Target predictability influences the distribution of coordinated eye-head gaze saccades in patients with homonymous hemianopia

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In hemianopic patients target predictability plays a differential role for the distribution of different types of initial saccades. A linear correlation was shown to exist between the adaptive state of reading capability and the probability of a correct initial eye–head gaze saccade that hit the target accurately. A constant target frequency of 0.8 Hz was found to be the optimum frequency for hemianopic patients to follow square step targets with an eccentricity of ± 20°. Variability of the compensatory eye movement velocity gain was lowest at this frequency. We were able to use this target frequency as a test for a clinical classification of the status of adaptation of hemianopic patients in combination with simple reading tests. The repetition of this manoeuvre could correct the synkinesis and the balance of the VOR during active gaze of hemianopic patients. [Neurol Res 1996; **18**: 425–439]

Keywords: Homonymous hemianopia; eye–head co-ordination; vestibulo–ocular reflex; adaptation of hemianopia; reading eye movements and compensatory reading strategies

INTRODUCTION

Homonymous hemianopia signifies an equilateral visual field defect caused by a lesion of the central visual pathway or by a lesion of the primary visual center and neighboring higher centers in area 17 (V1), area 18 (V2, V3), area 19 (V3a, V4, V5). In humans V5 corresponds to the middle temporal area[1,2]. In the absence of any other neurological or pathophysiological deficit a hemianopic visual field defect is most often caused by a discrete occipital lesion produced by a stroke related infarction of the calcarine artery. As the macula is represented for the most part in the primary visual cortex, it is generally spared in these cases[3]. To what extent even subcortical structures modify and influence the perception of visual stimuli has been a major theme in many studies since 1973. The term 'blindsight' was coined by Weiskrantz[4–6], for a particular kind of unconscious perception. The theory is based on the 'two visual systems, hypothesis. It assumes that in the phylogenesis of humans, two qualitatively different visual pathways were developed to work together in parallel: the first visual system (the geniculostriate pathway) is concerned with 'what things are' and the second (the midbrain pathway) is concerned with 'where things are'[7].

To some extent hemianopic patients can learn to compensate for their visual handicap. This was first established by Poppelreuter[8] and later supported by Gassel and Williams[9], who emphasised the value of compensatory strategies for coping with visual tasks. Earlier studies showed that patients with pure hemianopia and foveal sparing optimally learn to compensate their visual reading handicaps by active and motivated visual training. The mean reading rate and the number of acoustical reading errors of such patients were directly correlated to the relative status of ocular motor adaptation and to the etiology of the visual field defect[10,11]. Zangemeister, Meienberg, Stark and Hoyt[12–15] reported on distinct adaptive ocular motor strategies in hemianopic patients to search for objects in their blind hemifield: it was possible to predict target locations from eye movements with a high degree of probability – much more than from head movements. The authors demonstrated that in humans a sensory handicap such as homonymous hemianopia can influence and disturb the co-ordination of the eye and head motor systems. Hemianopic patients seemed to simplify search and fixation strategies by minimising or entirely eliminating head movements because of highly asymmetrical compensatory eye movement (CEM) gains. The CEM plays a critical role in co-ordinated eye–head gaze movement. Eye and head motor systems work together and are controlled through the vestibulo ocular reflex (VOR). The velocity of the head rotation serves as the input signal that controls and directs the velocity of the CEM, the output signal. CEM gain describes the ratio of maximum compensatory eye movement velocity and the corresponding head velocity in a co-ordinated eye–head gaze saccade ('gaze' is defined as the sum of horizontal eye movement and horizontal synkinetic head movement). These two phylogenetically different systems are precisely balanced and timely tuned in normal subjects. The VOR can be influenced by different experimental settings such as target amplitude and presentation time, and individual factors such as

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0161—6412/96/050425-15

vigilance and attention[16–19]. In addition, several neurological disorders affect the co-ordination and balance of the VOR depending on the afflicted regions of the central nervous system, as in vestibular disturbances, diseases of the cerebellum, Parkinson's disease, Huntingdon's chorea, and in cases of homonymous hemianopia[12,20–22].

In this study the ocular motor and head scanning behavior of hemianopic patients was investigated with particular regard to the influence of target predictability on the distribution of co-ordinated eye–head gaze saccades. We tested a group of twelve hemianopic patients to different etiologies using reading tests as well as recordings of targets. The latter consisted of spots of green light that were either predictable in time and amplitude or temporally randomised. We have analysed the data with special reference to the distribution and accuracy of initial eye–head gaze saccades and for the variability of the VOR concerning the CEM phase. The results of the present study were compared with the reading efficiency of the same patients, that have been previously published in part[10,11]. An easy clinical test based on our results was developed to facilitate the immediate marking of the status of adaptation of a hemianopic patient without further neuropsychological tests.

METHODS

Subjects

The experimental group was composed of twelve patients with homonymous hemianopia (mean age: 55.6 years, range 24–86 years) and ten younger normal subjects as a control group (mean age 31 years, range 24–41 years). All subjects had undergone a complete neuropsychological assessment which included the following: Mosaic and Figure Test (Hawie), Line Bisection Test, Cross Out Test, Benton Test – Form C, Instruction A – [23], Several Option Vocabulary Test, Body Scheme Test, remembering and recalling of twelve different geometrical figures, and spontaneous drawing of a face, a sunflower and a clock. In these tests two patients showed additional signs of visual hemineglect. The terms 'neglect' and 'visual hemi-inattention' both designate various kinds of failures to orientate or to respond to stimuli appearing at the side contralateral to a right cerebral lesion of the parietal cortex. This defect cannot be explained by primary sensory or motor disorders[24,25]. The other ten patients showed no signs of inattention that could be attributed to neglect phenomena. The patient AS had an isolated neuritis of the right optic nerve that caused a wedge-shaped defect of his right visual field reaching from the papilla into the periphery. A sudden right hemianopic visual field defect with no participation of higher visual centers was simulated by covering his left eye during the recordings. The intelligence of all patients was at an average level. Visual acuity examinations, perimetries and cranial CT or MRI scanning quantified the extensions of the anatomical defects as being limited to the occipital region. With respect to acuity, all patients were fully sight-corrected. The patients had not participated in any special visual rehabilitation training before. Eight patients of the experimental group were ranked according to their relative state of ocular motor adaptation in the reading experiment. The adaptive state of reading was marked according to the mean reading rate, the frequency of acoustical reading errors, and the most frequently applied reading strategies. The etiology of the visual field defects are described more fully in *Table 1*: five patients with right homonymous hemianopia (RHH), and three assessed patients with left homonymous hemianopia (LHH).

Experimental Set-up

Reading experiment

Subjects had to read two groups of four different short texts with distinct context. In a low-density mode the texts had 28 letters per line, in high letter density mode they had 46 letters per line. The task was performed under two varying conditions: a head fixed condition and a head-free-to-move condition. Size of characters and spaces within words was 1.5 degrees, between words 4 degrees[10,11] (*Table 2*).

Predictable target experiment

Four different paradigms were designed, which were recorded successively in three different head conditions: 1. In head-fixed condition (HFC), the head was immobile. 2. In head-forced condition (HFOC), the target had to be followed as fast as possible with the head. 3. In head-natural condition (HN, i.e. head-free-to-move), the subjects were able to use their head free. Constant target amplitudes (CA) of either $\pm 5^\circ$ and $\pm 20^\circ$ target shifts were either time-constant (CT) at frequencies of 0.4 Hz, 0.8 Hz, 1.2 Hz, or randomised in time (RT) changing the interstep interval at frequencies ranging from 0.4 Hz to 1.2 Hz. The order of testing these paradigms was randomly varied. Patients were instructed to search for the target and to fixate on it as long as it did not move. We assessed position errors and latencies of the first eye–head gaze saccade towards a target in more than 8000 saccades. This showed that the 1.2 Hz paradigm and the random paradigm were too fast for all patients, i.e. many targets were lost in both hemifields. We evaluated digitally in detail the data for the best adapted left hemianopic patient GS in all paradigms ($n = 432$ saccades). In order to show the correlation between the adaptive state of reading capability and the probability of a correct initial eye–head gaze saccade that hit the target accurately we analysed in the seven more fully described patients (*Table 1*) the two first paradigms at 40° target amplitudes. In total, more than 1500 eye–head gaze saccades were evaluated and analysed in detail.

Apparatus

The apparatus for the reading experiment was the same as described in the paper from 1993 ([10] *Table 2*).

Table 1: Descriptions of visual field defects, etiology, and history of eight out of twelve hemianopic patients of the experimental group: Five patients with right homonymous hemianopia, and three patients with left homonymous hemianopia

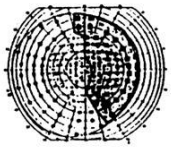
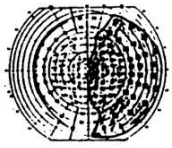
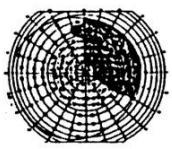
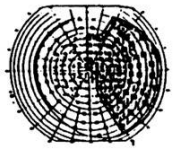
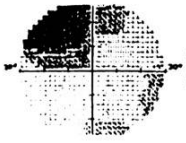
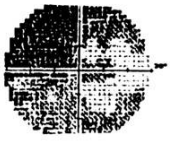
RHH Patients	Age	Visual field defects			Etiology	Neuropsychological tests
			Left eye	Right eye		
DH	24	Complete right hemifield loss without macular sparing Slow development over four years			Stenosis of the basilaris artery No CCT or MRI correlation Psychogenic etiology in question	No signs of visual hemiinattention
ES	56	Complete dense right lower hemifield loss reaching far over the horizontal meridian into the right upper quadrant			Infarction of the left lower occipital lobe CCT correlation Acute event 12 months before	No signs of visual hemiinattention
AS	36	Right wedge-shaped defect reaching from the papilla into the periphery Additional right paracentral scotoma Left eye patched			Isolated neuritis of the right optic nerve No other neurological deficits	
ZZ	46	Incomplete right hemifield loss with determination of the upper quadrant Macular sparing (3–5°)			Infarction of the left PCA Old temporal contusion CCT correlation Acute event 11 months before	No signs of visual hemiinattention
RK	48	Incomplete right hemifield loss with determination of the upper quadrant Macular sparing (3–5°)			Recurrent cerebral embolism with transient dysphasia and hemiparesis CCT correlation	Poor outcome with additional signs of visual neglect syndrome
LHH Patients						
GS	56	Irregular left hemifield loss reaching into the right upper quadrant Macular sparing (3–5°)			Vascular embolism Infarction of the right PCS CCT correlation Acute event 22 days before	No Signs of visual hemiinattention
KU	73	Incomplete left hemifield loss Macular sparing (5°)			Vascular embolism Infarction of the right PCA CCT correlation Acute event 31 days before	No Signs of visual hemiinattention
JS	59	Complete dense left hemifield loss of the upper quadrant Visus right eye 0.1 Visus left eye 1.0			Vascular embolism CCT correlation Acute event 31 days before	No signs of visual hemiinattention

Table 2: Ocular motor scanning paradigm in reading (eye and head reading paths). Horizontal binocular and vertical monocular DC EOG signals (analogue filtered at 10 Hz) were recorded on-line. Subjects had to read the texts aloud and they were asked to read them as accurately and as quickly as possible. Gaze (head free-to-move condition) is defined as sum of horizontal eye-movement and horizontal head-rotation

Sequential reading of different short-texts	
First: Head fixed condition	Recordings
1 Short-text 2 Short-text 3 Short-text 4 Short-text	Horizontal and vertical eye-movements Horizontal head torque (newton micrometer) Acoustical back-up
Second: Head free-to-move condition	
5 Short-text 6 Short-text 7 Short-text 8 Short-text	Horizontal gaze and vertical eye-movements Horizontal head-rotation Acoustical back-up

For the predictable target paradigm subjects were seated in front of a white semicircular screen (distance 1.2 m). The room was completely darkened and a minimum of ten minutes was left for adaptation before recording. The target consisted of a small spot of green light (LED, luminance 20.6 cd/m, spot size 0.5 cm) that disappeared and immediately reappeared at a new position. Horizontal monocular DC-EOG signals were simultaneously recorded on-line with a 80386 16CPU computer running at 21 MHz, and with a photorecorder for direct and later visual evaluation. Eye movements were always co-ordinated, i.e. showed the same velocities and position with respect to the left and the right eye. Sampling rate of the system was 200 Hz, overall bandwidth was DC to 100 Hz. In addition, a low torque-high resolution potentiometer (linearity 0.13%) and a high-resolution accelerometer (SCHAEVITZ) were used for horizontal head rotations. Control measurements showed that there was no delay between the beginning of the head movement and that of the accelerator measurement. In HFC the head of a subject was completely immobile. This was achieved with a high resolution torquemeter (accuracy ± 0.7 newton micrometer). Summed-up eye movements of both eyes and head rotations were digitally low-pass filtered (zero phase lag) with a cut off frequency of 35 Hz and 20 Hz with respect to eye and head. With this procedure, the mean base-line drift of the EOG was almost negligible. Compensatory eye movements and corresponding head rotations were filtered with 10 Hz to calculate the CEM gain at 40° target steps in HFOC. The latency of a head rotation in HFOC was calculated at the time the head rotation reached a velocity of 15°. Target eccentricity for EOG calibrations varied from 0° to 40° ($\pm 20°$ around the midposition of the eye), using calibrations of five degree target amplitudes in both hemifields. Overall accuracy of the EOG was $\pm 0.6°$, $\pm 0.5°$ for the potentiometer, calculated with a regression curve before and after the recordings. The statistical significance between means was calculated by using the two sample U-Test of Wilcoxon, Mann and Whitney for paired and unpaired samples[26].

Definitions

There was a general distinction between isolated eye saccades generated when the head was immobilised and co-ordinated gaze saccades generated when the head was horizontally rotated[27]. In humans, co-ordinated gaze saccades up to 40° do not significantly differ in dynamic parameters (velocity, amplitude) and latencies compared with isolated eye saccades. A relatively slow head movement component and a well balanced intrasaccadic VOR gain are responsible for this effect[19]. To simplify the presentation, isolated eye saccades and co-ordinated gaze saccades are subsumed under the term eye–head gaze saccades in the following, if not otherwise stated. Eye–head gaze saccades in response to the described stimulus were differentiated and classified into four categories: 1. A correct saccade hit the target immediately with one single saccade and no further corrective saccades at a range of $\pm 0.6°$. 2. Undershooting saccades were defined as initially hypometrical saccades that hit the target with further corrective saccades during the time it stayed in a definite position. 3. An overshooting saccade was defined as an initially hypermetrical saccade that at first overshot the eccentricity of a target, but reached it with following regressive eye movements during the time it stayed in one position. 4. In cases where the target was not within a range of $\pm 1.5°$ during the time it stayed in one position, it was defined as a missed target.

RESULTS

Accuracy

Depending on vigilance and attention, the probability of hitting a target with the initial saccade was about 65% in normal subjects (mean $64.3\% \pm 5.6$). Especially at temporarily randomised targets, undershooting saccades occurred with a mean percentage of $24.3\% \pm 2.8$. The portion of overshooting saccades rarely exceeded 15% (mean $11.4\% \pm 2.1$), in no paradigm targets were missed. Hemianopic patients showed a close relationship between the distribution of co-ordinated eye–head

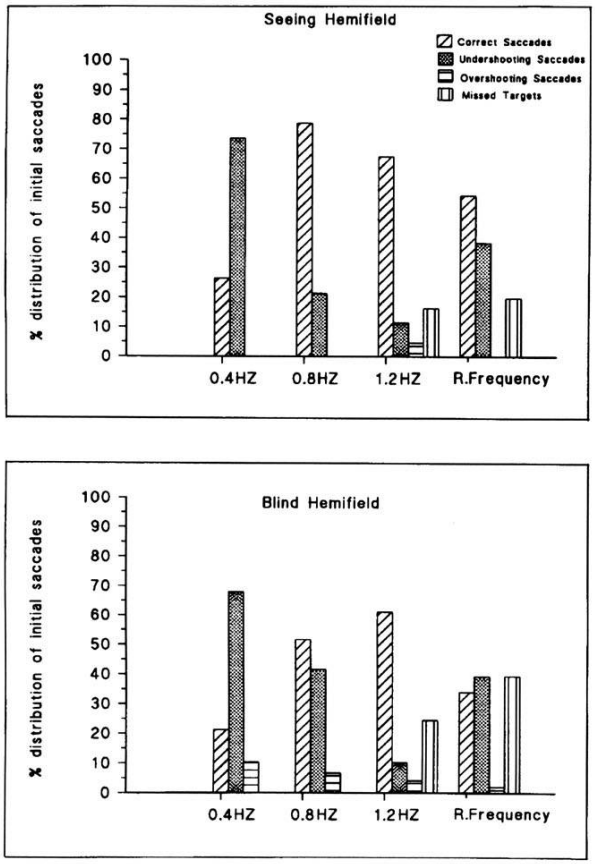


Figure 1: Accuracy and distribution of eye–head gaze saccades at different CT and RT target frequencies (pooled data of saccades at all head conditions and both target eccentricities of ±57 and ±20° ($n=469$)

gaze saccades and the predictability of a target. Targets were missed in both hemifields when target shifts became faster than 0.8 Hz, or when targets appeared RT, as shown in *Figure 1* for patient GS. In both cases, the percentage of missed targets was higher in the blind (mean 32% ± 7.5) than in the seeing hemifield (SHF, mean 18.1 ± 1.75). When targets appeared RT in the blind hemifield (BHF), the percentage of correct saccades (29.4%), undershooting saccades (34%) and missed targets (34.5%) were well balanced. Overshooting saccades rarely occurred with a percentage of 2.1%. All less adapted patients missed a higher percentage of targets even at lower frequencies than better adapted patients. The varying percentual distribution of primary types of saccades between CT target shifts of 0.4 Hz and 0.8 Hz at 40° target eccentricities is shown in *Figure 2* for normal subjects and left and right hemianopic patients. At the low target frequency of 0.4 Hz, undershooting eye-head gaze saccades (mean 56.6% ± 2.2) predominated over correct saccades in both hemianopic groups (mean 34.2% ± 3.4). At 0.8 Hz, the predominating type of saccades that were directed into the seeing hemifield consisted of correct saccades (mean 56.1% ± 5.2). There were no significant differences in distribution compared to normal subjects. Patients with right homonymous hemianopia demonstrated a comparable percentual distribution of correct saccades in both hemifields (mean 60.3% ± 3.2); in left hemianopic patients, the percentage of undershooting and correct saccades was nearly the same and stayed around 40% in the BHF (median 38.5%, range 35.9% to 41.1%). *Table 3* demonstrates the correlation between the adaptive state of reading capability and the probability of hitting accurately ± 20° targets at CT shifts of 0.8 Hz. The two 'poorly adapted' patients ZZ and RK lost targets even in the SHF at CT target shifts of 0.8 Hz.

Latencies

Normal subjects

Earlier reports[19,28] on latencies of head-fixed saccades showed that they were either triggered by the peripheral visual stimulus (visually guided saccades [VGS]) or by the predictability of the target (anticipatory saccades [AS]). The minimal latencies of fully visually guided saccades are around 120 to 150 msec in humans. In normal subjects the degree of prediction depends on the frequency of the target and therefore its predictability. Anticipatory saccades predominated at all targets that appeared CT, as is shown in *Figure 3a* for two normal subjects: 1. A considerable number of visually guided saccades occurred especially at the beginning of a new record, depending on the frequency of the target, the vigilance of the subject, and its attention. 2. At slow CT target shifts of 0.4 Hz anticipatory saccades predominated over visually guided saccades (mean latency 39.8 msec ± 13.9, VGS 35.8% ± 2.8, AS 64.2% ± 3.2). 3. At both faster frequencies of 0.8 Hz and 1.2 Hz mean latencies of anticipatory saccades became more negative and the portion of visually guided saccades was decreased (0.8 Hz: latency −32.3 msec ± 4.9, VGS 14.9% ± 3.2; AS 85.1% ± 4.7; 1.2 Hz: latency−282.9 msec ± 17.2, VGS 0%, AS 100%). 4. When targets appeared RT, the portion of visually guided saccades (55.7% ± 6.1) exceeded the portion of anticipatory saccades (43.3% ± 5.8), and the distribution of latencies was largest.

Hemianopic patients

In comparison to normal subjects, the four patients GS, KU (left homonymous hemianopia), AS and DH (right homonymous hemianopia) demonstrated a side-inverted cumulation of latencies. This is shown in *Figure 3b* for the patient GS for all CT target frequencies and RT targets. 1. At slow target shifts of 0.4 Hz, mostly undershooting saccades occurred in combination with negative latencies (SHF − 547.2 msec ± 38.7, BHF −637.7 msec ± 48.2). The strategy of these patients was to shift their focus as early as possible to the next expected target position. At the same time, the accuracy of the corresponding saccades was lower than in the other patients in this paradigm (*Figure 3b*, left upper graph). 2. At higher frequencies more positive latencies

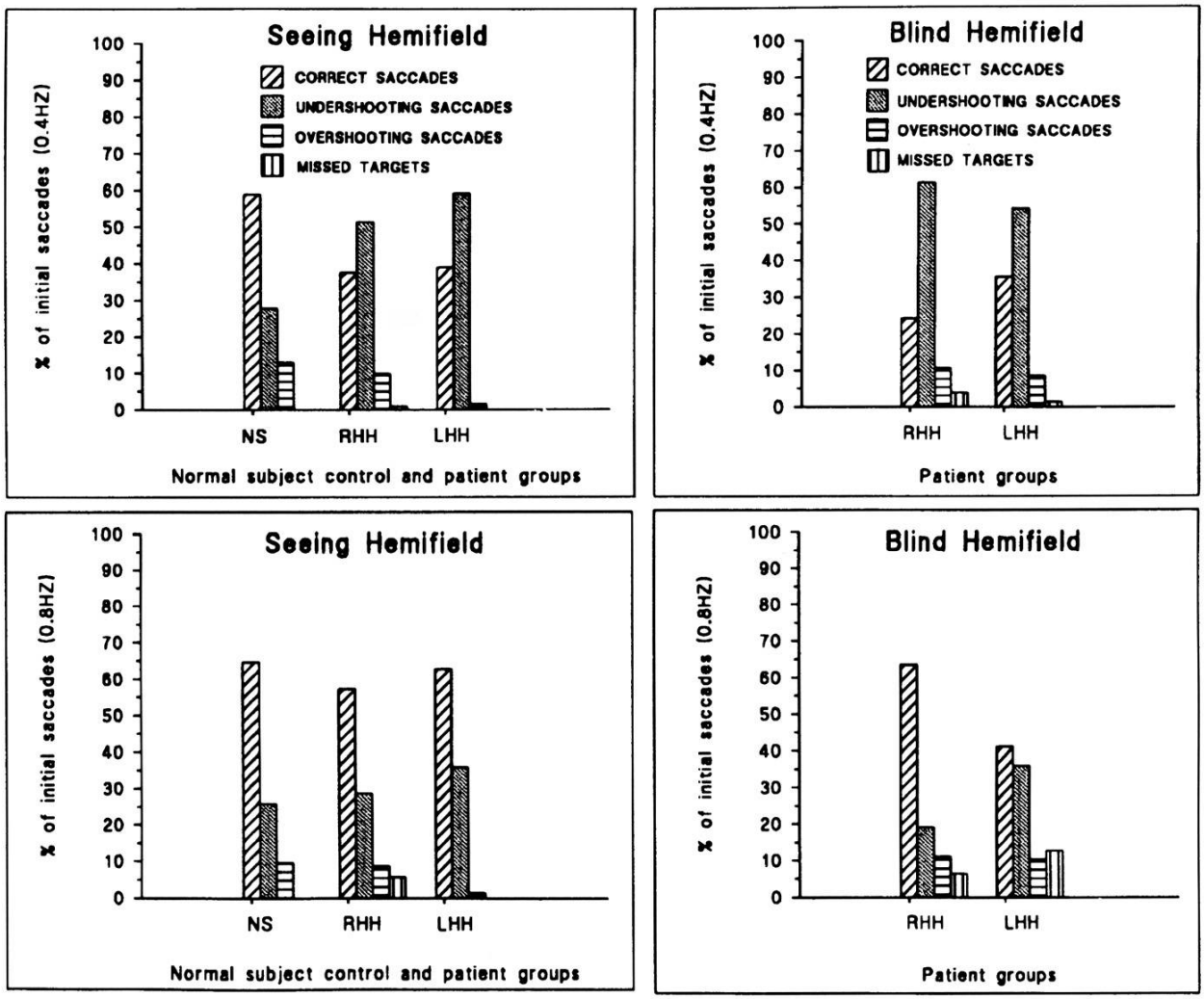


Figure 2: Percentual distribution of eye–head gaze saccades at CT target shifts of 0.4 Hz and 0.8 Hz with an eccentricity of ±20°. Comparison of normal subjects (NS) with left (LHH) and right hemianopic patients (RHH) ($n = 960$)

occurred (0.8 Hz: SHF −152 msec ± 18.7, BHF −210.3 msec ± 35.1; 1.2 Hz: SHF 23.2 msec ± 37.5, BHF − 35.1 msec ± 39.9). Correct saccades (64.8% ± 5.7) predominated over undershooting saccades (21.2% ± 7.3) at both target eccentricities (*Figure 3b*, right upper and left lower graphs). 3. As in normal subjects the distribution of latencies from anticipatory saccades to visually guided saccades (median −25 msec, range −990 msec to 440 msec) was largest when targets were RT (*Figure 3b*, right lower graph). The other four patients ES, ZZ, RK (right homonymous hemianopia) and JS (left homonymous hemianopia) demonstrated a less flexible distribution of latencies and amplitudes, as shown in *Figure 3c* for patients ES and ZZ. Statistically, the portion of visually guided saccades was higher compared to the former described patients at both target frequencies of 0.4 Hz and 0.8 Hz (0.4 Hz: 135.7 msec ± 15.8, VGS 64% ± 3.2, AS 35.6% ± 2.1; 0.8 Hz: 48.1 msec ± 13.7, VGS 31.1% ± 4.2, AS 68.9% ± 3.7). The only difference between well (ES, JS) and poorly adapted patients (RK, ZZ) was that the latter missed more targets when target shifts became faster or randomised in time.

Dynamics

In correlation with reading capacities (*Table 3*) dynamic parameters of co-ordinated eye–head gaze saccades were influenced differently by varying levels of target prediction. Since right hemianopic patients showed a less flexible latency pattern compared with left hemianopic patients we describe them in more detail. In the better adapted RHH patients (DH, ES, and AS) amplitudes of eye–head gaze saccades became significantly increased and corresponding velocities faster with increasing target frequencies, following the normal limits of the main sequence[29], as shown in *Table 4* in CT target shifts from 0.4 Hz to 0.8 Hz. According to the side of target appearance there were

Table 3: A qualitative ranking of five RHH patients and three LHH patients according to their adaptive state of reading shows the correlation between reading capability and the probability of accurately hitting square step targets at CT target shifts of 0.8 Hz

Patients	Mean reading rate (letter/s)	Mean number of reading errors/short text	Mostly used oculomotor reading strategies	% of Accurately hit 40° CT targets	Relative status of adaptation
DH (RHH)	11.5	0.0	Blind hemifield overshooting strategy Increased end of line lexical duration strategy	95	Outstanding
ES (RHH)	7.1	0.0	Blind hemifield overshooting strategy (End of line Detective strategy) (Saccadic resolution strategy)	100	Excellent
GS (LHH)	8.3	0.5	General overshooting/regression strategy	100	Very good
KU (LHH)	7.9	0.0	Beginning of line detective strategy (other part of the reading pattern in accordance with the classical staircase pattern)	81	Good
AS (RHH)	7.5	0.7	(Blind hemifield overshooting strategy) End of line detective strategy Saccadic resolution strategy	100	Good
JU (LHH)	6.7	1.3	Beginning of line detective strategy (other part of the reading pattern not in accordance with the classical staircase pattern)	77	Unsatisfactory
ZZ (RHH)	6.6	2.7	End of line detective strategy Saccadic resolution strategy	65	Unsatisfactory
RK (RHH)	< 4	4.3	Disorganized reading pattern	53	Not evaluated

In the eye and head reading path paradigm hemianopic patients demonstrated six different reading strategies that represented different levels of adaptation. Simple adaptive strategies mostly used by poorly adapted patients were as follows: the 'beginning of line detective' strategy, the 'end of line detective' strategy, and the 'saccadic resolution' strategy. Higher level subfeatures of the above strategies used by better adapted patients included the 'general overshooting/regression' strategy, the 'blind hemifield overshooting' strategy, and the 'increased end of line lexical duration' strategy. For example: Patient AS read in the middle 0.4 letters per second faster than patient ES. But he produced acoustical reading errors and the application of the different reading strategies was not interchangeable. Therefore he was marked as less adapted.

no significant differences between saccades directed either into the seeing or into the blind hemifield. The patients RK and ZZ appeared to be less adapted in the reading experiments. In both patients' velocities and amplitudes of initial eye–head gaze saccades directed into the blind hemifield were significantly lower than saccades that were aimed into the seeing hemifield (*Table 5*). The patient RK, who demonstrated signs of a visual neglect syndrome in the neuropsychological testing was not able to find and fixate systematically CT targets faster than 0.4 Hz. The lesions of these two patients did not affect the right posterior parietal cortex, the lesion of the patient RK affected the adjacent upper part of the angular gyrus (Brodman area 39). Therefore, the adaptive state of patient ZZ was low, whereas the bad performance of patient RK can be attributed to the destruction of area 5a. Altogether, these two patients were characterised by significantly decreased velocities and amplitudes of initial eye–head gaze saccades into the blind hemifield. The target border frequency to hit a target accurately was significantly reduced.

Head employment

Compared with our earlier results[10,13], the head movement component of gaze shift was often reduced or altogether omitted in HF and HN conditions. Consequently the eye movement component was more pronounced. This is demonstrated in *Figure 4a* for patient GS: In HN condition head rotation was minimised at a target eccentricity of ±20° to ±4° at RT targets. Only at ±5° target shifts, head employment was increased continuously. *Figure 4b* shows that the mean percentage of head amplitude in co-ordinated

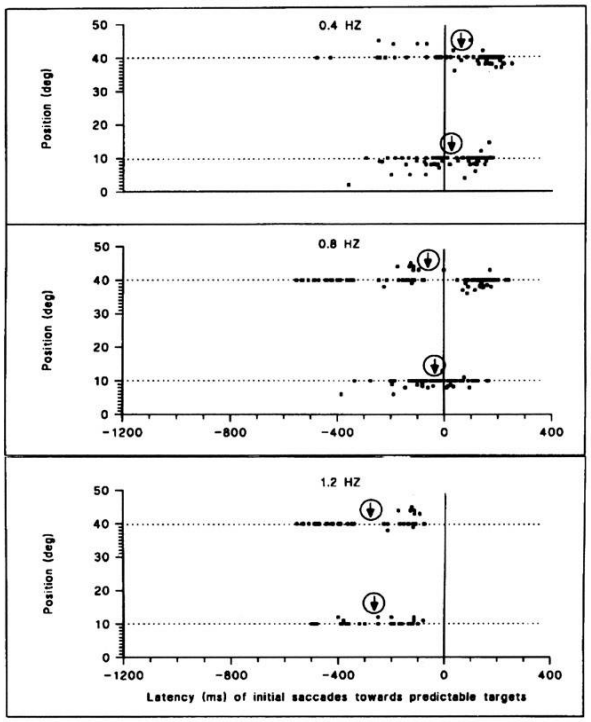


Figure 3a: Cumulative distribution of latencies and amplitudes of eye–head gaze saccades at different CT target frequencies (0.4 Hz, 0.8 Hz, 1.2 Hz) of two normal subjects ($n=320$). Abscissa: Latencies lower than 120 msec or negative latencies indicate anticipatory saccades. Ordinate: Amplitudes of initial eye–head gaze saccades towards target eccentricities of ±5° and ±20°. Arrows mark the respective mean latencies at different target frequencies

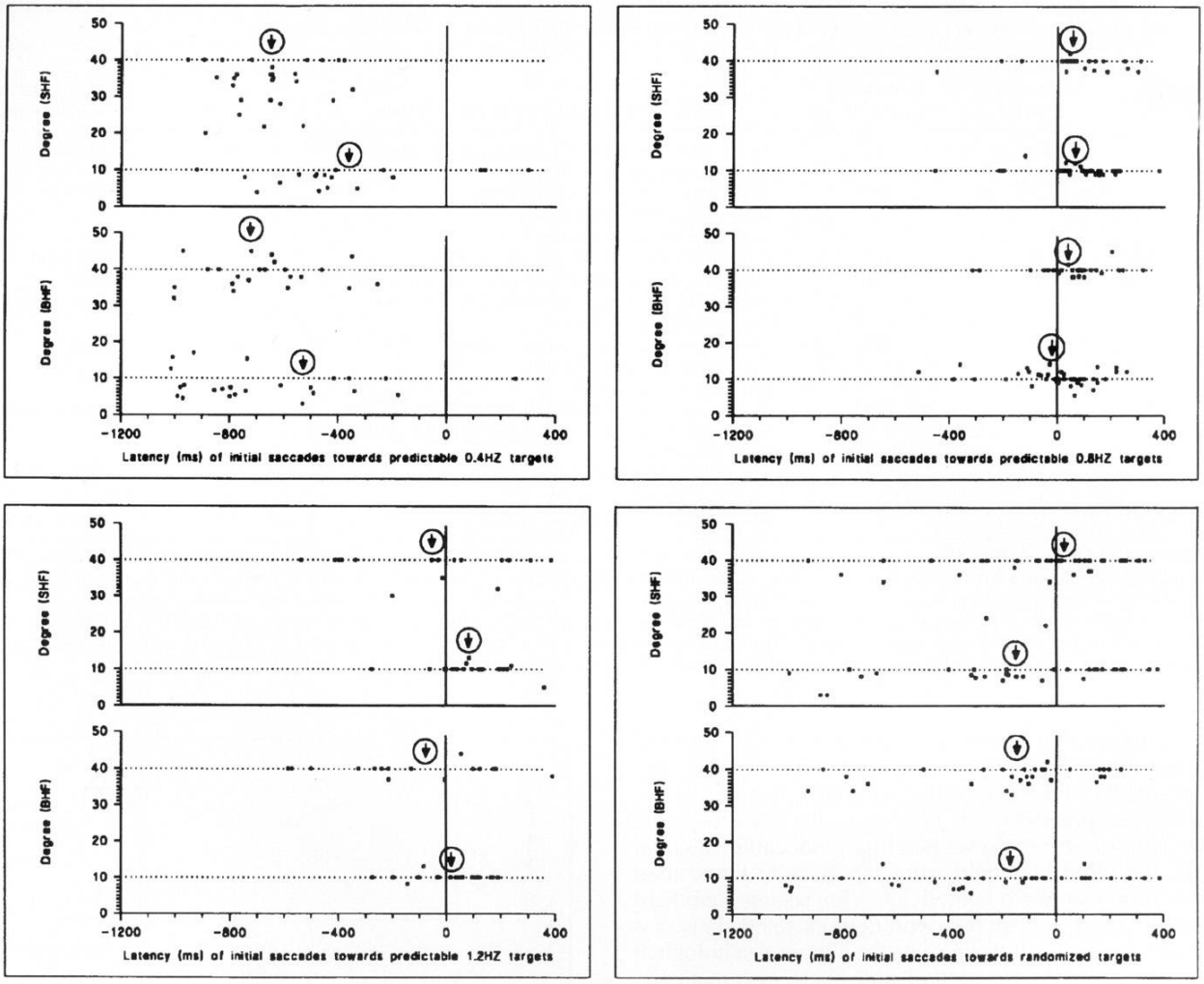


Figure 3b Cumulative distribution of latencies and amplitudes of eye–head gaze saccades at different CT and RT target frequencies (0.4 Hz, 0.8 Hz, 1.2 Hz) and eccentricities (±5°, ±20°). Patient GS with incomplete left homonymous hemianopia ($n=469$). Axes: as in *Figure 3a*. Additionally, differentiation between saccades that are directed either into the seeing hemifield (SHF) or into the blind hemifield (BHF)

gaze saccades was significantly smaller in HN condition (40° target amplitude: 5.2% ± 1.1, 10° target amplitude: 34.8% ± 1.2) than in head forced condition (40° target amplitude: 46.1% ± 3.6, 10° target amplitude: 93.2% ± 2.75). Therefore something prevented the patient from using his head more actively at target shifts greater than 10°. Unlike in the former study[13], the present ten patients that did not show signs of visual neglect in the neuropsychological tests never demonstrated bilaterally increased latencies of eye and head movements. Early onset of head movement was generally favored by patients that appeared to be better adapted. In the two other patients that demonstrated signs of visual hemi-inattention in the neuropsychological tests we found unilaterally prolonged latencies of head movements in the blind hemifield (mean 150 msec ± 41.2).

Interaction of the eye and head motor systems (variability of CEM gains)

The VOR produces promptly generated slow-phase compensatory eye-movements (CEMs) that compensate for head movements. When the vestibulo–ocular reflex is functioning normally with a gain (peak eye velocity vs. peak head velocity) of approximately 1.0, the head movement itself does not move the eyes in space. To change gaze, an additional eye movement command (a saccade or quick phase) must be generated to overcome the powerful, obligatory gaze-stabilising effect of the VOR[30]. Humans have developed a high degree of independent control of both systems that control the head and eyes[16–20]

In normal subjects CEM gains were relatively constant for eye–head gaze saccades into the left and right

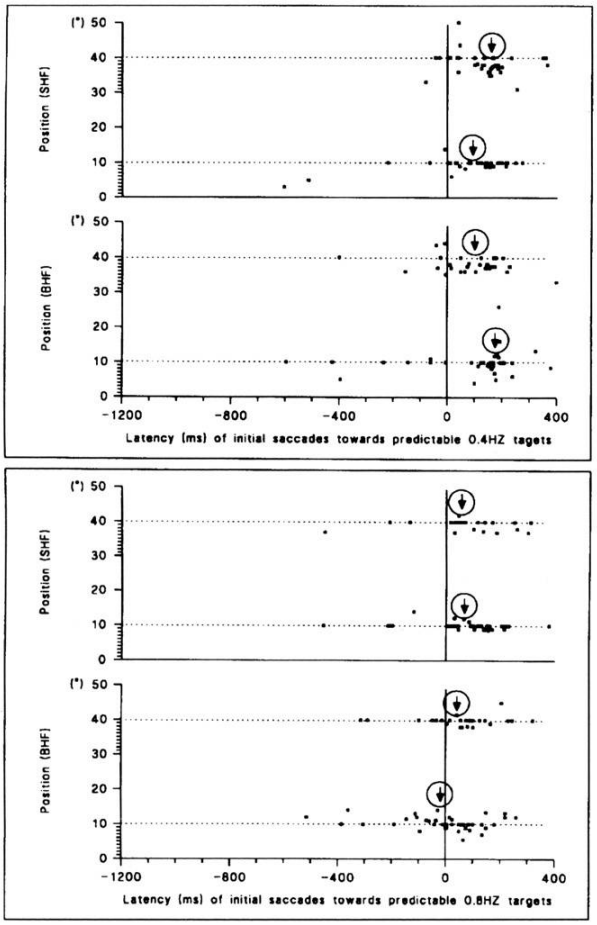


Figure 3c: Cumulative distribution of latencies and amplitudes of eye–head gaze saccades at different CT target frequencies (0.4 Hz, 0.8 Hz) and eccentricities (±5°, ±20°). Patients ES and ZZ with right homonymous hemianopia. Axes: as in *Figures 3a* and *3b*

hemifield at all target frequencies. In comparison, in all hemianopic patients CEM gains fluctuated more than in normal subjects, especially at slower target shifts. In left hemianopic patients the fluctuation of CEM gains was considerably higher in the BHF than in the SHF

Table 5: Poorly adapted RHH patients. Mean percentual differences and corresponding statistical significancies between dynamic parameters of eye–head gaze saccades that were directed either into the SHF or into the BHF

	Target frequency 0.4 Hz	
Dynamics	(BHF– SHF) Mean % difference	Significancy Paired-samples)
Mean velocity (HF)	−11.5	$p < 0.02$
Mean amplitude (HF)	−32.9	$p < 0\ 02$
Mean velocity (HFOC)	−9.8	$p < 0.02$
Mean amplitude (HFOC)	−17.4	$p < 0.02$

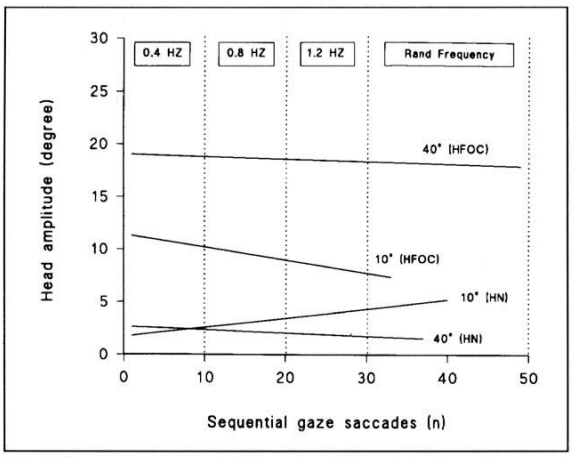
(*Figures 5* and *6a*). Maximum CEM gains at CT target frequencies of 0.4 Hz, 1.2 Hz and RT targets are represented graphically for patient GS with left homonymous hemianopia in *Figure 5*. Target eccentricity was ±20°. The ratio of CEM velocities and corresponding head velocities (CEM gains) significantly increased at a target frequency of 1.2 Hz compared with 0.4 Hz (unpaired samples, U-test: SHF $p < 0.01$, BHF $p < 0.05$). *Figure 6a* represents the typical asymmetry of CEM velocity in two consecutive co-ordinated eye–head gaze saccades with a high fluctuation of CEM velocity at the saccade directed into the BHF and low fluctuation of CEM velocity at the saccade directed into the SHF. The three better described left hemianopic patients (*Table 1*) were recorded within one month of the acute events that caused their visual field defects. The time for a possible modification of the VOR was thus relatively short. In right hemianopic patients CEM gains fluctuated even in the seeing hemifield at a low target frequency of 0.4 Hz. *Figures 6b* and *6c* present examples of this unnormal function of the VOR at ±20° target shifts in HFOC. In *Figure 6b* a highly asymmetrical CEM gain of the saccade directed into the BHF contrasts with a well-balanced CEM gain of the previous saccade directed into the SHF. *Figure 6c* shows the reverse functioning of the VOR with a higher fluctuation of CEM velocity at the saccade directed into the SHF compared with the saccade directed into the BHF. Times from the acute event to the day of EOG recordings varied from three months to four years in these patients.

We concluded that the time span between EOG recordings and the acute lesion that caused the visual

Table 4: Well adapted RHH patients. Mean percentual differences and corresponding significancies of dynamic parameters in eye–head gaze saccades

	Seeing hemifield		Blind hemifield	
Dynamics	(0.4–0.8 Hz) Mean % difference	Significancy (Unpaired-samples)	(0.4–0.8 Hz) Mean % difference	Significancy (Unpaired-samples)
Mean Velocity (HF)	−13.2	$p < 0.01$	− 13.1	$p < 0.01$
Mean Amplitude (HF)	−19.5	$p < 0.002$	− 36.6	$p < 0.005$
Mean Velocity (HFOC)	−10.5	$p < 0.05$	− 5.3	NS
Mean Amplitude (HFCO)	−17.3	$p < 0.02$	− 1.7	NS

CT target shifts of 0.4 and 0.8 Hz. Additionally, differentiation between HF and HFOC.



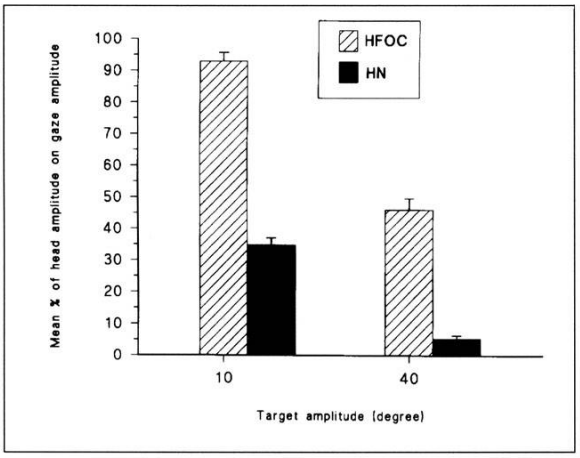


Figure 4a: Patient GS. Head employment at different target frequencies and eccentricities. Regression curves of maximal amplitudes of horizontal head rotations recorded at different head conditions ($n=246$) **b:** Comparison of the percentual portion of head amplitude on gaze amplitude in coordinated eye-head gaze saccades with special respect to HFOC and HNC ($n=246$)

field defect was responsible for the differences in the variability of CEM gains between left and right hemianopic patients. For this reason CEM gains were more variable at slow target shifts than at faster target frequencies. These results were in accordance with the head motor strategies employed by the same patients during the reading tasks in head natural condition[10, 31]. In the reading tasks hemianopic patients at first had the intention of compensating their hemifield loss with forced and active head employment to the affected side. However, in doing so they could not gain an advantage in such a complex, high level task as reading because of the greater variability of CEM gains. Successively they reduced their head movements and relied on eye movements instead.

DISCUSSION

Influence of target predictability on the distribution of initial eye–head gaze saccades

Quantitative studies of hemianopic field defects show that some spontaneous recovery takes place in about 10–20% of patients but ceases within three month after brain damage in most cases[32–34]. Most patients with homonymous hemianopia will not regain normal visual fields. One principal problem in patients with acquired hemianopia are their staircase saccades into the hemianopic field which are too small and slow[35,36]. An increase in the saccadic amplitude will therefore have to be the primary aim in visual rehabilitation training. Furthermore the patients have to develop appropriate ocular motor strategies for efficient use of the remaining half of the visual field[8,9–15,35–40]. Recent studies concerning rehabilitation have shown that saccade training programmes can lead to a significant and stable improvement in visual search in these patients[35–41]. In the present study we demonstrated that different levels of target predictability produced varying changes in the distribution of isolated eye and coordinated gaze saccades. Depending on the velocity and the time continuity of a visual target, successful prediction enabled hemianopic patients to optimise the process of target fixation in the blind hemifield. 1. Correct saccades predominated over hypometrical saccades with increasing time constant target shifts. 2. Depending on the adaptive state and on the etiology of the hemianopic visual field defect, earlier a break frequency of the target was reached than in normal subjects with the consequence that more targets were lost. 3. If patients demonstrated visual neglect phenomena in the neuropsychological tests, targets were hit accurately only at slow CT target shifts of 0.4 Hz with a low accuracy of the primary saccade, i.e. mainly staircase saccades were generated. 4. A constant target frequency of 0.8 Hz was found to be the optimum frequency for patients with pure homonymous hemianopia to follow square step targets with an eccentricity of $\pm 20°$. 5. A correlation was pointed out between reading capacity and the probability of hitting accurately $\pm 20°$ square step targets at CT shifts of 0.8 Hz. Zihl reported[41] that the presentation time of a target has no influence on visual training success in visual rehabilitation of hemianopic patients: training-related increase of saccadic amplitudes, reduced number of therapy sessions, and recovery of striate and extrastriate cortex. Our results, on the other hand clearly demonstrate that target predictability and therefore the presentation time of a target, plays an important role for finding and fixating visual targets accurately. The parametrics of gaze saccades in response to highly predictable visual stimuli at time constant target shifts of 0.8 Hz were obviously modified by the preprogrammed output of higher level control systems. Efficacy of prediction in normal subjects and, more importantly in hemianopic patients depended on the attention of a subject, vigilance and experience. In general, better adapted patients achieved a higher accuracy than worse

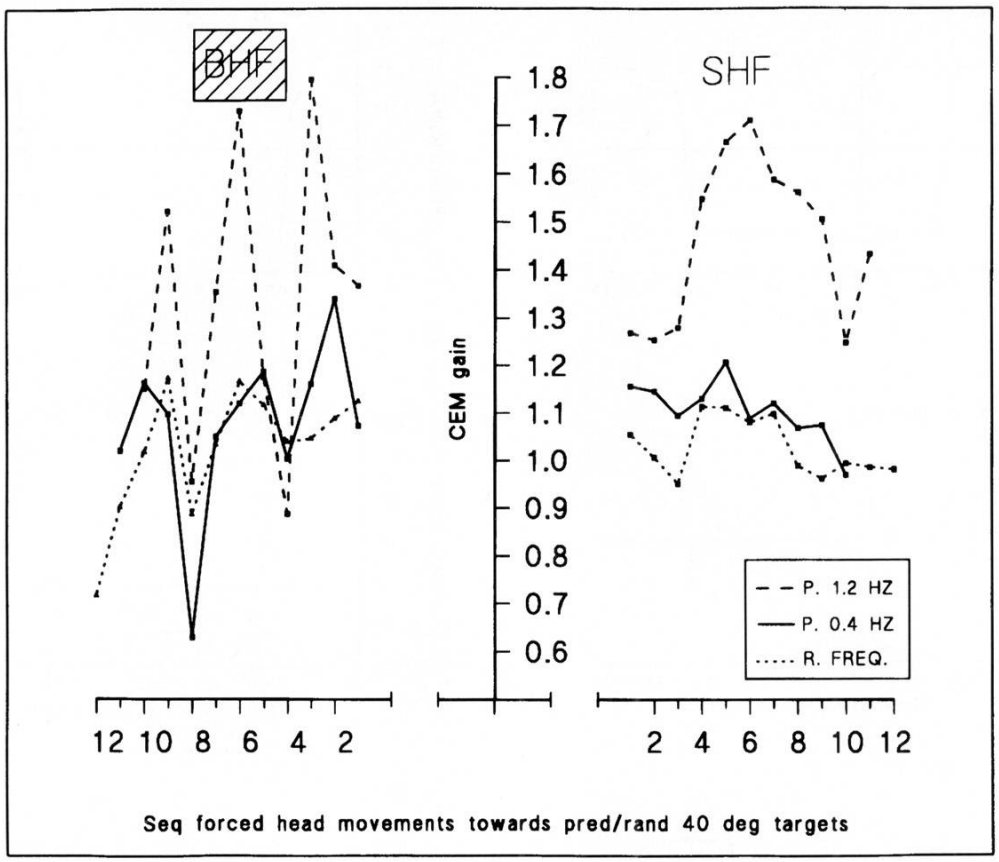
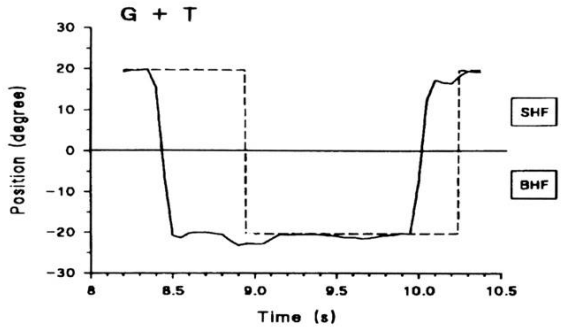


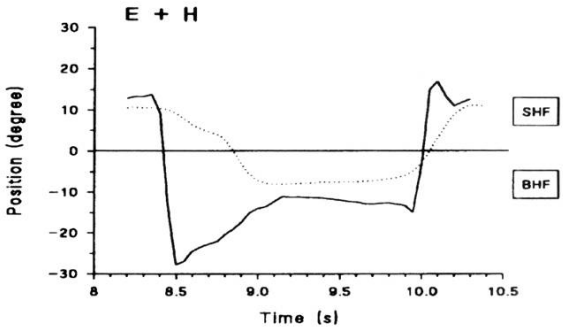
Figure 5: Patient GS. Graphical presentation of the variability of maximal CEM gains during a sequence of gaze shifts at different CT target frequencies ($n=72$)

adapted patients. In the present study the time span that lay between the acute lesion of a patient and the day EOG recordings were done was shorter than in the earlier study. We concluded that the divergent results concerning the latencies of co-ordinated eye-head gaze saccades resulted from this varying time distance. This is corroborated by the earlier observation that head movements tended to be more reduced in patients with congenital hemianopia than in patients with an acquired defect[10,13]. It seems to be a possible explanation for the bilaterally increased latencies of eye and head movements that were found in those former patients with significantly longer delays in head movements towards the blind hemifield. Only patients with parietal lesions and signs of visual hemineglect demonstrated these characteristics of eye and head movements in the present study. It is difficult to demonstrate how far the second visual system can help hemianopic patients deal with their handicap[10–13,15]. Recently, Celesia *et al.*[42] pointed out that rudimentary vision does not help patients with cortical blindness or bilateral hemianopia, to deal with their visual loss, nor does it affect the patient's awareness of the deficit. In our patients there was no evidence that the ocular motor responses to targets presented in the blind hemifield were modified by extrastriate vision. Patient DH, in particular, who clinically demonstrated a maximum statokinetical dissociation[43], generated the typical staircase strategy[12–15] to search for targets in the blind hemifield when target shifts were randomised in time.

Modification of the interaction of the VOR (CEM Phase) by target predictability

A sensory deficit such as homonymous hemianopia may disturb the control of vision in different ways, depending on which areas of the central nervous system are affected. Finding and fixating targets in the presence of homonymous hemianopia presents a sensory–motor adaptive challenge so complex that the brain responds by simplifying the task: it eliminates the head-movement component of the synkinesis, stabilising the head in the service of vision. During combined eye–head tracking, stimulation of the labyrinths and neck proprioceptors elicits compensatory responses not only of the vestibulo–ocular, but also of the vestibulo–collic and the cervico–ocular reflex. Even after months and years, patients frequently fail to learn to make larger


G + T
Position (degree)
Time (s)
SHF
BHF


E + H
Position (degree)
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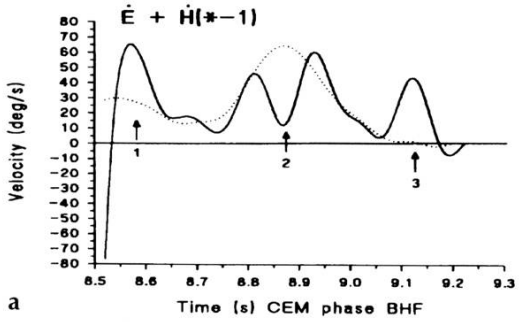
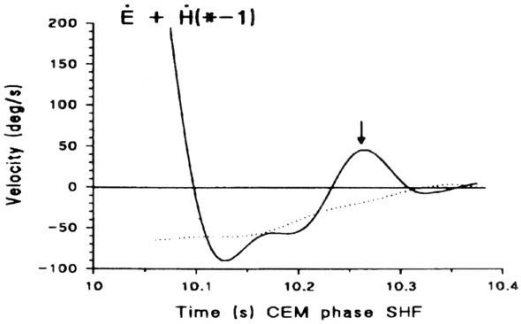

Ė + Ḣ(*−1)
Velocity (deg/s)
Time (s) CEM phase BHF
1
2
3

a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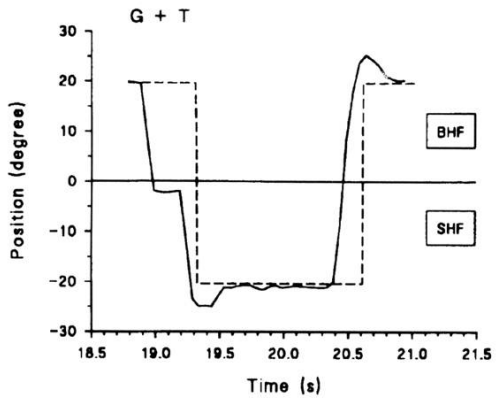
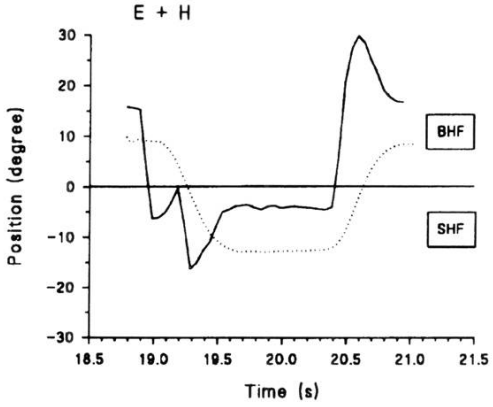
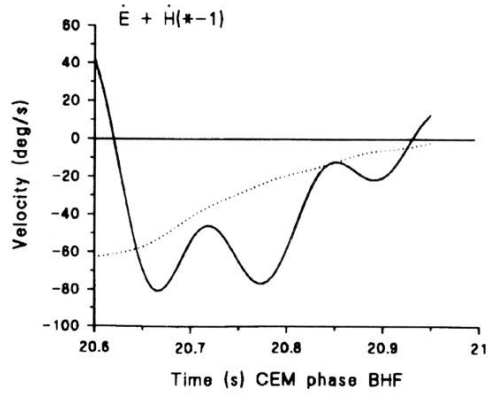
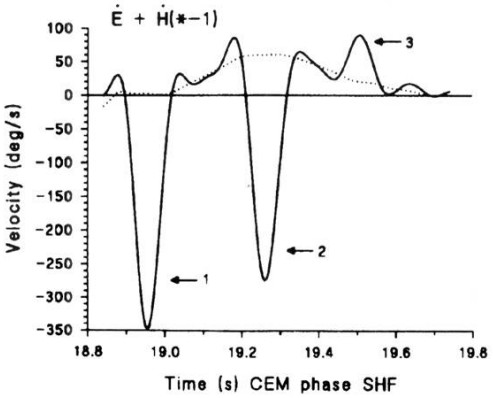
Velocity (deg/s)
Time (s) CEM phase SHF


G + T
Position (degree)
Time (s)
BHF
SHF


E + H
Position (degree)
Time (s)
BHF
SHF


Ė + Ḣ(*−1)
Velocity (deg/s)
Time (s) CEM phase BHF

b


Ė + Ḣ(*−1)
Velocity (deg/s)
Time (s) CEM phase SHF
1
2
3

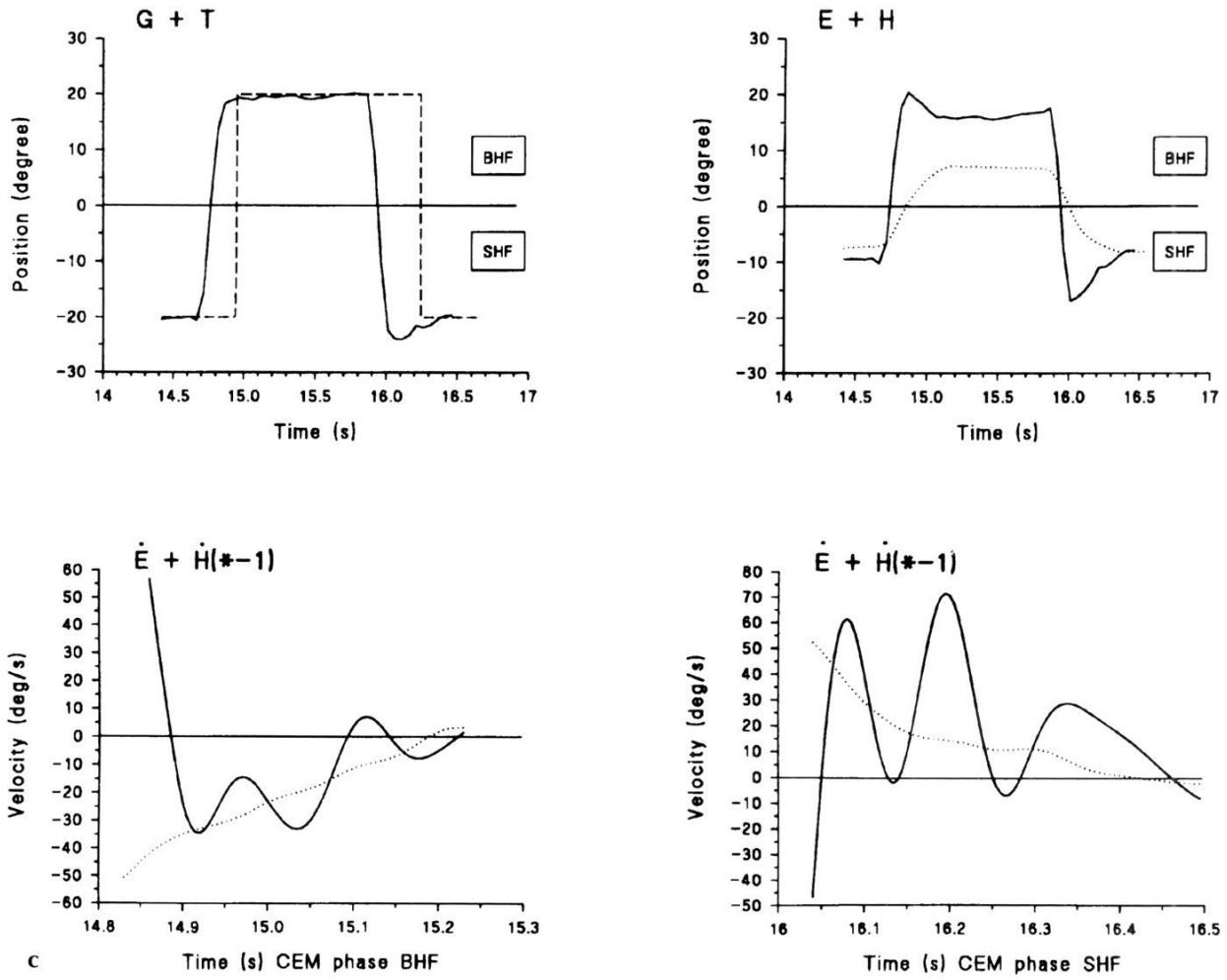


Figure 6: (a, LHH, b and c, RHH) Graphical presentation of typical coordinated eye (E, solid lines) – head (H, dotted line) – gaze (G, solid line) saccades as time functions in the upper graphs. Corresponding continual CEM velocity (solid line) and inverted head velocity (dotted line) as time functions in the lower graphs with distinction between SHF and BHF. **a,b:** Asymmetry of CEM velocity with high fluctuation of CEM gain in the BHF in comparison to a well balanced CEM gain in the SHF (a, BHF: 1 = high CEM gain, 2 = low CEM gain, 3 = back-up saccade, SHF: arrow = catch-up saccade, b, SHF: 1 = initial undershooting saccade, 2 = consecutive overshooting saccade, 3 = finally catch-up saccade). **c**: Reverse functioning of the VOR with high fluctuation of CEM velocity in the SHF and well balanced CEM gain in the BHF

saccades[35,36]. This may lead to the adoption of a chronically oblique or horizontally rotated head position that is sometimes observed in hemianopic patients in order to compensate the sensory deficit at high level visual challenges, as represented in reading a text time-optimally. It results in a hardening of the neck muscles that counteracts the natural co-ordination of eye and head motor systems; it has been reported to be negative throughout[35,36,40,43–49]. The modification of the VOR in the slow compensatory eye movement phase is a low-level generated adaptive change for the worse: because of asymmetrical CEM gains these patients become more and more handicapped in their natural ocular and head motor responses to visual stimuli. Our results demonstrate that there might be a temporal development of the disbalance of the VOR: the longer the time span between the acute event that caused the sensory handicap and the time the EOGs were recorded, the more variable CEM gains were found. The fluctuation in CEM gains as well as the distribution of initial eye–head gaze saccades depended on the predictability of a target. In all hemianopic patients the variability in CEM gains was lowest at a target frequency of 0.8 Hz. At this frequency the eye and head motor systems showed optimum co-ordination, and correct initial eye–head gaze saccades into both hemifields predominated. For visual rehabilitation training the repetition of this manoeuvre could stabilise the balance and correct synkinesis of the VOR during active gaze of hemianopic patients. Humans are capable of suppressing their VOR by mental effort in darkness while fixating an imaginary target[50–53]. These results show the high level predictive control of the VOR. Head latency and velocity during co-ordinated gaze shifts are also modified by the

subjects intention and vigilance[54–56]. We consequently suggest that patients should start to train against this kind of handicap as early as possible after the appearance of a hemianopic visual field defect. This includes the active and forced use of head movements in a special rehabilitation training with a visual or acoustical feedback to suppress the fluctuation of CEM gains by higher-level control, and inhibition of the CEM phase of the VOR.

CONCLUSION

In homonymous hemianopia the central nervous system responds to the sensory deficit in different ways, depending on the etiology of the visual field defect and on the individual motivation of a patient to train and eventually change the ocular motor scanning behavior. Target predictability influences the distribution of co-ordinated eye–head gaze saccades as well as the interaction of the eye and head motor systems. A constant target frequency of 0.8 Hz is optimal for hemianopic patients to follow square step targets with an eccentricity of $\pm 20°$. This target frequency in combination with simple reading tests could be used as a test for the immediate clinical classification of the status of adaptation of hemianopic patients; in addition, for the purposes of visual rehabilitation training a repetition of this manoeuvre could stabilise the balance and correct synkinesis of the VOR during active gaze of hemianopic patients.

ACKNOWLEDGEMENTS

Thanks are due to our colleague Carsten Moschner for his technical assistance and Mrs Jutta Kleim for doing the psychological tests. We would also like to thank Prof F. Dannlheim and PD Dr Kai Uwe Hamann for referring patients to us.

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