

# Visual Imagery in Hemianopic Patients

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## Abstract

■ In this article we report some findings about visual imagery in patients with stable homonymous hemianopia compared to healthy control subjects. These findings were obtained by analyzing the gaze control through recording of eye movements in different phases of viewing and imagery. We used six different visual stimuli for the consecutive viewing and imagery phases. With infrared oculography, we recorded eye movements during this presentation phase and in three subsequent imagery phases in absence of the stimulus. Analyzing the basic parameters of the gaze sequences (known as "scanpaths"), we discovered distinct characteristics of the "viewing scanpaths" and the "imagery scanpaths" in both groups, which suggests a reduced extent of the image within the cognitive representa-

tion. We applied different similarity measures (string/vector string editing, Markov analysis). We found a "progressive consistency of imagery," shown through raising similarity values for the comparison of the late imagery scanpaths. This result suggests a strong top-down component in picture exploration: In both groups, healthy subjects and hemianopic patients, a mental model of the viewed picture must evolve very soon and substantially determine the eye movements. As our hemianopic patients showed analogous results to the normal subjects, we conclude that these patients are well adjusted to their deficit and, despite their perceptual defect, have a preserved cognitive representation, which follows the same top-down vision strategies in the process of visual imagery. ■

## INTRODUCTION

### Scanpath and Feature Ring Hypothesis of Vision

Although recent studies show remarkable progress in enlightening different aspects of structural and functional compounds of "high-level vision" processes, there still remain various questions about the visual process as a whole. One question is to what amount the object recognition process is mostly parallel or serial and what kind of internal representation is used by the brain in selecting and integrating the numerous complex and rapidly changing visual data that it is permanently exposed to.

The serial model originally developed by Noton and Stark (1971a,b) suggests that the internal representation consists of single components and features that are sequentially "matched" to the object(s) seen in the recognition phase. Because viewing consists of a sequence of alternating saccades and fixations, its measurable correlate can be described as the so-called "scanpath." This term was introduced by Noton and Stark. Their theory is based upon the idea that top-down processes associate single features of a scene on a higher cognitive level in a step-by-step manner. Within their studies they found marked similarities in recorded intra-subjective scanpaths of their subjects when repetitively viewing the same picture. From this Noton and Stark concluded the "feature ring hypothesis," which claims

that the internal representation of a seen object is given by its cardinal sensory features and the motor traces (saccades) that connect these features. Thus, recognition of objects works through a step-by-step scanning that corresponds to the actual "feature ring," a model that has been revised during the past decades. Figure 1 shows an actual version from Stark et al. (1999).

The foveal regions of interest (ROIs) are sequentially visited by a string of fixations, shifted by a string of saccades, and are simultaneously matched by top-down, symbolic, spatial, and sequential representations or bindings of the hypothesized image.

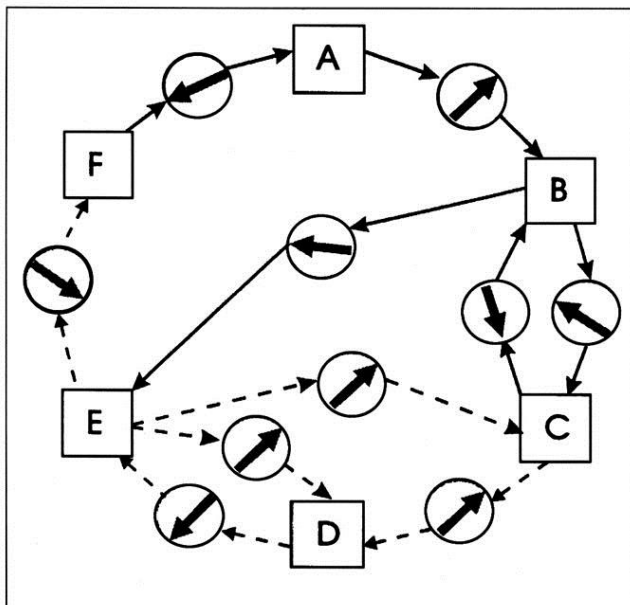
Based upon this model, our approach to obtain information on the visual system was to register the eye movements of our subjects during a visual task and then to analyze the resulting scanpaths. A variety of different scanpath properties like global/local saccade ratio were investigated in the past decades (Zangemeister, Oechsner, & Freksa, 1995; Zangemeister, Stiehl, & Freksa, 1996; Zangemeister, 1997), especially eye movements recorded during reading (readingpath, Schoepf & Zangemeister, 1993) or visual search (searchpath) showed certain characteristics abnormally modulated within pathological conditions like hemianopia or visual neglect syndrome.

### Visual Imagery

The basic assumption of common anatomic structures serving the functions of perception ("vision") and visual

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**Figure 1.** Scanpath theory: Eye movement positions (ROIs) shown as a connected sequence resulting in a sequential string of visited ROIs. Alternating perceptual ROIs (lettered squares) and saccadic eye movements (circles with arrows) shown by solid arrows form the "feature ring" of the scanpath theory in the noniconic model of this example. The variability of ROI sequences is represented by the dashed arrows.

imagery ("imagery") in high-level vision was confirmed in recent structural and imaging studies: Evidence for this was found by positron emission tomography (PET) (Roland and Gulyas, 1994a,b; Kosslyn et al., 1993; Kosslyn & Shin, 1994), functional magnetic resonance imaging (fMRI; LeBihan et al., 1993), regional blood flow recording (Goldenberg, Poderka, Steiner, Suess, & Deecke, 1989), and event-related potentials during imagery and viewing (Farah, Peronnet, Gonon, & Girard, 1988) studies localizing these functions in parieto- and temporo-occipital areas of the human cortex.

On the basis of these results, Farah and Ratcliff (1994) and Kosslyn and Shin (1994) developed an integrated model of active vision and visual imagery. This model basically postulates an interactive exchange of information between various cortical areas of different complexity. According to this theory the process of imagery works very much like the recognition of previously seen pictures (matching them to the mental prototype) through projection of the visual information onto a common medium. This projection of an extrastriate "high-level" area most probably onto the retinotopical organized area finally corresponds to the visualization of the constructed image and represents the visual working memory. This means that the striate cortex could play the role of a visual "buffer" providing incoming data for an "attention window" (Treisman & Gelade, 1980) that selectively focuses on the interesting features of the whole picture. As in the process of analyzing external images, different subsystems are involved to define

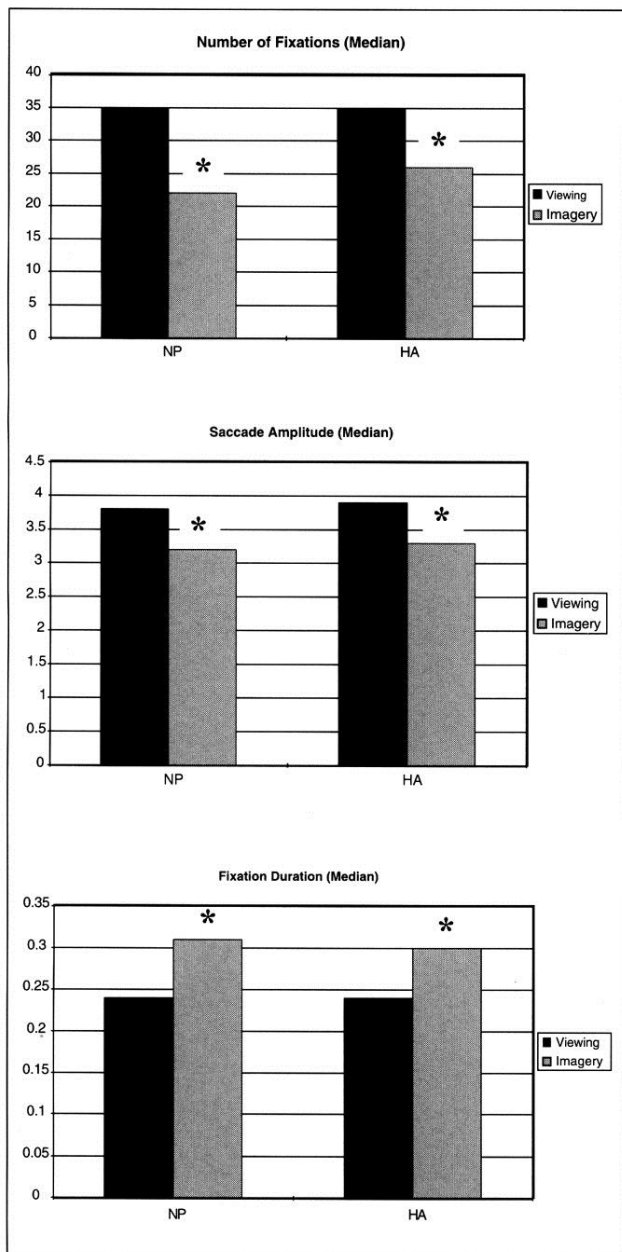
objects concerning their major aspects like shape, color, localization, and size (Kosslyn, 1994). There is a direct link between the lateral geniculate nucleus (LGN) and V1 in the sulcus calcarinus of the occipital cortex through the radiatio optica. Further connections exist from the LGN to the extrastriate cortex in areas 18 and 19. Zeki (1976, 1978, 1983, 1993) was the first to show an association of the areas V2 to V5 in the integration of different modalities of visual information like color, shape, and motion in the rhesus monkey.

In the literature few works can be found that address the analysis of eye movements during visual imagery. In 1968, Hebb asked in "Concerning Imagery" whether eyes scan a visualized scene the same way they do in reality (Hebb, 1968). He concluded that eye movements have to play an essential organisatory role in completing the fragments of a whole picture.

Our paradigm of comparing "viewing" scanpaths with "imagery" scanpaths was first carried out by Brandt and Stark (1997), using just one kind of abstract stimulus and a small number of healthy subjects. They were able to show that after presentation of a stimulus to the subjects, eye movements also occur in the subsequent imagery phase. Furthermore, using string editing methods in the scanpath analysis, they found that these scanpaths were not random but similar to those of the viewing phase.

### Homonymous Hemianopia and Rehabilitative Aspects

Hemianopia, defined as a complete visual field defect, is divided into different forms according to the site of the lesion. The predominantly occurring homonymous form usually shows macular sparing. The ischemic cerebrovascular event is a common etiology of this disorder followed by bleeding and trauma. Often, hemianopia is associated with other cognitive dysfunctions like aphasia and visual hemineglect. Rossi, Kheyfets, and Reding (1990) found that more than 20% of patients with stroke treated in rehabilitation centers expose hemianopic symptoms. The impact of this sensory deficit depends on size and localization of the lesion, impairing patients in visual information processing in many ways. Hemianopia usually leads to problems exploring the blind hemifield causing patients to perform hypometric, low-amplitude saccades and handicaps them more or less severely in orientation and safety in everyday living. Prospective studies of the natural course of vascular retrogenicular visual field defects show that spontaneous restitution (e.g., axon sprouting) in the blind hemifield takes place within the first 6 months after the event and that the average visual field gain is about 16% (Messing & Gänshirt, 1986; Hier, Mondlock, & Kaplan, 1983) in perimetry. To some degree, oculomotor training strategies can compensate the sensory deficit (Schöpf & Zangemeister, 1993; Zangemeister, Meien-

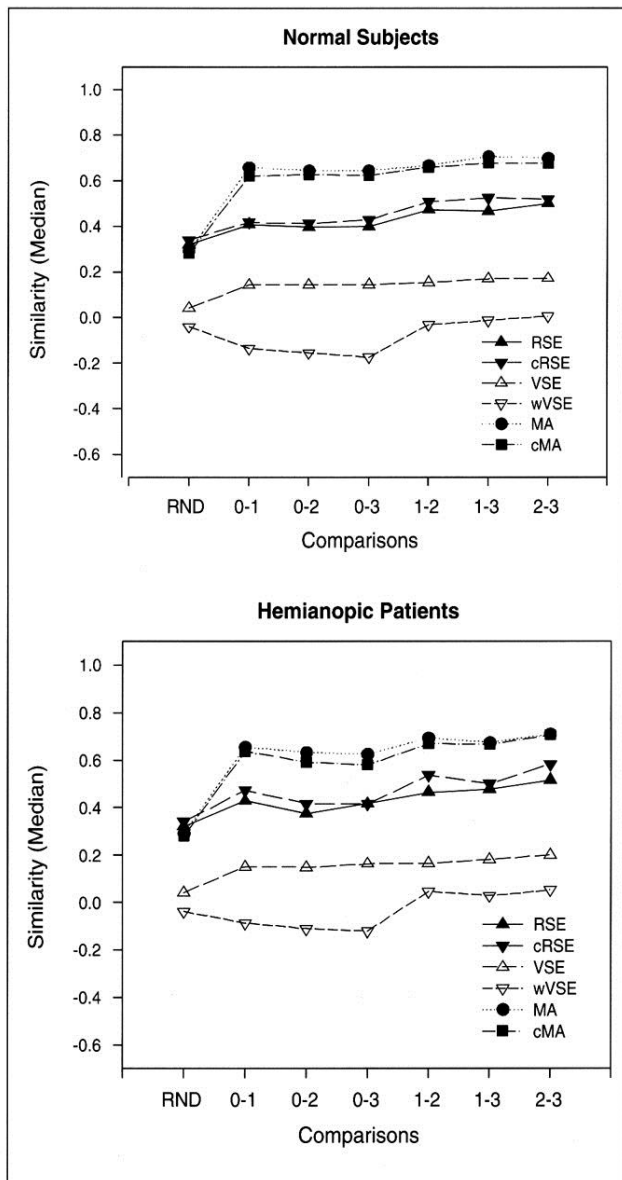


**Figure 2.** Cumulative data representative of basic scanpath parameters during visual imagery and viewing periods. Analogous results for the median of number of fixations, saccade amplitude, and fixation duration are shown for normals (NP) and patients (HA) with highly significant ( $p < .01$ ) differences.

berg, Stark, & Hoydt, 1982; Zangemeister, Dannheim, & Kunze, 1986; Meienberg, Zangemeister, Rosenberg, Hoyt, & Stark, 1981; Meienberg, 1983; Zihl, 1981; Zihl & Cramon, 1988; Gassel & Williams, 1963; Poppelreuter, 1917; Riddoch, 1917). Pommerenke and Markowitsch (1989) found that a specific systematic exploration practice through perimetric saccade training improves visuo-spatial orientation in these patients. Furthermore, Zangemeister, Poppensieker, and Hoekendorf (1999) investigated the influence of cognitive motor gaze con-

trol strategies on the rehabilitation of visual field defects in hemianopic patients and found significant improvement in their visual behavior after taking part in a special cognitive training of gaze control.

A study of Butter, Kosslyn, Mijovic-Prelec, and Riffle (1997) tested visual imagery in hemianopic patients with occipital lesions using special imagery and perceptual control tasks. Based on their results, they postulated impaired visual imagery in these patients because compared to a control group they performed worse in the imagery task when perceiving the stimulus ipsilateral to their visual field defect. They concluded that this result supports the view that visual imagery involves topographically organized visual areas of the occipital lobe.



**Figure 3.** Illustration of the median similarities resulting from each of the applied methods. Comparisons between random (RND), viewing (0) and imagery 1-3 (1, 2, 3) strings. Symbols and methods as shown in Figure 4.

The aim of our study was to obtain information about the consistency and reproducibility of internal visual image representations in hemianopic patients using top-down mechanisms (in the context of active “high-level vision”). Therefore, the question was whether, in comparison with healthy subjects, this mental image can be thought of as being intact despite the visuocortical sensory deficit.

RESULTS

Patients and Controls Basic Scanpath Parameters of Visual Imagery

At first we compared the basic gaze movement parameters: saccade amplitude, number of fixations, and fixation duration of both patient and healthy subjects groups in the viewing and in the subsequent imagery phases. For all subjects we found analogous results with significantly different parameters for the imagery scanpaths compared to the viewing scanpaths. The median saccade amplitudes and the median number of fixations were lower during the imagery phases in both groups. Correspondingly, the fixation duration was significantly higher in the imagery scanpaths than in the viewing scanpaths. This result was consistently reproducible for all picture stimuli as shown in Figure 2.

Common Results of Patients and Controls Scanpath Similarity Analysis

Comparing the similarities of the viewing scanpaths (marked as “0”) and of the imagery scanpaths (marked as “1,” “2” and “3”) we found with all applied methods higher similarities within the group of viewing versus imagery comparison (0–1, 0–2, 0–3 in Figures 3 and 4) and imagery versus imagery comparison (1–2, 1–3, 2–3 in Figures 3 and 4) than in comparison with the random strings. The imagery versus imagery string comparison resulted in higher similarities than the viewing versus imagery string comparison. This was reproducible and consistent both in single-subject analysis and in single-task (picture) analysis. Figure 3 shows the cumulative medians of the calculated similarity values of the hemianopic patients and of the control subjects for all comparisons with the random strings for all applied comparison methods. In Figure 4, a rank variance analysis including all comparison methods and the summary of significantly different medians are presented.

Hemianopic Patients

The first substantial result was a significantly higher similarity in viewing versus imagery and imagery versus

**Figure 4.** Result of the Kruskal and Wallis variance analysis on ranks. Where the medians of the methods are significantly different ( $p < .05$ ), the respective symbol is shown (▲ region-string editing, ▼ compressed region-string editing, Δ vector-string editing, ∇ weighted vector-string editing, ● Markov analysis, ■ compressed Markov analysis), otherwise (–). Results for the normal subjects are located above the main diagonal, those for the hemianopic patients below.

		Normal subjects							
		RND	0-1	0-2	0-3	1-2	1-3	2-3	
Hemianopic patients	RND		▲ △ ● ▼ ▽ ■	▲ △ ● ▼ ▽ ■	▲ △ ● ▼ ▽ ■	▲ △ ● ▼ - ■	▲ △ ● ▼ - ■	▲ △ ● ▼ - ■	Normal subjects
	0-1	▲ △ ● ▼ - ■		- - - - - -	- - - - - -	- - - ▼ ▽ -	- - - ▼ ▽ -	▲ - - ▼ ▽ -	
	0-2	- △ ● ▼ ▽ ■	- - - - - -		- - - - - -	▲ - - ▼ ▽ -	▲ - - ▼ ▽ -	▲ - - ▼ ▽ -	
	0-3	▲ △ ● ▼ ▽ ■	- - - - - -	- - - - - -		▲ - - ▼ ▽ -	▲ - - ▼ ▽ -	▲ △ - ▼ ▽ -	
	1-2	▲ △ ● ▼ - ■	- - - - ▽ -	▲ - - - ▽ -	- - - - ▽ -		- - - - - -	- - - - - -	
	1-3	▲ △ ● ▼ - ■	- - - - ▽ -	▲ - - - ▽ -	- - - - ▽ -	- - - - - -		- - - - - -	
	2-3	▲ △ ● ▼ - ■	- - - - ▽ -	▲ - - ▼ ▽ -	- - - ▼ ▽ -	- - - - - -	- - - - - -		
Hemianopic patients									



imagery comparisons than to the random strings. This result was consistent over all comparison methods (except for wVSE). Furthermore, we found a significantly increased similarity in the group of imagery versus imagery comparisons compared to the viewing versus imagery group, a result that could be reproduced with all methods applied. There were no significant differences in similarity among the three viewing versus imagery comparisons (0-1, 0-2, 0-3). The imagery versus imagery comparisons showed a trend (especially in the last two imagery phases, 2-3) to give the highest overall similarities although no significant difference could be shown between the imagery versus imagery comparisons (1-2, 1-3, 2-3). One reason for the smaller number of significant differences between viewing versus imagery and imagery versus imagery similarities in hemianopic patients compared to normal subjects is the higher variability in the distributions obtained for these patients.

If we look at the different comparison methods, we see that there basically is an analogous pattern of results for all of them (Figure 3). Highest similarity values (especially of gaze sequence comparisons against random strings) resulted from Markov analysis (MA, cMA). The lowest values were obtained with vector string editing methods (VSE, wVSE). In weighted vector string editing (wVSE) we found negative similarity values for viewing versus imagery comparisons, indicating a lower similarity as calculated for random strings with this method. Otherwise, the difference between viewing versus imagery and imagery versus imagery similarities shows the highest difference with this method.

There was no relevant difference for the compressed (cRSE, cMA) and the uncompressed (RSE, MA) variants of region string editing and Markov analysis.

### Normal Subjects

In general the medians found for our healthy control group were similar to the results of the hemianopic patients with no significance of the minor differences (Figures 3 and 4).

Accordingly we found reproducible significantly higher similarities in viewing versus imagery and imagery versus imagery comparisons compared to random strings for all methods (except for wVSE). Furthermore, there was a significantly higher median similarity in imagery versus imagery comparisons than in the viewing versus imagery comparisons just as it was in the patients group.

It should be noted that the lower variability in the distribution of results of the control group led to more significant results of viewing versus imagery comparisons versus imagery versus imagery comparisons corresponding to the analogous trends in the hemianopic patients (Figure 4).

## DISCUSSION

The basic findings can be summarized as follows: First, as formally described by Brandt and Stark (1997) subjects perform scanpaths during the imagery phase. Second, the imagery scanpaths exhibit specific characteristics (described in full detail further) that clearly distinguish them from the viewing scanpaths. The increased similarity of viewing and imagery scanpaths in all subjects points to a strong top-down component in the imagery scanpaths of both groups. The maximal similarity values within the imagery scanpaths indicate a "progressive consistency of imagery" in accordance with the evolution of a constant mental prototype of the viewed picture. The analogous results of our patients show preserved top-down mechanisms in this collective despite their sensory deficit.

### Common Visual Imagery Basic Scanpath Properties in Both Groups

The highly significant differences in basic imagery scanpath parameters (compared with the corresponding viewing scanpath) like saccade amplitude, number of fixations, and fixation duration could be summarized as "minimization" of the viewing scanpath. This strongly supports the identical findings of Brandt and Stark (1997), although in our picture presentations we explicitly provided a "reference frame" during the imagery period supplying our subjects with the dimension of the original stimulus. In accordance with their conclusions, we also think that these different spatial and temporal characteristics of the imagery scanpath (smaller saccades, longer and less fixations) can be explained by an underlying cognitive process in terms of the feature ring hypothesis. Rayner and McConkie (1976) formerly suggested in their process-monitoring hypothesis that eye movement parameters like fixation duration are obviously affected by the cognitive process occurring during fixation time. Thus, the sequential scanning of subfeatures (which constitute a complete scene) needs these prolonged fixations in the process of (re)constructing the mental image. The decreased saccade amplitudes indicate that in imagery there is no need for eye movements with the full-scale amplitudes like in perception, but just maintaining the correct relative spatial distances between the subfeatures of a complex scene seems to be sufficient for the generation of a regular mental image. We further think that the need for reduction of spatial properties for the underlying cognitive process is compatible with a serial time-consuming "feature ring" model of visual imagery in all subjects (regardless of a hemianopic deficit). It is worth noting that other investigators found a similar phenomenon, micropsia, in healthy volunteers after mescaline consumption (L. Stark, personal communication, 1998).

## String Comparison Methods

The evaluation of the different string comparison methods demonstrated that all implemented methods are suited for this kind of investigation. Their parallel usage seems to be rational as they supply complementary information. However, the similarities calculated by different methods are not directly comparable to each other; they rather show variant aspects of the scanpath tested. For example, the finding of the increased similarities cannot be explained by reduced repetitive fixations during the imagery phases. This is shown through the fact that the results for compressed (cRSE, cMA) and uncompressed (RSE, MA) variants do not differ.

We feel that Markov analysis (MA, cMA) turned out to be the most suitable string comparison method for comparison of viewing imagery scanpaths producing the highest similarity values. As this method describes the transition probability of fixations from one ROI to another it reflects in terms of gaze control on the cortical level the spatial aspect of “*where* does a fixation occur” reflecting functions located in the parietal lobe. The string editing methods (RSE, cRSE), on the other hand, did elucidate our finding of a “progressive consistency of imagery” with high string similarity correlations representing the *sequence* of fixations (“*when* does a fixation occur”), predominantly involving cortical structures like the prefrontal cortex and the SMA. Weakest correlations were found for the new vector string editing methods (VSE, wVSE) combining the sequence of saccades and their spatial vectorial orientation with the advantage of making a priori regionalisation unnecessary. While previous numeric simulations (Zangemeister & Oechsner, 1996) showed a superiority of the weighted vector string editing (wVSE) for comparison of gaze sequences against the unweighted vector string editing (VSE), we found this method, in comparison to the normal string editing and Markov analysis methods, unable to support our finding of similar imagery scanpaths in both groups. Further studies should clarify in which cases this method is suitable to describe and compare eye movements in human subjects.

## Progressive Consistency of Imagery Resulting from Top-Down Control in All Subjects

Eye movements performed within viewing and subsequent visual imagery are very similar in both healthy subjects and hemianopic patients. This indicates a strong top-down component in active looking for all subjects. It also supports the feature ring hypothesis by Noton and Stark (1971a,b), who hypothesized that eye movements are controlled by centrally coded processes rather than depending randomly on peripheral features (bottom-up). In their information processing approach to visual perception the repetitive sequences of eye movements are interpreted as a result of a control

sequence of representation coding “*what*” the subfeatures of a picture are and “*where*” they are located in the scene. They already showed this in their eye movement recordings on ambivalent figures. Different subjects produced different but reproducible scanpaths if they were exposed to the same pictures (Stark & Ellis, 1981; Ellis & Stark, 1978). Another study could show a strong top-down component in more sophisticated viewers when looking at realistic versus abstract pictures (Zangemeister, Oechsner, et al., 1995). This stands in contrast to studies, which suggest that peripheral vision might be the major force driving the scanpath (Parker, 1978). Our experiments concerning the visual imagery process provide additional evidence for the top-down nature of the human scanpath even in patients with the sensory deficit of homonymous hemianopia. According to the abovementioned visual perception studies, the subjects in our experiment first naively scanned an unknown picture in a mixture of bottom-up (new features/patterns) and top-down (recognition of known features/patterns) strategies. Within a few seconds, they constructed a mental image that was reproduced constantly and with increasing similarity as we could show in our scanpath similarity analyses. Thus, we can conclude that the content of the viewed scene is stored in a mental image that can be accessed through the top-down driven scanpaths during visual imagery. Brandt and Stark (1997) already found this in healthy subjects using an abstract stimulus for presentation and string editing methods for similarity analysis. They could demonstrate that in healthy subjects eye movements are made during visual imagery and that the imagery scanpath is not random but reflects the content of the visualized scene. We confirmed this in our study using several different visual stimuli and furthermore could show that in subsequent imagery phases the similarities between the imagery scanpaths increase. We refer to this as “progressive consistency of imagery” and assume that this is a consequence of consolidation of the mental image.

However, our special interest was the behavior of the hemianopic patients. Would it be correct to assume a different and probably impaired visual imagery in a subject with unilateral occipital damage? There seems to be no relevant difference in the gaze control of the patients compared to our control subjects. Thus, top-down processes seem to play an important role in our patients as well. Compensatory eye movements into the blind hemifield play a crucial role in the perception process of these patients (Zangemeister et al., 1982, 1986, 1996; Zihl, 1981; Zihl & Cramon, 1988). Most of the patients showed no exploration problems into the blind hemifield during the stimulus presentation phase of our experiment, indicating a generally high degree of adaptation to the impairment. We think that although complete perception for these patients requires increased oculomotor activity and, presumably, adaptation

and reorganization of their initial scanpath, they seem to use similar top-down strategies using a reproducible cognitive model for imagery just like normals do. In the literature, controversial sights about visual imagery in sensory deficit patients are found. Several investigators have reported loss of imagery for objects, faces, or spatial relations after extensive bilateral occipital injury although other investigators did not (Goldenberg, 1993; Goldenberg, Mullbacher, & Nowak, 1995). There are also reports about spared imagery in the context of perceptual (agnostic) deficits (Behrmann, Winicur, & Moscovitch, 1992; Jankowiak, Kinsbourne, Shalev, & Bachmann, 1992), and one study (Chatterjee & Southwood, 1995) asserted that at least some forms of imagery may exist even following cortical blindness. Kosslyn (1994) expected that imagery would exist even after some forms of perceptual disruption, because not all perceptual organization processes are necessary for imagery. Butter et al. (1997) were the first to study the visual imagery capacity of a small group of patients with homonymous hemianopia (due to unilateral occipital infarcts) using a defined task demanding the patients to report information about orientation and spatial relations of symbols in both hemifields. They found a significantly higher rate of errors in imagery of objects ipsilateral to their hemianopia than in the contralateral field and concluded that these patients have field-specific deficits in imagery supporting the view that visual imagery involves topographically organized visual areas of the occipital cortex.

### Implications for the Visual Cognitive Model

Putting our results into the context of the question of functionally identical cortical structures for visual perception and visual imagery we deduce that there must be a common central processing mechanism for both cognitive functions. The crucial role (in terms of the feature ring hypothesis) of the eye movements (scanpaths) measured by us is supported by a PET study (Gulyas, Persson, Stone-Elander, & Eriksson, 1992). Gulyas et al. demonstrated that the cortical regions that are homologous to the frontal eye fields controlling eye movements in monkeys showed a marked increase in metabolic activity during visual imagery. Interestingly, their subjects had a considerable level of eye movement activity, although they were requested to suppress eye movements during imagery. Another study using repetitive transcranial magnetic stimulation (rTMS) by Brandt, Ploner, Meyer, Leistner, and Villringer (1998) localized the connection of sensory and motor components of the visual systems. Stimulation of different cortical areas revealed a parieto-prefrontal network for the representation of visuospatial information. In their paradigm, they decreased "memory-guided" saccade acuity selectively when stimulating the dorsolateral prefrontal cortex (DLPFC) and the posterior parietal cortex (PPC).

Zangemeister, Canavan, & Hoemberg (1995) previously already reported disturbed predictive saccades when stimulating frontal and parietal cortex with TMS.

Further structural and functional experimental evidences (see introduction) using different electrophysiological and neuroimaging techniques support the concept of a shared representational medium for imagery and perception. As already mentioned, the integration of these results into a model that takes into account a shared representation of perception and imagery was done by Kosslyn and Shin (1994) and Farah and Ratcliff (1994). They postulated a retinotopically organized "visual buffer" (V1) that should serve as the visual working memory presenting visual information from outside (perception) and from inside (visual imagery generated by higher level cortical areas). However, one of the main theoretical problems of this buffer obviously is the capacity of information that can be stored parallel at a time. Presumably, there is just a restricted amount of visual information that can be presented at a time. This favors a sequential activation of visual memory content from underlying long-term representations in accordance with the scanpath feature ring theory, as additional mechanism for presenting complex scenes without overloading the "visual buffer."

But what kind of implications follow from the results of our hemianopic patients, who showed no significant deviations in their scanpath performance from normal subjects? One might hypothesize that impaired perception due to unilateral damage in the striate cortex ("visual buffer") obligatory leads to deficits in imagery as shown by Butter et al. (1997) in a different paradigm. Considering the fact that most of our patients had unilateral occipital cortical lesions in the CT scans (of different extent and in some patients involving adjacent areas but mainly confined to the occipital area) we found that the cardinal process of constructing a mental prototype of the viewed image that can be reliably reproduced, as shown by the gaze movement analysis, must be intact. Thus, undamaged extrastriate areas that project the mental prototypes must exist in these patients. But in what kind of "buffer" do they project if the medial ipsilateral occipital cortex does not exist anymore? In terms of brain plasticity, one possible explanation lies in the projection of the internal representation into the intact contralesional low-level brain regions via associate extrastriate connections through the corpus callosum. But apart from the construct of a "visual buffer" the crucial reason for the preserved patterns of eye movements in our patients are the intact extrastriate temporo-parietal mechanisms, which include a map of space (see Mesulam, 1990) and guide the eye movements. However, although our study can tell us something about intact top-down processes in these patients, it might not be appropriate to tell us about a possible loss of "quality" of these patients' imageries when using an imagery task paradigm like Butter et al. (1997).



Nevertheless, maintained top-down vision with the capability of forming a stable mental representation of the stimulus as shown here would also be a promising base for a rehabilitative cognitive training of such patients. First positive reports of such attempts can be found in Zangemeister et al. (1999).

On the basis of these results larger studies with different paradigms and a subdivision into adapted patients (most patients in our study and the other studies were relatively well adapted to their deficit) and patients in a very early phase after the lesion (Zangemeister, 1997; Zangemeister et al., 1999) would be valuable to confirm and elaborate these findings.

## METHODS

### Subjects and Apparatus

The patient group consisted of 14 subjects from our university hospital with predominant homonymous hemianopia. The age range was 20–77 (median 53 years), the etiology of the sensory deficit was heterogeneous (mostly stroke, trauma, operation), as was the degree of adaptation to the deficit (varying from 5 days to 16 years, median 8 months). Perimetry showed left hemifield blindness in seven patients, right hemifield blindness in six patients, and a bitemporal deficit in one. All patients showed foveal sparing in perimetry, no relevant oculomotor or cognitive dysfunctions, and no neglect syndromes either. In the control group, 20 normal subjects participated in our study. They did not show current or preceding neurological disorders and their age ranged from 19 to 58, median 26 years.

We used a 21-in. monitor and a head fixation device for the presentation of stimuli to the subjects. Under standardized conditions, the eye movements were recorded with infrared reflection oculography (ASL 210). The sampling rate was 200 Hz, the overall band width 100 Hz, and the resolution 0.1°.

### Experimental Protocol

Each subject was measured during a standardized routine that consisted of one stimulus presentation phase and three subsequent imagery phases. We used six different stimuli that were all bordered by a reference frame. The subjects first had 10 sec for viewing the presented picture according to varying instructions (see Table 1). In the following three separate imagery phases the subjects were asked to recall the pictures by looking at the blank reference frame on the monitor and scan it freely from their imagination (Figures 5 and 6).

The first two presentations (Picture 1 served as “training” picture for acquiring of some routine with the task and was excluded from analysis) were used to measure the so-called “searchpath,” containing the task of searching objects within a picture. The next four pic-

**Table 1.** Pictures Shown and Associated Tasks for the Viewing Period (Before Imagery)

<i>Title</i>	<i>Task</i>
Training picture	Arrow search
Landscape	Search for blue trees
Checkerboard	Free viewing
Ambiguous picture	Interpretation change
Lady face	Free viewing
Pool player	Free viewing

tures showed abstract, ambiguous, and realistic stimuli. During this phase, different scanpath tasks of increasing cognitive complexity were performed (Table 1).

### Data Analysis

The analysis was carried out with standardized computer programs that included evaluation of basic saccade parameters first using Student's *t* test and the Whitney rank sum test ( $p < .05$ ) for group comparison. We calculated the viewing/imagery scanpath similarities using all the comparison methods mentioned below.

Kruskal and Wallis (1952) rank variance analysis with  $p < .05$  was performed in the visual imagery evaluation for comparing the similarities of the computed strings (random, viewing, imagery I–III).

### Methods for the Comparison of Eye Movements

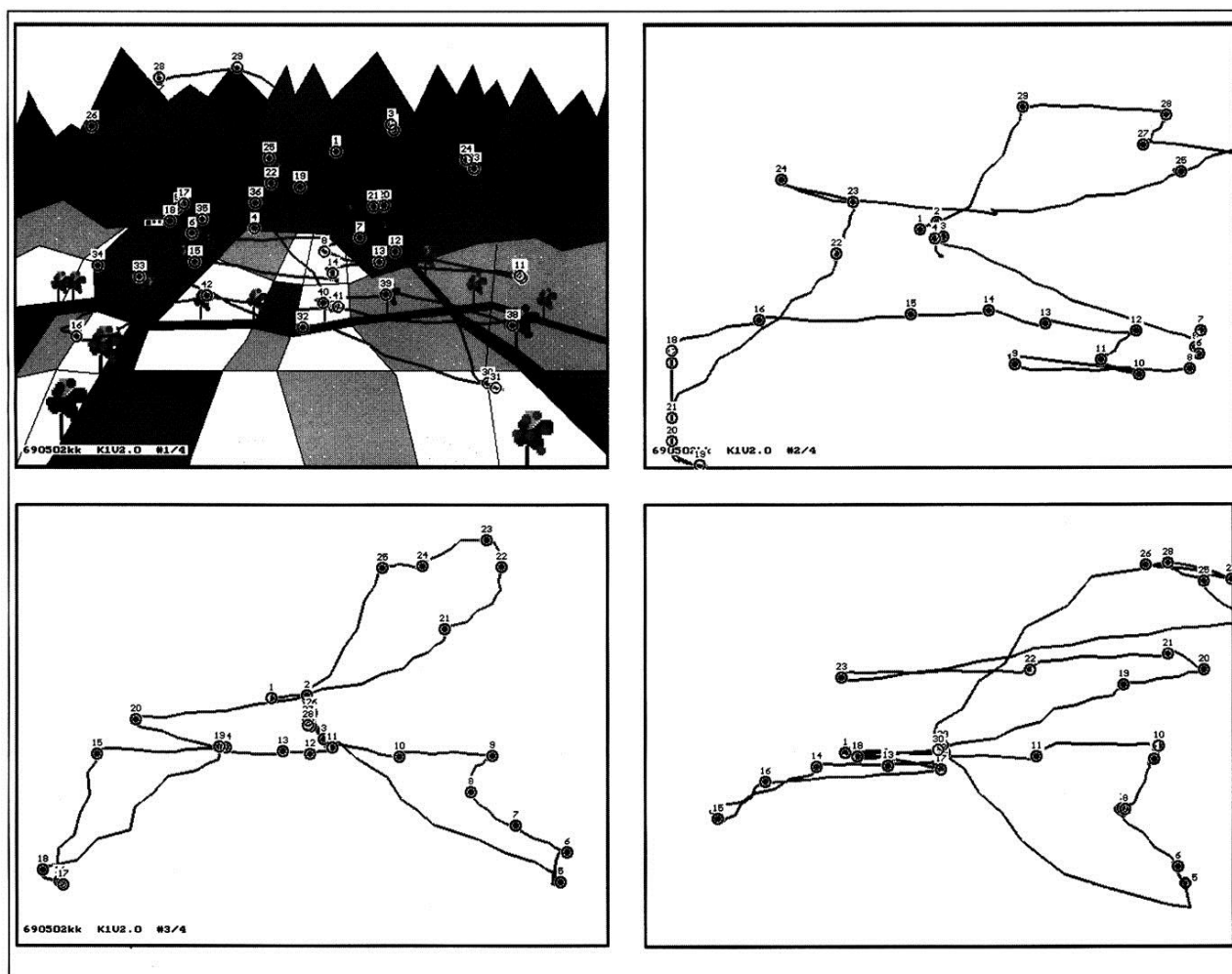
#### *Methods With A Priori Regionalization:*

##### *Markov Analysis and String Editing*

Most frequently used methods for the comparison of scanpaths (Choi, Mosley, & Stark, 1995; Zangemeister, Oechsner, et al., 1995; Zangemeister & Oechsner, 1996; Hacısalihzade, Stark, & Allen, 1992; Stark & Ellis, 1981; Stark & Choi, 1996) first divide the presented picture into regions (ROIs) and attach unique labels to each region (e.g., letters). We also chose a priori principal interesting features of our visual stimuli to regionalize them into different ROIs. Substituting each fixation with the letter of the ROI in which it is located leads from the sequence of fixations to a sequence of ROI labels. Afterwards, these strings representing the gaze sequences can be compared using Markov analysis (Rabiner, 1986; Kemeny & Snell, 1983; Dynkin & Juschkewitsch, 1969) or string editing (Sankoff & Kruskal, 1983; Wagner & Fischer, 1974; Morgan, 1970).

**Markov analysis.** First-order Markov analysis (MA) calculates the transition probability between two conditions, for example, the probability that ROI “C” is fixated just before ROI “A” is fixated. These transition probabilities can appropriately be described by matrices,





**Figure 5.** Illustration of the recorded viewing/imagery saccade-fixation sequences, scanpaths (SP), in a normal subject, second picture. First, in the viewing phase (left upper SP) the landscape picture is scanned (for the blue trees) with a searchpath. After 5 sec the first imagery of the picture is done (right upper SP), subsequently after 30 sec (left lower SP) and 60 sec (right lower SP), imagery 2 and 3. The similarity between viewing and imagery SPs and among the three imagery SPs apparently could be shown here. In this scanpath presentation the fixations were calculated off-line, marked (circles), and numbered.

where matrix element  $p_{ij}$  represents the possibility, that condition (ROI)  $i$  is followed by condition (ROI)  $j$ . Hacısalihzade et al. (1992) developed a model based on a Markov analysis for the comparison of ROI strings. The Markov distance between two sequences of fixations was defined as average total difference of the respective Markov matrix elements.

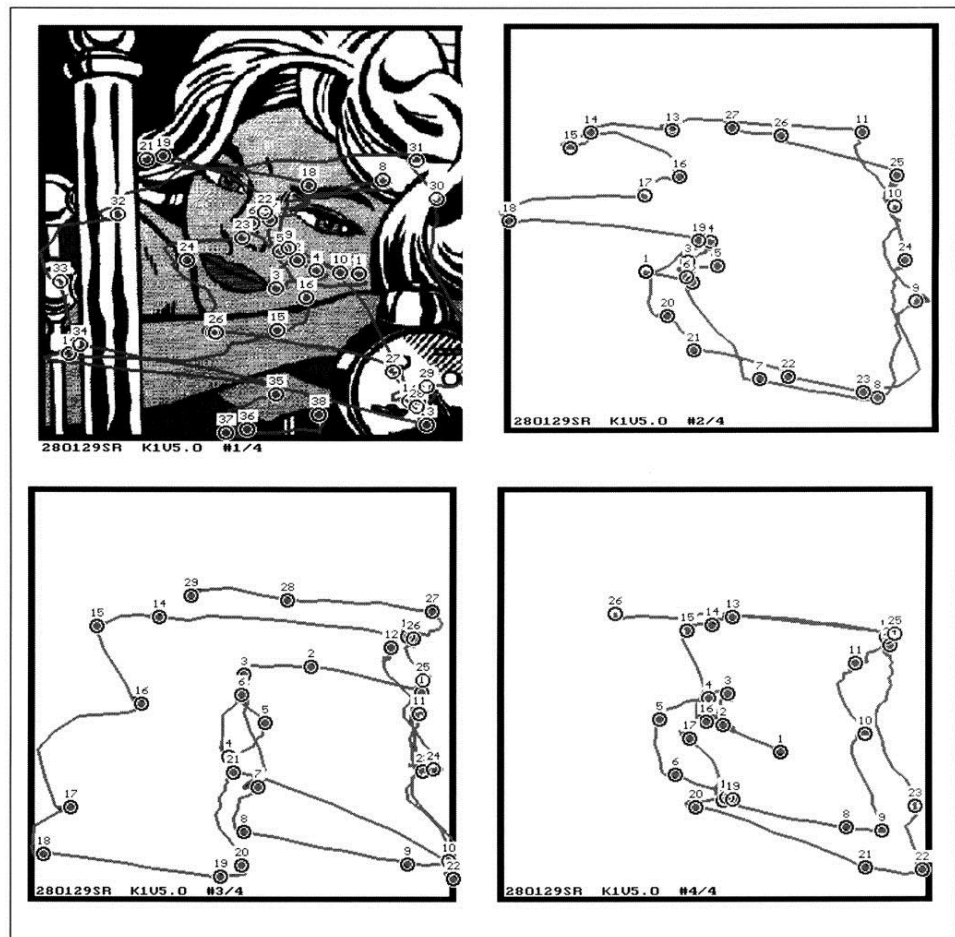
**String editing.** In string editing, the minimal number of editing operations such as deleting, inserting, or substituting of letters needed to transfer one string into the other is calculated (Sankoff & Kruskal, 1983; Wagner & Fischer, 1974; Morgan, 1970). For example, "ROOM" is turned to "GLOOM" inserting "G" at the beginning and substituting "R" for "L." Weights or costs are assigned to these editing operations, so insertion and deletion cost "1," substitution "2." Thus, there is a string distance (D) of 3 between "ROOM" and "GLOOM."

For both Markov analysis and string editing there exists a variant in which repetitive identical letters are removed before analysis. In this "string compression" variant, multiple repetitive fixations in one ROI are summarized to one fixation (Choi et al., 1995). This compressed form of region string editing (RSE) is known as "compressed" RSE (CRSE); for Markov analysis (MA) the corresponding form is compressed MA (cMA).

#### *Methods Without Regionalization: Vector String Editing*

To avoid a priori regionalization of a picture in vector string editing (VSE), a discretization of the fixation connecting saccades is done. These saccades are described by vectors between the fixations. The saccade angles are split up into  $n$  direction intervals and the lengths into  $m$  length intervals. These bins define a saccade vector alphabet. The real saccade vector is replaced by the most similar vector from the alphabet,

**Figure 6.** Illustration of the recorded viewing/imagery saccade-fixation sequences, scanpaths (SP), in a hemianopic patient, fifth picture. First, in the viewing phase (left upper SP) the lady face picture ("blonde waiting," R. Lichtenstein) is scanned. After 5 sec, the first imagery of the picture (right upper SP) is performed; after 30 sec (left lower SP) and 60 sec (right lower SP), imagery 2 and 3 follow. The similarity between viewing and imagery SPs apparently could be shown in this example. In this scanpath presentation the fixations were calculated off-line, marked (circles), and numbered.



thereby defining a representation of the gaze sequence through a "vector string."

We tested two variants of this method. In the first variant, the same string editing methods as for the region strings were applied. The second variant, referred to as weighted vector string editing (wVSE), assigns the lengths of the inserted or deleted vectors as costs to the editing operations insert or delete and using the amount of the difference vector in case of replacements.

### Similarity Measures for Gaze Sequences

A similarity measure  $S = 1 - D/D_{\max}$  (referred to as "S" for similarity) between two compared strings is obtained by standardization with the actual string distance ( $D$ ) and the maximal distance ( $D_{\max}$ ) of both of these strings. This results in similarity values in the range from 0 to 1 where the value 1 reflects an identical result of comparison and 0 maximal dissimilarity of compared strings. Using the included direction information in weighted vector string editing the similarity measure  $S$  was defined as  $S = 1 - 2D/D_{\max}$ . Identical vector strings then have the similarity  $S = 1$ , those strings that describe opposite paths amount to  $S = -1$ . For all

methods, we used randomly generated "random strings" as reference.

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### REFERENCES

- Behrmann, M., Winicur, G., & Moscovitch, M. (1992). Dissociation between mental imagery and object recognition in a brain-damaged patient. *Nature*, 359, 636-637. [Comments in *Nature* 1992; 359: 590-591.]
- Brandt, S., Ploner, C., Meyer, B.-U., Leistner, S., & Villringer, A. (1998). Effects of repetitive transcranial magnetic stimulation over dorsolateral prefrontal and posterior parietal cortex on memory-guided saccades. *Experimental Brain Research*, 118, 197-204.
- Brandt, S., & Stark, L. W. (1997). Spontaneous eye movements during visual imagery reflect the content of the visual scene. *Journal of Cognitive Neuroscience*, 9, 27-38.
- Butter, C. M., Kosslyn, S., Mijovic-Prelec, D., & Riffle, A. (1997). Field-specific deficits in visual imagery following hemianopia due to unilateral occipital infarcts. *Brain*, 120, 217-228.
- Chatterjee, A., & Southwood, M. H. (1995). Cortical blindness and visual imagery. *Neurology*, 45, 2189-95.

- Choi, Y. S., Mosley, A. D., & Stark, L. W. (1995). String editing analysis of human visual search. *Optometry and Vision Science*, 72, 439–451.
- Dynkin, E. B., & Juschkevitch, A. A. (1969). *Sätze und Aufgaben über Markoffsche Prozesse*. Heidelberg, Germany: Springer-Verlag.
- Ellis, S. R. & Stark, L. (1978). Eye movements during viewing of Necker cubes. *Perception*, 7, 575–581.
- Farah, M., Peronnet, F., Gonon, M. A., & Girard, M. H. (1988). Electrophysiological evidence for a shared representational medium for visual images and visual percepts. *Journal of Experimental Psychology: General*, 117, 248–57.
- Farah, M., & Ratcliff, G. (1994). *The neuropsychology of high-level vision*. Collected tutorial essays.
- Gassel, M. M., & Williams, D. (1963). Visual function in patients with homonymous hemianopia. Part 2. Oculomotor mechanisms. *Brain*, 86, 1–36.
- Goldenberg, G. (1993). The neural basis of mental imagery. Review. *Bailliere's Clinical Neurology*, 2, 265–286.
- Goldenberg, G., Mullbacher, W., & Nowak, A. (1995). Imagery without perception—a case of anosognosia for cortical blindness. *Neuropsychologia*, 33, 1373–82.
- Goldenberg, G., Poderka, I., Steiner, M., Suess, E., & Deecke, L. (1989). Regional cerebral blood flow patterns in visual imagery. *Neuropsychologia*, 27, 641–664.
- Gulyas, B., Persson, H., Stone-Elander, S., & Eriksson, L. (1992). Neuroimaging studies in visual imagery of reading with positron emission tomography (PET), nuclear magnetic resonance (MR) imaging and brain electric activity mapping (BEAM). *European Journal of Neuroscience*, Supplement, 5, 22.
- Hacisalihzade, S. S., Stark, L. W., & Allen, J. S. (1992). Visual perception and sequences of eye movement fixations: A stochastic modeling approach. *IEEE Transactions Systems, Man, Cytb.*, 22, 474–481.
- Hebb, D.O. (1968). Concerning imagery. *Psychological Review*, 75, 466–477.
- Hier, D. B., Mondlock, J., & Caplan, L. R. (1983). Recovery of behavioural abnormalities after right hemisphere stroke. *Neurology*, 33, 345–350.
- Jankowiak, J., Kinsbourne, M., Shalev, R. S., & Bachmann, D.L. (1992). Preserved visual imagery and categorization in a case of associative visual agnosia. *Journal of Cognitive Neuroscience*, 4, 119–31.
- Kemeny, J. G. & Snell, J. L. (1983). *Finite Markov Chains*. New York: Springer.
- Kosslyn, S. M. (1994). *Image and brain*. Cambridge: MIT Press.
- Kosslyn, S. M., Alpert, L. M., Thopson, W. L., Maljkovic, V., Weise, S. B., Chabris, C. F. et al. (1993). Visual mental imagery activates topographically organized visual cortex: PET investigations. *Journal of Cognitive Neuroscience*, 5, 263–287.
- Kosslyn, S. M., & Shin, L. M. (1994). Visual mental images in the brain: Current issues. In M. Farah & G. Ratcliff (Eds.), *The neuropsychology of high-level vision, collected tutorial essays* (pp. 269–296).
- Kruskal, W. H., & Wallis, W. A. (1952). Use of ranks in one-criterion variance analysis. *Journal of the American Statistical Association*, 47, 583–621.
- LeBihan, D., Turner, R., Zeffiro, T. A., Cunod, C. A., Jezzard, P., & Bonnerot, V. (1993). In D. LeBihan, R. Turner, M. Mosley, & J. Hyde (Eds.) *Functional MRI of the brain: A workshop presented by the Society of Magnetic Resonance in Medicine and the Society for Magnetic Resonance Imaging*. Society of Magnetic Resonance in Medicine, 183–190.
- Meienberg, O. (1983). Clinical examination of saccadic eye movements in hemianopia. *Neurology*, 33, 1311–1315.
- Meienberg, O., Zangemeister, W. H., Rosenberg, M., Hoyt, W. F., & Stark, L. W. (1981). Saccadic eye movement strategies in patients with homonymous hemianopia. *Annals of Neurology*, 9, 537–544.
- Messing, B., & Gänshirt, H. (1986). Spontanverlauf vaskulärer, retrogenikulärer Gesichtsfeldstörungen. *Verhandlungen der Deutschen Gesellschaft für Neurologie*, 1986, 228–236.
- Mesulam, M. M. (1990). Large-scale neurocognitive networks and distributed processing for attention, language and memory. *Annals of Neurology*, 28, 597–613.
- Morgan, H. L. (1970). Spelling correction in system programs. *Communications of the ACM*, 13, 90–94.
- Noton, D., & Stark, L. W. (1971a). Eye movements and visual perception. *Scientific American*, 224, 34–43.
- Parker, R. E. (1978). Picture processing during recognition. *Journal of Experimental Psychology: General*, 4, 284–292.
- Pommerenke, K., & Markowitsch, H. J. (1989). Rehabilitation training of homonymous visual field defects in patients with postgeniculate damage of the visual system. *Restorative Neurology and Neuroscience*, 1, 47–63.
- Poppelreuter, W. (1917). *Die psychischen Schädigungen durch Kopfschuß im Kriege*, vol. 1, *Die Störungen der niederen und höheren Sebleistungen durch Verletzungen des Okzipitalhirns*. Leipzig, Germany: Voss.
- Rabiner, L. R. (1986). A tutorial on hidden Markov models and selected applications in speech recognition. *Proceedings of the IEEE*, 77, 257–286.
- Rayner, K., & McConkie, G. W. (1976). What guides a reader's eye movements? *Vision Research*, 16, 829–837.
- Riddoch, G. (1917). Dissociation in visual perception due to occipital injuries, with special reference to appreciation of movement. *Brain*, 40, 15–57.
- Roland, P. E., & Gulyas, B. (1994a). Visual representations of scenes and objects: retinotopic or non-retinotopic? *Trends in Neurosciences*, 17, 294–297.
- Rossi, P. W., Kheifets, S., & Reding, M. J. (1990). Fresnel prisms improve visual perception in stroke patients with homonymous hemianopia or unilateral visual neglect. *Neurology*, 40, 1597–1599.
- Sankoff, D., & Kruskal, J. B. (1983). *Time warps, string edits, and macromolecules: The theory and practice of sequence comparison*. Reading, MA: Addison-Wesley.
- Schoepf, D., & Zangemeister, W. H. (1993). Correlation of coordinated gaze strategies to the status of adaptation in patients with hemianopic visual field defects. *Annals of the New York Academy of Sciences*, 682, 404–409.
- Stark, L. W., Azzariti, M., Blackmon, T., Chernyak, D., Ho, Y. F., Privitera, C.M., & Yang, H. (1999). *Representation of human vision in the brain: How does human perception recognize images?* Memorandum No. UCB/ERL M99/49. Berkeley: Electronics Research Laboratory.
- Stark, L. W., & Choi, Y. S. (1996). Experimental metaphysics: The scanpath as an epistemological mechanism. In W. H. Zangemeister, H. S. Stiehl, & C. Freksa (Eds.), *Visual attention and cognition* (pp. 3–69). Amsterdam: Elsevier.
- Stark, L. W., & Ellis, S. (1981). Scanpaths revisited: Cognitive models in active looking. In B. Fisher, C. Monty, & M. Sanders (Eds.), *Eye movements, cognition and visual perception* (pp. 193–226). NJ: Erlbaum.
- Treisman, A., & Gelade, G. (1980). A feature integration theory of attention. *Cognitive Psychology*, 12, 97.
- Wagner, R. A., & Fischer, M. J. (1974). The string-to-string correction problem. *Journal of the ACM*, 21, 168–173.
- Zangemeister, W. H. (1997). Virtual reality hemianopic scotomas induce eccentric fixation: Scanpath strategies to optimize high level vision in healthy subjects. *IEEE 97CH36136-EMBS*, 561–570.
- Zangemeister, W. H., Canavan, A. G. M., & Hoemberg, V.

- (1995). Frontal and parietal transcranial magnetic stimulation (TMS) disturbs programming of saccadic eye movements. *Journal of the Neurological Sciences*, 133, 42–52.
- Zangemeister, W. H., Dannheim, F., & Kunze, K. (1986). Adaptation of gaze to eccentric fixation in homonymous hemianopia. In E. L. Keller, & D. S. Zee (Eds.), *Adaptive processes in visual and oculomotor systems*. Pergamon Press.
- Zangemeister, W. H., Meienberg, O., Stark, L., & Hoydt, W. F. (1982). Eye-Head Coordination in Homonymous Hemianopia. *Journal of Neurology* 225, 243–254.
- Zangemeister, W. H., & Oechsner, U. (1996). Evidence for scanpaths in hemianopic patients shown through string editing methods. In W. H. Zangemeister, H. S. Stiehl, & C. Freksa (Eds.), *Visual attention and cognition* (pp. 197–221).
- Zangemeister, W. H., & Oechsner, U. (1999). Adaptation to visual field defects with virtual reality scotoma in healthy subjects. *Current oculomotor research* (pp. 89–95). New York: Plenum.
- Zangemeister, W. H., Oechsner, U., & Freksa, C. (1995). Short-term adaptation of eye movements in patients with visual hemifield defects indicates high level control of human scanpath. *Optometry and Vision Science*, 72, 467–477.
- Zangemeister, W. H., Poppensieker, K., & Hoekendorf, H. (1999). *Kognitive Gesichtsfeldrehabilitation mittels Strategien-koordinierter Blickmotorik*. Aachen, Germany: Shaker Verlag.
- Zangemeister, W. H., Stiehl, H. S., & Freksa, C. (1996). *Visual attention and cognition* (404 pp). Amsterdam: Elsevier.
- Zeki, S. (1976). The functional organization of projections from striate to prestriate visual cortex in the rhesus monkey. *Cold Spring Harbor Symposia on Quantitative Biology*, 40, 591–600.
- Zeki, S. (1978). Uniformity and diversity of structure and function in rhesus monkey prestriate cortex. *Journal of Physiology (London)*, 277, 273–290.
- Zeki, S. (1983). The distribution of wavelength and orientation selective cells in different areas of monkey visual cortex. *Proceedings of the Royal Society of London, Series B: Biological Sciences*, 217, 449–470.
- Zeki, S. (1993). *A vision of the brain* (pp. S. 22–32). Oxford: Blackwell Scientific.
- Zihl, J. (1981). Recovery of visual functions in patients with cerebral blindness: Effect of specific practice with saccadic localization. *Experimental Brain Research*, 44, 159–169.
- Zihl, J., & Cramon, D. (1988). *Neuropsychologische rehabilitation* (pp. 105–131).