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An increase in a virtual hemianopic field defect enhances the efficiency of secondary adaptive gaze strategies

Wolfgang H. Zangemeister and Peter Utz

Neurological University Clinic Hamburg, Germany

Abstract

We report findings about search and scan path eye movements (EMs) in normal healthy subjects that had to deal with a virtual homonymous hemianopia (VHH) that compared exactly to the deficit of patients with stable full homonymous hemianopia. We posed three questions: 1. Does a sensory-motor adaptation occur in these virtual hemianopic patients? 2. Is it possible to enhance the effect of this adaptation through "training" by enlargement of the 50% vertical field defect towards the "healthy" seeing side (SHF) by +10 deg, and 3. How large is the additional effect of training? We used high resolution infrared-oculography for recording EMs in 16 healthy subjects. Eight subjects *("early training group")* were trained for 20 minutes with 10 deg off-field defect towards the healthy side and directly afterwards. The other 8 subjects ("*late training group*") underwent 20 minutes of viewing *without any training*. They were recorded directly afterwards. Our healthy subjects responded to VHH quite similarly as hemianopic patients: the training of parafoveal eccentric viewing of up to 10° together with specific advice to improve saccadic strategies helped the adaptation of VHH subjects significantly. We conclude from this study of VHH adaptation in normal subjects that hemianopic patients might use an increase of their field

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Correspondence should be sent to Pr. W. H. Zangemeister, Neurological University Clinic, Martinistr. 42, 20251 Hamburg, Germany
(email: Whiz@uke.uni-hamburg.de)

defect so that they become aware of the increased gaze efficiency (being faster and more accurate) when shifting the vertical null point of their visual field towards the side of the BHF.

Key words: homonymous hemianopia, virtual hemianopia simulation, scanpath eye movements, visual attention, visual feedback training, hemianopia rehabilitation.

INTRODUCTION

Although recent studies showed remarkable progress in analyzing different aspects of structural and functional compounds of "High-Level-Vision" processes there still remain various questions about the visual process as a whole. Two fundamental questions are whether the object recognition process is mostly parallel or serial and what kind of internal representation is used by the brain selecting and integrating the numerous complex and rapidly changing visual data that it is permanently exposed to.

The serial model suggests that the internal representation consists of single components and features which are sequentially "matched" to the object seen in the recognition phase. Because viewing consists of a sequence of alternating saccades and fixations, its measurable correlate can be described as the so called "scanpath". This term was introduced by Noton and Stark (Noton & Stark, 1971 a & b; Ellis & Stark, 1978; Hacisalihzade, Stark, & Allen, 1992; Chernyak & Stark, 2001). Their theory based upon the model that top-down processes associate single features of a scene on a higher cognitive level in a step-by-step manner. Within their studies, they found marked similarities in recorded intra-subjective scanpaths of their subjects when repetitively viewing the same picture. When viewing an object for an extended time the scanpath was repeated. From this, Noton and Stark developed the "feature ring hypothesis", which claims that the internal representation of a seen object is given by its cardinal sensory features and the motor traces (saccades) which connect these features. So recognition of objects works through a sequential step-by-step scanning which corresponds to the actual "Feature Ring".

Since the early seventies, however, many other researchers have preferred a more bottom-up view of oculomotor activities related to reading (Rayner & McConkie, 1976) and visual attention (Taub et al., 1993). But more recently, experimental evidence for the feature ring and the importance of sequential visual top-down mechanisms in vision has accumulated during the last ten years, specifically with the advent of neuroimagery, i.e., functional magnetic resonance tomography (fMRI) (Butter, Kosslyn, Mijovic-Prelec, & Riffle, 1997; Roland & Gulyas, 1994) and positron emitting tomography (PET) studies (Goldenberg, Poderka, Steiner, Suess, & Deecke, 1989; Goldenberg, 1993; Kosslyn et al., 1993). In addition, transcranial magnetic stimulation (TMS) studies (Brandt, Ploner, Meyer, Leistner, & Villringer, 1998; Brandt & Stark, 1997; Zangemeister, Canavan, & Hoemberg, 1995) have demonstrated the functional interdependence of occipital, parietal and frontal - visual, memory, and motor - areas when disturbed through single or repetitive focal electromagnetic stimulation (Stark et al., 2001; Chernyak & Stark, 2001; Zangemeister, Sherman, & Stark, 1995; Zangemeister & Oechsner, 1996).

Based upon this model, our approach to obtain information on the visual system was to register the eye movements of our subjects during a virtual visual task and then to analyze the resulting scanpaths with respect to the side of the blind and the seeing hemifield.

Homonymous hemianopic patients are blind on one half of their horizontal visual field that extends to about 95° to left and right from the vertical zero degree primary position. Most often they suffer from an occipital stroke. Hemianopic patients show a multi-stairstep saccadic strategy (Gassel & Williams, 1963; Meienberg, 1983; Poppelreuter, 1917; Teuber, Battersby, & Bender, 1960; Zangemeister, Oechsner, & Freksa, 1995) when first confronted with their deficit that appears to be dominated by a bottom up mechanism like a primitive search. Patients with pure hemianopia, i.e., without deficits of attention (visual neglect) and/or motor deficits of eye movements, in the first stages of the disease are rare. Using specific training regimes, they may be able to adapt and

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Abbreviations: VHH: virtual homonymous hemianopia; BHF: blind hemifield; SHF: seeing hemifield; G/L index: global/local index - ratio between frequency of occurrence of saccades > 1° / < 1°; HP: hemianopic patient; NS: normal subject; TMS: transcranial magnetic stimulation; 2ndVFB: secondary visual feedback: fMRI: functional magnetic imaging; VDT: visual display terminal; ROI: region of interest; PET: positron emitting tomography.

circumvent efficiently this half-field blindness (Gbadamosi & Zangemeister, 2001; Hier, Mondlock, & Caplan, 1983; Meienberg, Zangemeister, Hoyt, & Stark, 1981; Pommerenke & Markowitsch, 1989; Schoepf & Zangemeister, 193; Zangemeister, Dannheim, & Kunze, 1986; Zangemeister et al., 1995; Zangemeister & Oechsner, 1996; Zangemeister, Poppensieker, & Hoekendorf, 1999; Zihl, 1988) in applying a top-down governed strategy of one-large-step overshooting saccades when looking towards the side of the blind hemifield (BHF).

As the hemianopic field defect is a pure sensory deficit, many of these patients stay with their ophthalmologist and never present at a clinical neurology department. Therefore we developed a *virtual homonymous hemianopia*(VHH), i.e., an on-line simulation of homonymous hemianopia (Zangemeister, 1997; Zangemeister & Oechsner, 1999), allowing us to record and analyze the adaptation of normal healthy subjects to this pure *sensory* deficit: a deficit that always shows adaptive *motor* consequences with a change of eye movement strategy (Gassel & Williams, 1963; Meienberg, 1983; Messing & Gänshirt, 1986; Zihl, 1981). An additional advantage of this experimentally simulated deficit was that VHH subjects (virtual "patients") had to adapt to a *complete and pure* homonymous hemianopia.

Normal Subjects show a stairstep/overshoot saccadic strategy similar to that used by hemianopic patients (Gassel & Williams, 1963; Meienberg, 1983; Poppelreuter, 1917; Zangemeister et al., 1995b) either when confronted with a virtual reality model of artificial hemianopia using eye position feedback (VHH), or when achieving eccentric fixation using secondary visual feedback (2ndVFB) (Zangemeister et al., 1986): here gaze position is displayed simultaneously with the target and the subject learns either to superimpose target and eye position feedback, or to position the gaze feedback target up to 10 deg off the target - eccentric fixation -; this helps to keep the "blind side" in sight, namely, the target of interest within the SHF, usually within a parafoveal region of 2 to 10 deg. This "technique" is regularly used in the natural course of amblyopia in early childhood.

Normal subjects confronted with VHH minimize their deficit faster and more efficiently with than without 2ndVFB training (Zangemeister et al., 1986): similarly to real hemianopic patients when they undergo a specific sensory-motor training that we have developed (Zangemeister et al., 1999). Using this previously (Zangemeister, 1997; Zangemeister & Oechsner, 1999) described computer simulation of such a visual field defect on a visual display terminal (VDT) - as a "virtual hemianopia" (VHH) in normal healthy subjects –, we posed three questions:

1. Does a sensory-motor adaptation occur in these virtual hemianopic subjects without 2ndVB?
2. Is it possible to enhance the effect of this adaptation through "training", i.e., specific advice to the subjects how to improve their gaze strategies; and by enlargement of the 50% vertical field defect towards the "healthy" seeing side (SHF) by +10 deg, in analogy to the "forced used therapy" developed by Taub et al. (1993) in hemiparetic patients, where patients were forced to use only their paretic limb, i.e., in our paradigm *the side of the blind hemifield*?
3. How large is the additional effect of training compared to just viewing for the same amount of time?

METHODS

Subjects and Apparatus

Our group consisted of 16 subjects recruited from our department with no visual disturbances or any other neurological disease. The age range was 22 to 34. All subjects gave their informed consent to participate in this study.

Virtual Hemianopia. Subjects sat in a comfortable chair with their heads fixed, tightly strapped to a circular head holder that was firmly attached to the chair. Their viewing distance was 57 cm such that their eye movements subtended maximally a visual angle of ± 15 deg horizontally and ± 10 deg vertically when they viewed the pictures and stimuli displayed on a VDT (75Hz, 22"). We used high resolution infrared-oculography (Ober 1000) for recording of horizontal and vertical eye movements with a sampling rate of 200 Hz.

Using the horizontal eye movement recording as trigger we generated a "field defect" on the (in that case blank) screen of 50% off the foveal eye position (accuracy ± 0.5 deg, delay 4 ms); for the special training we applied an additional +10 deg increase of the virtual blind hemifield (BHF) that would always move together with the eyes. Fifteen subjects (heads fixed) could not see what was going on on their "blinded" side (BHF) on the screen.

Experimental protocol

After calibration (5 × 5 matrix) that was repeated at least two times during the session, subjects had initially two minutes to get used to the virtual hemianopia. A series of 2 × 8 pictures were then presented during VHH, each for 5 sec, 2 sec center fixation, and 5 sec visual imagery, adding up to 96 sec for one sequence, or 192 sec for the whole series. The very limited time of 5 sec viewing a complex or a hidden picture put some pressure (forced situation) on the subjects. After this, sinusoidal pursuit (0.5Hz, 1Hz), predictive steps (0.5Hz, ± 10°, ± 15°) and random steps were presented horizontally and vertically.

Visual stimuli

Visual stimulation included a sequence of various pictures each shown for 5 sec, ranging from simple realistic, hidden search pictures, to artistic abstract images. To enforce viewing of the different stimuli with respect to the effect of adaptation, subjects were advised to search and scan for detection of hidden images and also to recollect verbally the main features of the pictures. Subjects also followed predictive and random saccadic and pursuit stimuli (a white cross subtending smaller than 0.25 deg) each for 10 sec. The first 4 presentations were used to measure the so called "searchpath", containing the task of searching objects within a picture. The next 4 pictures showed abstract, polyvalent and realistic stimuli. During this phase different scanpath tasks of increasing cognitive complexity were performed.

Each subject was measured during a standardized routine that consisted of one stimulus presentation phase and one subsequent imagery phase. We used 8 different stimuli of graduated complexity which were all bordered by a reference frame. The subjects first had 5 seconds for viewing the presented picture according to varying instructions. In the following separate imagery phase, subjects then were asked to recall the picture, just looking at the blank reference frame on the monitor and scan it again freely from the imagination.

Training

"Training" was defined as 20 minutes of viewing in the VHH condition with an additional offset of the VHH by 10° off the vertical meridian towards the side of the SHF. We used 20 minutes to make sure that our subjects would spent enough time so as to achieve a solid training effect; also, this length of time appeared to be reasonable since comparable therapies in the clinical setting take a similar amount of time. We were not interested to find the shortest possible time of training that would be long enough to enhance our subjects' performance significantly. Also, specific advice was given by us: subjects were explicitly told to keep the target of interest off the fovea inside the SHF; they were also advised to use one-step large overshooting saccades instead of sequences of small-stairstep undershooting saccades to reach targets of interest.

After the initial recordings, 8 subjects *(Group 1, "early training")* were trained for 20 minutes with the additional 10 deg off-field defect towards the healthy side and were a second time recorded directly afterwards. After 14 days, their responses to the the same tasks were recorded a third time.

The other 8 subjects *(Group 2, "late training")* underwent 20 minutes of viewing without any training. They were a second time recorded directly afterwards. After 14 days, their responses to the the same tasks were recorded a third time after 20 minutes of training.

With and without training was then compared in all subjects for probability of fixation durations and amplitudes; as a measure of efficient adaptive change, the normalized ratio of overshoot one-step to undershoot stairstep saccades was calculated.

Analyses

For eye movement analyses, first all fixations were calculated and sequentially linked (fixation: > 150 msec, 0-5°/sec, ± 1° area), and amplitudes and direction of gaze as well as frequency and duration of fixations in the BHF versus SHF were calculated, including their statistics (SPSS and specially developed software ET 1.24 by Oechsner and Zangemeister (Stark & Choi, 1996; Zangemeister et al., 1995 a & c, 1999).

We also calculated the ***global/local index*** (G/L index) , i.e., the ratio between saccades larger than 1.° to saccades smaller than 1° (ampl. > 1°/ampl. < 1°), a ratio of global amplitudes over local amplitudes while viewing or imagining a picture. This is an indicator of efficacy in improving gaze by use of larger amplitude saccades towards the side of the BHF, as a measure of consistent picture viewing (see Zangemeister et al., 1995 a & c; Zangemeister & Oechsner, 1996). In addition we used the ratio of overshoot one-step/undershoot stair-step saccades towards the BHF as a measure of efficient adaptation.

RESULTS

The first result we obtained was that all 16 subjects were able to maintain and follow through our VHH setting. Of course, there occurred differences of performance between subjects. Figure 1 shows an example (upper) of saccades towards a predictively alternating ± 10 deg target that is initially not predicted, such that stairstep saccades towards the BHF occur until at the fifth repetition of the target the first (predictive) overshoot occurs (arrow), followed by several more overshoots until the cycle is completed. On the lower part, one normal subject's (NS) and one real hemianopic patient's (HP) scanpath of the Mona Lisa Picture is shown: average of 10 responses each including 85 to 105 saccades with the ordinate as normalized frequency of occurrence of saccades. Note that fixation durations of HP are significantly longer (median 0.71 s to 0.26 s, $p < 0.01$), and saccadic amplitudes are significantly smaller, which is also demonstrated by the smaller *Global/Local index*: the ratio between saccades larger than 1° to saccades smaller than 1° (ampl. > 1°/ampl. < 1°), a ratio of global amplitudes over local amplitudes while viewing or imagining a picture. This is an indicator of efficacy in improving gaze by use of larger amplitudes saccades towards the side of the BHF, as a measure of consistent picture viewing (see Zangemeister et al., 1995 a & c; Zangemeister & Oechsner, 1996).

The second result was that both training groups gained significantly from the training (+10° BHF enlargement, specific advice) (Tables 1 and 2). Table 1 shows results from the early training group that underwent 20 minutes training after the first recording and immediately afterwards, and after 14 days recorded. Their results pre- and post-training including forced viewing with 10° enlarged BHF show signifi-

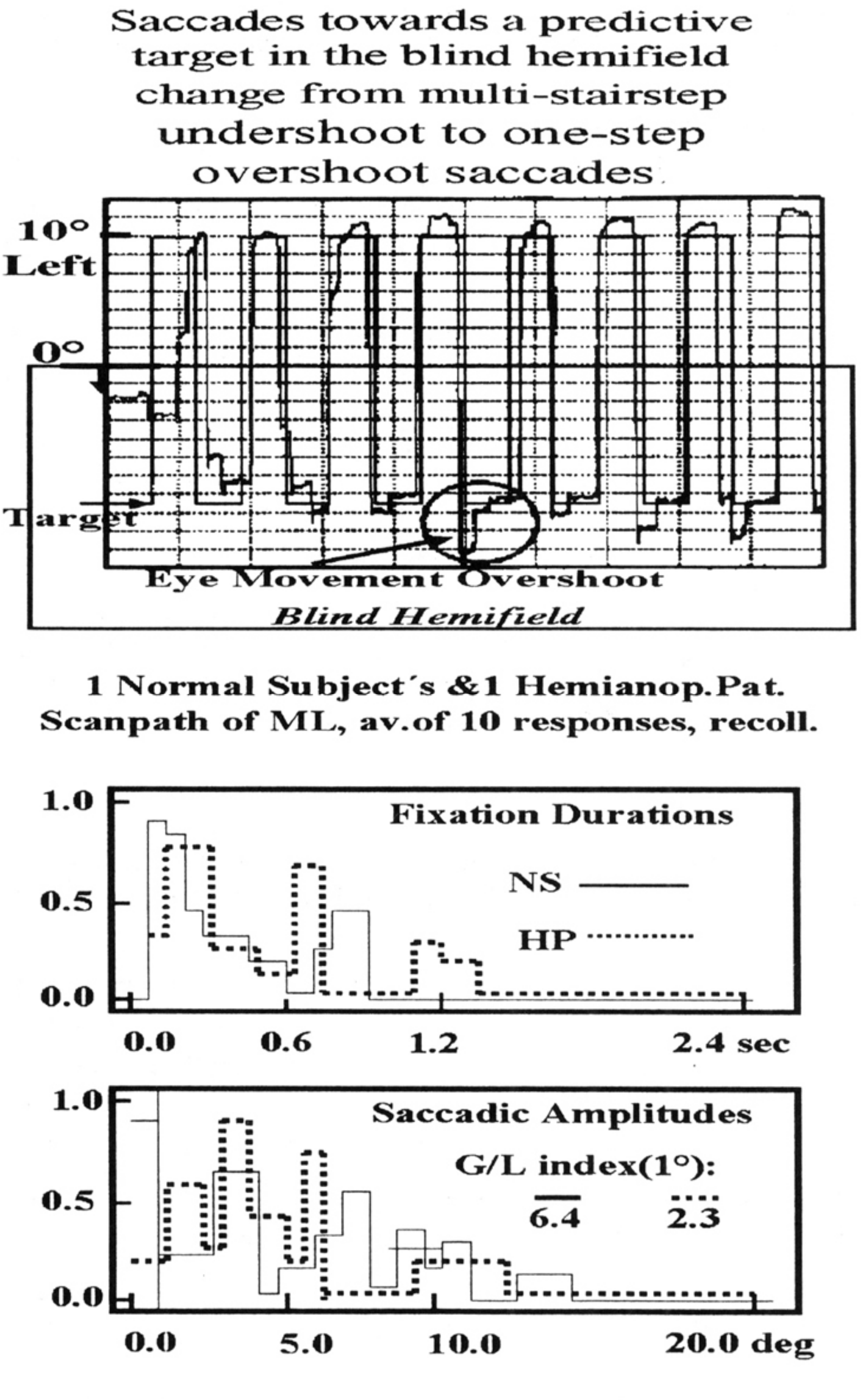

Figure 1. Upper: example of saccades towards a predictively alternating +/- 10 deg target that is initially not predicted. Lower: one normal subject's (NS) and one real hemianopic patient's (HP) scanpathof Mona Lisa picture; ordinate: normalized frequency of occurrence.

Table 1
Early training group (n = 8): results of pre- and post-training (with 20 minutes of training with forced viewing, 10° enlarged BHF: day 0), and after 14 days

Parameter	Pre-training on day 0	Task Post-training on day 0	Post-training on day 14
Fixation durations (s)	0.43	0.26***	0.39**
Saccadic amplitudes (°)	3.4	6.2**	4.9*
Ratio of overshoot one-step/ undershoot stair-step saccades to BHF	0.37	0.76***	0.52*

Note. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$, ns: not significant. (0) recording directly after 20 minutes of training; (14) recording 14 days after training. Upper two rows: relative frequency of occurrence of fixation durations and saccadic amplitudes. Ratio: normalized ratio between 0 and 1.

Table 2
Late training group (n = 8): results of pre-and post-20 minutes viewing (no training; day 0), and after 14 days, with 20 minutes of training, with forced viewing, 10° enlarged BHF

Parameter	Pre-training on day 0	Task No training day 0	Post-training on day 14
Fixation durations (s)	0.41	0.38 (ns)	0.29**
Saccadic amplitudes (°)	3.5	3.9 (ns)	5.8*
Ratio of overshoot one-step/ undershoot stair-step saccades to BHF	0.36	0.41 (ns)	0.67**

Note. * $p < 0.05$, ** $p < 0.01$, ns: not significant. (0) recording directly after 20 minutes of training; (14) recording 14 days after training. Upper two rows: relative frequency of occurrence of fixation durations and saccadic amplitudes. Ratio: normalized ratio between 0 and 1.

cant effects with respect to all measures: fixation durations decreased, saccadic amplitudes increased, together with the global/local index, and also the ratio of overshoot one-step to undershoot stair-step saccades when looking to the side of the BHF.

Table 2 shows the results from the late training group that first underwent no training and only after 14 days the training. Their results show similar effects as in the early training group, but less pronounced. This significantly positive training effect demonstrated in the "early training group" also shown in the "late training group" yielded some smaller effect of about 75%. The "early training group" still gained from their ealy training after 14 days.

The measured parameters (fixation duration, normalized frequency of occurence of saccadic amplitudes, ratio of overshoot one-step to undershoot stair-step saccades when looking to the side of the BHF) demonstrated consistently our prediction and particularly showed that there is an effect of about 75% that could be ascribed to our specific training that is not due to some general adaptation taking place while experiencing VHH.

Within each group of 8 subjects, we found a similar number of adapted versus non-adapted subjects, i.e., good and bad responders, independently of the training. The non-adapted subjects amounted to 2 in the early group and 3 in the late group. We judged as non-adaptive a non significant change of our three measure parameters between pre- and post-training. The non-adaptive subjects of both groups showed great difficulties to adapt correctly to the tasks within the given time. They were slower and significantly less efficient in both situations, adaptation to VHH and adaptation plus the 10 deg off task training. Often this had to do with the short time of picture presentation (5 s) and the relatively fast sequence of presentation, imagery, center fixation which was repeated 8 times. Therefore non-adapted responses had also to do with low and misdirected attention, a characteristical obstacle in the therapy of real hemianopic patients who perform badly.

To illustrate the actually obtained single response changes in early trained as compared to late trained subjects' eye movement, statistics of single subjects are depicted with the scanpath responses on top (Figure 2, lower parts of Figures 3 and 4).

In Figure 2, virtual hemianopic scanpaths of a sequence of 8 pictures recollection task are shown, *pre- (upper)* and *post- (lower) training*. On the ordinate, the normalized frequency of occurrence is depicted. Note the longer fixation durations in VHH (0.49 s to 0.22 s) and smaller amplitudes and G/L index (3.9° to 7.6° and 2.1 to 7.4) in pre-training stages.

In Figure 3, the search paths of the dog search picture *with (upper)* and *without (lower)* training is shown. Note the significantly ($p < 0.001$) increased amount of larger amplitude saccades (up to 17°) towards the blind hemifield with training as compared to without training (zero saccades in the BHF). Also note the much improved search path performance in detecting the dog.

In Figure 4, the scan path of the Mona Lisa picture *with (upper)* and *without (lower)* training is depicted. Note the significantly ($p < 0.001$) increased amount of larger amplitude saccades (up to 17°) towards the blind hemifield with training as compared to without training (only few saccades in the BHF). Also note the much improved scan path performance in scanning face,bust and field of view of the Mona Lisa.

DISCUSSION

The main findings of our study were:

- Normal subjects respond to a Virtual Hemianopia quite similarly as hemianopic patients.
- A training of parafoveal eccentric viewing helps the adaptation of VHH subjects significantly.
- There are adapted and non-adapted responders in the VHH group, which again resembles the two patient groups of adapted and non-adapted responders in real hemianopia.
- It is important to note that our subjects had their heads fixed. A secondary gaze strategy could possibly additionally increase the efficacy of hemianopic gaze movement strategy (Zangemeister, Meienberg, Stark, & Hoyt, 1982; Zangemeister & Stark, 1982).

Homonymous hemianopia and rehabilitative aspects related to VHH

Hemianopia, defined as a complete visual field defect is divided into different forms according to the site of the lesion. The homonymous form more often shows macular sparing, leaving the foveal center of the visual field undamaged, which is responsible for the often occurring

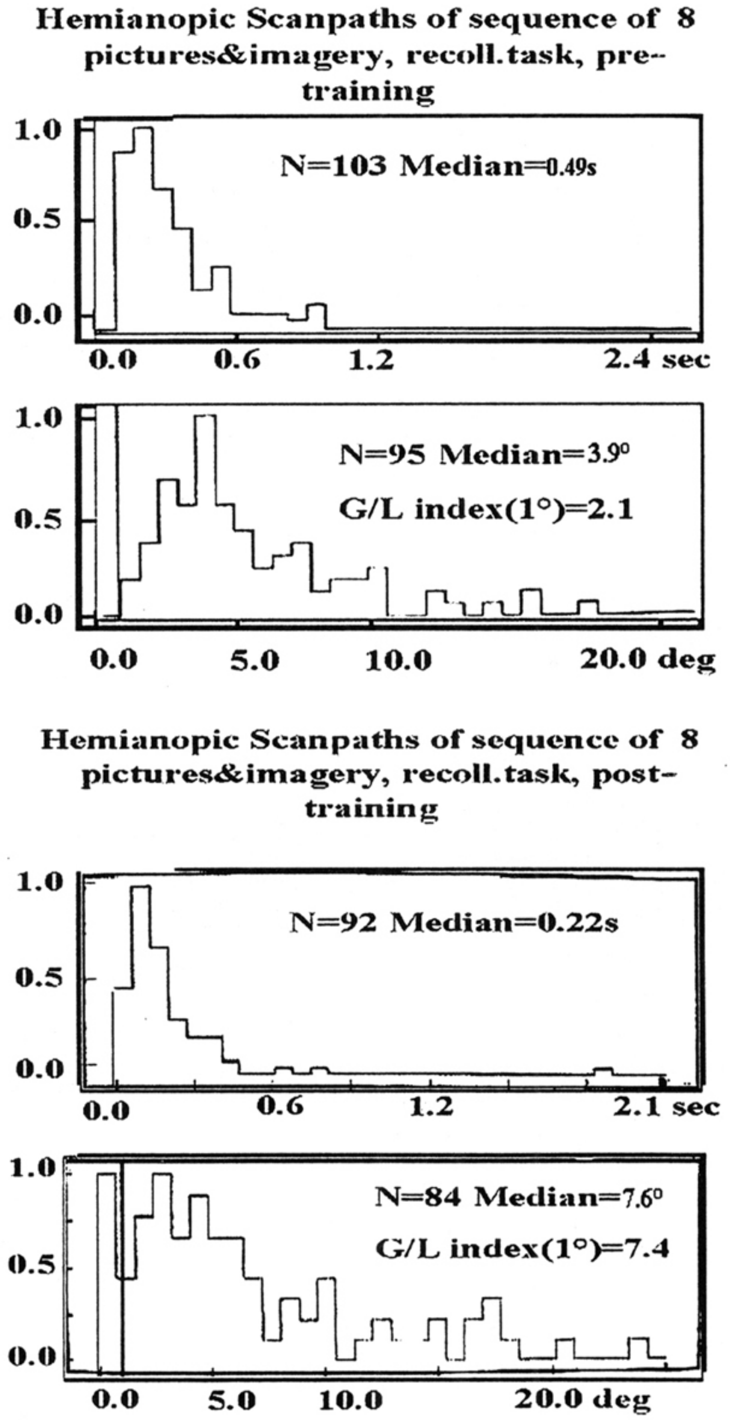

Figure 2. Virtual hemianopic scanpaths of a sequence of 8 pictures recollection task, pre- (upper) and post- (lower) training. Ordinate: normalized frequency of occurrence.

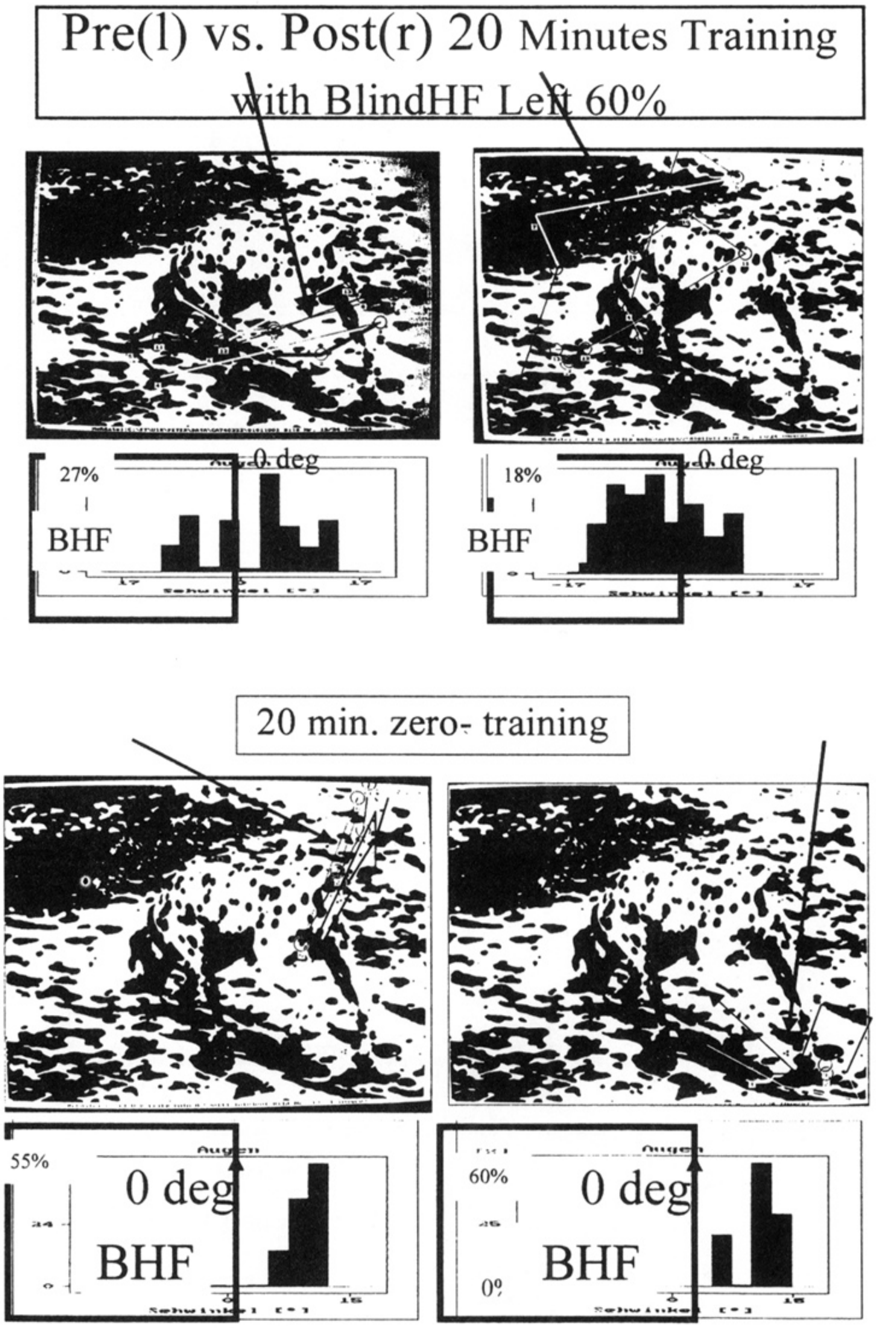

Figure 3. Search path of the dog search picture with (upper) and without (lower) training. Block diagrams below show the distribution of of saccades within the field of view: abscissa 16° left and 16° right, ordinate calibrated to maximum: upper 27% left, 10% right; lower 40% left, 50% right.

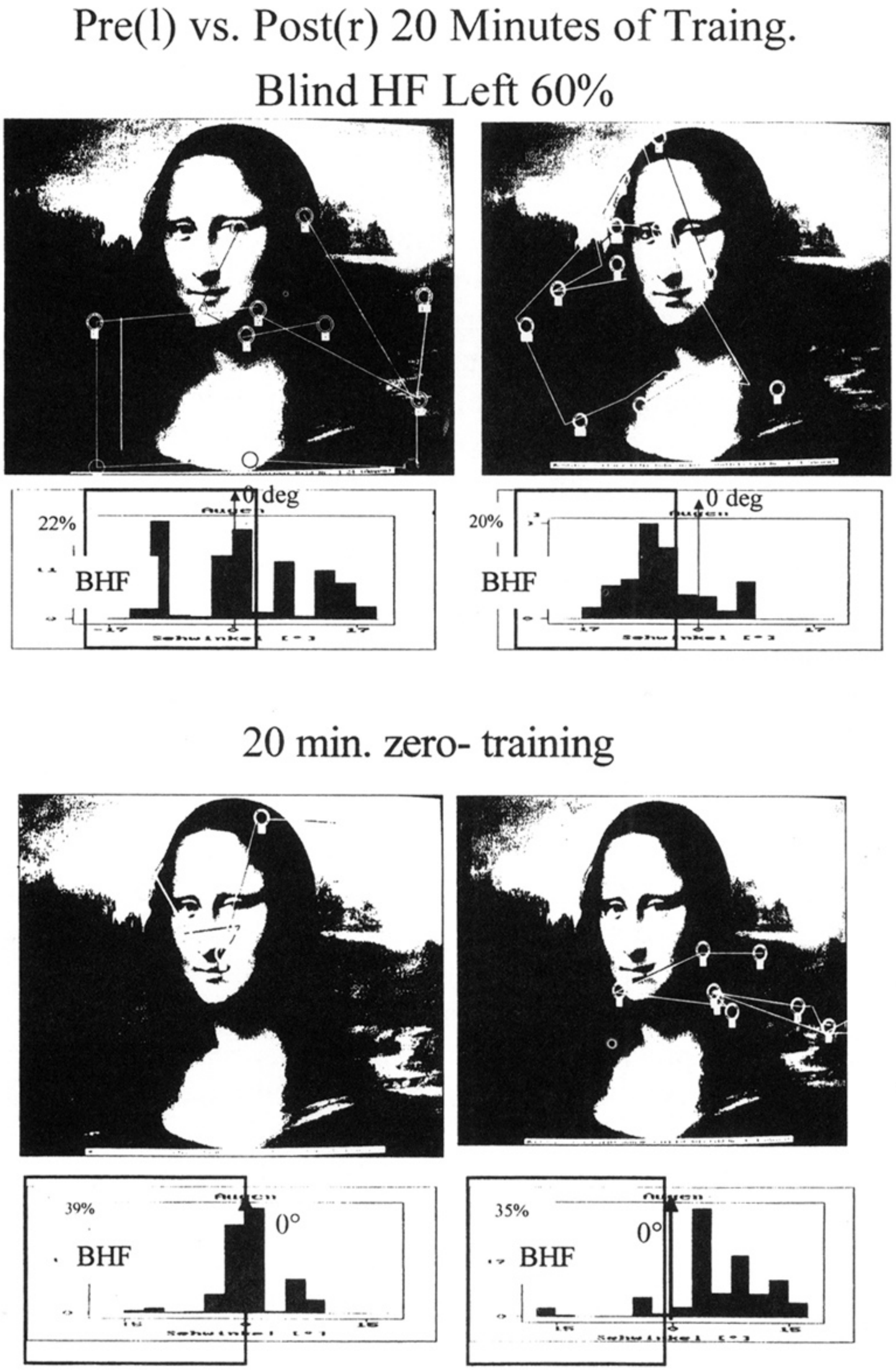

Figure 4. Scan path of the Mona Lisa picture with (upper) and without (lower) training. Block diagrams below show the distribution of of saccades within the field of view: abscissa 16° left and 16° right; ordinate calibrated to maximum: upper 22% left, 20% right; lower 35% left, 36% right.

relatively adapted spontenuous recovery; a complete full hemianopia – such as we simulated it – often leads to enduring more pronounced visual disabilities: this is an obvious reason why a specific therapy in these cases is of great importance (Zeki, 1978, 1983, 1999). Common etiologies of this disorder are the ischemic cerebrovascular event, followed in frequency by bleedings and trauma. Often hemianopia is associated with other cognitive dysfunctions like aphasia and visual hemineglect. Rossi, Kheyfets, and Reding (1990) found that more than 20% of patients with stroke treated in rehabilitation centers present hemianopic symptoms. The impact of this sensory deficit depends on size and localization of the lesion, impairing patients in visual information processing in many ways. Hemianopia usually causes problems exploring the blind hemifield causing patients to perform hypometric, slow down head movements and generate low amplitude saccades, therefore handicapping them more or less severely in orientation and safety in everyday living. Prospective studies of the natural course (Zangemeister et al., 1982; Meienberg, 1983) of vascular retrogenicular visual field defects showed that spontaneous restitution – e.g., axon-sprouting – in the blind hemifield takes place within the first 6 months after the event and that the average visual field gain may be up to 16% in perimeter (Chatterjee & Southwood, 1995; Messing & Gänshirt, 1986). To some degree oculomotor training strategies can compensate the sensory deficit (Poppelreuter, 1917; Gassel & Williams, 1963; Meienberg et al., 1981; Zihl, 1981, 1988; Zangemeister et al., 1982, 1995a; Zangemeister & Oechsner, 1996).

Pommerenke and Markowitsch (1989) found that a specific systematic exploration practice through perimetric saccade training improves visuo-spatial orientation in these patients. Furthermore, Zangemeister et al. (1999) investigated the influence of cognitive motor gaze control strategies on the rehabilitation of visual field defects in hemianopic patients and found significant improvement in their visual behavior after taking part in a special cognitive training of gaze control.

A study of Butter et al. (1997) tested visual imagery in hemianopic patients with occipital lesions using special imagery and perceptual control tasks. On the basis of their results, they postulated an impaired visual imagery in these patients because, compared to a control group, they performed worse in the imagery task when perceiving the stimulus ipsilateral to their visual field defect. They concluded that this finding supports the view that visual imagery involves topographically organized visual areas of the occipital lobe (Kosslyn, 1994; Kosslyn & Shin, 1994; Kosslyn et al., 1993; Farah, Peronnet, Gonon, & Girard, 1988; Goldenberg et al., 1989).

Scanpaths in hemianopic patients when compared to normal subjects

In a previous study (Gbadamosi & Zangemeister, 2001), we discovered distinct characteristics of scanpaths in hemianopic patients when compared to normal subjects viewing the same stimuli, suggesting a reduced extent of the image within the cognitive representation. Differential similarity measures demonstrated that the gaze sequences of the picture exploration phase exhibited less (but non random) similarity with each other and a reduced field of view in the hemianopic patients compared to normal subjects. This finding suggested a strong top-down component in picture exploration: in both groups, healthy subjects and hemianopic patients, a mental model of the viewed picture evolved very soon, which substantially determined the eye movements. As hemianopic patients showed analogous results to the normal subjects, we concluded that well-adapted patients have a preserved cognitive representation despite their perceptual defect, which follows the same top down vision strategies in the process of viewing (Gbadamosi & Zangemeister, 2001; Kosslyn et al., 1993; Kosslyn, 1994; Kosslyn & Shin, 1994; Goldenberg et al., 1989).

In an earlier quantitative evaluation of human scanpaths (Zangemeister et al., 1999), we compared eye movements of hemianopic patients with normal subjects' eye movements while viewing abstract and realistic pictures before and after a special training. This training included special advice concerning eye movement strategies as in the present study but also several different settings of training; also, it lasted for 14 and 28 days, respectively, with control recordings after each time span: after the training the viewed pictures were presented again. The correlated scanpaths were divided into *a priori* geometric regions of interest (ROI's) and subjective *a posteriori* ROI's. The evaluation of the scan paths was done using Markov analysis and String-Editing. The results showed, despite long latencies between the time of lesion and the beginning of the training (6-12 months), that our specific rehabilitative training was significantly successful when quantified by probabilistic and sequential measurements of the resulting scanpaths. Especially the comparison of *a priori* and *a posteriori* measurements permitted a differentiation of the training effects more closely.

This result correlated to a *facilitated mobilization of information* of extrastriatal high level information. The visual information was transmitted through a quick fill of the striatal visual buffer within which an *attention window* was located (Kosslyn & Shin, 1994; Taub, 1993), that appeared to be opened (or enlarged) through the training. We took this as an expression of the subjective enlargement of interest through stimulation of the associative cortex. After the training, there was a strong top-down component during the picture-view that alternated with a non-adapted bottom-up component before the training. This demonstrated that it is particularly significant that the cognitive aspect of human vision in a rehabilitation of hemianopic patients has to consider special training methods.

Our results in virtual hemianopic subjects reported here are consistent with these earlier observations: healthy subjects show quite similar oculomotor behavior when confronted with the VHH simulation. This is true for simple pursuit and saccadic stimuli as well as search and scanpath tasks. Therefore, top-down mechanisms and the feature ring hypothesis explain the consistency and convergence of the oculomotor behavior also in normal subjects confronted with the same sensory deficit as homonymous hemianopic patients as well as their similar response to our special training.

CONCLUSION

In previous studies we tried to obtain information about the consistency and reproducibility of internal visual image representations in hemianopic patients in the context of active "high-level-vision" and about the quantitative effect of training in these patients even up to 12 months after the time of lesion. The mental image of the hemianopic patients was found to mirror their visuocortical sensory deficit. Special training evidently helped in this aspect.

In this study we analyzed the degree of adaptation that normal healthy subjects show when suddenly exposed to a virtual complete homonymous hemianopia under different training conditions.

Their saccadic, scan and search path strategies showed the same consistency and reproducibility of internal visual representations as hemianopic patients in the context of active "high-level-vision". Particularly those VHH subjects that where well adapted with the aid of our special training did show this effect using a top-down strategy, when viewing targets and pictures on the side of their blind hemifield. Non-adapted subjects failed to show this effect. They stayed with a bottom-up strategy of viewing targets on the side of their blind hemifield.

We conclude that - in addition to earlier described therapeutic tasks - hemianopic *patients* should use an additional increase in their field defect (described here in healthy subjects) as a "forced use therapy", so that they become faster aware of the increased gaze efficiency when shifting the zero meridian of their visual field towards the side of the BHF.

RÉSUMÉ

Nous rapportons des résultats à propos de mouvements oculaires (MO) de recherche et d'exploration chez des sujets normaux en bonne santé confrontés à une hémianopsie homonyme virtuelle (VHH), comparable au déficit de patients atteints d'une hémianopsie homonyme complète et stable. Nous avons posé trois questions : 1. L'adaptation sensorimotrice intervient-elle chez ces patients avec une hémianopsie virtuelle ? 2. Est-il possible d'augmenter l'effet de cette adaptation avec un entraînement par déplacement de 10° du demi-champ vertical défectueux vers le côté voyant sain (SHH) ? Et 3. Quel est l'amplitude de l'effet additionnel de l'entraînement ? Nous avons utilisé l'oculographie infrarouge à haute résolution afin d'enregistrer les MO chez 16 sujets sains. Huit sujets ("*entraînement précoce*") ont été entraînés pendant 20 minutes avec un décalage de 10° vers le côté sain, et ont été enregistrés juste après. Les huit sujets restants ("*entraînement tardif*") ont subi 20 minutes de vision, *sans entraînement*, et ont été enregistrés juste après. Les sujets sains ont réagi au VHH d'une façon assez similaire aux patients hémianopsiques : l'entraînement à une vision para-fovéale décentrée de 10°, ainsi que des conseils spécifiques afin d'améliorer les stratégies saccadiques ont significativement amélioré l'adaptation des sujets à VHH. Nous concluons de cette étude de l'adaptation au VHH chez des sujets sains qu'on devrait utiliser chez des patients hémi-

anopsiques une augmentation de leur champ défectueux afin de leur faire prendre conscience de l'efficacité augmentée des déplacement du regard (plus rapides et plus précis) lors d'un décalage du point nul vertical de leur champ visuel vers le côté du BHF.

REFERENCES

Brandt, S., Ploner, C., Meyer, B.-U., Leistner, S., & Villringer, A. (1998). Effects of repetitive transcranial magnetic stimulation over dorsolateral prefrontal and posterior parietal cortex on memory-guided saccades. *Experimental Brain Research, 118,* 197-204.

Brandt, S., & Stark, L. W. (1997). Spontaneous eye movements during visual imagery reflect the content of the visual scene. *Journal of Cognitive Neuroscience, 9*, 27-38.

Butter, C. M., Kosslyn, S., Mijovic-Prelec, D., & Riffle, A. (1997). Field-specific deficits in visual imagery following hemianopia due to unilateral occipital infarcts. *Brain, 120,* 217-228.

Chatterjee, A., & Southwood, M. H. (1995). Cortical blindness and visual imagery. *Neurology, 45,* 2189-2195.

Chernyak, D. A., & Stark, L. W. (2001). Top-down guided eye movements. *IEEE Transactions on Systems, Man, and Cybernetics, 31,* 514-522.

Ellis, S. R., & Stark, L. (1978). Eye movements during viewing of Necker cubes. *Perception, 7,* 575-581.

Farah, M., Peronnet, F., Gonon, M. A., & Girard, M. H. (1988). Electrophysiological evidence for a shared representional medium for visual images and visual percepts. *Journal of Experimental Psychology: General, 117,* 248-257.

Farah, M., & Ratcliff, G. (1994). *The neuropsychology of high-level vision. Collected tutorial essays*. London: Blackwell Publ.

Gassel, M. M., & Wiliams, D. (1963). Visual function in patients with homonymous hemianopia. Part 2. Oculomotor mechanisms. *Brain, 86,* 1-36.

Gbadamosi, J., & Zangemeister, W. H. (2001). Visual imagery in hemianopic patients. *Journal of Cognitive Neuroscience, 13,* 45-56.

Goldenberg, G., Poderka, I., Steiner, M., Suess, E., & Deecke, L. (1989). Regional cerebral blood flow patterns in visual imagery. *Neuropsychologia, 27,* 641-664.

Goldenberg, G. (1993). The neural basis of mental imagery. Review. *Baillieres Clinical Neurology, 2,* 265-286.

Hacisalihzade, S. S., Stark, L. W., & Allen, J. S. (1992). Visual perception and sequences of eye movement fixations: A stochastic modeling approach. *IEEE Transactions on Systems, Man, and Cybernetics, 22,* 474-481.

Hier, D. B., Mondlock, J., & Caplan, L. R. (1983). Recovery of behavioural abnormalities after right hemisphere stroke. *Neurology, 33,* 345-350.

Kosslyn, S. M. (1994). *Image and brain*. Cambridge, MA: MIT Press.

Kosslyn, S. M., Alpert, L. M., Thompson, W. L., Maljkovic, V., Weise, S. B., Chabris, C. F., Hamilton, S. E., Rauch, S. L., & Buonanno, F. S. (1993). Visual mental imagery activates topographically organized visual cortex: PET investigations. *Journal of Cognitive Neuroscience, 5,* 263-287.
Kosslyn, S. M., & Shin, L. M. (1994). Visual mental images in the brain: Current issues. In M. Farah & G. Ratcliff (Eds.), *The neuropsychology of high-level vision* (pp. 269-296). London: Blackwell Publ.
Meienberg, O. (1983). Clinical examination of saccadic eye movements in hemianopia. *Neurology, 33,* 1311-1315.
Meienberg, O., Zangemeister, W. H., Hoyt, W. F., & Stark, L. W. (1981). Saccadic eye movement strategies in patients with homonymous hemianopia. *Annals of Neurolology, 9,* 537-544.
Messing, B, & Gänshirt, H. (1986). Spontanverlauf vaskulärer, retrogenikulärer Gesichtsfeldstörungen. *Verhandlungen der Deutschen Gesellschaft für Neurologie, 228-236.*
Noton, D., & Stark, L. W. (1971a). Eye movements and visual perception. *Scientific American, 224,* 34-43.
Noton, D., & Stark, L. W. (1971b). Scanpaths in eye movements during pattern perception. *Science, 171,* 308-311.
Pommerenke, K., & Markowitsch, H. J. (1989). Rehabilitation training of homonymous visual field defects in patients with postgeniculate damage of the visual system. *Restorative Neurology and Neuroscience, 1,* 47-63.
Poppelreuter, W. (1917). *Die psychischen Schädigungen durch Kopfschuß im Kriege Vol. 1: Die Störungen der niederen und höheren Sehleistungen durch Verletzungen des Okzipitalhirns*. Leipzig: Voss.
Rayner, K., & McConkie, G. W. (1976). What guides a reader's eye movements? *Vision Research, 16,* 829-837.
Riddoch, G. (1917). Dissociation in visual perception due to occipital injuries, with special reference to appreciation of movement. *Brain, 40,* 15-57.
Roland, P. E., & Gulyas, B. (1994a). Visual imagery and visual representation. *Trends in Neuroscience, 17,* 281-287.
Roland, P. E. & Gulyas, B. (1994b). Visual representations of scenes and objects: retinotopical or non-retinotopical? *Trends in Neuroscience, 17,* 294-297.
Rossi, P. W., Kheyfets, S., & Reding, M. J. (1990). Fresnel prisms improve visual perception in stroke patients with homonymous hemianopia or unilateral visual neglect. *Neurology, 40,* 1597-1599.
Schoepf, D., & Zangemeister, W. H. (1993). Correlation of coordinated gaze strategies to the status of adaptation in patients with hemianopic visual field defects. *Annals of the New York Academy of Sciences, 682,* 404-409.
Stark, L. W., & Choi, Y. S. (1996). Experimental metaphysics: The scanpath as an epistemological mechanism. In W. H. Zangemeister et al. (Eds.), *Visual attention and cognition* (pp. 3-69). Amsterdam: Elsevier Publishers.
Stark, L. W., & Ellis, S. (1981). Scanpaths revisited: Cognitive models in active looking. In B. Fisher, C., Monty, & M. Sanders (Eds.), *Eye*

movements, cognition and visual perception (pp. 193-226). Hillsdale, NJ: Erlbaum Press.
Stark, L. W., & Privitera, C. (2001). Representation of human vision in the brain: How does human perception recognize images? *Journal of Electronic Imaging, 10,* 123-151.
Taub, E. (1993). Technique to improve chronic motor deficit after stroke. *Archives of Physical Medicine and Rehabilitation, 74,* 347-354.
Teuber, H. L., Battersby, W., & Bender, M. B. (1960). Visual field defects after penetrating missile wounds of the brain. Cambridge, MA: MIT Press.
Treisman, A., & Gelade, G. (1980). A feature integration theory of attention. *Cognitive Psychology, 12,* 97-112
Zangemeister, W. H. (1997). Virtual reality hemianopic scotomas induce eccentric fixation: Scanpath strategies to optimize high level vision in healthy subjects. *IEEE Proceedings of EMBS, 97CH36136EMBS,* 560-565.
Zangemeister, W. H., Canavan, A. G. M., & Hoemberg, V. (1995a). Frontal and parietal transcranial magnetic stimulation (TMS) disturbs programming of saccadic eye movements. *Journal of Neurological Sciences, 133,* 42-52.
Zangemeister, W. H., Dannheim, F., & Kunze, K. (1986). Adaptation of gaze to eccentric fixation in homonymous hemianopia. In E. L. Keller & D. S. Zee (Eds.), *Adaptive processes in visual and oculomotor systems.* London: Pergamon Press.
Zangemeister, W. H., Meienberg, O., Stark, L., & Hoyt, W. F. (1982). Eye-head coordination in homonymous hemianopia. *Journal of Neurology, 225,* 243-254.
Zangemeister, W. H., & Oechsner, U. (1996). Evidence for scanpaths in hemianopic patients shown through string editing methods. In W. H. Zangemeister et al. (Eds.), *Visual attention and cognition* (pp. 197-221). Amsterdam: Elsevier Publishers.
Zangemeister, W. H., & Oechsner, U. (1999). Adaptation to visual field defects with virtual reality scotoma in healthy subjects. In Becker et al. (Eds.), *Current oculomotor research* (pp. 89-95). New York: Plenum Press.
Zangemeister, W. H., Oechsner, U., & Freksa, C. (1995b). Short-term adaptation of eye movements in patients with visual hemifield defects indicates high level control of human scanpath. *Optometry and Visual Sciences, 72,* 467-477.
Zangemeister, W. H., Poppensieker, K., & Hoekendorf, H. (1999). *Cognitive neurovisual rehabilitation using coordinated gaze strategies.* Aachen: Shaker Publ.
Zangemeister, W. H., Sherman, K., & Stark, L. (1995c). Evidence for global Scanpath strategy in viewing abstract compared with realistic images. *Neuropsychologia, 33,* 1009-1025.
Zangemeister W. H., & Stark, L. (1982). Gaze latency: variable interactions of eye and head movements in gaze. *Experimental Neurology, 75,* 389-406
Zeki, S. (1978). Uniformity and diversity of structure and function in rhesus monkey prestriate cortex. *Journal of Physiology (London), 277,* 273-290.

Zeki, S. (1983). The distribution of wavelength and orientation selective cells in different areas of monkey visual cortex. *Proceedings of the Royal Society, London (Biology), 217,* 449-470.
Zeki, S. (1999). *A vision of the brain*. Oxford: Blackwell Scientific Publications.
Zihl, J. (1981). Recovery of visual functions in patients with cerebral blindness: Effect of specific practice with saccadic localization. *Experimental Brain Research, 44*, 159-169.
Zihl, J. (1988). Homonyme Hemianopsie und ihre Rehabilitation. *Kl. Monatsblätter. Augenheilkunde, 192*, 555-558.

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