

“Starkfest” Vision and Clinic Science Special Issue

Short-Term Adaptation of Eye Movements in Patients with Visual Hemifield Defects Indicates High Level Control of Human Scanpath

W. H. ZANGEMEISTER*

U. OECHSNER†

Neurology Department, University of Hamburg, Hamburg, Germany

C. FREKSA‡

Institute of Informatics and Computer Science, University of Hamburg, Hamburg, Germany

ABSTRACT

In continuation of earlier studies, we recorded gaze movements in patients with hemianopic visual field defects primarily due to stroke. Use of high resolution infrared oculography enabled us to record and analyze a variety of tasks including paradigms of visual search, reading, and scanpath eye movements. The tasks were recorded several times in sequential order. Through these sequences, we observed short-term adaptation, i.e., training effects of eye movement strategies to improve the initially deficient result on the side of the blind hemifield with respect to the relative difficulty of the specific task. This quantitative and statistically confirmed finding adds new evidence for the top-down control of the human scanpath even in hemianopic patients.

Key Words: homonymous hemianopia, scanpath eye movement, short-term adaptation, functional rehabilitation of field defect

How do we view pictures and scenes in our environment? Often, the eye movements are guided by catchy, visually interesting or seemingly important points of interest. Our eye may be guided directly to this spot of a picture by its special design, which reflects the arrangement of contrasts, borderlines, colors, depth, and special subfeatures, especially with respect to the primary region of interest (ROI). This type of viewing strategy would resemble a bottom-up control of viewing, where no cognitive model of the picture (i.e., perceptual hypothesis which has to be

tested against sensory experience) is present and the eyes' movements and fixations are controlled by the features of the image.

Or we, that is “our mind's eye,” might look around following an implicit cognitive plan that guides us from here to there, and eventually to the destination we were originally looking for, or were somewhat anticipating: i.e., “we had the final target in mind.” This resembles a search-path that applies to the so called top-down control^{1, 2} of viewing, where the eyes' movements and fixations are driven by a cognitive model of the picture. In general, we apply a similar pattern of visual control when we read and scan pictures or scenes, which we then could call a reading-path and scan-path, respectively.¹⁻⁵

Multi-item boundary and surface groupings influence visual search. They may indeed represent the perceptual components upon which the search process is based. The identification of a grouping that includes multiple items speeds the search process by reducing the total number of candidate visual regions that have to be investigated serially. Factors which influence boundary and surface grouping, such as featural contrast, item spacing, and spatial arrangement, alter the number of visual regions to be explored, yielding variations in search time.

If bottom-up mechanisms drive the formation of these emergent perceptual units, then limits must exist on the capacity of semantic or even visual definitions of target items to exert top-down influence over preattentive grouping mechanisms. The ability of bottom-up processing to distinguish ecological objects accurately depends on a certain amount of autonomy or resistance to top-down interference. Otherwise, it would routinely result in perceptual illusions. Of course, perceptual grouping indeed will often be guided by top-down process.⁵⁻⁷ However, some groupings

Presented at the Berkeley “Starkfest” Meeting, Berkeley, California, June, 1994.

Received April 18, 1995.

* M.D., Member of Faculty.

† M.Sc., Physicist.

‡ Ph.D., Member of Faculty.

may "emerge" from the structure of the scene input without the help of top-down influences.

Of course, the enforced bottom-up control of viewing is the primary domain of our everyday modern life through movies, TV, and visual public relation in particular. We learn and we apply these different kinds of top-down control of viewing during our whole life. However, *diseases* of the eyes, the optical pathways, the visual or motor cortex, and its interconnections may cause at least one of the three parts of this control to become disturbed: the sensory, the cognitive, or the motor connection that contributes to the proper functioning of these higher levels of visual control.

In the case of deficiencies in at least one of these three functional parts, there is a need to recover from the given deficit, which may be feasible through certain strategies of adaptation.

The typical, most frequent deficits that can be found clinically and may be simulated experimentally are the following.

1. Motor deficits of one or both eyes involving coordinated eye movements that may cause diplopia as well as slowness and inaccuracy of eye movement and fixation. They can be overcome comparatively easily by moving only the healthy eye and neglecting, i.e., suppressing, the information of the eye with the movement deficits, or by helping interocular deficits through adaptive eye and head coordination, as found in internuclear ophthalmoplegia.
2. More importantly, sensory deficits may disturb top-down control of vision by producing visual field defects of one eye, or both eyes in the case of more centrally located disturbances such as found in homonymous hemianopia (HH).
3. Most variant difficulties and therefore a whole variety of adaptive strategies may occur with deficits of visual attention and cognition, like visual apraxia and hemineglect.

We put forward the following question: What kind of adaptation may occur in a comparatively simple case, i.e., with a typical sensory visual deficit such as HH, where the site of the lesion lies "more peripheral" compared to the above noted higher visual functions?

When looking at the variant adaptive strategies that may be obtained, one has to consider the basic distinction between movements of the eyes only⁸ without any head or body movement and, on the other hand, coordinated eye and head movements in coordinated gaze.⁹⁻¹³ This distinction is practically important, because the head as the moving platform of the eyes may be used differentially to increase the effective viewing angle for large objects of interest, like in large screen movies, searching around in natural environments, or reading of large scale advertisements.

It is theoretically important because strategies may be different in the case of a retinal frame of reference with a fixed head, as compared to a head frame of reference. Often, the latter may be

identical with the body frame of reference equalizing position of gaze in space, as in the case of a pilot or car driver. Here, functional processing of coordinated gaze may be more flexible¹⁴ and therefore more efficient in terms of sophisticated performance; it may be, however, less efficient in terms of time, i.e., take much longer than the 250 ms of a typical saccade plus saccadic latency.^{15, 16}

Here, we shall report solely various adaptive strategies of high level controlled eye movements, when the head and body are fixed.

METHODS

During the last 3 years we observed and recorded eye movements from patients with various visual field defects, the most important of which consisted of HH. After checking the basic eye movement dynamics, we looked at the searchpath and scanpath eye movements in response to specific tasks. These included horizontal and diagonal searching of targets in pictures, the position of which was changed randomly on a large TV screen; they also included scanpath recordings of viewings of abstract pictures of contemporary famous artists like Ken Noland, and one of the three colored Rorschach pictures to test for symmetry perception. As a kind of intermediate test that included both qualities of a searchpath and of a scanpath, we used ambiguous figures to test the ability to search for and scan two or three possible interpretations. Patients were also tested for reading capabilities without and with using free head movements, which has been published in part previously.^{17, 18}

Subjects

We compared a group of normal healthy and full sighted subjects ($N = 10$) (median age 35 ± 6 years) with a group of patients ($N = 10$) (median age 52 ± 7 years) that had suffered a stroke of the posterior cerebral artery of one side resulting in a pure HH that was distinguished from hemineglect through a sequence of neuropsychological tests (Rivermead¹⁹). Visual hemifield defects with and without foveal sparing were quantified through high resolution computer perimetry (Octopus). Extension of the anatomical defect was quantified through cranial CT or MRT. Only patients with strokes older than 3 months were tested, and this precondition permitted us to discard effects of spontaneous recovery from HH. All subjects had normal vision or corrected visual acuity and had no difficulty in adjusting to the apparatus.

Recording of Eye Movements

Measurement techniques for recording eye movements and eye blinks have been well described.^{15, 20} Eye movements were measured using an infrared system (ASL210) that provided measurements of horizontal movements with a resolution of 0.05° over a range of $\pm 20^\circ$ and of

vertical measurements with a resolution of 0.1° over a range of $\pm 10^\circ$ and also permitted detection of eyelid blinks. A calibration process, which assumed a nonlinear (polynomial) relation between the eye movements and the output of the ASL210 did ensure linearity over this range. Overall system bandwidth was 0 to 100 Hz.

Low Level Visual Stimuli

A white cross on a dark background which was predictively alternating with an amplitude of 5° to 30° was used as the target for the measurement of saccadic time functions and main sequences²¹ (i.e., the saccade peak velocity/amplitude relation). The vertical and horizontal size of the target was 1° .

Higher Level Visual Stimuli

Six pictures ranging from nonrealistic search pictures to ambiguous pictures to more artful realistic and abstract pictures were chosen. The artful color pictures were by Lane Terry, "Dead-eye," 1971 and Ken Noland, "Spring Cool," 1962. We also used a picture of the Necker Cube, a trivalent picture (i.e., an ambiguous picture with three possible interpretations, from Stark and Ellis²), the largest of the three colored Rorschach pictures, and the above noted diagonal and horizontal search sub-picture (see Fig. 2).

Experimental Procedure

Subjects were seated comfortably in a ground-fixed dental chair that allowed complete immobilization of the head through a tight head band and chin fixation firmly linked to the chair.

Protocol

Of importance were the different tasks defined by explicit instructions to our cooperative subjects.

The basic task was to look carefully at the pictures to be able to remember the pictures and recall their specific features. Afterward the subject had to describe the picture content and provide some details on request. The subjects were unaware that their eye movements were being recorded, as they believed their pupil size and blink frequency were being measured. To create even more stable experimental conditions, the subjects received written instructions informing them about their task. Shortly after the run of the last group of pictures, an additional run was appended in which the patients had to imagine the pictures they just saw in the same sequence and within the same time. This provided us with some new data on imagined scanpaths in hemianopic patients.

Calibration runs were then performed to assure that eye movement and blink recordings were accurate. Presentations of the pictures were timed for 10 s with a 1-min rest period between

presentation groups. Six different pictures made up a presentation group. A short rest period of 10 s was requested between each picture within one presentation group. With a calibration run before and afterward, and with intervening rest periods, the entire duration of the experiment was approximately 35 min.

Presentation of pictures was done on a large screen VDT (21-in diagonal). They were viewed with high resolution under photopic vision. The screen was relatively large such that relatively large sized eye movements would be necessary to cover the material on the screen with a vertical and horizontal visual angle of 15° in each direction for the presented pictures. Room lighting was dim so as to focus the subject's attention on the screen.

Data Acquisition Analysis of the Data

A number of menu-driven software programs operating both in an on-line and a follow-up mode were used. These presented the sequence of eye movements with saccades between fixation points. As is well-known in the literature,²⁰⁻²³ saccadic eye movements often do not have a straight trajectory. We thus created a simplified presentation made of "interfixational vectors" that is a straight line vector going from one fixation point to the next. It is generally considered in studies of visual physiology that information of high resolution is not acquired to any great extent during the rapid saccadic eye movement. Therefore, for the present tasks, the exact path of the saccades is not important in itself; however, the location of each fixation lasting approximately 200 to 500 ms as well as the sequences of these fixations, was important. The analyzing software also counted the number of saccades in each of the fixed, 10 s picture presentations. Average fixation duration, which is inversely related to the number of saccades, was also calculated. Distributions of fixational durations were also plotted.

Graphic displays were obtained which included interfixational vectors of eye movements and superimposed sequentially numbered fixations on the visual scene.

Eye blinks, which appeared in the original data as very rapid oblique jumps of the trace, have been removed by computer editing.

Global/Local Ratio

A particular pattern of eye movements occurred which differed according to the relative percentage of time the eye movements spent in making either a global scan or a local scan, using smaller eye movements in a particular region. We determined the ratio of global vs. local viewing for each subject in each presentation from the statistics of saccadic sizes. The boundary between local and global eye movements was assumed to be 1° ; that is, eye movements of the order of 1° of amplitude

or less were considered local eye movements, whereas eye movements greater than 1.6° were considered global eye movements. If one changes this boundary from 1.6° to 4.6° , 7.9° , and 11° , so that the definition of local becomes larger and larger, any discrimination provided by the global/local (g/l) ratio disappears.^{3, 4}

The statistical evaluation of differences between early and late presentations, pictures, and conditions involved a nonparametric analysis of variance (ANOVA).²⁴ It was performed using the ANOVA software BMDP2, UC California, Los Angeles, ANOVA and covariance with repeated measures, program version 1987.

Scanpath Evaluation

For identification of short- or long-term adaptation effects it is necessary to record and compare the eye movements of a subject who is repeatedly viewing the same scene. For qualitative purposes this comparison can be done by visual inspection of the recorded eye movement traces. To obtain objective results which do not depend on the subjective observer, however, it is necessary to use a quantitative method.

For quantification of the term "similarity of eye movements" Markov matrices and string editing have been used previously.²⁵⁻²⁸ Both methods are applied to preprocessed eye movement data. The first step consists of defining ROI in the image under study. Each region is then labeled by a letter. Possible ROI in the image of a face are the eyes, the nose, the mouth, the ears, etc. The second step is the determination of the location of the subject's fixations while viewing the image. Here an area-velocity-time criterion is used; it is assumed that a fixation took place if the subject's gaze velocity, v , was slower than $5^\circ/\text{s}$ and did not leave a circular area with radius, r (1°), for at least a time of t (0.2 s). Then the center of the corresponding eye movements is taken as the position of the subject's fixation. In a third step these points of fixation are sequentially numbered and linked through sequential interfixational vectors that lead to one or several search or scanpaths, depending upon the time that the subject was allowed to spend for a single task (normally 10 s). In the fourth step, using the defined ROI, the two-dimensional fixation-saccade sequence is then reduced to a one-dimensional sequence of letters; if successive fixations are located in the ROI "C," "D," "C," and "A," the resulting sequence of letters is "CDCA." Thus the task of comparing the eye movements of a subject while repeatedly viewing an image is reduced to the comparison of such strings. See the paper by Choi et al. in this issue for details.

The use of string editing to measure the similarity of strings was first developed in the context of algorithms for spelling correction.^{25, 27} If a certain word is not found in the program's dictio-

nary, similar words shall be searched and proposed as correct spellings. The distance of two words is defined as the minimum number of editing operations like deletion, insertion, and substitution of a letter, which is necessary to transform one word into the other. Thus between "brown" and "town" the distance is 2 (deletion of b, substitution r- > t), between "house" and "mouse" it is 1 (substitution h- > m).

Transition probabilities between N states can be described by second order $N \times N$ Markov matrices.^{26, 28} The element (i, j) is the probability of state j following state i . Applied to the comparison of strings, each letter defines a state and, e.g., the letter D following after the letter H is understood as a transition from state D to state H. As an example consider four ROI labeled by the letters A to D and a fixation sequence represented by the string CDBCADB. In this string B always follows D (the probability is 1), but D follows both C and A (the probability is $\frac{1}{2}$ for each transition). To measure the difference between repeated image viewings with the help of Markov matrices, the transition probabilities of all letter combinations are computed for each viewing. The difference between the fixation strings is then defined as the mean difference of the transition probabilities.

Although obtaining differences in fixation sequences with Markov matrices of the second order only takes into account transitions between two ROI, string editing is better adapted to the sequential character of the fixations. Furthermore, with string editing there are more possibilities for further developments (the use of Markov matrices of higher order is also possible but consumes much computation time). Up to now, it is usual to define different "costs" for the operation's deletion, insertion, and substitution. Thus, e.g., it is possible to assign a higher cost to substitution of a letter than to deletion or insertion. Other possible lines of development are context sensitivity ("it is more expensive to delete B in ABA than to delete B in CBC") and subgroup sensitivity ("in GHAKKDFAGHAKK there are the substrings DFA, GHA, and KK").

Because of the subjectively defined ROI, both string editing and the use of Markov matrices are not completely objective methods. However, in comparison to a completely subjective visual inspection of the eye movements, they both result in a quantitative measure of the similarity between eye movements. Thus, the experimental results, adaptation effects, and strategies may be tested statistically, and the success of a neuropsychological therapy can be verified.

RESULTS

Saccadic Time Functions and Main Sequences

Original recordings of responses of hemianopic patients to low level visual stimuli, i.e., a predic-

tively alternating target of 5 to 30 in amplitude demonstrate the characteristic eye movement pattern.^{8,10} Initial stairsteps of small saccades toward the blind hemifield were followed after two to four repetitions by overshooting saccades (Fig. 1A). These show sometimes fast glissades that move the fovea effectively backward onto targets, and occur with increasing frequency when the hemianopic subject has gone through many repetitions of predictive target presentations. An early example of this is marked in Fig. 1A.

Comparison of main sequences²¹ (i.e., the saccade peak velocity/amplitude relation) of these saccades with a large group of normal saccades demonstrated that duration and dynamics of these saccades lie within the normal standard deviation (Fig. 1B).

One way that global/local patterning could be ascertained was in terms of probability density of saccadic amplitude. Plots of probability density of eye movement size and of fixation duration have been calculated for each picture (Fig. 1C). Fixation durations did not discriminate between normal and hemianopic responses. However, size histograms showed highly peaked, exponential monotonic distributions for patients indicating large numbers of small saccades (which mostly occurred in the gaze direction to the blind hemifield), i.e., a small global/local index. Conversely, histograms of the eye movement size of normal healthy subjects showed a wider distribution with peaks at mid-sized saccades and reliance on larger saccades to overview the pictures, i.e., a large g/l index.

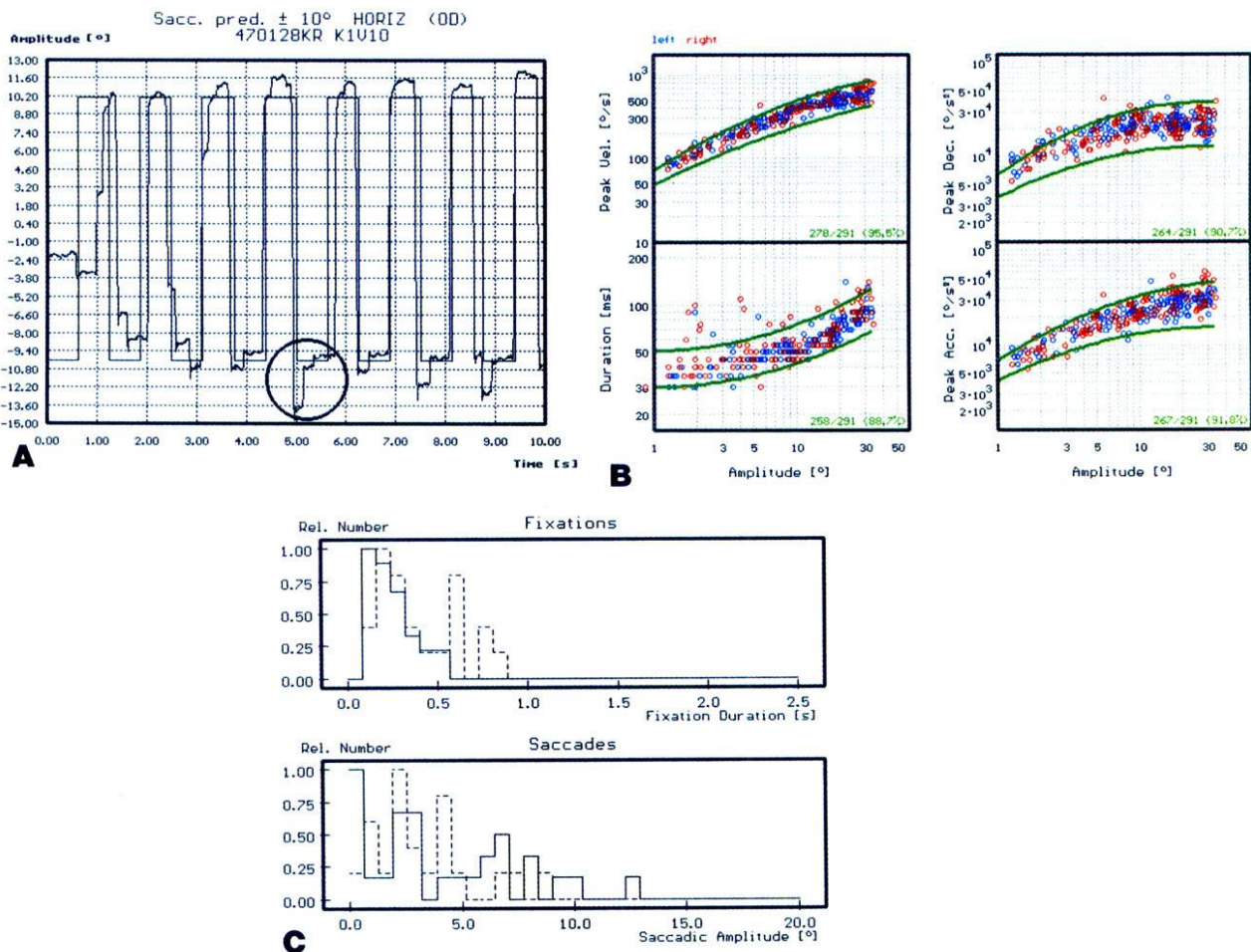


Figure 1. A: staircase pattern of saccades toward the blind hemifield (down) with time (s) on abscissa and amplitude (deg) on ordinate, showing eye movements superimposed on a predictive step stimulus. Note the hypometric staircase saccades at the beginning and fast adaptation to this simple and anticipated stimulus within three repetitions with static overshooting or hypermetric saccades thereafter. The circle marks an early example for overshoot and successive fast glissades backward to the target. B: main sequence double logarithmic plots of a typical patient's saccades (red = to right = blind hemifield; blue = left = seeing hemifield). Green lines enclose the 95% confidence limit of our normal data base (N = 40). Abscissas amplitude (deg), ordinates from left clockwise: peak velocity of saccade, peak deceleration, peak acceleration, and duration. Note that the saccadic dynamics are within the normal range. C: probability density curves of a normal subject's fixation durations and saccadic amplitudes during the scanpath (dashed lines) and of a hemianopic patient (solid lines). Note the relative high incidence of small saccades and shorter fixation durations in the patient. The ratio of global ($>1^\circ$) and local ($\leq 1^\circ$) saccades is 3.8 for the patient and 20.0 for the normal subject.

Visual Search Tasks (Figs. 2 to 4)

The search for a very small object on the hemianopic side of the patients was initially performed by a sequence of many small saccades that often erroneously clustered around the wrong side of the horizon (Fig. 2A), whereas to the seeing hemifield, they resembled a normal pattern (Fig. 2B). After 10 repetitions on the hemianopic side, the sequence of saccades in search of this small target became almost normal (Fig. 2C) and mirrored the searchpath for targets in the seeing hemifield.

Markov as well as string editing analyses demonstrate here (as in most other hemianopic cases) a significant difference ($p < 0.01$) between the 1st and 10th response pattern. This suggests a very efficient short-term adaptation and optimization of the search paths in these patients.

With other visual stimuli, we could obtain very similar behaviors. When looking for the "symmetry" of one of the three colored Rorschach pictures (Fig. 3), in spite of this very specific task, the patients did not look toward the part of the picture that fell into the blind hemifield. After addi-

tional repetitions, however, they changed their behavior to a more symmetrical searchpath, so they were able to compare the symmetries of the picture. Note that our patients were extensively tested for and did not show any signs of visual neglect. Again string editing, Markov analyses, and statistics demonstrated significant differences and optimization in terms of time between first and last trial ($p > 0.01$ in all cases).

When the patients viewed a more realistic picture (Fig. 4), again they tended not to look at that part of the picture that fell within their blind hemifield. After some repetitions, however, they started to view the picture more symmetrically, which difference was again significant ($p < 0.01$).

In Fig. 5, A and B, four examples of an enlarged view of eye movements during fixation are depicted of a sequence of eye movements of 0.1° to 1° . It appears that these sequences of small eye movements were also divided with respect to the blind hemifield, such that most clustered around that part of the picture item that lies within the seeing hemifield. This is demonstrated for Fig. 3

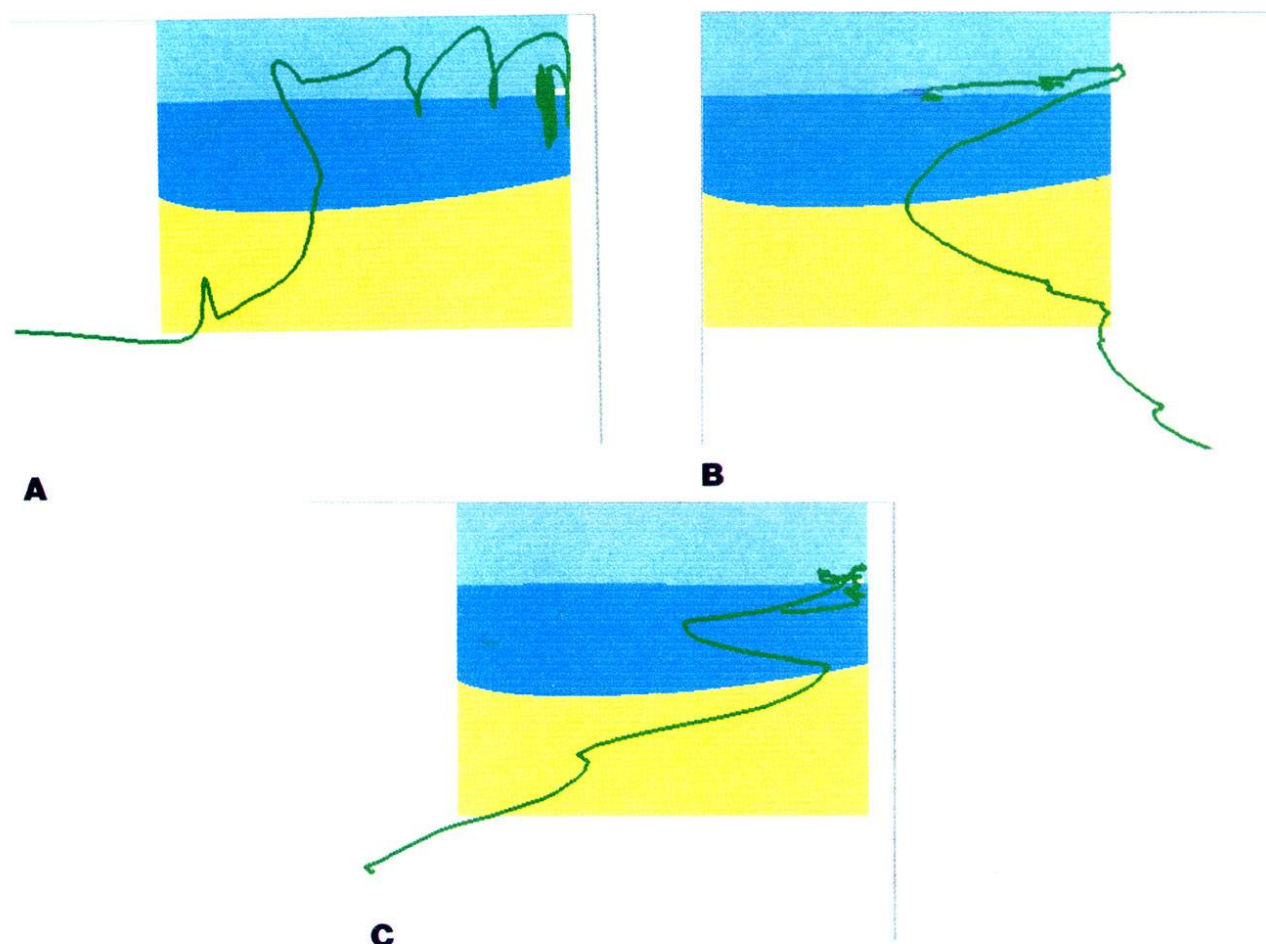


Figure 2. Search pattern of eye movements when viewing a test stimulus with the target on the small dark target on the horizontal line on the right (side of the blind hemifield) and on the left (side of the seeing hemifield). A: first presentation on the blind side; B: first presentation on the seeing side; and C: 10th presentation on the blind side (presentation duration: 3 s, the pictures show about a $\frac{1}{3}$ of the screen). Note: the search path to right (= blind hemifield side) after the 10th presentation resembles the searchpath to the left (= seeing hemifield side), i.e., shows short-time adaptation.

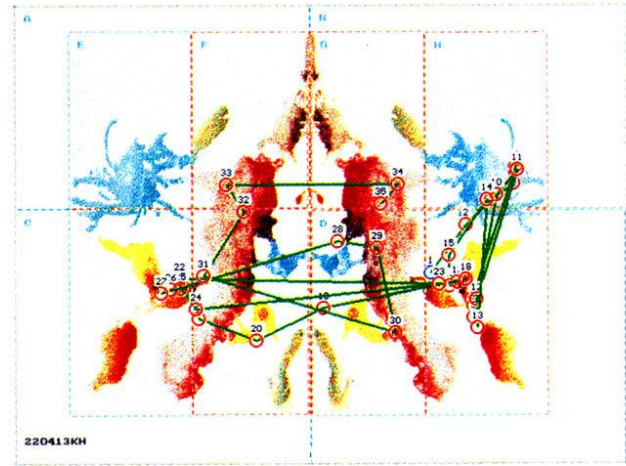
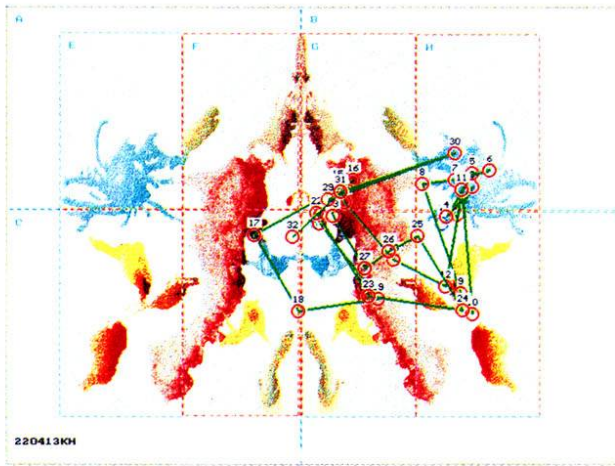


Figure 3. Patient with hemianopia to left viewing the colored Rorschach picture for 10 s: left = first, right = sixth presentation. Fixations, which were defined by combined time/area/velocity criteria (the eye movements do not leave a circular area with radius 1° for at least 200 ms, velocity $<5^\circ/\text{s}$), are encircled. Eye movements are abstracted with lines connecting successive fixations that are also numbered.

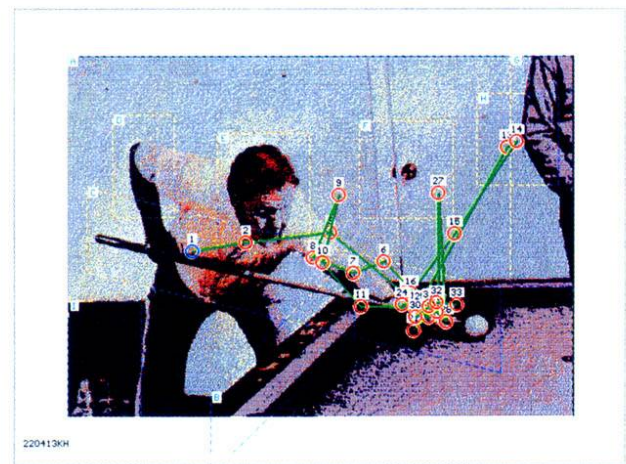
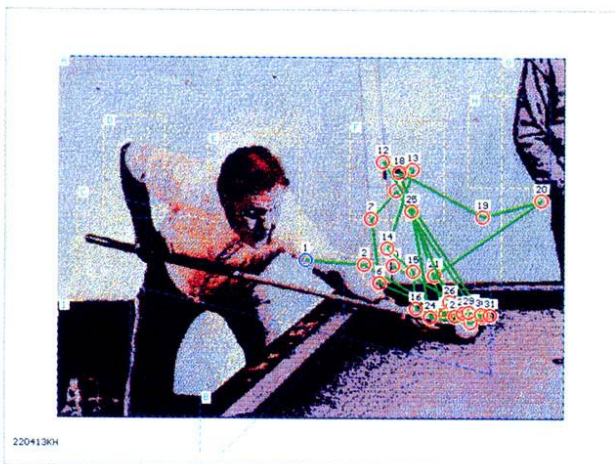


Figure 4. Patient with hemianopia to left viewing a realistic picture. Same explanations as in Fig. 3.

(Rorschach) and 4 (Pool Player) by the skewed distribution of eye movements as shown in Fig. 5C. The tail of the curve resembles the small successive saccades toward the blind hemifield; the skewed peak of the curve reflects the higher probability of medium sized or larger saccades toward the seeing hemifield. So far we have seen the effect only in patients with macular splitting ($N = 5$).

Nachmias³⁰ found directional nonuniform distributed saccadic and drift motions, where drift and saccadic motion were opposed to each other. Different subjects showed characteristic directional preferences. Gaarder³¹ found that the average saccade of a normal subject fixating one corner of an irregular stimulus pattern was directed away from the pattern. It is beyond the scope of this paper to decide if such an asymmetric visual field stimulation causes the asymmetrically distributed miniature eye movements or if it is the manifestation of an asymmetric microscanpath in hemianopic patients.

The global/local ratios of search and scanpath saccades of the HH patients when looking toward

the their blind hemifield side were generally low and high when looking toward their seeing hemifield. The positive finding for normal healthy subjects, i.e., more global scans, and the negative finding for patients looking toward their blind hemifield, i.e., less global scans, was not only determined for the first viewing tasks but also for the last viewing tasks, as shown by the overall high g/l ratios of healthy as compared to the low g/l ratios of hemianopic patients. Statistical evaluation demonstrated this size effect seen in the probability functions to be significant, i.e., the comparison of the most often occurring saccadic amplitudes of the two groups showed a significant ($p < 0.001$, Wilcoxon nonparametric test²⁴) difference.

DISCUSSION

Basic Findings

Patients with hemianopic field defects exhibited an ocular motor strategy of sequences of eye fixations similar to healthy subjects, i.e., scan and searchpath eye movements, in complex visual

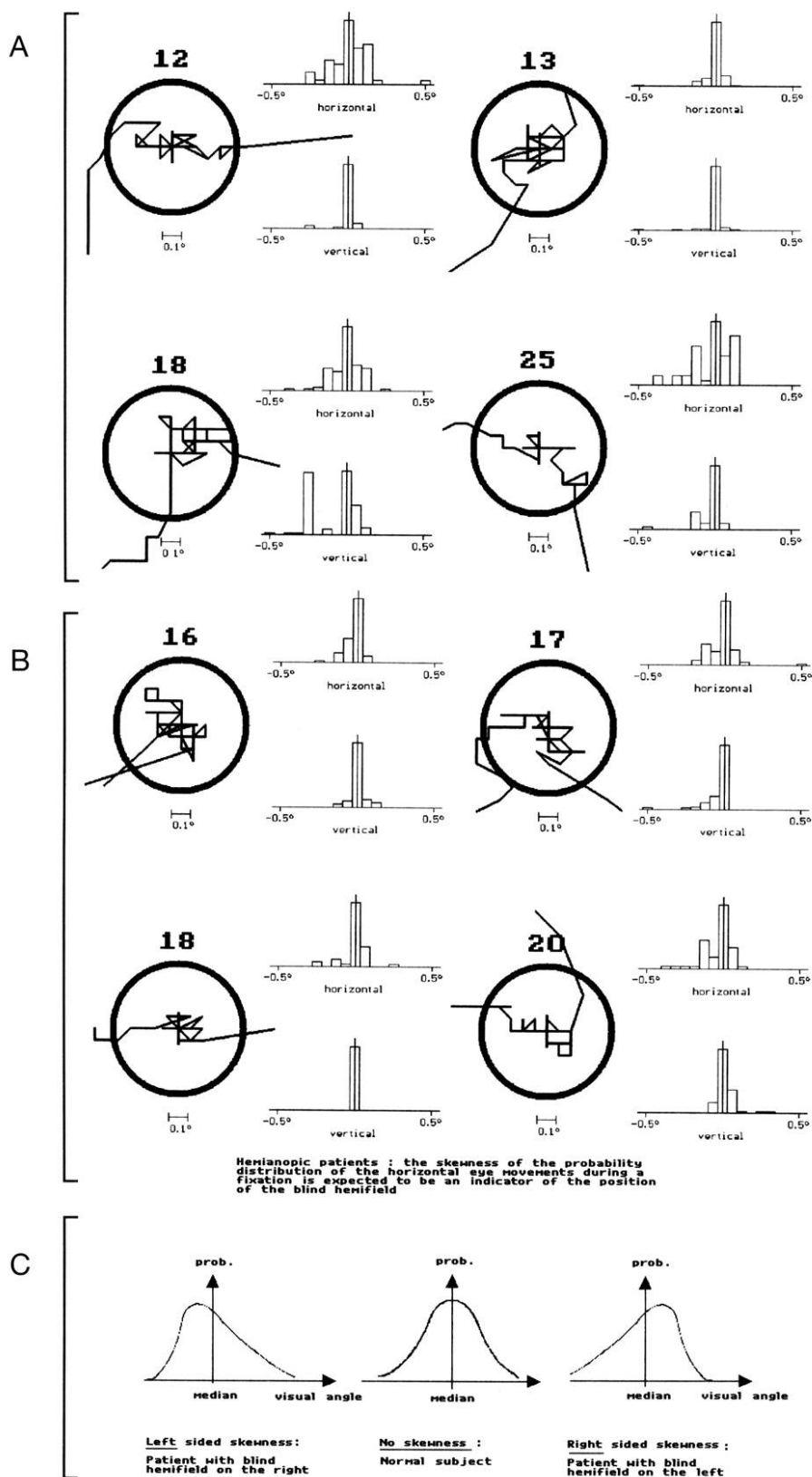


Figure 5. A: patient from Fig. 3, left: four selected and numbered fixations with high resolution recording of miniature eye movements within the fixational area of $\pm 1^\circ$ (left). On the right the statistical distribution of these movements, showing a "tail" in the blind hemifield, and a "skewness" toward the seeing hemifield. This suggests that most movements are made within the seeing hemifield. B: patient from Fig. 4, left: four selected and numbered fixations with high resolution recording of miniature eye movements within the fixational area of $\pm 1^\circ$ (left). On the right the statistical distribution of these movements, showing a tail in the blind hemifield, and a skewness toward the seeing hemifield. C: explanatory statistical figure, showing the above mentioned skewness of miniature eye movements with respect to the seeing hemifield in comparison to a normal symmetrical distribution of these intrafixational eye movements.

tasks. They also used short-term adaptation of their ocular motor strategy to overcome in a more optimal manner their hemifield blindness.

The goal of this study was to compare exploratory eye movement strategies when looking at

realistic, nonrealistic, and ambiguous pictures of a simple and complex structure and content between normal healthy subjects and HH patients with several repetitions. Eye movement recordings documented that scanpaths, i.e., repetitive

sequences of saccadic eye movements having a sensory-motor-perceptual basis, occurred when they viewed such scenes. Global/local indices, string editing, and Markov weighted measures of eye movement patterns were obtained by computer processing. These showed reduced local scanning by healthy normal viewers who relied on more global viewing, particularly in ambiguous and nonrealistic pictures. HH patients did not show this difference; they exhibited their local scanpath patterns throughout the whole sequence of visual stimuli, particularly when they shifted gaze to the side of their blind hemifield.

This suggests four conclusions. First, patients view pictures using the same top-down perceptual-cognitive processes that drive active looking or scanpaths in viewing ordinary realistic images, scenes, and objects. Second, patients use primarily a low level strategy that implies more local scanning and probably a bottom-up type of control, particularly with respect to their blind hemifield. Third, patients as well as normal healthy subjects are able to improve their search and scanning performance within a short time during several alternating repetitions of different tasks: they change from a bottom-up to a top-down type of control to optimize the outcome of their search and scanning tasks. And, fourth, patients demonstrate more difficulties to perceive complex and ambiguous or nonrealistic images.

Cognitive Models Control Active Viewing of Realistic, Ambiguous, and Nonrealistic Pictures in Hemianopic Patients

One main result of these experiments is that eye movement patterns of patients scanning complex images are similar to those of normal healthy subjects. Therefore, it can be concluded that both subjects and patients use a similar top-down approach to optimize their search and scan of pictures that were originally unknown and during the actual task sequences became more familiar. They viewed via a similar active perceptual process, using cognitive schemas to drive their scanpath.

Similar to Helmholtz,³¹ Yarbus³² also believed in a high level "outflow" guidance of eye movements controlled through the viewer's mental image. Both Helmholtz and Yarbus suggested that changing the instructions given to their subjects altered their pattern of viewing.

The repetitive nature of the eye movement patterns for a subject continually viewing a picture was explained by Noton and Stark¹ as a consequence of their "scanpath theory," in which eye movements are cognitively driven through an eye movement scanpath by a perceptual sensory and motor representation, to check if the picture agrees with what the observer imagines the object/scene really is. This representation was related to the "schematic diagram" of Hochberg.³³

Noton and Stark used more realistic art, namely a figure of Klee's, whereas Stark and Ellis² used realistic art and ambiguous figures to provide further evidence that cognitive models, i.e., perceptual hypotheses, rather than peripheral vision, control the scanpath for active-looking perceptual processes. Brandt and Stark³⁴ compared sequences of eye movements of subjects looking at a real visual stimulus and afterward at its remembered mental image. Using string edit analyses,²⁸ they were able to provide firm evidence for scanpath sequences of their subjects' eye movements in both conditions. Groner et al.³⁵ have recently proposed that global scanpaths adhere to the Noton-Stark proposal, whereas smaller intermixed local scanpaths may be controlled peripherally.

Global vs. Local Scanning

Because the underlying hypothesis for the scanpath theory is that an internalized cognitive model drives the eye movements, then from this observational evidence we inferred that in our experiments such models drive the eye movement patterns similarly for both healthy and patient subjects searching and scanning realistic, ambiguous, and abstract pictures. Therefore the cognitive model should guide the eye movements in every condition, i.e., scanpath eye movements should occur also in searching and scanning toward the side of the blind hemifield.

Indeed, a particular pattern of eye movements occurred according to the relative percentage of time the eye movements spent in making a global scan vs. a local scan, using smaller eye movements in a particular region, depending if the subjects looked to the seeing or to the blind side of their hemifield. These observations were confirmed by the evaluation of the *g/l* ratio of each subject for each picture and task. A clearcut difference was also demonstrated in the much higher *g/l* ratio of healthy as compared to the patient viewers when looking at abstract images, especially in the search task.

Increased Local Scanning for Patients as Compared to Healthy Subjects

A second important result is the relatively high frequency of local scanning when patients viewed the complex visual test stimuli. Evidently, global viewing is the preferred strategy for the healthy subject that tries to evaluate both at the same time, the visual content and the complexity of the picture. The patients, however, were busier developing a more optimal sequence of eye movements to detect the overall features of the picture when searching or scanning, because they primarily had to rely on more local and therefore limited picture evaluations that also included more bottom-up control than in the healthy subjects.

What is local scanning? Although Noton and Stark¹ and Stark and Ellis² showed that peripheral information can be excluded as the immediate control for the scanpath, their results also relate to local scanpaths. Groner et al.³⁵ and also Finke and Pinker³⁶ support their top-down, cognitive model scanpath theory for a global scanpath, but argue in favor of an immediate peripheral bottom-up control of local scanning as Grossberg^{6, 7} does, although evidence for the latter is not conclusive at the present time. Although interesting, it is beyond the scope of the present paper to provide conclusive evidence of a mini- or micro-search/scanpath as a special case of a local scanpath in hemianopic patients.

Jeannerod et al.³⁷ have argued for an exchange between local and global scanning in free exploration, as in the Rorschach task. Evidently, the normal healthy viewer avoids this type of immediate bottom-up control in favor of the top-down controlled global scanpath, whereas the patient when viewing to the side of the blind hemifield relies strongly on such an exchange, which permits him to develop a more efficient strategy of searching and scanning with almost every repetition. This change with repetition is gradual and progressive in patients, whereas we would expect it to be a brisk change (switch) in normal subjects with a digitally simulated hemianopic field defect.

In a previous study,^{3, 5} our paradigms for viewing realistic and nonrealistic images probably enforced this ability that was not present in the patient viewers. There, the naive subjects had equal g/l ratios for both realistic and abstract images. These ratios were similar to those of sophisticated subjects viewing realistic images. Whether the local scanpath is driven immediately by peripheral, bottom-up information or by small-scale cognitive models remains unknown. Locher and Nodine³⁸ claimed immediate bottom-up control in symmetry "that catches the eye"; Mackworth and Morandi³⁹ showed evidence for top-down active selection of informative details through active gaze. In any case, this detailed looking is apparently usual for realistic images, where anticipation of details may be balanced by a permanent exchange of bottom-up and top-down control. The patients carry this behavior to the ambiguous and nonrealistic images. They use a more bottom-up-like strategy when they first view pictures that extend also in their blind hemifield, which has also been described by Zihl and Wohlfast-Englert.⁴⁰ Only after many repetitions do they apply a more top-down-like strategy that mirrors the one they use primarily when looking toward their seeing hemifield.

Realistic vs. Nonrealistic and Ambiguous Pictures

Healthy subjects demonstrated more global scanning of the ambiguous and nonrealistic im-

ages than they showed for their scanning of the realistic images, as was expected from earlier results.^{3, 4} These differences showed up not only in the significantly increased g/l ratios, but also directly in the scanpath patterns of the eye movements when fixation frequency, duration, and interfixational saccadic amplitudes were compared. HH patients, however, first showed sequences of small amplitude fixational saccades as a local scanpath in both visual hemifields: i.e., they searched for some primarily relevant detail by use of which they could then generate a global scanpath. During this phase, their sequences of eye fixations appeared to be bottom-up influenced. Only after several repetitions were they able to change to the more efficient global scanpath while perceiving the different faces of the ambiguous figure, preferably on the side of the seeing hemifield, and rarely also on the side of the blind hemifield.

Conclusions: Evidences for Top-Down Control and Future Lines of Work

Our study shows that it is feasible and quantifiable to observe short-term adaptation as an effect of short-term training in patients with hemianopic field defects who apply and optimize a high level, top-down visuo-motor strategy to search and scan for targets and sequences of targets in complex visual tasks.

Evidence for top-down vs. bottom-up control from our study is given with respect to: first, seeing vs. blind hemifield: the paradox that top-down cognitive models prevail when we see (seeing hemifield), whereas local (stair-)steps of bottom-up control prevail when we are blind (blind hemifield); second, we find a strategy improvement with repetition; third, the "complexity" of the picture (Berlyne^{41, 42}) influences the control of eye movement sequences of fixations; fourth, the task influence can induce more global top-down control; and, fifth, the size of the region that is viewed (ROI) highly influences the type of control that is applied: global vs. local scanpath.

Future studies should try to simulate digitally a hemianopic field defect through the experimental set-up using healthy subjects. Finally it should be possible to set up a neural network model that simulates the short-term adaptation that we have found in our patients.

ACKNOWLEDGMENT

We thank Prof. L. Stark, UC Berkeley, for his very helpful discussions. We are grateful to the Homann Foundation, Hamburg. Finally, we thank Dieter Schoepf and Steffen Egner for their critical advice.

REFERENCES

1. Norton D, Stark L. Scanpaths in eye movements during pattern perception. *Science* 1971;171:308-11.
2. Stark L, Ellis S. Scanpaths revisited: cognitive models direct active looking. In: Fisher DF, Monty RA, Senders JW, eds.

- Eye Movements, Cognition and Visual Perception. New Jersey: Erlbaum Press, 1981:193–226.
3. Zangemeister WH, Sherman K, Stark L. Eye movements and abstract images. In: Schmid R, Zanbarbieri D, eds. ECEM5. Pavia: University of Pavia Press, 1989:165–72.
 4. Stark LW, Yamashita I, Tharp G, Ngo HX. Search patterns and searchpaths in human visual search. In: Brogan D, Gale A, Carr K, eds. Visual Search: Proceedings of the Second International Conference on Visual Search. London: Taylor & Francis, 1992:37–58.
 5. Zangemeister WH, Sherman K, Stark L. Looking at abstract and realistic pictures: evidence for global Scanpath strategy in abstract pictures. *Neuropsychologia* 1995.
 6. Allman J, Miezin F, McGuinness E. Stimulus specific responses from beyond the classical receptive field: neurophysiological mechanisms for local-global comparisons in visual neurons. *Ann Rev Neurosci* 1985;8:407–30.
 7. Desimone R. Neural circuits for visual attention in the primate brain. In: Carpenter GA, Grossberg S, eds. Neural Networks for Vision and Image Processing. Cambridge, MA: MIT Press, 1993:343–64.
 8. Meienberg O, Zangemeister WH, Rosenberg M, Hoyt WF, Stark L. Saccadic eye movement strategies in patients with homonymous hemianopia. *Ann Neurol* 1981;9:537–44.
 9. Zangemeister WH, Stark L. Active head rotations and eye-head coordination. *Ann NY Acad Sci* 1981;374:540–59.
 10. Zangemeister WH, Meienberg O, Stark L, Hoyt WF. Eye-head coordination in homonymous hemianopia. *J Neurol* 1982;226:243–54.
 11. Zangemeister WH, Dannheim F, Kunze K. Adaptation of gaze to eccentric fixation in homonymous hemianopia. In: Keller EL, Zee DS, eds. Advances in the Biosciences. 1986; 57:247–52.
 12. Zangemeister WH, Stark L. Gaze movements: patterns linking latency and VOR gain. *Neuro-Ophthalmology* 1989;9: 299–308.
 13. Zangemeister WH. Voluntary influences on the stabilization of gaze during fast head movements. In: Ellis SR, Kaiser MK, Grunwald AC, eds. Pictorial Communication in Virtual and Real Environments. London: Taylor & Francis, 1991:404–17.
 14. Zangemeister WH, Stark L. Types of gaze movements: variable interactions of eye and head movements. *Exp Neurol* 1982;77:563–77.
 15. Zangemeister WH, Stark L. Gaze latency: variable interactions of eye and head latency. *Exp Neurol* 1982;75:389–406.
 16. Gauthier G, Mandelbrojt P, Vercher JL, Marchetti E, Obrecht G. Adaptation of the visuo-manual system to optical correction. In: Stark L, Obrecht G, eds. Presbyopia—Recent Research and Reviews from the Third International Symposium. New York: Fairchild Publ, 1985:165–71.
 17. Schoepf D, Zangemeister WH. Eye and head reading path in hemianopic patients. In: Wright SF, Groner R, eds. Facets of Dyslexia and its Remediation. Amsterdam: North-Holland, 1992:267–91.
 18. Schoepf D, Zangemeister WH. Correlation of coordinated gaze strategies to the status of adaptation in patients with hemianopic visual field defects. *Ann NY Acad Sci* 1993;682: 404–9.
 19. Wilson B, Cockburn J, Halligan PW. Behavioral Inattention Test. Titchfield, Hants: Thames Valley Test Company, 1987.
 20. Stark L, Vossius G, Young LR. Predictive control of eye tracking movements. *IEEE Trans Hum Fac Electron* 1962; HFE-3:52–67.
 21. Bahill AT, Clark MR, Stark L. The main sequence: a tool for studying human eye movements. *Math Biosci* 1975;24:191–204.
 22. Bahill AT, Stark L. Oblique saccadic eye movements: independence of horizontal and vertical channels. *Arch Ophthalmol* 1977;95:1258–61.
 23. Viviani P, Berthoz A, Tracey D. The curvature of oblique saccades. *Vision Res* 1977;17:661–4.
 24. Winer BJ. Statistical Principles in Experimental Design. London: McGraw Hill, 1971.
 25. Wagner RA, Fischer MJ. The string-to-string correction problem. *J Assoc Comp Mach* 1974;21:168–73.
 26. Kemeny JG, Snell JL. Finite Markov Chains. New York: Springer, 1983.
 27. Morgan HL. Spelling correction in systems programs. *Comm Assoc Comp Mach* 1970;13:90–4.
 28. Hacisalihzade SS, Stark LW, Allen JS. Visual perception and sequences of eye movement fixation: a stochastic modeling approach. *IEEE Trans Sys Man Cyb* 1992;22:474–81.
 29. Helmholtz HLF von, Southall JPC. Physiological Optics. New York: Dover Publ, 1962. Transl from original German version published in 1866.
 30. Nachmias J. Two-dimensional motion of the retinal image during monocular fixation. *J Opt Soc Am* 1959;49:901–8.
 31. Gaarder K. Relating a component of a physiological nystagmus to visual display. *Science* 1960;132:471–2.
 32. Yarbus AL. Eye Movements and Vision, chap 7. New York: Plenum Press, 1967.
 33. Hochberg J. In the mind's eye. In: Haber RN, ed. Contemporary Theory and Research in Visual Perception. New York: Holt, Rinehart & Winston Publ, 1968:309–31.
 34. Brandt S, Stark L. Experimental evidence for scanpath eye movements during visual imagery. *IEEE Biomed Engin Proc* 11th Ann, Seattle, 1989:A317–8.
 35. Groner R, Walder F, Groner M. Looking at faces: local versus global aspects of scanpaths. In: Gale AG, Johnson F, eds. Theoretical and Applied Aspects of Scanpaths. Amsterdam: North Holland, 1984:58–9.
 36. Finke RA, Pinker S. Directional scanning of remembered visual patterns. *J Exp Psychol* 1983;9:398–410.
 37. Jeannerod M, Gerin P, Pernier J. Déplacements et fixation du regard dans l'exploration libre d'une scène visuelle. *Vision Res* 1968;8:81–97.
 38. Locher PJ, Nodine CF. Symmetry catches the eye. In: O'Reagan JK, Levy-Schoen A, eds. From Physiology to Cognition. Amsterdam: North Holland Publ Company, 1977: 353.
 39. Mackworth NH, Morandi AJ. The gaze selects informative details within pictures. *Percept Psychophys* 1967;2:547–52.
 40. Zihl J, Wohlfart-Englert A. The influence of visual field disorders on visual identification tasks. *Eur Arch Psychiatr Neurol Sci* 1986;236:61–4.
 41. Berlyne DE. The influence of complexity and novelty in visual figures on orienting responses. *J Exp Psychol* 1958;55:289–96.
 42. Berlyne DE, Crozier JB. Effects of complexity and prechoice stimulation on exploratory choice. *Percept Psychophys* 1971;10:242–6.

AUTHOR'S ADDRESS:

Prof. Dr. Med. W. H. Zangemeister
Neurological University Clinic
Martinistr. 52
D 20251 Hamburg, Germany