

# Spontaneous Eye Movements During Visual Imagery Reflect the Content of the Visual Scene

**Stephan A. Brandt**

Charité, Humboldt-University, Berlin, Germany

**Lawrence W. Stark**

University of California, Berkeley

## Abstract

■ In nine naïve subjects eye movements were recorded while subjects viewed and visualized four irregularly-checked diagrams. Scanpaths, defined as repetitive sequences of fixations and saccades were found during visual imagery and viewing. Positions of fixations were distributed according to the spatial arrangement of subfeatures in the diagrams. For a particular

imagined diagrammatic picture, eye movements were closely correlated with the eye movements recorded while viewing the same picture. Thus eye movements during imagery are not random but reflect the content of the visualized scene. The question is discussed whether scanpath eye movements play a significant functional role in the process of visual imagery. ■

## INTRODUCTION

Do the eyes scan a visualized image in much the same way as they look at an external scene or object? This question was already raised by Hebb (1968) in a theoretical analysis of imagery in his conceptual framework of cell assemblies. Hebb proposed that eye movements have an essential organizing function in visual imagery suggesting that "if the image is a reinstatement of the perceptual process it should include eye movements." As in perception, eye movements would serve to put together the part-images, which then construct the visualized image. Neisser (1967) following the idea that imagining activates a "top down" process of perceptual representation and speculated that the better a visualized image, the more likely eye movements are involved.

Early studies (Jacobson, 1932; Lorenz & Darrow, 1962) reported increased oculomotor activity during visualization and during mental arithmetic. In a nonquantitative approach, Totten (1935) actually measured eye movements with a photographic technique and suggested that eye movements commonly correspond to the shape of the object the subject was instructed to visualize. Several groups later attempted to find experimental support for the notion that visualized image quality corresponds to occurrence of eye movements by relating vividness ratings to overall ocular activity during active visual imagery. Hale and Simpson (1970) obtained equal vividness ratings when subjects had to either fixate a target, when

they were encouraged to move their eyes or when eye movements were imagined. Brown (1968) compared the ocular activity of vivid and poor visualizers during imagined pursuit and found no consistent differences between groups. Marks (1973) recorded eye movements and correlated an overall rate of ocular activity with the subjective vividness of pictures in a memory task. He found no evidence that vivid visualizers showed more scanning activity than a group of subjects operationally defined to be poor visualizers.

Some excitement was caused by Decker's technique provoking smooth pursuit eye movements through imagining a moving stimulus such as a swinging pendulum (Decker, 1964). Later more careful analysis substituted quasi-sinusoidal strings of saccadic eye movements for real smooth pursuit eye movements (Zikmund, 1966; Lenox, Lange, & Graham, 1970); nonetheless, these experiments showed eye movements actually measured during imagery.

Some support for the concept that eye movements play a role in imagery is related to the "looking at the dream picture theory." Originally suggested in 1892 by Ladd and extensively studied by Aserinsky and Kleitman (1953), Dement and Kleitman (1957), and Herman, Erman, Boys, Peiser, Taylor, and Roffwarg (1984), rapid eye movements (REM) during the paradoxical phase of sleep and dreaming were perhaps related to the visual content of the dream images. Subsequent studies cast doubt upon this theory (Moskowitz & Berger, 1969; Jacobs,

Feldman, & Bender, 1972). REM may also be observed in the sleep pattern of the congenitally blind (Gross, Byrne, & Fisher, 1965) and of kittens and monkeys reared in total darkness (Berger & Meier, 1965). In normal subjects a one-to-one relation between REM and dreaming was not observed. Reliable self-reporting of dream pictures is difficult to achieve and therefore a qualitative comparison to REM seems impossible. Accordingly, Kamiya (1961) has suggested that the relationship between eye movements and mental activity might be more profitably examined in the waking state.

A different approach using psychophysical methods shed light on the spatial characteristics of mental images. Scanning times were used as a measure for spatial distance between points in the visualized image (Kosslyn, 1973; Finke & Pinker, 1982). The scanning times were found to be linear with the spatial distance between points in the mental image, a finding that supported Kosslyn's (1978) theory of a visual working memory with intrinsic two-dimensional properties. Experiments with Necker cubes (Ellis & Stark, 1978) suggest that the output of the memory representation has a three-dimensional structure, even when viewing two-dimensional drawings. Mental rotation of three-dimensional objects (Shepard & Metzler, 1971; Cooper, 1975) also revealed spatial properties for visual imagery that are analogous to visual perception. Experiments showing that imagery can cause illusions and after-effects normally caused by visual perception (Finke & Schmidt, 1977) support the claim that imagery is not just spatial, but specifically visual.

Early studies on eye movements while subjects view scenes and pictures showed that visual exploration or search is not random, but that eye movements are related to the content of the scene (Stratton, 1902; Brandt, 1940; Buswell, 1935; Llewellyn-Thomas, 1968; Jeannerod, Gerin, & Pernier, 1968; and especially Yarbus, 1967). The pattern of eye movements, mainly consisting of fixations and saccades, could be altered by the pictures that were observed and by the instructed task. Noton and Stark (1971a, 1971b) experimentally measured sequences of eye movements while pictures were viewed and suggested that the repetitive sequences of saccadic eye movements, *the scanpath*, represented a playing out of an internal control sequence from a sensory-motor representation of a picture or scene in the brain.

So far no study has analyzed eye movement patterns during imagery and correlated the distribution of fixations and saccades with the visual content of the mental image nor with the eye movement patterns when viewing the picture that is to be imagined. The aim of the present study was to define patterns of eye movements, the scanpaths, while naïve subjects view a particular diagram, an artificial, irregularly-checked grid. We then compared this viewing pattern with the imagery pattern of eye movements while the subjects imagine that particular grid. Similarities and differences were determined quantitatively using string editing algorithms.

## RESULTS

### Eye Movement Characteristics

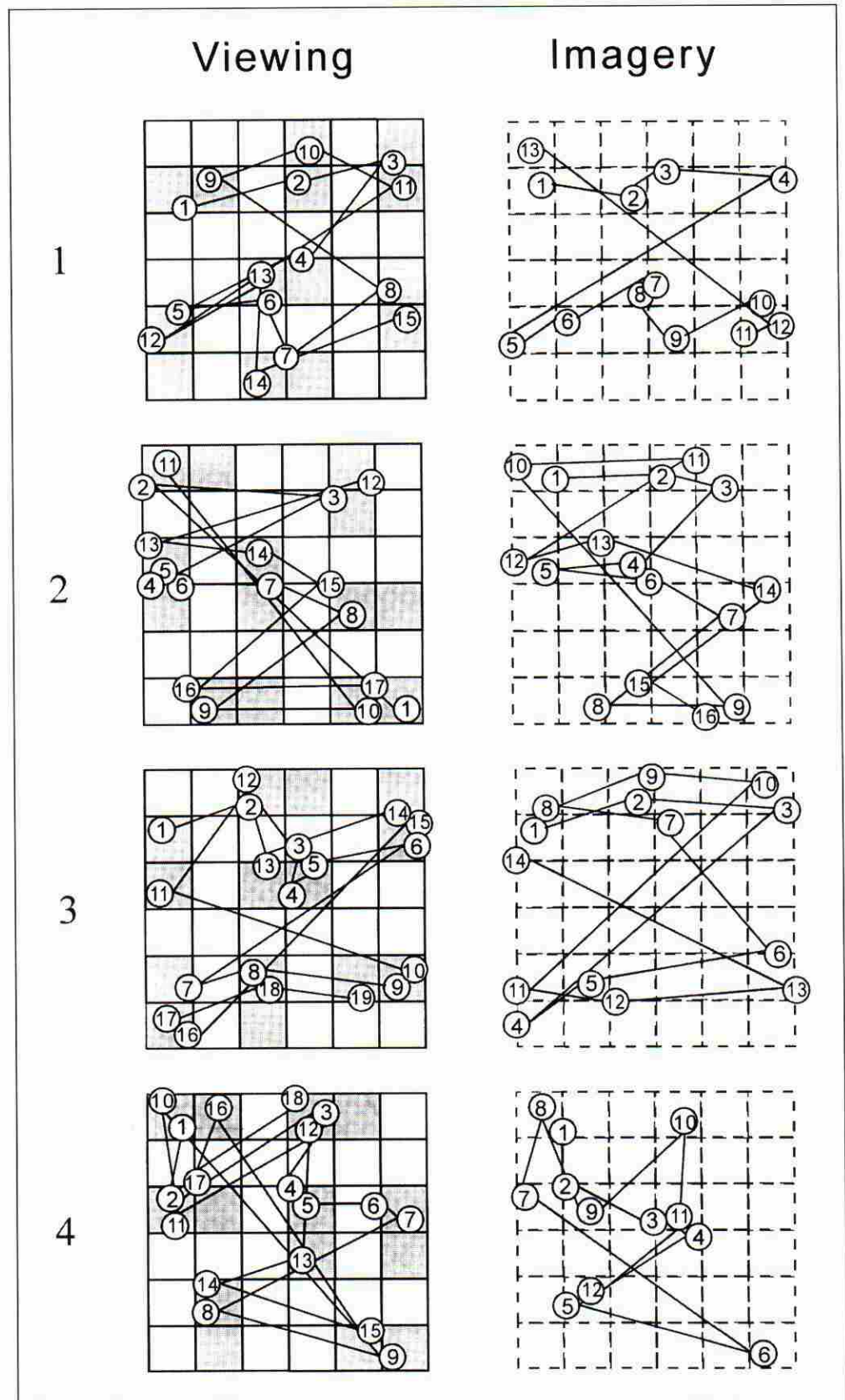
Visual examination and comparison of eye movement patterns superimposed on the stimulus diagrams (Figures 1 and 4) showed that recordings under both experimental conditions consisted of eye movements with scanpath characteristics. Repetitive sequences of visual fixations (the basic definition of a scanpath) could be seen in almost all recordings. Depending on the mean fixation times (see below) subjects completed one or two and sometimes three scanpath repetitions during the 10 second recording period (Figures 1 and 4). Fixations were numbered to give the sequence of eye movements forming the scanpath. In the viewing condition the distribution of fixations reflected the distribution of the shaded areas. Note that most fixations lay within one of the black double squares. The same was in general also true for the distribution of fixations in the imagery conditions, although more fixations lay outside the shaded areas and some of the shaded areas were neglected totally (see stimulus rotations I, III, and IV). If the eye movements during the imagery period of the experiment were not random but indeed reflected the content of the visualized diagram, then any eye movement pattern recorded during imagery should be more similar to the corresponding viewing pattern of eye movements than to any other eye movement pattern obtained from different stimulus rotations. The string editing analysis tested this hypothesis.

### String Editing Analysis

The string editing analysis confirms the high degree of similarity in the recorded eye movements between the viewing period and the imagery period (with the same stimulus rotation). Table 1 shows examples of string editing results calculating the similarity of scanpaths obtained from corresponding (same stimulus rotation) and noncorresponding (different stimulus rotation) viewing-imagery trials. For subjects 1 and 7 the table clearly documents with low diagonal values a high degree of similarity in corresponding trials in contrast to higher off-diagonal values, indicating a high editing cost and relative dissimilarity. Subject 4 was the subject who realized that the second and the following stimulus diagrams were rotated versions of the first one. Obviously he recalled and reconfirmed the correct spatial layout of the diagram in the same spatial sequence as he had done during the first trial. This was reflected in a rotation of the scanpath according to the four stimulus rotations. Consequently the string editing analysis showed similar values in both the corresponding ( $M = 0.37$ ) and noncorresponding ( $M = 0.42$ ) cross matches (Tables 1 and 2).

In eight subjects (Table 2) the mean editing cost for viewing-imagery eye movements of the same stimulus rotations was lower ( $M$  ranging between 0.26 and 0.51),

**Figure 1.** An experimental trial with four rotated stimuli. A complete set of eye movement patterns recorded during viewing (left panels) and imagery (right panels) in one subject using the same basic diagram to create four different runs; each time the diagram was rotated 90°. Note the similarity in the distribution of fixations and the direction of saccades in corresponding viewing-imagery trials, and differences in noncorresponding viewing-imagery trials.



**Table 1.** String editing distances for three subjects. String editing distance between imagery and viewing scanpaths. For each of the four diagrams, a string editing distance was calculated to assess the degree of similarity of scanpaths in imagery and viewing conditions. As controls, the string editing distances were also calculated between imagery of one diagram and viewing of another; these values form the off-diagonal coefficients of the matrices.

<i>String editing distances comparing viewing-imagery eye movements</i>					
<i>Subject 1</i>		<i>Viewing</i>			
		<i>1</i>	<i>2</i>	<i>3</i>	<i>4</i>
Imagery	1	<b>0.25</b>	0.71	0.71	0.71
	2	0.73	<b>0.13</b>	0.73	0.80
	3	0.71	0.78	<b>0.28</b>	0.78
	4	0.90	0.72	0.63	<b>0.36</b>

<i>Subject 4</i>		<i>Viewing</i>			
		<i>1</i>	<i>2</i>	<i>3</i>	<i>4</i>
Imagery	1	<b>1.00</b>	0.70	0.55	0.20
	2	0.35	<b>0.57</b>	0.44	0.35
	3	0.00	0.57	<b>0.42</b>	0.28
	4	0.50	0.60	0.44	<b>0.50</b>

<i>Subject 7</i>		<i>Viewing</i>			
		<i>1</i>	<i>2</i>	<i>3</i>	<i>4</i>
Imagery	1	<b>0.50</b>	0.66	0.85	0.85
	2	0.83	<b>0.66</b>	1.00	0.66
	3	1.00	1.00	<b>0.44</b>	0.77
	4	0.85	0.83	0.66	<b>0.40</b>

than for different stimulus rotations ( $M$  ranging between 0.42 and 0.82). One subject (#8) had head movement artifacts that interfered with the accurate recording of eye movements. The recorded movements were outside the calibrated viewing region during trial one and two and therefore could not be superimposed on the stimulus diagram. Five of the eight subjects showed highly significant ( $p \leq 0.001$ ) differences in editing costs and hence in similarity between eye movement patterns. The results for subject nine showed a trend ( $p \leq 0.1$ ); this subject's eye movements recorded during imagery were comparable in amplitude and rate with viewing eye movements, but did not very well reflect the particular spatial components of the stimulus.

A second recording session with subject one, who had demonstrated very consistent results in his first experimental session, was performed a week later. Thus we could not only compare the scanpath structure between

trials but also between trials of different sessions and different viewing trials and imagery trials with each other. In a total of 120 cross-matches, 24 corresponding trials averaged a mean difference of  $M = 0.25$ , and 96 non-corresponding trials averaged in a mean difference of  $M = 0.78$  (Table 3). Interestingly, comparison between trials of intervening sessions led to similar diagonal and off-diagonal values as between trials of the same session, clearly documenting a persistence in scanpath structure over time.

### Additional Results

In the process of identifying components of the recorded eye movements, the data analysis program also calculated the duration of each visual fixation. Averaged fixation durations of all imagery trials for each of the four stimulus rotations was about 20% longer ( $p \leq 0.001$  for rotations I, II, and III and  $p \leq 0.1$  for rotation IV) than in

**Table 2.** Means and standard deviations of eight subjects to assess the significance of differences between similarity for imagery-viewing pairs of same stimulus rotations (Column 3) and that of different stimulus rotations (Column 4). Five of the subjects showed highly significant differences ( $p \leq 0.001$  and  $p \leq 0.01$ ), one subject showed a trend ( $p \leq 0.1$ ).

<i>Similarity between scanpath eye movements: Viewing-imagery of same and different stimuli</i>			
<i>Subject</i>		<i>Viewing-imagery Same stimulus</i>	<i>Viewing-imagery Different stimulus</i>
1***	<i>M</i>	0.26	0.74
	<i>sd</i>	0.10	0.07
2***	<i>M</i>	0.29	0.80
	<i>sd</i>	0.33	0.09
3**	<i>M</i>	0.44	0.72
	<i>sd</i>	0.34	0.16
4	<i>M</i>	0.37	0.42
	<i>sd</i>	0.26	0.19
5**	<i>M</i>	0.51	0.80
	<i>sd</i>	0.24	0.17
6***	<i>M</i>	0.36	0.72
	<i>sd</i>	0.36	0.13
7***	<i>M</i>	0.50	0.82
	<i>sd</i>	0.11	0.13
9*	<i>M</i>	0.46	0.66
	<i>sd</i>	0.24	0.20

**Table 3.** String editing distances for repetition experiment. Selected comparisons between viewing-imagery trials within and between sessions and comparisons of viewing and imagery scanpaths between sessions (rows 1-8). Mean and standard deviations of all 24 corresponding cross-correlation are shown in row 9 and those of all 96 noncorresponding cross-correlations in row 10. Repetition experiment documented persistence of scanpath structure in spite of an intervening week between experimental sessions.

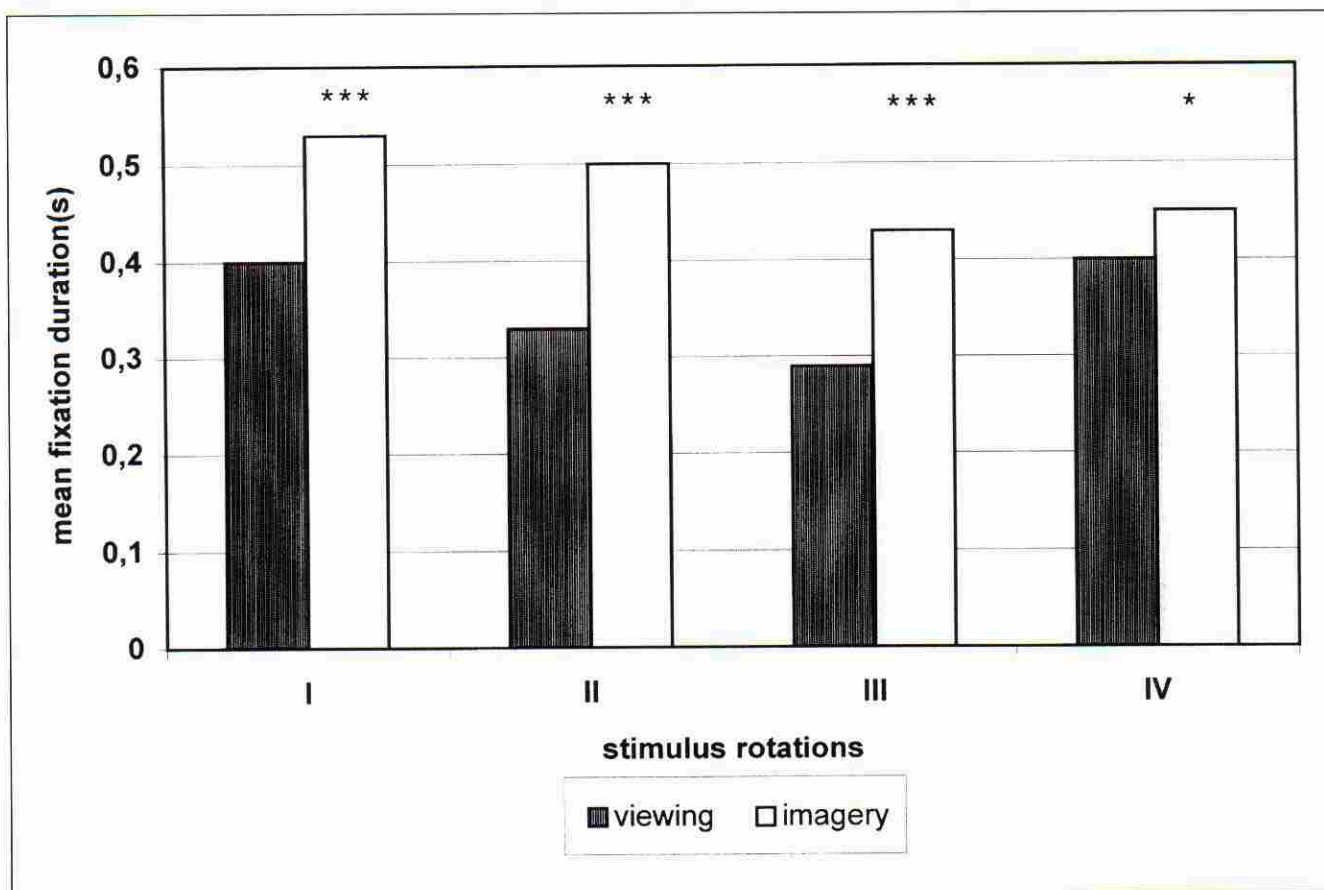
*Repetition experiment comparing similarity of scanpaths within and between sessions*

		<i>M</i>	<i>sd</i>	<i>n</i>
Viewing I / imagery I	same stimuli	0.21	0.13	4
	different stimuli	0.69	0.21	12
Viewing II / imagery II	same stimuli	0.18	0.11	4
	different stimuli	0.72	0.22	12
Viewing I / viewing II	same stimuli	0.18	0.17	4
	different stimuli	0.67	0.20	12
Imagery I / imagery II	same stimuli	0.23	0.21	4
	different stimuli	0.77	0.24	12
All	same stimuli	0.25	0.15	24
	different stimuli	0.78	0.08	96

the viewing trials (Fig. 2). This was, of course, reflected in a higher number of fixations in the viewing periods of the experiments, and thus allowed more scanning cycles of eye movements in the same time periods. Only in 6 out of 40 imagery/viewing trials was the fixation duration during viewing longer than during imagery. Another interesting difference between eye movements during imagery and viewing became apparent when analyzing the absolute amplitude of saccades. Although subjects visualized the grid pattern in about the same size and location as the stimulus seen previously, the scanpaths recorded during imagery were about 20% smaller than during viewing. This finding was consistent for six of the nine subjects.

### DISCUSSION

The results may be summarized as follows: Repetitive sequences of fixations, the basic definition of the scanpath, are found during visual imagery. For a particular imagined diagrammatic picture, they are closely related to the scanpaths recorded while the same diagram is viewed. This is in contrast to the control trials, where scanpaths in visual imagery are dissimilar to scanpaths



**Figure 2.** Longer fixation duration in imagery. For ten experiments on nine subjects, fixation durations were significantly longer ( $p \leq 0.001$  and  $p \leq 0.1$  for rotation IV) while imagining diagrams, as opposed to actually looking at the stimulus.

when subjects view different diagrams. Therefore eye movements during imagery are not random but seem to relate to the content of the visualized image.

### Scanpath Theory

What theoretical explanation should be advanced for these results? One theory of picture perception predicts the results obtained and makes their possible significance clear. The theory, which is described in more detail in Noton and Stark (1971a), is based on an information-processing approach to visual perception, proposing that a picture is internally represented as a sequence of sensory and motor activities. In this model, during each recognition-phase the subfeatures of this internal cognitive model are checked against the subfeatures of the pictures, and thus the picture is "recognized." The repetitive sequences of eye movements are interpreted as a playing out of a control sequence of a representation coding "what" the subfeatures are and "where" they are located in the scene. In contrast, it has been speculated that peripheral vision might be the major force driving the scanpath (Parker 1978). But eye movement studies on ambiguous and fragmented figures (Ellis & Stark, 1978; Stark & Ellis, 1981) showed that the same physical stimulus results in different scanpaths depending upon the changing perceptual representation of the viewer. Therefore, a major role in peripherally generating the scanpath does not seem very likely. Another experimental evidence showing the "top down" component of the scanpath can be derived from the imagery experiments described here. Since there is no actual diagram or picture to be seen during the imagery period, it is likely that an internalized cognitive perceptual model must be in control of these scanpaths. Input from foveal or peripheral vision cannot play a role in generating scanpath eye movements during imagery.

### Mental Imagery Uses Mechanisms Similar to Vision

Does the occurrence of similar scanpath eye movements during imagery and viewing support a unitary top-down central nervous system mechanism for visual imagery and visual percepts? The fact that subjects spontaneously exhibit eye movements during mental imagery with no actual stimulus present suggests that mental imagery uses the same central processing mechanisms as perception. Moreover, the spatio-temporal characteristics of mental image exploration correspond very closely to the exploration during perception. Thus our results strengthen the concept of a shared representational medium for both cognitive functions. The validity of our findings must be discussed in relation to possible artifacts. Three major alternative accounts—task-induced demand characteristics, experimenter bias, and tacit knowledge—should be excluded in order to interpret

the results as being in favor of a structural equivalence of imagery and perception (see Finke, 1985 for details). We tried to avoid task-induced demand characteristics and experimenter bias by working with naïve subjects and a careful experimental design. In fact, none of the subjects suspected that eye movements were measured. Neither the experimental setting nor the written instructions suggested a systematic scanning of the stimuli, and it would be very difficult for a subject to anticipate the particular scanpath characteristics obtained. Moreover some of the results, such as differences in fixation duration and eye movement amplitude were unanticipated.

It is more difficult to rule out that the "tacit knowledge" people possess about the physical or perceptual processes might account for these findings. Asking someone to imagine an object might induce the same kind of behavior as actually looking at this object not because of any structural equivalence but simply because the person has acquired "tacit knowledge" about how one is supposed to look at objects (Pylyshyn, 1981). One way to make "tacit knowledge" unlikely is to find imagery-perception correspondences that cannot be explained by tacit knowledge alone. We believe that, with respect to the consistency and high precision of the scanpath phenomenon observed during the imagery period in all of our naïve subjects, it does not seem very likely that an unspecific arousal of the eye movement system or a miming of a perceptual process is the case. In fact there is only weak extraretinal proprioceptive information provided by the eye muscle spindles (the "Gauthier effect," Gauthier, Nommay, & Vercher, 1990; Bridgeman & Stark, 1991) and about position of gaze in space. Hence a miming of scanning eye movements on the basis of tacit knowledge alone would be very inaccurate. Indeed experimental evidence supporting the concept of a *shared representational medium* for imagery and perception come from electrophysiological studies in which event-related potentials are recorded during imagery and viewing (Farah, Peronnet, Gonon, & Giard, 1988) and from Single Photon Emission Computer Tomography in which relating regional changes in cerebral blood flow are related to different experimental conditions (Goldenberg et al., 1989). Gulyas, Persson, Stone-Elander, and Eriksson (1992) demonstrated with Positron Emission Tomography 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.

What could be the *functional role* of eye movements during imagery? One possibility is that eye movements merely reflect the scanning of a complete mental scene present in a visual working memory. This "visual buffer," which is a hypothetical functional unit for presenting

visual information suggested by Kosslyn (1987) is, however, probably capable of presenting only a restricted amount of visual information at a time. Therefore it is necessary to assume an additional mechanism for presenting complex scenes on the visual buffer without overloading its capacity. Sequential activation of visual memory content from underlying long-term representations could be an adequate strategy for dealing with this problem. The scanpath theory of perception (Noton & Stark, 1971a, 1971b) suggests a particular sequence of eye movements link together the subfeatures of a complex scene. Accordingly we suggest that eye movements during imagery reflect the mental process of activating and arranging the part images of a complex scene into their proper locations. As in visual perception this process is responsible for creating the illusion of "seeing" a complex scene as a whole. Kosslyn (1987) formulated a theory of imagery generation upon a similar principal as the scanpath theory. He based his theory on electrophysiological evidence for two visual subsystems computing separately information about "what" and "where" an object is (Mishkin, Ungerleider, & Macko, 1983). Then he argued that "two classes of processes are used to form images—those that activate stored memories of the appearances of parts and those that arrange parts into the proper configuration" (Kosslyn, 1988). Our results present experimental evidence supporting this concept. We conclude that eye movements are an adequate tool for monitoring the wandering of the internal focus of attention during imagery, and thus are an important cognitive process underlying, perhaps constituting, imagery.

What can we learn from the rate and amplitude of eye movements and sequence of fixations about the spatial and temporal properties of visual imagery? First, the eye movements recorded during imagery have certain characteristics that make them distinct from eye movements during viewing. The lower eye movement rate in the imagery period of the experiment reflects a longer average fixation duration. The process-monitoring-hypothesis (Rayner & McConkie, 1976) suggest that eye movements and fixation durations are affected by the cognitive process occurring during the time period of the fixation. Accordingly, we believe that the longer "fixations" during imagery reflect a more difficult attempt to construct a mental image by sequentially placing the subfeatures constituting a complete scene into their proper locations. The amplitude of eye movements indicates that the spatial extent of the mental images projected into outer space was smaller than those of the percepts, despite the fact that the subjects were asked to visualize the stimulus in about the same size as they had seen it before. It is possible that the execution of motor activity with correct relative spatial distances is sufficient to support an undistorted mental image of a complex scene. In imagery there is no need for eye movements with the full range of amplitudes as in per-

ception where fixations are essential for correctly identifying subfeatures of a scene.

A question remains as to whether the phenomenon described here is essential to the visualization of such a pattern. It is conceivable that eye movements do not need to be executed but could be imagined as well. In previous studies on scanning mental images, eye movements were observed but only eye movement rates recorded (Hale & Simpson, 1970; Brown, 1968; Marks, 1973). Lack of correlation of such nonspatially defined eye movements with the subjective vividness of mental images led to the premature conclusion that eye movements are not related to the content of mental images (Marks, 1973). Obviously eye movements frequently accompany visual imagery and recordings of eye fixations during mental rotation tasks suggest that they even influence a subject's performance (Carpenter & Just, 1978). We have deliberately chosen a stimulus that has almost all its structure in the spatial layout. Serial processing of the subfeatures of the diagram is required to fully understand and remember the complete spatial structure. It is possible that the similarity between scanpaths during imagery and viewing would be less tight with stimulus material based on better known objects arranged in a more intuitive way. Pilot studies have shown that extremely simple geometrical figures (e.g., circles, squares, rectangles) do not provoke consistent scanpath eye movements.

In this demonstration of scanpath eye movements during imagery, we have not fully explored the effects of repetitive presentation of the stimuli on the occurrence of scanning phenomenon. In one subject, a week's interval did not affect the high correlation between corresponding imagery and viewing trials.

## METHODS

The vulnerability of imagery paradigms by set expectations has been a matter of concern expressed by several authors (Pylyshyn, 1981; Intons-Peterson, 1983). By working with naïve subjects and by suggesting to them that the experimental goal was the measurement of pupil size rather than eye movements, and by using a noninvasive eye movement recording method, we hoped to eliminate these kinds of artifacts.

## Subjects

Nine subjects (3 female and 6 male students from the School of Architecture of the University of California, Berkeley) aged between 18 and 28 participated in the experiments. Due to the methodological design of the experiment, subjects wearing contact lenses or glasses were excluded. Subjects were told that their pupil size was being measured during the performance of a visualization task. When the detailed purpose of the study was explained after the experiment we found that all

subjects have been naïve about the fact that their eye movements were recorded.

### Apparatus

Eye movements were recorded by means of a video-based eye monitoring system (built by MMI of Berkeley, California) designed for tracking eye movements and measuring pupil size under infrared light conditions. A number of similar instruments exist; their most complex features are analog circuitry, creating a binary image at a contrast level that defines the iris-pupil border and also the Purkinje image from background (Myers, Sherman, & Stark, 1991a, 1991b). The digital circuitry computed (at 30 or 60 Hz) the centroids of pupil and Purkinje images and used these values to compute the visual axes of the eye. Calibration with a grid of  $3 \times 3$  or  $5 \times 5$  points allowed nonlinearities to be evaluated and to produce linearized records when the calibration was found to be nonlinear.

It was a point of high priority in the design of the experiment to leave the subjects naïve about the task of the recording. Therefore, it was important to choose a noninvasive eye movement recording technique. Also, we did not want to disturb the natural viewing behavior by any mechanical devices attached to the pupil or the orbital region. As we were only interested in recording eye movement patterns and did not want to measure speed or acceleration of saccades, it was not a disadvantage to work with a relatively low sampling rate (60 Hz) and coarse resolution ( $\pm 0.5^\circ$ ). The picture displayed on the computer screen subtended a visual angle of 20 degrees; thus our technique enabled a maximum precision of 1 part in 40. In fact, it was more important to create favorable experimental conditions, allowing the subjects to visualize vividly without interfering with methodological requirements of the protocol. Any distracting condition, either subject related or environment related, is antagonistic to the production of more vivid imagery (Antrobus, Antrobus, & Singer, 1964). As this is in particular true for visual distraction (Sheehan & Neis-

ser, 1969), we thoroughly darkened the room and collected data under infrared light conditions. A black hood surrounding the subject's head, the monitor used for stimulus presentation and the camera lens created a "visual Ganzfeld" during the imagery periods of the experiment.

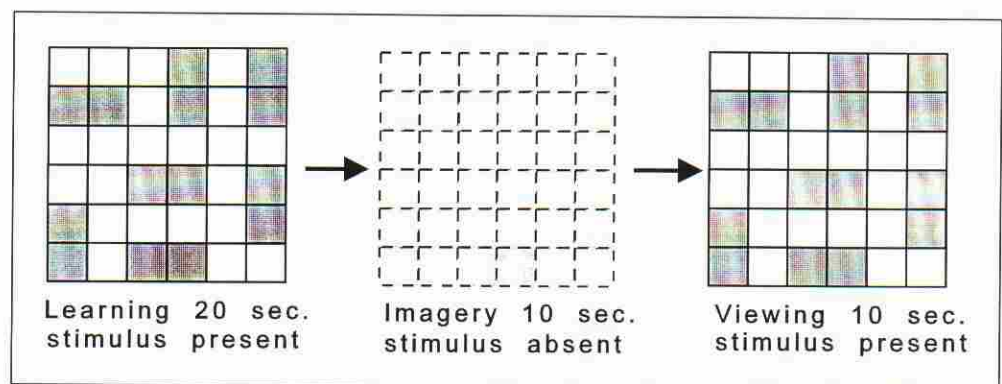
### Stimulus

The diagrams used as stimuli were chosen after a number of early exploratory studies (Brandt, Stark, Hacısalıhazade, Allen, & Tharp, 1989). Initially we tried chess diagrams with a full  $8 \times 8$  grid and chess pieces superimposed. Those studies indicated that the diagram should be simple but also have a certain amount of complexity in order to require checking foveations and sequential processing of the subfeatures, and thus producing the necessary sequential eye movements that define a scanpath. We also wanted a set of subfeatures whose positional encoding required careful review of the spatial layout by the subject.

Our regular diagrammatic stimuli consisted of seven black double-squares on a grid background ( $6 \times 6$  grid subtending  $20^\circ$ , see Fig. 3) that were separated such that a priori regionalization could be automatic. Experimenter bias was thus removed from the definition of regions to be used in later analyses. Also, a posteriori regionalization based upon subjects actual clustering of fixations might be too diverse to allow comparison of different diagrams. The stimulus diagram was then used in four rotations to generate a full set of four distinct stimuli, all having the same degree of complexity. We suspected that subjects would not realize the generating mechanism; indeed only one subject (#4) cracked the code, which had an interesting effect on his scanpath characteristics (see below).

The simplicity of the diagram removed most of the spatially local scanpath activity, a phenomenon observed when detailed subfeatures of a figure are explored (Groner, Walder, & Groen, 1984). To prevent aftereffects—although these were not a likely source of persist-

**Figure 3.** Protocol of imagery-viewing experiment. Each diagram-session was automatically sequenced by computer; first a 20 second exploration of the diagram occurred, next 10 seconds of imagery, with only faint corner dots visible, and then 10 seconds of viewing. Grid presentations ( $6 \times 6$  grid subtending  $20^\circ$ ) were followed by masking homogeneous grey screens to prevent screen persistence and afterimages. Eye movements were recorded during the 10 seconds of imagery and viewing periods for quantitative comparison of scanpath patterns.





ent visual information—each presentation of a viewed grid was followed by a masking homogeneous grey screen for 20 seconds, so that any screen persistence or any physiological afterimage would be prevented. Imagery stage was initiated by the monitor turning black.

### Experimental Protocol

Each experimental session included a number of presentations of viewing and of imagery trials automatically sequenced by computer screen presentations, with each viewing or imagining trial lasting 10 seconds (Fig. 3). In an initial exposure to each particular diagram the subject was given 20 seconds of viewing for familiarization. Eye movements were recorded during the full 10 seconds of viewing and imagining. Written instructions read by the subject explained the viewing and imagining trials and explained also that the task was to “recall by visualizing exactly the particular spatial layout of the grid blocks.” This protocol was then repeated three times, the only difference being that the stimulus was rotated by 90° in each successive run. Hence a full experimental trial consisted of two eye movement recordings (viewing and imagery) for each of the four stimulus rotations.

### Calibration and Eye Movement Analysis

Before and after each experimental session a calibration data file was recorded, informing the experimenter about the quality of the optical alignment between camera and subject and about small changes in position of the subject's head. Except in one subject (#8) no changes in head position during experimental trial affected the quality of the recordings. Calibration was over a matrix of  $3 \times 3$  points, each 10° apart; viewing distance was 57 cm. Thus the diagram was 20 cm across. After calibration, a linearization program eliminated nonlinear effects. With this linearized eye movement signal, the data could be filtered and smoothed over three successive sampled values in time. Then the eye movement trajectories were analyzed for fixation points and sequences of fixation points (Fig. 4a). Data analysis methods are further discussed in Ellis and Stark (1986).

### Data Analysis

A persistent problem in the analysis of scanpath eye movements has been how to achieve quantitative comparison of different eye movement patterns. When comparing the distribution of fixations and sequences of saccades in the eye movement records the similarities are striking (Fig. 1), but it was our task to determine exactly the degree of similarity in order to decide whether eye movement patterns during imagery and viewing reflect the underlying cognitive model. To do so an objective measure of similarity between sequences of visual fixations was developed. The two-dimensional fixa-

tion pattern superimposed on the stimulus was first translated into an information string about the sequence and location of fixations in regions. We then correlated the strings in regard to their similarity by calculating the editing cost needed to translate one string into the other (Hacisalihzade, Allen, & Stark, 1992).

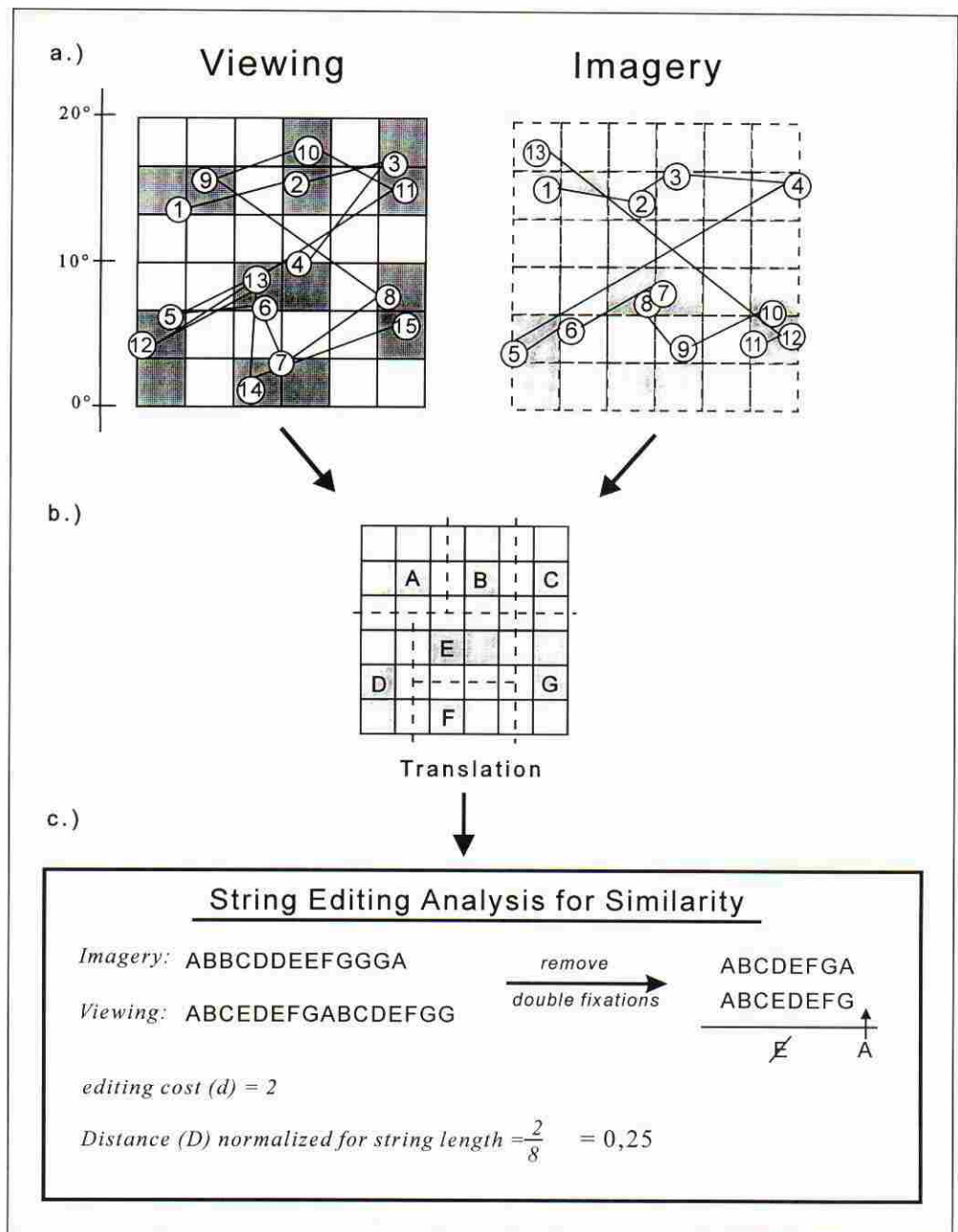
In the first step of this process, the stimulus was subdivided into seven regions of interest each labeled with a letter (Fig. 4b). The superimposed fixation pattern was then translated into a letter-string sequenced according to the successive fixations. In order to separate local from global scanning behavior, any double fixation (with respect to sequence and locus) was compressed into one letter. The resulting letter-string contained all of the relevant temporal and spatial information that defines a scanpath, but now in a one-dimensional format, which could be handled in the computational part of the comparison for similarity. The particular spatial layout of the stimulus with seven clear-cut subfeatures in the stimulus diagram helped to make the fixation sequence to letter-string translation error free.

The actual comparison of strings was automatized by computer analysis of the “editing cost” needed to transform one string into another (Fig. 4c). The problem was to determine the distance, or similarity, between two strings as measures of the minimum cost sequence of “editing operations” needed for changing one string into the other. Three basic editing operations—deletions, insertions, and substitutions—were allowed to be used for such a transformation.

Computer scientists (Wagner & Fisher, 1974) as well as biologists studying RNA and DNA sequences (Eigen, Winkler-Oswatitsch, & Dress, 1988) have been concerned with this problem. Comparison of the fixation strings was done using an algorithm based on discrete dynamic programming, which guarantees that the minimum distance between two strings can be found (Wagner, 1983, see next section). The resulting cost of transformation was normalized by dividing by the length of the analyzed strings; this relative distance,  $D$ , between two strings is the raw cost ( $d$ ) divided by the length ( $l$ ) of the strings. An estimate from computer simulation of the distances of two random strings with 7 symbols and a string length equal to 13–15 is  $0.77 \pm 0.1$  (Choi, Mosley, & Stark, 1995).

The present experiments present an attempt to refine automatic analysis independent of possible experimenter bias. The string editing method explores the entire sequence and its relation in order to assess similarities and differences. The string editing algorithms provide an important measure, perhaps the defining measure, of a scanpath. In another study (Hacisalihzade, Allen, & Stark, 1992) we have explored the characteristics of generating Markov matrices and the resulting string editing measures of the constraining structures in a Markov matrix as its set of coefficients (see also Ellis & Stark, 1986). A failing of the Markov matrix scheme is

**Figure 4.** Viewing and imagery scanpaths compared. (a) Sequences of eye movements with visual fixations identified by computer and numbered in order for viewing (left) and imagery (right). (b) A priori regionalization of the stimulus for translation of the eye movements pattern into a string of letters representing (below) the relevant temporal and spatial characteristics. (c) Quantitative analysis of similarities of eye movement patterns by string editing analysis calculating the minimum editing cost (d) to transform one letter string into the other. The cost was then normalized by dividing by the length of the analyzed strings to get the relative distance (D) as a measure for similarity between eye movement patterns.



that the higher order matrix representation explodes either as a series of a larger number of matrices up to the necessary order or as a sparse, enormously dimensioned no-memory first order matrix.

### Algorithm for String Editing

The two descriptions below complement each other: The first is the actual computer statements in **bold**; these statements are in the C programming language. The second are comments in English.

#### **compute\_distance ( )**

Compute distance from string 2 to string 1 using D-matrix.

**D [first\_to\_second] [0] [0] = 0;**  
**for (i=1; i<= comp\_trun\_size [first\_file]; i++)**

1. Initialize D-matrix to zero; calculate truncation size.

**D[first\_to\_second] [i] [0] = D[first\_to\_second] [i-1] [0]+cost\_of\_first\_to\_null [first\_file] [i];**

2. Cost of first to null—do this by deleting each character in string1 one by one; in most this will equal string length.

**for (j=1; j<=comp\_trun\_size [second\_file]; j++)**  
**D[first\_to\_second] [0] [j] = D[first\_to\_second] [0] [j-1] + cost\_of\_null\_to\_second [second\_file] [j];**

3. Using the D-matrix proceed to calculate distance.

```
for (i=1; i <= comp_trun_size [first_file]; i++)
for (j=1; j <= comp_trun_size [second_file]; j++)
```

4. Control scanning from row to row and from top to bottom.

```
m1 = D[first_to_second] [i-1] [j-1] +
cost_of_first_to_second [first_to_second] [i] [j];
m2 = D[first_to_second] [i-1] [j]
cost_of_first_to_null [first_file] [i];
m3 = D[first_to_second] [i] [j-1] +
cost_of_null_to_second [second_file] [j];
D[first_to_second] [i] [j] =m1;
if (m2<D[first_to_second] [i] [j])
D[first_to_second] [i] [j] = m2;
if (m3<D[first_to_second] [i] [j])
D[first_to_second] [i] [j] = m3;\
```

5. This triple computation takes into account the effect of deletions and insertions on shifting the matching of the D-matrix elements and providing the possibility of sidewise matches. Wagner and associates proved this operation to be valid; this extends the discreet dynamic programming algorithm. The algorithm will select the minimum cost taking advantage of possible shifting.

```
distance = D[first_to_second] [comp_trun_size
[first_file]] [comp_trun_size [second_file] ];
```

6. Lowermost right corner of D-matrix will be the minimum total cost of making string 2 identical to string 1.

Reprint requests should be sent to Stephan A. Brandt, Department of Neurology, Charité, Humboldt-University, 10098 Berlin, Germany. E-mail: sbrandt@neuro.charite.hu-berlin.de.

## REFERENCES

- Antrobus, J. A., Antrobus, J. S., & Singer, J. L. (1964). Eye movements accompanying daydreaming, visual imagery, and thought suppression. *Journal of Abnormal Sociology and Psychology*, *69*, 244-252.
- Aserinsky, E., & Kleitman, N. (1953). Two types of ocular motility occurring in sleep. *Journal of Applied Physiology*, *8*, 1-10.
- Berger, R. J., & Meier, G. W. (1965). Eye movements during sleep and waking in infant monkeys (*Macacca mulatta*) deprived of pattern vision. *Developmental Psychobiology*, *12*, 257-277.
- Brandt, H. F. (1940). Ocular patterns and their psychological implications. *American Journal of Psychology*, *53*, 260-268.
- Brandt, S. A., Stark, L. W., Hacısalihzade, S. S., Allen, J. S., & Tharp, G. (1989). Experimental evidence for scanpath eye movements during visual imagery. *IEEE Transactions on Systems, Man, and Cybernetics*, *19*, 470-471.
- Bridgeman, B., & Stark, L. (1991). Ocular proprioception and efference copy in registering visual direction. *Vision Research*, *31*, 1903-1913.
- Brown, B. B. (1968). Visual recall ability and eye movements. *Psychophysiology*, *4*, 300-306.
- Buswell, G. T. (1935). *How people look at pictures*. Chicago: University of Chicago Press.
- Carpenter, P. A., & Just, M. A. (1978). Eye fixations during mental rotation. In J. W. Senders, D. F. Fisher, & R. A. Monty (Eds.), *Eye movements and the higher psychological functions* (pp. 115-133). Hillsdale, NJ: Lawrence Erlbaum.
- Choi, Y. S., Mosley, A. D., & Stark, L. W. (1995). String editing analysis of human visual search. *Optometry and Vision Science*, *72*, 439-451.
- Cooper, L. A. (1975). Mental rotation of random two-dimensional shapes. *Cognitive Psychology*, *7*, 20-43.
- Decker, G. H. (1964). Pursuit eye movements in the absence of moving visual stimulus. *Science*, *143*, 1192-1193.
- Dement, W., & Kleitman, N. (1957). The relation of eye movements during sleep to dream activity: An objective method for the study of dreaming. *Journal of Experimental Psychology: General*, *55*, 339-346.
- Eigen, M., Winkler-Oswatitsch, R., & Dress, A. (1988). Statistical geometry in sequence space: A method of quantitative comparative sequence analysis. *Proceedings of the National Academy of Science USA*, *85*, 5913-5917.
- Ellis, S. R., & Stark, L. (1978). Eye movements during the viewing of Necker cubes. *Perception*, *7*, 575-581.
- Ellis, S. R., & Stark, L. (1986). Statistical dependency in visual scanning. *Human Factors*, *28*, 421-438.
- Farah, M. J., Peronnet, F., Gonon, M. A., & Giard, M. H. (1988). Electrophysiological evidence for a shared representational medium for visual images and visual percepts. *Journal of Experimental Psychology: General*, *117*, 248-257.
- Finke, R. A. (1985). Theories relating mental imagery to perception. *Psychological Bulletin*, *98*, 236-259.
- Finke, R. A., & Pinker, S. (1982). Spontaneous imagery scanning in mental extrapolation. *Journal of Experimental Psychology: General*, *8*, 142-147.
- Finke, R. A., & Schmidt, M. J. (1977). Orientation specific colour aftereffects following imagination. *Journal of Experimental Psychology: Human Perception and Performance*, *3*, 599-606.
- Gauthier, G., Nommay, D., & Vercher, J. L. (1990). Ocular muscle proprioception and visual localization of targets in man. *Brain*, *113*, 1857-1871.
- Goldenberg, G., Podreka, I., Steiner, M., Willmes, K., Suess, E., & Deecke, L. (1989). Regional cerebral blood flow patterns in visual imagery. *Neuropsychologia*, *27*, 641-664.
- Groner, R., Walder, F., & Groen, M. (1984). Looking at faces: Local and global aspects of scanpaths. In A. G. Gale, & F. Johnson (Eds.), *Theoretical and applied aspects of eye movement research* (pp. 523-533). Amsterdam: North Holland.
- Gross, J., Byrne, J., & Fisher, C. (1965). Eye movements during emergent stage I EEG in subjects with life-long blindness. *Journal of Nervous and Mental Disease*, *141*, 365-370.
- 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.
- Hacısalihzade, S. S., Allen, J. S., & Stark, L. W. (1992). Visual perception and sequences of eye movement fixations: A stochastic modelling approach. *IEEE Transactions on Systems, Man, and Cybernetics*, *22*, 474-481.
- Hale, S. M., & Simpson, H. M. (1970). Effects of eye movements on the rate of discovery and vividness of visual images. *Perception and Psychophysics*, *9*, 242-264.
- Hebb, D. O. (1968). Concerning imagery. *Psychological Review*, *75*, 466-477.
- Herman, J. H., Erman, M., Boys, R., Peiser, L., Taylor, M. E., & Roffwarg, H. P. (1984). Evidence for a directional correspon-

- dence between eye movements and dream imagery in REM sleep. *Sleep*, 7, 52-63.
- Intons-Peterson, M. J. (1983). Imagery paradigms: How vulnerable are they to experimenters' expectations? *Journal of Experimental Psychology: Human Perception and Performance*, 9, 394-412.
- Jacobs, L., Feldman, M., & Bender, M. B. (1972). Are the eye movements of dreaming sleep related to the visual images of the dreams? *Psychophysiology*, 9, 393-401.
- Jacobson, E. (1932). Electrophysiology of mental activities. *American Journal of Psychology*, 44, 677-694.
- Jeannerod, G. M., Gerin, P., & Pernier, J. (1968). Deplacements et fixation du regard dans l'exploration libre d'une scene visuelle. *Vision Research*, 8, 81-97.
- Kamiya, J. (1961). Behavioral, subjective, and physiological aspects of sleep. In D. W. Fiske, & S. R. Maddi (Eds.), *Functions of varied experience* (pp. 145-174). Homewood, Illinois: Dorsey Press.
- Kosslyn, S. M. (1973). Scanning visual images: Some structural implications. *Perception and Psychophysics*, 14, 90-94.
- Kosslyn, S. M., Ball, T. M., & Reiser, B. J. (1978). Visual images preserve metric spatial information: Evidence from studies of image scanning. *Journal of Experimental Psychology: Human Perception and Performance*, 4, 47-60.
- Kosslyn, S. M. (1987). Seeing and imagining in the cerebral hemispheres: A computational approach. *Psychological Review*, 94, 148-175.
- Kosslyn, S. M. (1988). Aspects of a cognitive neuroscience of mental imagery. *Science*, 240, 1621-1626.
- Ladd, G. T. (1892). Contribution to the psychology of visual dreams. *Mind*, 1, 299-304.
- Lenox, J. R., Lange, A. F., & Graham, K. R. (1970). Eye movement amplitude in imagined pursuit of a pendulum with eyes closed. *Psychophysiology*, 6, 773-777.
- Llewellyn-Thomas, E. (1968). Movements of the eye. *Scientific American*, 219, 88-95.
- Lorens, S. A., & Darrow, C. W. (1962). Eye movements, EEG, GSR and EKG during mental multiplication. *Electroencephalography and Clinical Neurophysiology*, 14, 739-746.
- Marks, D. F. (1973). Visual imagery differences and eye movements in the recall of pictures. *Perception & Psychophysics*, 14, 407-412.
- Mishkin, M., Ungerleider, L. G., & Macko, K. A. (1983). Object vision and spatial vision: Two cortical pathways. *Trends in Neurosciences*, 6, 414.
- Moskowitz, E., & Berger, R. J. (1969). Rapid eye movements and dream imagery: Are they related? *Nature*, 224, 613-614.
- Myers, G. A., Sherman, K. R., & Stark, L. W. (1991a). Eye monitor: Microcomputer-based instrument uses an internal model to track the eye. *Computer*, 24, 14-21.
- Myers, G. A., Sherman, K. R., & Stark, L. W. (1991). Eye monitor: Examples of eye movements recorded by computer-based "smart" instrument. *Computer*, 24, 8-23.
- Neisser, U. (1967). *Cognitive psychology*. New York: Appleton-Century-Crofts.
- Noton, D., & Stark, L. W. (1971a). Scanpaths in saccadic eye movements while viewing and recognizing patterns. *Vision Research*, 11, 929-942.
- Noton, D., & Stark, L. W. (1971b). Scanpaths in eye movements during perception. *Science*, 171, 308-311.
- Parker, R. E. (1978). Picture processing during recognition. *Journal of Experimental Psychology: General*, 4, 284-292.
- Pylyshyn, Z. W. (1981). The imagery debate: Analogue media versus tacit knowledge. *Psychological Review*, 88, 16-45.
- Rayner, K., & McConkie, G. W. (1976). What guides a reader's eye movements? *Vision Research*, 16, 829-837.
- Sheehan, P. W., & Neisser, U. (1969). Some variables affecting the vividness of imagery in recall. *British Journal of Psychology*, 60, 71-80.
- Shepard, P. N., & Metzler, J. (1971). Mental rotation of three-dimensional objects. *Science*, 171, 701-703.
- Stark, L. W., & Ellis, S. R. (1981). Scanpath revisited: Cognitive models direct active looking. In D. F. Fisher, R. A. Monty, & J. W. Senders (Eds.), *Eye movements: Cognition and visual perception* (pp. 193-226). Hillsdale, NJ: Lawrence Erlbaum.
- Stratton, G. M. (1902). Eye movements and aesthetics of visual form. *Philosophische Studien*, 20, 336-359.
- Totten, E. (1935). Eye movements during visual imagery. *Comparative Psychology Monographs*, 11, 1-46.
- Wagner, R. A. (1983). On the complexity of the extended string-to-string correction problem. In D. Sankoff & J. B. Kruskal (Eds.), *Time warps, string edits, and macromolecules: Theory and practice of sequence comparison*. Reading, MA: Addison-Wesley.
- Wagner, R. A., & Fisher, M. J. (1974). The string-to-string correction problem. *Journal of Association of Computing Machinery*, 21, 168-173.
- Yarbus, A. L. (1967). *Eye movements and vision*. New York: Plenum Press.
- Zirkmund, V. (1966). Oculomotor activity during visual imagery of a moving stimulus pattern. *Studia Psychologica*, 8, 254-273.