions of subject W.D.'s vergence in all tracking conditions. Gain (Fig. 3A, B) decreased more or less linearly with increasing target frequency, in both light and dark viewing conditions. Target amplitude did not have a consistent effect on both the gain and maximum of the cross-correlation functions. Similar results were found for the other subjects with one exception, namely subject C.E. For this subject, gain of vergence also decreased as target amplitude increased but only during tracking by the eyes alone in the dark. Comparison of Fig. 3A and 3B shows that simultaneous tracking with the hand did not have a consistent effect on the gains of vergence in subject W.D., in both the light and the dark. This independence of the tracking condition was found in the other subjects as well.

The maxima of the cross-correlation functions (Fig. 3C, D) slightly decreased from near unity to approximately 0.8–0.9, with increasing target frequency for subject W.D. when tracking in the light. In the dark, these maxima were close to unity for all target frequencies. Target amplitude did not affect the maxima. Similar observations were made for the other subjects. As was found for gain, no significant differences were found for the maxima of the cross-correlation functions between tracking by the eyes alone and tracking by the eyes and the right hand together. This result was obtained in all subjects. Apparently, simultaneous tracking with the hand did not affect the quality of vergence eye movements during tracking of sinusoidal target motions.

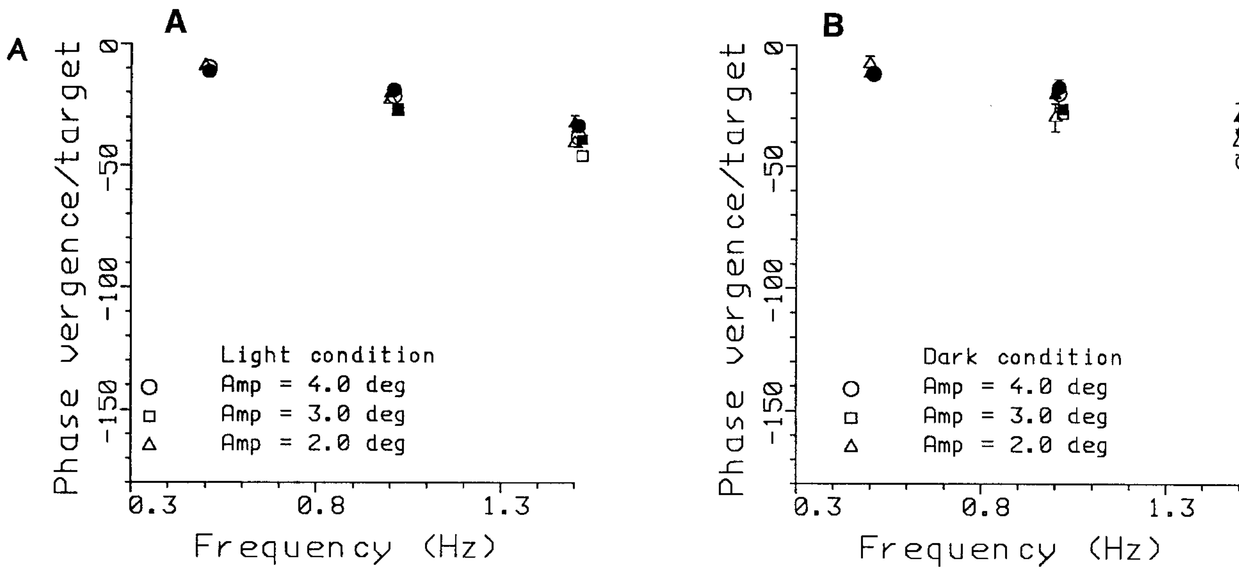

Fig. 4. A Phase lag versus target frequency when subject W.D. tracked in the light with the eyes alone *(open symbols)* and with the eyes and hand together *(filled symbols)*. Negative phase values indicate that the eye movements lagged behind the target movements. Different symbols refer to different target amplitudes, as indicated. **B** As **A**, but in the dark condition

Table 1. Means and standard deviations of delay values calculated from phase lags of vergence responses for all subjects when tracking by the eyes alone and with the eyes and hand together, in the light and in the dark ($n = 6$)

Tracking condition		Subjects			
		CE	CG	JD	WD
Eyes alone	Delay in light (ms)	39 ± 18	24 ± 27	25 ± 41	71 ± 17
	Delay in dark (ms)	58 ± 15	37 ± 16	45 ± 29	65 ± 12
Eyes and hand together	Delay in light (ms)	47 ± 4	32 ± 7	39 ± 24	63 ± 4
	Delay in dark (ms)	60 ± 8	46 ± 12	61 ± 29	63 ± 2

Phase lags of vergence tracking

Figure 4 shows phase lags for vergence tracking as a function of target frequency in subject W.D. For all tracking conditions phase lag increased with increasing target frequency and did not depend on target amplitude. Ocular vergence lagged behind target vergence for all target frequencies and amplitudes for all subjects, except subject J.D. For this subject, the eyes led the target by about 42 ms when the target amplitude was 2° and the target frequency was 0.5 Hz, and by about 2 ms when the target frequency was 1 Hz. For all other target frequencies and amplitudes, phase lags were negative for this subject. Phase lags were relatively small. The largest phase lag of about 50° was observed for a target frequency of 1.5 Hz and a target amplitude of 4° (subject W.D.).

Phase lag increased almost linearly with increasing target frequency and depended neither on target amplitude nor on the tracking condition. The linear relationship between the phase lag of vergence pursuit and the frequency of target vergence oscillations means that the lag can be expressed as a constant time delay between the stimulus and the response. Table 1 shows means and standard deviations of delays computed from the mean phase lags.

For all subjects there was no significant difference found in delays between the light and dark conditions, or between tracking by the eyes alone, or by the eyes and hand together. Also no significant difference was found between subjects. This allowed us to compute the mean delay over all subjects and over all conditions. The mean delay between changes in target vergence and vergence pursuit was 48 ms.

Discussion

Speeds of vergence

For all subjects, vergence eye movements were asymmetrical when target movements were tracked with a frequency of 1 Hz or higher. For such stimuli, ocular vergence oscillated about a smaller vergence angle than target vergence. This asymmetry seems to be caused by the occurrence of saccades, which were more frequent and larger (causing vergence velocities up to 70°/s) during diverging eye movements. During converging eye movements saccades were smaller or even absent. Consequently, the velocities of vergence during diverging eye movements were higher than during converging eye movements. This asymmetry has been reported before by Mitchell (1970), Jones (1977), and Erkelens et al. (1989b).

Gains and maxima of the cross-correlation functions of vergence

No significant differences in gains and maxima of the cross-correlation functions were found between the conditions in which the eyes tracked alone or in which the eyes and hand tracked together. In other words, simultaneous tracking movements of the hand did not affect vergence eye movements when sinusoidal target movements (expressed in vergence angles) were tracked, for all frequencies and amplitudes tested. This finding is in contrast to the effect of simultaneous hand tracking on the smooth pursuit system (e.g. Gauthier et al. 1988), for which it is known that simultaneous tracking with the hand gives rise to larger smooth pursuit eye movements when the target frequency is 1 Hz or higher (Koken and Erkelens 1990, 1992).

Gains of the horizontal vergence eye movements decreased as target frequency increased. This result has been reported before in monkey (Cumming and Judge 1986) and in man (Erkelens and Collewijn 1985). Target amplitude has been found to have no consistent effect on the gain, in both the light and dark conditions. For the dark condition, this contrasts with the findings of Erkelens and Collewijn (1985), who claimed that gain decreased as target amplitude increased. In an earlier report (Koken and Erkelens 1993) we have argued that this difference is due to the type of target that was used.

Maxima of the cross-correlation function slightly decreased from near unity to approximately 0.8–0.9 when target frequency increased (when tracking in the light). In the dark, however, maxima of the cross-correlation function did not alter significantly from unity when target frequency increased. This small difference between the light and dark conditions was the only one we found. We do not have a satisfactory explanation for this difference.

Delay of vergence

The phase lags of the vergence responses could be expressed as a constant time delay of 48 ms between the target and eye oscillations. This delay is much shorter than delays that have been reported for vergence induced by disparity alone. Erkelens and Collewijn (1985), for example, have found phase lags which suggest a constant delay of around 220 ms. This delay is almost five times longer than the delay reported here. Previously (Koken and Erkelens 1993) we have argued that this contradiction is due to the type of target used. Most important to note here is that in the experiments by Erkelens and Collewijn (1985) the vergence movements were imposed on the subjects, and, moreover, the subjects were not aware of any target motion in depth. In our experiments the subjects made eye movements by free will to a target that was seen to move in depth. The fact that experimental conditions have a large influence on the performance of the (human) vergence subsystem has recently been shown by Erkelens et al. (1989a). When a subject moved the upper torso to a fixed target, the eyes led the target by about 5 ms. On the other hand, when the subject controlled the target movement with the hand, the eyes led the target by as much as 90 ms. Apparently, the vergence subsystem anticipates the target motion.

Another result we reported is that delay (or phase) of vergence motion with respect to target motion does not depend on any of the experimental conditions used in the present study. It is interesting to note that tracking with or without the hand does not affect the delay in the (human) smooth pursuit subsystem (Koken and Erkelens 1992). However, the delays we have found in smooth pursuit tracking (about 20 ms) are even shorter than for vergence tracking.

Implications for understanding pursuit

In the previous paragraphs we have shown a few aspects of vergence that are in common with smooth pursuit and a few that are not. We have shown that delay is short for both subsystems and that simultaneous tracking with the hand does not affect the delay. However, tracking with the hand does affect smooth pursuit, but not vergence. What consequences do the present findings have on our understanding of smooth pursuit and vergence?

Disparity-induced vergence has been modeled by feedback mechanisms (Rashbass and Westheimer 1961; Krishan and Stark 1977; Schor 1979; Hung et al. 1986). Such models cannot describe the control of tracking of a real target moving in depth. The very short delays suggest that target motion is predicted. For modeling vergence pursuit we probably have to include a predictive mechanism, similar to that which has been suggested to exist in the control of smooth pursuit (e.g., Dallos and Jones 1963). The methodology used in earlier studies, in which only retinal disparity was controlled (e.g., Rashbass and Westheimer 1961; Erkelens and Collewijn 1985), has led to the impression that the vergence subsystem is purely reflexive by nature because of the long delays that were found. The effectiveness of the vergence subsystem was therefore underestimated, as shown by Erkelens et al. (1989a). They showed that when the subject controls the target motion by himself the delay can be positive, i.e. the eyes lead the target motion. Previously (Koken and Erkelens 1993) and in this study we have shown that an externally generated (i.e. not by the subject himself), sinusoidal target motion is tracked with a short delay. This was already known for the smooth pursuit subsystem.

With respect to the smooth pursuit subsystem, we argued in Koken and Erkelens (1992) that the improvement of the smoothness of eye pursuit movements during simultaneous tracking movements by the hand can be interpreted in (at least) two ways: (1) The control mechanism of smooth pursuit is not functioning optimally during tracking by the eyes alone, and the tracking performance can be improved in specific tasks. (2) The balance between the amount of smooth pursuit and saccades is adjustable and can be adapted to the requirements of different tasks.

Supposing that these interpretations can be extended to smooth eye movements in general (thus also to vergence), then, if the first interpretation is valid, vergence would be improved by simultaneous hand tracking. If, however, the second interpretation is true, simultaneous hand tracking would not have an effect on vergence. Since no observer has ever observed "vergence saccades" (i.e. saccades in which the eyes purely move in opposite directions), a variable ratio of two types of eye movements is not likely to be possible for vergence movements. Our present findings suggest that the second interpretation is most likely. For modeling smooth pursuit and saccadic eye movements, this means that the control of the eye movements depends not only on the retinal position or velocity errors but also on the tracking conditions. We are presently testing such a model.

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References

Ackroyd MH (1973) Digital filters. Butterworth, London

Berg R van den, Mooi B, Denier van der Gon JJ, Gielen CCAM, Meulen JHP van der (1987) Equipment for the quantification of motor performance for clinical purposes. Med Biol Eng Comput 25:311–316

Collewijn H, Mark F van der, Jansen TC (1975) Precise recording of human eye movements. Vision Res 15:447–450

Collewijn H, Steinman RM, Steen J van der (1985) The performance of the smooth pursuit eye movements system during passive and self-generated stimulus motion. J Physiol (Lond) 366:19P

Cumming BG, Judge SJ (1986) Disparity-induced and blur-induced convergence eye movements and accomodations in the monkey. J Neurophysiol 55:896–914

Dallos PJ, Jones RW (1963) Learning behaviour of the eye fixation control system. IEEE Trans Autom Control 8:218–227

Erkelens CJ, Collewijn H (1985) Eye movements and stereopsis during dichoptic viewing of moving random-dot stereograms. Vision Res 25:1689–1700

Erkelens CJ, Steen J van der, Steinman RM, Collewijn H (1989a) Ocular vergence under natural conditions. I. Continuous changes of target distance along the median plane. Proc R Soc Lond B 234:417–440

Erkelens CJ, Steinman RM, Collewijn H (1989b) Ocular vergence under natural conditions. II. Gaze shifts between real targets differing in distance and direction. Proc of the R Soc London [Biol] 234:441–465

Gauthier GM, Vercher JL, Mussa Ivaldi F, Marchetti E (1988) Oculomanual tracking of visual targets: control learning, coordination control and coordination model. Exp Brain Res 73:127–137

Hung GK, Semmlow JL, Ciufredda KJ (1986) A dual model dynamic model of the vergence eye movement system. IEEE Trans Biomed Eng 33:1021–1028

Jones R (1977) Anomalies of disparity detection in the human visual system. J Physiol (Lond) 264:621–640

Koken PhW, Erkelens CJ (1990) Coordination of eye, head and hand movements in smooth pursuit tasks. Eur J Neurosci [Suppl 3], p 64

Koken PhW, Erkelens CJ (1992) Influences of hand movements on eye movements in pursuit tasks in man. Exp Brain Res 88:657–664

Koken PhW, Erkelens CJ (1993) Short delays of vergence eye movements in man during pursuit tasks in light and dark conditions. In: d'Ydewalle G, Van Rensbergen J (eds) Visual and oculomotor function: advances in eye-movement research. North-Holland, Amsterdam

Krishan VV, Stark L (1977) A heuristic model for the human vergence movement system. IEEE Trans Biomed Eng 24:44–49

Mather JA, Putchat C (1983) Parallel ocular and manual tracking responses to a continuously moving visual target. J Mot Behav 15 (1):29–38

Mitchell DE (1970) Properties of stimuli eliciting vergence eye movements and stereopsis. Vision Res 10:145–162

Rashbass C, Westheimer G (1961) Disjunctive eye movements. J Physiol (Lond) 159:339–360

Robinson DA (1963) A method of measuring eye movements using a scleral search coil in a magnetic field. IEEE Trans Biomed Eng 10:137–145

Schor CM (1979) The relationship between fusional vergence eye movements and fixation disparity. Vision Res 19:1359–1367

Steel RGD, Torrie JH (1981) Principles and procedures of statistics: a biometrical approach. McGraw-Hill, Singapore

Steinbach MJ (1969) Eye tracking of self-moved targets: the role of efference. J Exp Psychol 82 (2):366–376

Steinbach MJ, Held R (1968) Eye tracking of observer-generated target movements. Science 161:187–188

Young LR, Stark L (1963) Variable feedback experiments testing a sampled data model for eye tracking movement. IEEE Trans Hum Factors Electron 4:38–51