EVIDENCE FOR SCANPATHS IN HEMIANOPIC PATIENTS SHOWN THROUGH STRING EDITING METHODS

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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 analyse a variety of tasks including paradigms of visual search, reading and scanpath eye movements. The tasks were recorded several times in sequential order. By applying string-editing methods to the problem of quantitatively analysing search- and scanpaths of the half-blind patients in comparison to healthy subjects, we were able to observe 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, Vector String Editing.

1 INTRODUCTION

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 accounts for detecting the arrangement of contrasts, border lines, colours, depth and special subfeatures especially with respect to the primary region of interest (ROI). This type of viewing strategy would correspond to 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 corresponds to a searchpath, that applies to the so called top-down control (Noton & Stark

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1971, Stark & Ellis 1981) 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 readingpath and scanpath respectively (Noton & Stark 1971, Stark & Ellis 1981, Zangemeister, Sherman & Stark 1989, Stark, Yamashita, Tharp & Ngo 1992, Zangemeister, Sherman & Stark 1995).

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 up 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 processes (Zangemeister, Sherman & Stark 1995, Allman, Miezin & McGuinness 1985, Desimone 1993) . However, some groupings may "emerge" from the structure of the scene input without the help of top-down influences.

Of course, the enforced top-down 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 the eyes, the optical pathways, the visual or motor cortex and its interconnections may cause at least one of the three functional parts of the control to become disturbed: the sensory, the cognitive, or the motor connection that contribute to the proper functioning of the higher levels of visual control.

In the case of deficiencies in at least one of the 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:

1. Motor deficits of one or both eyes involving coordinated eye-movements that may cause dipliopia 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.

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 homonymous hemianopia, 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 only (Meienberg, Zangemeister, Rosenberg, Hoyt & Stark 1981) without any head- or body-movement, and, on the other hand coordinated eye- and head-movements in coordinated gaze (Zangemeister & Stark 1981, Zangemeister, Meienberg, Stark & Hoyt 1982, Zangemeister, Dannheim & Kunze 1986, Zangemeister & Stark 1989, Zangemeister 1991). This distinction is practically important, since the head as the moving platform of the eyes may be differentially used 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, since 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 to the body frame of reference equalling position of gaze in space, like in case of a pilot or a car driver. Here, functional processing of coordinated gaze may be more flexible (Zangemeister & Stark 1982*b*) 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 msec of a typical saccade plus saccadic latency (Zangemeister & Stark 1982*a*, Gauthier, Mandelbrojt, Vercher, Marchetti & Obrecht 1985).

In 1971 Noton & Stark found patterns in the eye movements of subjects recognizing a familiar object, which they called scanpaths. Each subject seemed to have a typical scanpath for each object. During longer inspections of the object, the scanpath was repeated several times. This observation led Noton & Stark to the feature ring hypothesis which states that an object is represented in memory by its principal features and by the eye movements (saccades) which are necessary to proceed from one feature to the next. The stored features and saccades were proposed to be organized in a repetitive structure, which was called feature ring (Fig. 1).

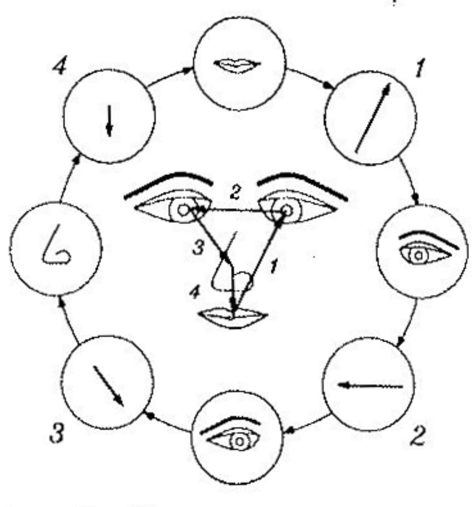

Figure 1: *Illustration of Noton & Stark's (1971) feature ring hypothesis. The internal representation of an object is supposed to consist of the principal features of the object and the eye movements (motor controls) necessary to get from one feature to the next. The features and motor controls are supposed to be organized in a repetitive structure.*

Since 1971 the proposals of scanpath and feature ring were widely discussed. Because the hypothesis of Noton & Stark at first was based entirely on the subjective inspection of recorded eye movement patterns, there has been some effort to develop an objective method for the comparison of eye movements. Here, we shall report on the specific methods we have applied to quantitatively evaluate search- and scanpath eye movements as well as on the training results, i.e., the adaptive strategies of high level controlled eye-movements that hemianopic patients use, when the head and body is fixed (Zangemeister, Oechsner & Freksa 1995).

2 METHODS

2.1 Patients, experimental setup, conventional analyses

During the last three years we observed and recorded eye movements from patients with various visual field defects, the most important of which consisted of homonymous hemianopia. 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 randomly varied on a large TV-screen; they also included scanpath recordings of viewings of abstract pictures of famous contemporary artists like *Ken Noland*, and one of the three coloured *Rorschach* pictures to test for symmetry perception. As a kind of intermediate test that included both qualities of a search 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 (Schoepf & Zangemeister 1992, Schoepf & Zangemeister 1993).

Subjects. We compared a group of normal healthy and full sighted subjects ($n = 10$) (mean age 35 ± 6 years) with a group of patients ($n = 10$) (mean age 52 ± 7) that had suffered from a stroke of the posterior cerebral artery of one side resulting in a pure homonymous hemianopia (HH) that was distinguished from hemineglect through a sequence of neuropsychological tests (Wilson, Cockburn & Halligan 1987). Visual hemifield defects with and without foveal sparing was quantified through high resolution computer perimetry (Octopus). Extension of the anatomical defect was quantified through cranial CT or MRT. Only patients with strokes dating back more 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 (Stark, Vossius & Young 1962, Zangemeister & Stark 1982*a*). Eye movements were measured using an infrared system (ASL210) that provided measurements of horizontal movements with a resolution of 0.05 degree over a range of ± 20 degree and of vertical measurements with a resolution of 0.1 degree over a range of ± 10 degree and permitted also detection of eyelid blinks. A calibration process, which assumed a nonlinear (polynomial) relationship between the eye movements and the output of the ASL210 did correct nonlinearities 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 (in time and amplitude) alternating with an amplitude of 5 to 30 degrees was used as target for the measurement of saccadic time functions and main sequences (Bahill, Clark & Stark 1975) (i.e., the saccade peak velocity/amplitude relationship). The vertical and horizontal size of the target was 1 degree.

Higher level visual stimuli. Six pictures ranging from non-realistic search pictures to ambiguous pictures to more artful realistic and abstract pictures were chosen. The artful colour pictures were by Lane Terry "Deadeye" 1971, 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 & Ellis (1981)), the largest of the three coloured Rorschach pictures, and the above noted diagonal and horizontal search sub-picture (see Fig. 10).

Experimental procedure. Subjects were seated comfortably in a ground-fixed dental chair that allowed a 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. Afterwards 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 were led to believe 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 seconds with a one minute rest period between presentation groups. Six different pictures comprised a presentation group. A short rest period of 10 sec was requested between each picture within one presentation group. With a calibration run before and afterwards, and with intervening rest periods, the entire duration of the experiment was approximately 35 minutes. Presentation of pictures was done on a large VDT screen (21 inches diagonal). They were clearly 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 degree in each direction for the presented pictures. Room lighting was dim so as to focus the subject's attention on to 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 utilized. These presented the sequence of eye movements with saccades between fixation points. As is well known in the literature (Stark et al. 1962, Bahill et al. 1975, Bahill & Stark 1977, Viviani, Berthoz & Tracey 1977), 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 milliseconds, 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 second 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* or a *local* scan, using smaller eye movements in a particular region. We determined the ratio of global versus 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 degree; that is, eye movements of the order of one degree of amplitude or less were considered local eye movements, whereas eye movements greater than 1.0 degree were considered global eye movements. This is in accordance with earlier reports on the range of micro-eye movements, particularly micro-saccades that range between 0.08 and 0.8 degree (see Brandt & Stark (1989) amongst others). If one changes this boundary from 1.6 to 4.6, 7.9, or 11 degrees, so that the definition of local becomes larger and larger, any discrimination provided by the global/local (g/l) ratio disappears (Zangemeister et al. 1989, Stark et al. 1992).

The statistical evaluation of differences between early and late presentations, pictures and conditions involved a non-parametric analysis of variance Winer (1971) . It was performed using the ANOVA software BMDP2, UC California, Los Angeles, analysis of variance and covariance with repeated measures, program version 1987.

2.2 Scanpath evaluation

Up to now Markov matrices and string editing have been used for quantification of the term "similarity of eye movements". Both methods work on sequences or "strings" of regions of interest (ROIs) which were visited by the eye during inspection of the object. At first the ROIs have to be defined a priori by the experimentator or a posteriori by clustering algorithms (regions that contain clusters of fixations are taken to be "of interest" to the patient). After defining, the regions are labeled by letters. Using the defined ROIs, the two-dimensional fixation-saccade sequence is then reduced to a one dimensional sequence of letters: if successive fixations are located in the ROIs "C", "D", "C", and "A", the resulting sequence of letters is "CDCA". Thus the task of comparing the eye movements of a subject or between subjects is reduced to the comparison of strings.

String editing was first used by programs for spelling correction (Morgan 1970, Wagner & Fischer 1974). Here it is necessary to find the words which are most similar to misspelled words. 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 $\rightarrow$ t). Transition probabilities between N states can be described by second order $N \times N$ Markov matrices (Kemeny & Snell 1983). 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 the sequence of letters is understood as a sequence of transitions between states. To measure the difference between eye movement patterns with the help of Markov matrices, the transition probabilities of all letter combinations are computed for each pattern. The difference between the fixation strings is defined as the mean difference of the transition probabilities (Hacisalihzade, Stark & Allen 1992).

The objectivity of both string editing and the use of Markov matrices depends on the objectivity of the ROI-definition. A priori defined ROIs are completely subjective. The use of a posteriori defined ROIs is an objective method, but here analysis of different image viewings may result in different ROIs and thus the comparability is lost.

On the other hand, while evidence for scanpath and feature ring was found using string editing with different experimental paradigms like search tests (Allman et al. 1985) or visual imagery (Brandt & Stark 1989, Finke 1983), some authors (e.g., Groner, Walder & Groner 1984) doubted especially the storage of the motion controls (the saccades) in the internal representation of a familiar object as proposed by the feature ring hypothesis. The feature ring consists of two interwoven sequences (comp. Fig. 1): the sequence of features (ROIs) and the sequence of motor controls (saccades). We propose to use the latter for comparison of image viewings. The object features (or ROIs) are still supposed to be the important part of the feature ring, but they no longer have to be known (neither a priori nor a posteriori). By constructing a vocabulary of vectors and replacing each actual interfixational vector by the vector out of the vocabulary most similar to it, a "vector string" is obtained. String editing can then be used to compare different vector strings. This method we called "vector string editing".

2.3 Vector String Editing

String Editing can only be applied to a finite set of elements. The set of two dimensional vectors is not finite but can be approximated by a finite subset of vectors. We chose to divide both the possible directions (0 to 360 degree) and the possible lengths (0 to maximal extension of the field of vision) of an interfixational vector into 16 parts. The result is an alphabet or vocabulary of 256 vectors where each vector represents a certain interval of vector directions and lengths. The vectors in the alphabet are labeled by byte numbers. The low nibble contains the number of the direction interval, the high nibble the number of the length interval (see Fig. 2).

It is necessary to pay special attention to the first saccade. It is the step from the more or less random position of the eyes just before the presentation of the object to the first object feature which was found of interest by the patient, and thus a step into the feature ring. The interfixational vector corresponding to the first saccade was replaced by a vector from the center of the object to the position of the first fixation. This vector is no longer arbitrary (as the first interfixational vector due to the initial random position of the eyes), but always points to the first feature which was found of interest by the patient.

To make vector string editing invariant against scaling operations, the "maximal extension of field of vision" (which defines the length of the longest vectors in the vocabulary) was adapted to the size of the presented object.

In string editing different costs can be assigned to the editing operations insertion, deletion, and change. In a first approach to vector string editing we chose equal costs (i.e., unity) for each editing operation. In a second approach we chose costs which were dependent on the displacement in two dimensional space which was caused by the editing operation. That is, the cost of insertion or deletion of a vector was given by its length, the cost of replacing vector by vector was given by the length of the difference vector. This kind of vector string editing we called "weighted vector string editing". The vector string distances resulting from weighted vector string editing were renormalized to get results which were in the same order of magnitude as the distances from string editing with ROIs and vector string editing without weights.

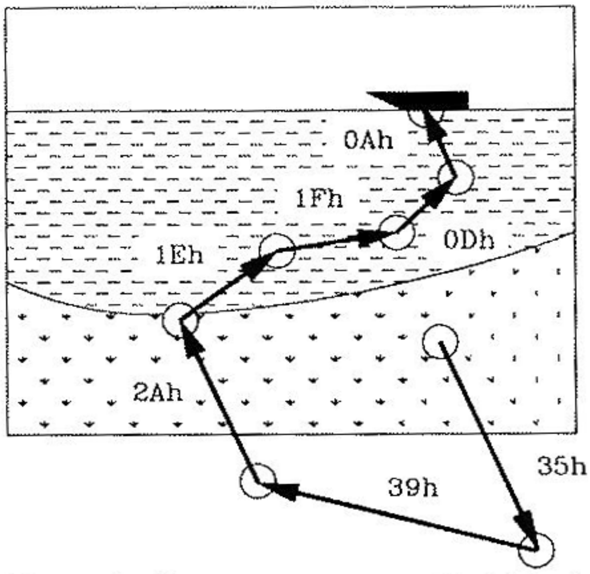

Figure 2: *Vector string editing. Each interfixational vector is classified by a byte number. The upper 4 bits encode the length, the lower 4 bits the direction. The vector string is the sequence of byte numbers, in the example (in hexadecimal notation) 35h, 39h, 2Ah, 1Eh, 1Fh, 0Dh, 0Ah.*

2.3.1 Numerical Simulations

We used numerical simulations to find the limits of vector string editing. In their 1992 paper Hacisalihzade et al. used a priori defined Markov matrices to generate sequences of fixations which were different realisations of the same Markov process. Application of string editing to groups of such sequences showed the ability of string editing to differentiate between different underlying processes.

In the first process (M_1) defined by Hacisalihzade et al. the transition probability from one state to the next was 90% and to the one after the next 10%. The other processes had increasing randomness (M_2: 70% from one state to the next, 30% to the one after the next, M_3: 50% from one state to the next, 10% to the one after the next, all other states equiprobable, M_4: all transitions are equiprobable). We chose M_1 and two matrices which were slightly different to M_1 (80% and 20% resp. 85% and 15% instead of 90% and 10%) to compare the discriminating abilities of string editing and vector string editing. These matrices are called $M(0.9, 0.1)$ ($= M_1$), $M(0.8, 0.15)$, and $M(0.8, 0.2)$ in the following. For four states they are given by

$$M(p_1, p_2) = \begin{pmatrix} 0 & p_1 & p_2 & 0 \\ 0 & 0 & p_1 & p_2 \\ p_2 & 0 & 0 & p_1 \\ p_1 & p_2 & 0 & 0 \end{pmatrix}.$$

The object chosen for the simulation of a scanpath was a 3×3 checker board (see Fig. 3). Each checker field was regarded as region of interest resulting in 9 possible states. For each Markov matrix 500 sequences with 30 elements were generated. String editing could be directly applied to these sequences (i.e., ROI-strings). For vector string editing we compared four different assumptions about the distribution of the fixations in each checker field (i.e. ROI) :

- A_0 – they were located exactly in the center of each checker field (Fig. 4a)
- $A_{0.25}$ – they were uniformally distributed in a centered square with 1/4 of the area of one checker field (Fig. 4b)
- $A_{0.5}$ – they were uniformally distributed in a centered square with 1/2 of the area of one checker field (Fig. 4c)
- A_1 – they were uniformally distributed across the whole checker field (Fig. 4d)

The simulation resulted in three distributions (there were three Markov matrices) of string distances obtained by string editing, and 12 distributions (there were three Markov matrices, and four assumptions) of vector string distances obtained by vector string editing and weighted vector string editing each. Subsequently we applied the Kolmogorov-Smirnov test to these distributions to get the probability of the assumption that all distributions had the same underlying Markov process.

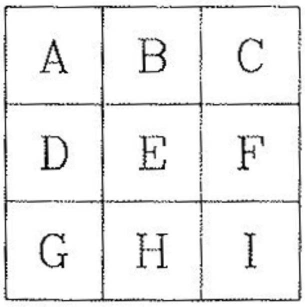

Figure 3: *Object used for simulation of eye movements. Each of the checker fields is a region of interest (ROI). The ROIs are labeled by the letters A to I.*

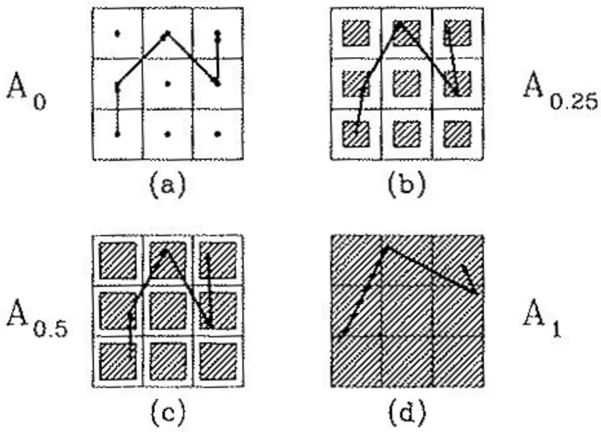

Figure 4: *Assumptions A_0 to A_1 while generating vector sequences from a ROI string (GDBFC, compare Fig. 3). In (a) the eye movements are supposed to start and end exactly in the center of a ROI (assumption A_0). In (b) to (d) the location of the start- and endpoints is getting increasingly uncertain (assumptions $A_{0.25}$ to $A_{1.0}$).*

2.3.2 Eye movement measurements

As a first test of (weighted and unweighted) vector string editing with data from eye movement measurements we used measurements with three hemianopic patients. The patients had to look for a small arrow in a coloured rectangle on a computer screen. The arrow systematically appeared on the diagonal of the rectangle, but the patients were not told where to look for it. We used string editing to show an adaptation effect : as the task and the object became more familiar, the string distances decreased.

String editing, vector string editing and weighted vector string editing were applied to two collection of strings. The first collection consisted of 16 strings from the pre-adaptation period, the second of 22 strings from the post-adaptation period. Again the Kolmogorov-Smirnov test was used to compare the resulting distribution of distances pre and post adaptation.

3 RESULTS

3.1 Results I: Vector String Editing versus String Editing

Numerical Simulations. Figure 5 shows the distributions which were calculated during simulation. The results of the Kolmogorov-Smirnov tests where we compared the distributions derived from the Markov matrices $M(0.9, 0.1)$, $M(0.85, 0.15)$, and $M(0.8, 0.2)$ are shown in Tab. 1. Here the logarithms of the probabilities of the distributions being the same are given. The distance between two distributions is taken to be significant if the probability p is less than 0.001 or $\log(p) < -3.0$.

As was to be expected, all distributions in Fig. 5 show increasing means with increasing uncertainty of the underlying process ($M(0.9, 0.1)$ to $M(0.8, 0.2)$. In case of vector string editing and weighted vector string editing the means are also increased if the positions of the start- and endpoints of the generated interfixation vectors are less certain (assumptions A_0 to A_1). Because of the greater number of elements in the vector alphabet, (unweighted) vector string editing soon reaches the maximum value of string and vector string distance, which is equal to the string length (30). As shown in Fig. 5 and Tab. 1, this results in very similar distributions for different Markov processes, which can no longer be discriminated by the Kolmogorov-Smirnov test. This is not the case for weighted vector string editing. Because of the weighting factors there is no fixed maximum distance and Tab. 1 shows significant differences for (almost) all comparisons of distributions. In case of assumption A_0 (all simulated fixations are located in the center of the ROI) weighted and unweighted vector string editing show almost equal discrimination properties. Surprisingly both methods are better than normal string editing. If the position of the simulated fixations in the ROIs is less certain (assumptions $A_{0.25}$, $A_{0.5}$, and A_1), normal string editing is always better than the vector methods. Unweighted vector string editing is not able to detect small differences in the underlying Markov processes if the fixations are uniformly distributed in at least half of the area of the ROI. Weighted vector string editing discriminates better but here the p-values also increase rapidly from assumption A_0 to A_1.

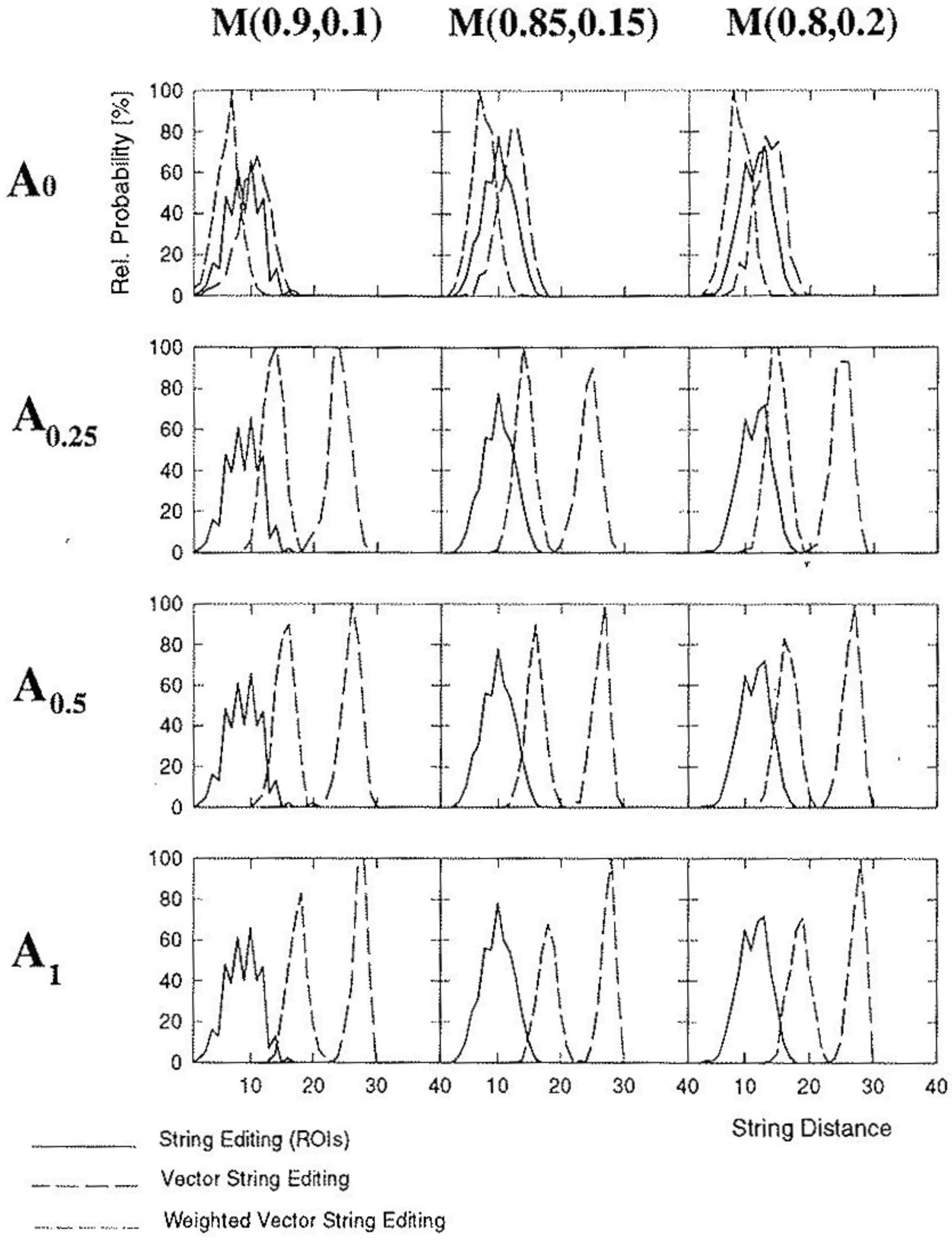

Figure 5: *String distance distributions resulting from numerical simulation. ROI strings were generated using the Markov matrices $M(0.9, 0.1)$, $M(0.85, 0.15)$, and $M(0.8, 0.2)$. Using the model of a 3×3 checker board (Fig. 3) and the additional assumptions A_0 to A_1 (see Fig. 4) vector sequences were derived from the ROI strings. The figure gives the string distance distributions resulting from normal string editing (solid lines), vector string editing (short dashed lines), and weighted vector string editing (long dashed lines).*

		log(p) for "M(0.9,0.1) = M(0.85,0.15)"	log(p) for "M(0.85,0.15) = M(0.8,0.2)"	log(p) for "M(0.9,0.1) = M(0.8,0.2)"
String Editing (ROIs)		−6.7	−10.2	−28.2
Vector String Editing	A_0	−17.9	−12.2	< −32
	$A_{0.25}$	−3.1	−2.7	−10.6
	$A_{0.5}$	−2.0	−1.5	−5.3
	A_1	−1.0	−0.1	−0.9
Weighted Vector String Editing	A_0	−16.5	−13.9	< −32
	$A_{0.25}$	−5.3	−5.5	−18.5
	$A_{0.5}$	−3.8	−5.0	−13.1
	A_1	−2.9	−4.1	−15.0

Table 1: *Logarithms of the probability of two string distance distributions with different underlying Markov process being the same (as computed by use of the Kolmogorov-Smirnov test).*

Eye movement measurements. Figure 6 shows the distributions of string distances obtained by application of the three string editing methods to the eye movement measurements pre and post adaptation. Tab. 2 gives the results of the Kolmogorov-Smirnov test.

All string editing methods have been able to discriminate between the distributions pre and post adaptation. The best discrimination is obtained by using (unweighted) vector string editing, normal string editing is the second best. Weighted string editing is worse but ($\log(p) < -3$) still able to find a significant difference in the distributions.

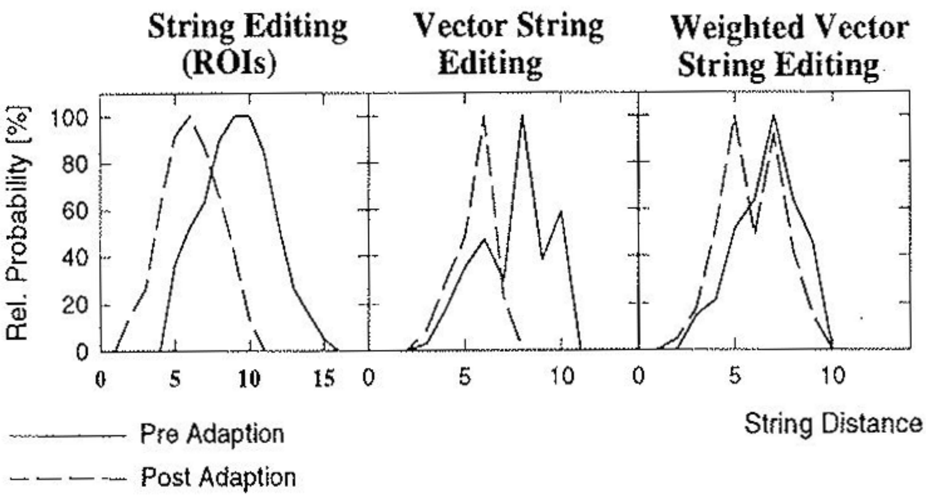

Figure 6: *Application of normal string editing (using ROIs), vector string editing and weighted vector string editing to actual eye movement data. Three hemianopic patients had to look for small arrows somewhere in a coloured rectangle on a computer screen. The string editing methods were used to look for differences between the string distance distributions before (solid lines) and after (dashed lines) adaptation of the patients to the given task.*

	String Editing (ROIs)	Vector String Editing	Weighted Vector String Editing
log(p) of "Pre Adaption = Post Adaption"	-18.0	-20.3	-3.2

Table 2: *The distributions of Fig. 6 corresponding to measurements before and after adaptation of the patients to the given task were compared using the Kolmogorov-Smirnov test. The table gives the logarithms of the probabilities of both distributions being the same.*

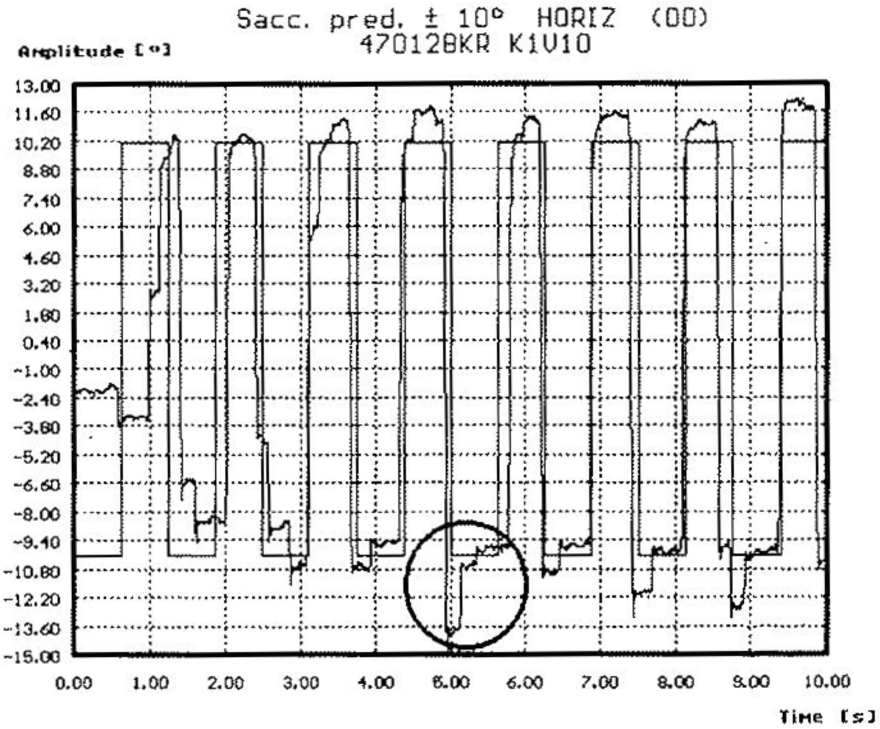

Figure 7: *Staircase pattern of saccades towards the blind hemifield (down) with time (sec) on abscissa and amplitude (deg) on ordinate, showing eye movements superimposed of a predictive step stimulus. Note the hypometric staircase saccades at the beginning and fast adaptation to this simple and anticipated stimulus within three repetitions with static overshooting or hypermetric saccades thereafter. The circle marks an early example for overshoot and successive fast glissades backwards to the target.*

3.2 Results II: Search- and scanpaths of hemianopic patients

Saccadic time functions and main sequences. Original recordings of responses of hemianopic patients to low level visual stimuli, i.e. a predictively alternating target of 5 to 30 degrees in amplitude demonstrate the characteristical eye movement pattern (Meienberg et al. 1981, Zangemeister et al. 1982). Initial stair steps of small saccades towards the blind hemifield were followed after two to four repetitions by overshooting saccades (Fig. 7). These sometimes show fast glissades that move the fovea effectively backwards to 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. 7.

Comparison of main sequences (i.e., the saccade peak velocity/amplitude relationship, Bahill et al. (1975)) 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. 8).

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. 9). Fixation durations did not discriminate between normal and hemianopic responses. However, size histograms showed highly-peaked, exponential monotonic distributions for patient subjects indicating large numbers of small saccades (which mostly occurred in the gaze direction to the blind

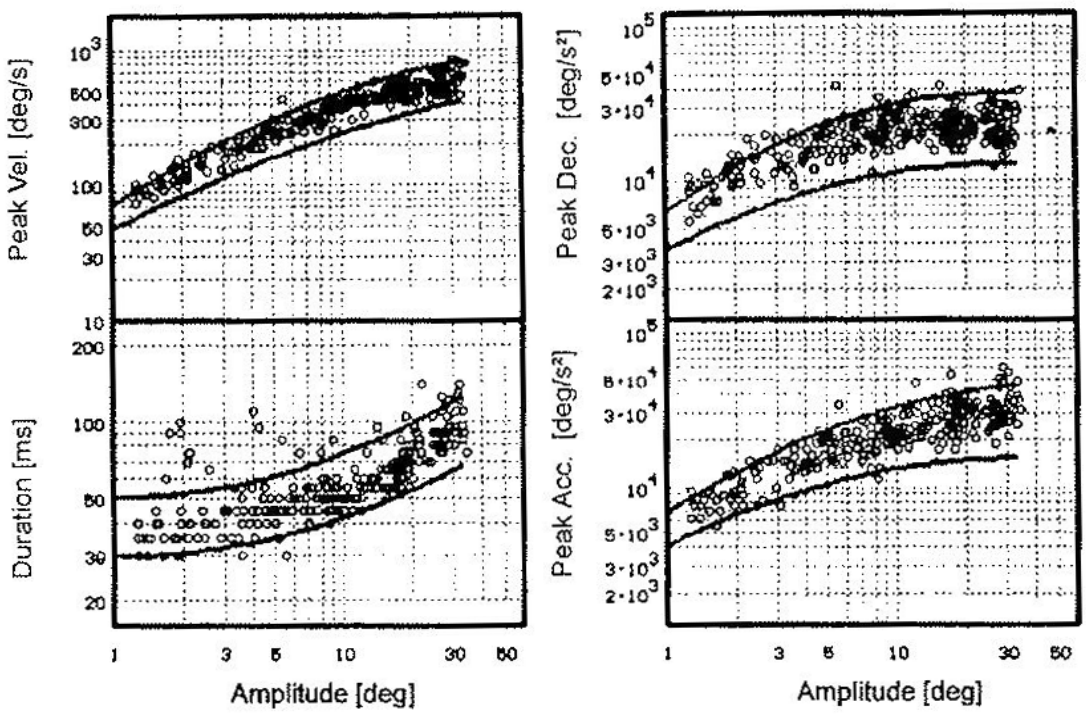

Figure 8: *Main Sequence double logarithmic plots of a typical patient's saccades. The two thick curves enclose the 95 % confidence limit of our normal data base ($n = 40$). Abscissas amplitude (deg), ordinates from left clockwise: peak velocity of saccade, peak deceleration, peak acceleration, and duration. Note that the saccadic dynamics are within the normal range.*

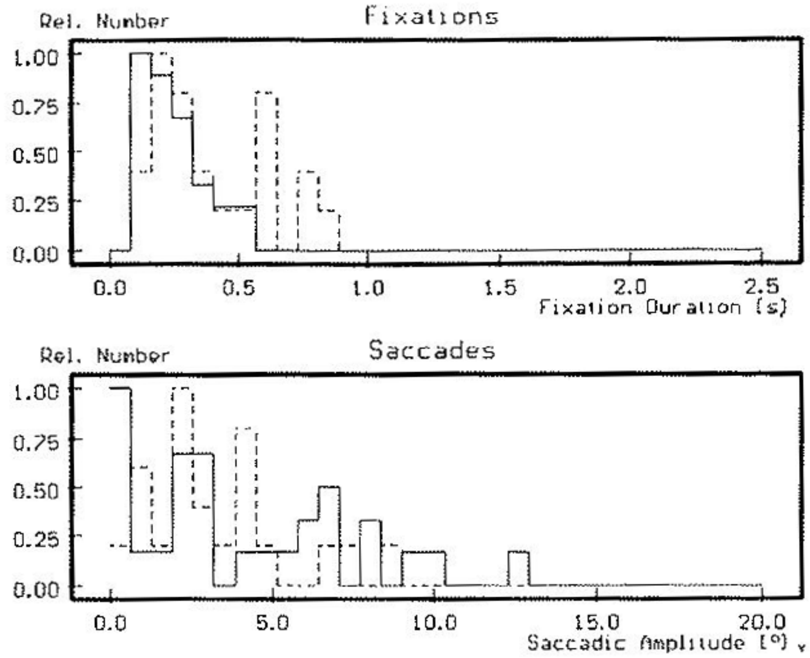

Figure 9: *Probability density curves of a normal subject's fixation durations and saccadic amplitudes during the scanpath (dashed lines) and of a hemianopic patient (solid lines). Note the relative high incidence of small saccades and shorter fixation durations in the patient. The ratio of global (> 1 deg) and local (≤ 1 deg) saccades is 3.8 for the patient and 20.0 for the normal subject.*

hemifield), i.e., a small global/local index. Conversely, histograms of 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.

Visual search tasks. The search for a very small object on the hemianopic side of the patient's visual field was initially performed through a sequence of many small saccades that often erroneously clustered around the "wrong" side of the horizon (Fig. 10a). Whereas to the seeing hemifield, they resembled a normal pattern (Fig. 10b). After 10 repetitions on the hemianopic side, the sequence of saccades in search of this small target became almost normal (Fig. 10c) 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 first and tenth response pattern. This suggests a very efficient short-term adaptation and optimization of the search paths in these patients.

With other visual stimuli, we obtained very similar behaviours. When looking for the "symmetry" of one of the three coloured Rorschach pictures (Fig. 11), in spite of this very specific task, the patients did not look towards the part of the picture that fell into the blind hemifield. After additional repetitions however, they changed their behaviour to a more symmetrical searchpath, so they were better able to compare the symmetries of the picture. It is noteworthy to recall that our patients were extensively tested for and did not show any signs of visual neglect. Again string editing, Markov analyses and statistics editing (based on ROIs) and vector string editing for the analysis of eye movement patterns could form a test for a part of the feature ring: the storage of the motor controls.

Vector String Editing: Discussion of Application to Eye Movement Measurements. Even if the comparison of p-values should not be taken too seriously ($\log(p) = -18$ is actually very similar to $\log(p) = -20$), the results in Tab. 2 imply that the sequence of interfixational vectors is as well defined as the sequence of ROIs and therefore support the "vector part" of the feature ring hypothesis.

The weighted vector string editing seems not to be well adapted to actual eye movement data. The cause may be that in weighted vector string editing more importance is placed on the larger saccades, while in human eye movements small saccades are much more abundant (and may be important) than big saccades. At present we are developing a vector alphabet with a nonlinear (logarithmic) partition of lengths.

Discussion of patients' results in scanning. These showed reduced local scanning by normal healthy viewers who relied on more global viewing, particularly in ambiguous and non-realistic 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 non-realistic images. Cognitive models control active viewing of realistic, ambiguous and non-realistic 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, utilizing cognitive schemas to drive their scanpath.

Similar to Gaarder (1960), Yarbus (1967) 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 instructional task of 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 & Stark (1971) 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 imagings the object/scene really is. This representation was related to the "schematic diagram" of Hochberg (1968) . Noton and Stark used more realistic art, namely a figure of Klee's, while Stark & Ellis (1981) 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 & Stark (1989) compared sequences of eye movements of subjects looking at a real visual stimulus and afterwards at its remembered mental image. Using string edit analyses (Hacisalihzade et al. 1992) , they were able to provide firm evidence for scanpath sequences of their subjects' eye movements in both conditions. Groner et al. (1984) have recently proposed that global scanpaths adhere to the Noton & Stark proposal, while smaller intermixed local scanpaths may be controlled peripherally.

Global versus local scanning. Since 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 towards 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 versus 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 clear-cut 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, since 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 & Stark (1971) and Stark & Ellis (1981) showed that peripheral information can be excluded as the immediate control for the scanpath, their results also relate to local scanpaths. Groner et al. (1984), and also Finke (1983), support their top-down, cognitive model scanpath theory for a global scanpath, but argue in favour of an immediate peripheral bottom-up control of local scanning as Allman et al. (1985) and Desimone (1993) 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 demonstrate conclusive evidence of a mini- or micro- search/scanpath as a special case of a local scanpath in hemianopic patients.

Jeannerod, Gerin & Pernier (1968) 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 favour 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 (Zangemeister et al. 1989, Zangemeister, Sherman & Stark 1995), our paradigms for viewing realistic and non-realistic images probably enforced this ability that was not present in the patient viewers. There, the naive subjects had equal global/local ratios for both realistic and abstract images. These ratios were similar to that 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. Mackworth & Morandi (1967) claimed immediate bottom up control in symmetry "that catches the eye"; Mackworth and Locher & Nodine (1977) 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 behaviour to the ambiguous and non-realistic 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 & Wohlfart-Englert (1986). Only after many repetitions do they apply a more top-down like strategy that mirrors the one they use primarily when looking towards their seeing hemifield.

Realistic versus non-realistic and ambiguous pictures. Healthy subjects demonstrated more global scanning of the ambiguous and non-realistic images than they showed for their scanning of the realistic images, as was expected from earlier results (Zangemeister et al. 1989, Stark et al. 1992). 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.

5 CONCLUSIONS

Evidences for top-down control and future lines of work. Our study demonstrates that it is feasible to observe and to quantify 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.

Regarding vector string editing, the experimental results presented here are preliminary. To further explore the feasibility of (weighted and unweighted) vector string editing to the comparison of eye movement data we are preparing experiments with paradigms like "recognition of familiar objects" and "visual imagery" (eye movement measurements during mental visualisation of a familiar object which is no longer visible, (compare Brandt & Stark 1989, Finke 1983).

Evidence for top-down versus bottom-up control from our study are given with respect to: First, seeing versus 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 1958, Berlyne & McDonnel 1971) 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 versus local scanpath.

Future studies should try to simulate digitally a hemianopic field defect through the experimental setup 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.

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