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EVIDENCE FOR A GLOBAL SCANPATH STRATEGY IN VIEWING ABSTRACT COMPARED WITH REALISTIC IMAGES

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Abstract—Scanpaths, the repetitive sequences of saccadic eye movements, occurred when subjects viewed slide projections of both realistic and abstract art. Variance analysis demonstrated that global/local eye movement indices were lower for local scanning by professional art viewers who relied on more *global* viewing, particularly in abstract images. Non-professional, unsophisticated subjects carried their *local* scanpath patterns from realistic images on to abstract images. The blink rate of professional subjects viewing abstract images was also significantly lower, indicating increased visual effort. Non-professional viewers showed no difference in blink rates.

Key Words: eye movements and cognition; scanpath eye movements; global–local scanpath; abstract pictures; realistic pictures; blink rate and workload.

INTRODUCTION

Using photographic and photoelectronic methods, Buswell [9] and Yarbus [48] explored eye movements of human subjects viewing works of art. The patterns of eye movements projected on to the pictures showed an alternation between fixational periods of around 300 msec and rapid saccadic eye movements lasting only tens of milliseconds. This pattern appeared to have constrained, deterministic fixational sequences embedded in stochastic eye movements, which overwhelmed initial analysis beyond the experimenters' own pattern recognition capabilities. Similar to Helmholtz [27] they believed in a high level 'outflow' control of eye movements effected by the viewer's mental image. Both Buswell and Yarbus suggested that changing the subject's instructed task changed their pattern of viewing. The repetitive nature of the eye movement patterns for a subject continually viewing a picture [48] was explained as a consequence of the 'scanpath theory' by Noton and Stark [35, 36] to which eye movements are guided through an eye movement scanpath by a perceptual sensory and motor representation. This representation was related to the 'schematic diagram' of Hochberg [22]. Noton and Stark used more realistic art, namely a figure of Klee's, while Stark and Ellis [38] used realistic art and *ambiguous* figures, to provide further evidence that *cognitive models*, rather than *peripheral vision*, control the scanpath in perceptual processes involving active viewing. Brandt and Stark [8] compared sequences of eye movements of subjects viewing the actual visual stimulus and then its mental image.

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Using string-edit analyses they were able to demonstrate firm evidence for scanpath sequences of their subjects' eye movements in both conditions. Groner *et al.* [18] recently proposed that global scanpaths adhere to the Noton–Stark proposal, while smaller intermixed local scanpaths may be controlled peripherally. More recently the first author of the present paper was able to differentiate short-term adaptation training effects in scan- and search-paths of hemianopic patients [49, 50].

The aim of this paper was to study patterns of eye movements of subjects viewing abstract and realistic art, under several instructed tasks. Strategies of professional artists, sophisticated, and naive viewers were compared.

METHODS

Stimuli

Five pictures ranging from realistic to less realistic and less abstract to more abstract, were chosen as representative of various styles. The selection of rather unknown works avoided contamination through familiarity. The selected paintings were (see Fig. 1, starting top right): "Deadeye", Lane Terry (1), 1971; "Surveillance", Stefanie Stark (2), 1977; "Table with Fruit and Coffeepot", Hans Hofmann (3), 1955; "Fantasia", Hans Hofman (4), 1958; "Spring Cool", Ken Noland (5), 1962. The first three works were considered "realistic", the other two "abstract".

Protocol

Experiments included varied tasks given to cooperative subjects in the form of explicit, written instructions. The first task (E), or *easy looking*, was simply to look at the pictures without further instruction. The second task (R), or *recollection*, was to look at the works carefully in order to be able to remember them and recall their specific features. Afterwards the subjects had to describe the picture's content and give some details on request. The third task (D), or *detailed looking*, was to look at the pictures carefully in regard to artistic details and to concentrate on aesthetic details. Subjects were then asked about their aesthetic impressions after each run. The subjects were unaware that their eye movements were being recorded, as they had been told that their pupil size was being measured.

Calibration runs were then performed in order to assure the accuracy of eye movement and blink recordings. Each of the five works were presented to each of the subjects three times for 30 sec under three different task assignments, such that each subject viewed and rated 15 presentations. Presentations were randomized with respect to order of presentation of the different pictures and with respect to the given task. A 5-min rest was allowed to the subjects between each viewing sequence (all five works) within a single task, the rest between the 30-sec viewing periods being about 1 min. Including the calibration run before and after, and including the intervening rest periods, the entire duration of the experiment was approximately 45 min per subject.

Presentation of the works was by rear screen slide projection (average luminance of the presented pictures: 28 cd/m^2). The projections were clearly visible at high resolution.

The subjects were placed approximately 1.15 m from the screen with the projected picture comprising a size of about 70×70 cm, allowing fairly good sized eye movements as would be necessary to cover the material on the screen with a vertical and horizontal visual angle of 35° in each plane for the presented pictures. Room lighting was dim (background luminance: 0.1 cd/m^2) allowing the subjects' attention to be focused on the screen.

Subjects

The six *naive* voluntary subjects participating in the study were recruited amongst bioengineering graduate students working in our laboratory. None were trained in art history, practical painting or self-reported frequent art appreciation. The four *sophisticated* subjects were acquaintances of the authors. They were either art collectors (two) and as such highly knowledgeable about art, or long-time museum and gallery visitors with a great and active interest in art. The four *professional* subjects were long-time practicing artists (painters) living in the Bay Area of San Francisco. All subjects had normal vision or corrected visual acuity and had no difficulty adjusting to the apparatus used.

Measurement techniques for recording eye movements and eye blinks have been described earlier [33, 39, 44]. Eye movements were measured using an i.r. video camera in connection with special-purpose computer boards allowing pattern recognition of video image and providing measurement of horizontal and vertical eye movements as well as eye blinks (Micromeasurements Inc., Berkeley, California). The temporal resolution of the system was 60 Hz, the spatial resolution was 0.25°. The subjects were not disturbed by the video camera since the light used for the camera was in the near i.r. or far red frequency range. Forehead and chin of the subjects were firmly affixed to prevent head movements.

Fig. 1. Colour reprints of paintings (beginning top right): "Deadeye", Lane Terry (1), 1971; "Surveillance", Stefanie Stark (2), 1977; "Table with Fruit and Coffeepot", Hans Hofmann (3), 1955; "Fantasia", Hans Hofmann (4), 1958; "Spring Cool", Ken Noland (5), 1962. The first three works were considered 'realistic', the other two 'abstract'.

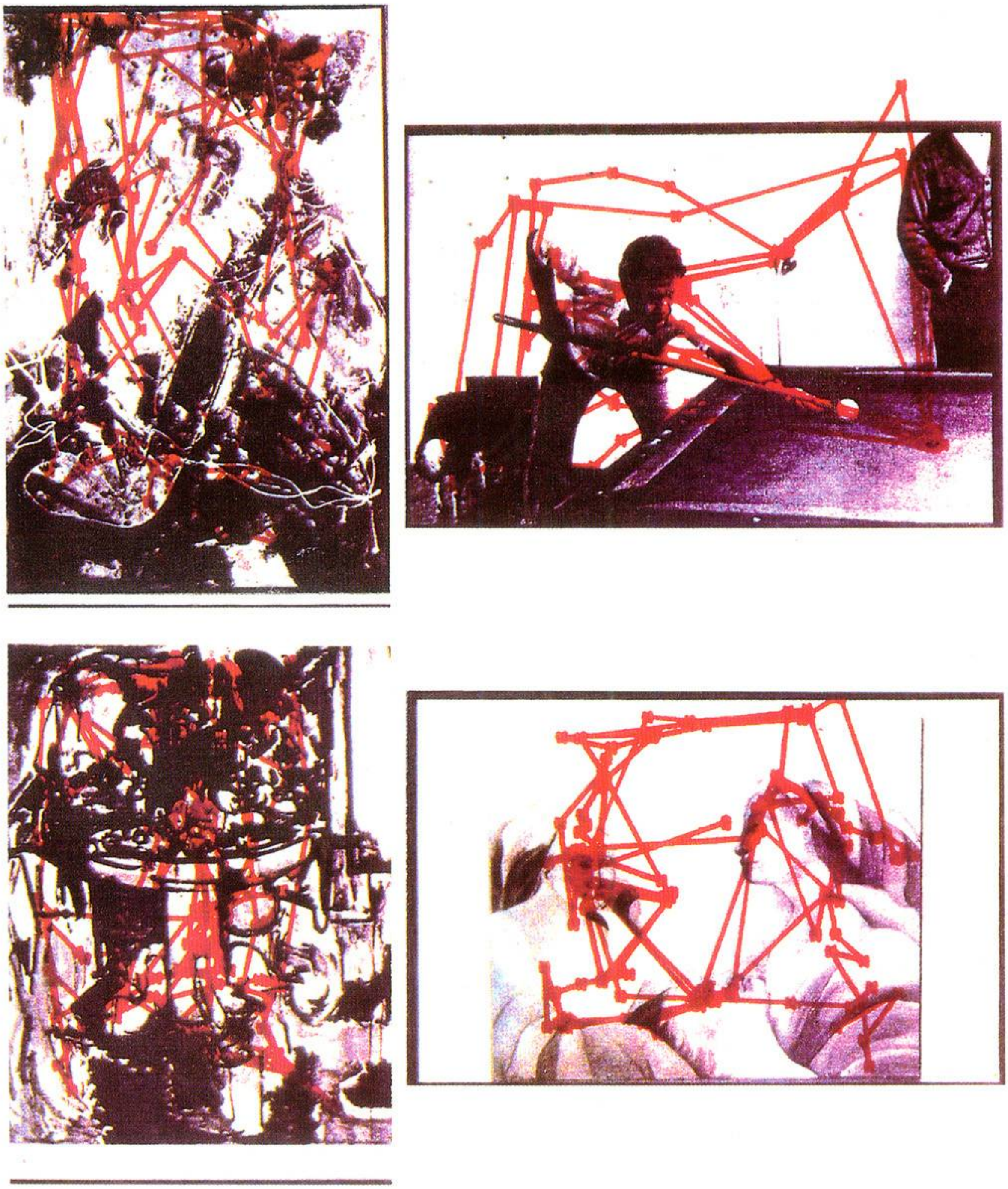


Fig. 2(b).

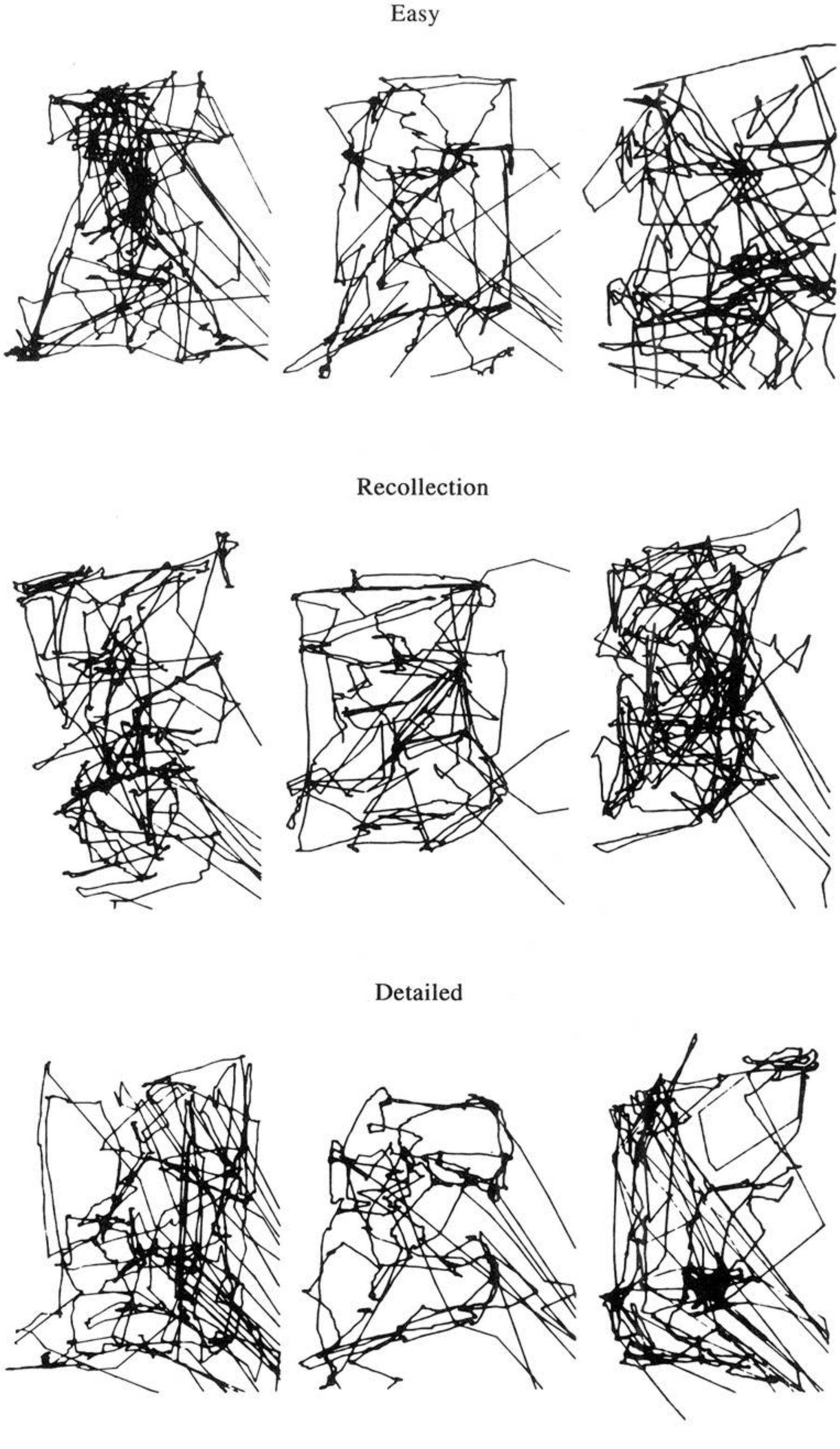


Fig. 2(a).

Fig. 2. (a) (above) Original recording of eye movements including blink artifacts before further editing; Ken Noland (5): "Spring Cool", easy looking task. Note: *individual* patterns of eye movement sequences in each subject; change of these patterns as function of task; blinks as diagonal deflections from the eye movement traces. (b) (see left) Four pictures of paintings ranging clockwise from realistic (upper right) to abstract (upper left) viewed by a sophisticated subject. Scanpaths, the repetitive sequences of saccadic eye movements, are superimposed in red with x's marking fixations and straightline vectors substituting actual eye interfixational movement trajectories. Here, eye blinks are removed by computer program.

Data acquisition/data analysis

A number of menu driven software programs operating in both on line and a follow-up mode were utilized. These presented the sequence of eye movements in saccades, jumping from fixation point to fixation point. As is well known in the literature [3, 4, 21, 45], saccadic eye movements are often not in a straight line from fixation to fixation. We thus created a simplified presentation consisting of 'interfixational vectors', that is, a straight line vector between one fixation point and the next. In studies of visual physiology it is generally considered that information of high resolution is not acquired to any great extent during rapid saccadic eye movement. Therefore, the exact path of the saccades is not important in itself. Important however, is where the eye fixates for approximately 200–500 msec, and *the sequences* of these fixations.

The analyzing software counted the number of saccades in each of the 30 sec artwork presentations, average fixation duration, clearly inversely related to the number of saccades, was calculated, and distributions of fixational durations were plotted. *Graphic displays* were obtained which included 'interfixational vectors' of eye movements and fixations superimposed over simplified drawings of the art stimuli.

The eye movement patterns can be noted as alternations between fixations and interfixational vectors, i.e. the straight lines connecting successive fixations. Eye blinks, which appeared in the original data as very rapid oblique jumps of the trace (Fig. 2), were removed by computer editing. It is evident from these figures that both naive and sophisticated subjects carry out similar repetitive sequences of eye movements, or scanpaths, for both realistic *and* abstract images.

Global/local (g/l) ratio

Certain eye movement patterns varied according to the relative percentage of time the eye spent in making a *global* scan or a *local* scan, involving smaller eye movements for a particular region of the stimulus.

These observations could be measured and confirmed quantitatively in two different ways. First, we determined the ratio of global vs local viewing for each subject in each presentation. The assumed boundary between local and global eye movements was initially assumed at 1.6°; that is, eye movements of the order of 1.6° in amplitude or less were considered local eye movements, whereas eye movements greater than 1.6° were considered more global eye movements. However, it was also possible to change this boundary from 1.6° to 4.6°, 7.9° or 11°. Increasing the size of the regions defined as "local" decreases the global/local (g/l) ratio and thus the discrimination capability [51], see Table 1. We used the threshold value of 1.6° since normal subjects apply saccades, and also drifts, in fixational eye movements *during maintained fixation* in the range between 0.08° and 0.8° [11, 34, 41, 42]. As we did not intend to study pure fixational saccades in the described sense but rather local vs global scanpath eye movements, i.e. sequences of saccades while viewing a particular picture, we chose approximately twice the value of large fixational saccades than described by the above-mentioned authors. This is shown in Table 1. The ratio of global over local viewing was determined for the three groups in each presentation.

The *statistical* evaluation of differences between groups, styles and tasks was carried out by means of non-parametric analysis of variance [37]. This was performed using the original values as inputs for the ANOVA software of BMDP2, U.C., Los Angeles: Analysis of variance and covariance with repeated measures, program version 1987.

RESULTS

Global vs local scanning

Since the underlying hypothesis for the scanpath theory is that an internalized cognitive model drives the eye movements, we inferred that in our experiments such an internalized cognitive model would drive the eye movement patterns for both sophisticated and naive subjects viewing both realistic and abstract artworks, independent of task. Indeed, a particular eye movement pattern differed according to the relative percentage of time the eye movements spent in making a *global* scan or a *local* scan, using smaller eye movements in a particular region. These observations were confirmed in two ways. One was the evaluation of the g/l ratio of each subject for each artwork and task. Then, a statistical analysis of variance was performed between realistic vs abstract styles, tasks and groups. Figure 3 gives a graphical overview and Table 2 (ANOVA analysis of variance) the statistical results.

Statistical analysis was carried out by three-way analysis of variance with repetition of measurements on the last two factors (BMDP UCLA 1987). The ANOVA of the global/local ratio for the variables 'group' (naive, sophisticated, professional), 'style' (realistic, abstract), and 'task' (easy, recollection, detailed) demonstrated (Table 2) highly significant differences

Table 1. Global local viewing indices

g/l (in.)	Bound. (°)	Viewing task	Realistic paintings: Sophist. and profess. ($n=8$)	Realistic paintings: Naive ($n=6$)	Abstract paintings: Sophist. and profess. ($n=8$)	Abstract paintings: Naive ($n=6$)
1	1.6	Easy	2.68 (0.24)	1.41 (0.16)	2.39 (0.22)	1.48 (0.16)
1	1.6	Recall	2.80 (0.27)	1.29 (0.14)	5.67 (0.44)	1.26 (0.13)
1	1.6	Detail	3.15 (0.29)	1.27 (0.13)	6.28 (0.45)	1.31 (0.15)
3	4.8	Easy	0.63 (0.07)	0.35 (0.04)	0.84 (0.09)	0.37 (0.04)
3	4.8	Recall	0.50 (0.06)	0.40 (0.05)	0.73 (0.08)	0.55 (0.06)
3	4.8	Detail	0.50 (0.04)	0.38 (0.04)	0.57 (0.07)	0.40 (0.04)
5	7.9	Easy	0.28 (0.02)	0.16 (0.01)	0.25 (0.03)	0.12 (0.01)
5	7.9	Recall	0.18 (0.02)	0.15 (0.01)	0.21 (0.02)	0.16 (0.01)
5	7.9	Detail	0.21 (0.02)	0.14 (0.01)	0.19 (0.02)	0.11 (0.01)
7	11.0	Easy	0.12 (0.01)	0.06 (0.007)	0.11 (0.01)	0.05 (0.007)
7	11.0	Recall	0.03 (0.004)	0.06 (0.007)	0.18 (0.03)	0.07 (0.008)
7	11.0	Detail	0.09 (0.008)	0.08 (0.006)	0.07 (0.008)	0.05 (0.006)

Upper rows with g/l boundary equal to 1 in. or 1.6° for these 32° diagonal paintings, turned out to provide the most discrimination. As one increased the g/l boundary, in lower and lower triplets of rows, the g/l discrimination disappeared (sophisticated subjects $n=4$, professional subjects $n=4$, naive subjects $n=6$; $\pm$S.E. in brackets.

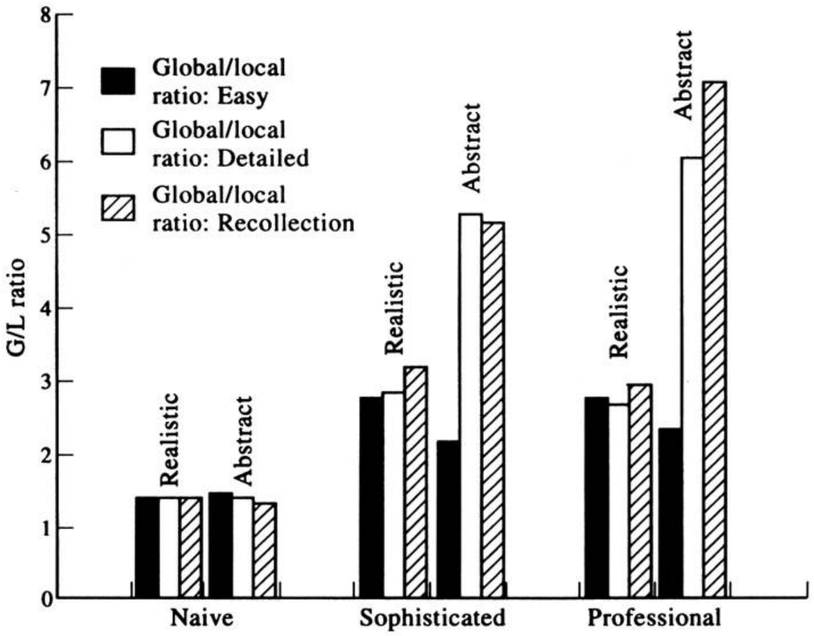


Fig. 3. Global vs local ratio of our professional, sophisticated, and naive subjects viewing realistic pictures (1, 2) (left three columns), and viewing abstract pictures (3, 4, 5) (right three columns) in three tasks: easy, recollection and detailed. Eye movements of 1.6° or smaller were considered local, whereas larger eye movements were considered global. Note the large g/l ratio for abstract pictures, particularly in sophisticated and professional subjects, whereas naive subjects show similar g/l ratios in all tasks for both realistic and abstract pictures.

Table 2. Three-way analysis of variance and covariance (ANOVA) with repetition of measurements on the last two factors [39] using the BMDP system UCLA 1987 for statistical evaluation of differences between subjects (naive, sophisticated, professional), pictures (realistic, abstract) and conditions (easy, recollection, detailed).

Source of variation	Sum of squares	d.f.	Mean square	F	Significance of F
Main effects	189.868	5	37.974	119.001	0.0005
Picture	30.770	1	30.770	96.427	0.0005
Subject	132.509	2	66.255	207.628	0.0005
Condition	26.588	2	13.294	41.660	0.0005
2-way Interactions	73.639	8	9.205	28.846	0.0005
Picture subject	23.528	2	11.764	36.866	0.0005
Picture condition	23.229	2	11.615	36.397	0.0005
Subject condition	26.882	4	6.720	21.060	0.0005
3-way Interactions	20.654	4	5.164	16.182	0.0005
Picture subject and condition	20.654	4	5.164	16.182	0.0005
Explained	284.161	17	16.715	52.382	0.0005
Residual	21.061	66	0.319		
Total	305.222	83	3.677		

Table 3. ANOVA for evaluation of differences within single groups with significance levels for picture (realistic vs abstract), condition (easy, recollection, detailed) and P & C (picture and condition)

Group	Picture	Condition	P & C
Naive	0.799	0.459	0.772
Sophisticated	0.246	0.0005	0.010
Professional	0.004	0.0003	0.0003

between main effects: the three subject groups, two styles, and three tasks significantly varied. In addition, the two-way interactions between style/group, style/task and group/task revealed a highly significant difference, as did the three-way interaction between all three variables.

Because of the highly significant lack of three-way interactions it was necessary to repeat the evaluation using a two-way ANOVA with repetition of measurements within the single groups (Table 3). Here, it became evident that the statistically most significant effects occurred within the professional group and, slightly less, with the sophisticated group. The naive group however, caused no significant differences. This statistical evaluation demonstrated, that the differences displayed in Fig. 3 were indeed highly significant in respect to global/local indices. Naive viewers neither differentiated between realistic and abstract pictures nor between tasks. Amongst sophisticated and professional subjects however, about a two-fold increase of global/local ratios occurred. Highly significant differences were found between all indices for realistic and abstract pictures, whereas this tendency was even more pronounced in professionals. Finally, a highly significant difference was found between the easy task and both the 'recollection' and the 'detailed' task for professional and sophisticated viewers. In conclusion, the most important statistical result was that *all* subjects viewed abstract artworks basically similar to realistic works. This confirmed our expectations. However, an equally important but lesser expected finding was that the sophisticated and professional subjects demonstrated a particular, more global scanpath strategy in viewing *abstract* images. This would evidently *not* be surprising for artists who painted abstract pictures such as Kandinsky [25]. 'Task' effected the g/l ratios of the sophisticated and professional viewers most clearly when viewing abstract pictures. Both for 'recollection' and the 'detailed' task this group showed a highly significant increased g/l ratio compared to the "easy" task. The naive group did not show a clear trend in this direction. Only a moderate difference was found between naive and professional subjects in the easy task category. A clear-cut difference was demonstrated in the much higher g/l ratio of professional as compared to sophisticated subjects when viewing abstract images, especially within the "recollection" task.

Differences between scanpaths of professional and sophisticated subjects while viewing realistic and abstract images

Professional and sophisticated subjects scanned abstract images more globally than realistic images. This was found not only in the significantly increased g/l ratios but also directly in the scanpath patterns of the eye movements. This was best confirmed through comparison of the most realistic with the most abstract image (Fig. 4). A characteristic individual example demonstrates the more globally oriented scanpath vectors of the professional subject compared with the fixational clusters around a very limited number of points of the naive subject. This difference was less pronounced in viewing abstract images. A *second* way to ascertain global/local patterning was in terms of probability density of saccadic amplitude. Plots of probability density of eye movements' amplitude and fixation duration were assigned to each image. Fixation durations showed no correlation with experimental parameters. However, size histograms showed highly-peaked, exponential monotonic distributions for naive subjects, indicating large numbers of small saccades, i.e. a small global/local index. Conversely, histograms of eye movements' size of sophisticated and professional subjects showed a wider distribution with peaks for mid-sized saccades and reliance on larger saccades to overview the paintings, i.e. a large g/l index. This effect is strongest in viewing abstract paintings. A task effect was only found in regard to the g/l ratio. Here, the professional *and* sophisticated viewers demonstrated a significantly increased g/l ratio for the recollection *and* detailed viewing task. This effect was only present when viewing abstract images.

The professional painter who viewed "Spring Cool", 1962, by Ken Noland (Fig. 5) gave a characteristical example of this. With the "easy" task both the blink rate and the local scanpath trajectories were high (upper right). During the 'detailed looking' task less blinks and many more global scanpath trajectories could be observed.

The analysis of the effect of task instructions on viewing patterns for professional subjects did not show significant changes of scanpaths with respect to saccadic amplitudes and fixation duration. A generally large amount of mid-sized to larger saccades was evident for all pictures and all tasks indicating high g/l indices or global viewing by professional viewers.

Viewing task and eye movement patterns

In our experiments the fixation durations when compared through analysis of variance did not differentiate between tasks or groups. Qualitative visual inspection of single experimental sets without the underlying picture (Fig. 2) of all subjects comparing the three tasks did not show obvious differences with respect to the task.

Through a simple observation of the graphical depictions of the sequential eye movements without the underlying picture no clear differences could be found between professional, sophisticated and naive viewers, neither between tasks or styles. In particular, blink artifacts from lid movements appeared to be quite similar for the three tasks too. These negative findings were most obvious in the naive subjects.

Task dependencies and blink rate

Observational and statistical studies on blink rate of our subjects showed no significant differences between the recollection and the detailed tasks (Fig. 2). These two tasks were then merged and considered as requiring high internal perceptual effort. Blink rate was significantly higher during the easy task than for the merged recollection and detailed tasks ($P<0.001$, Wilcoxon non-parametric test [37, 46]). Blinks in the raw data (Fig. 2) did not correlate with number of saccades, size of saccades, or global/local ratios.

DISCUSSION

Cognitive models control active viewing of abstract paintings

One main result of these experiments is that eye movement patterns for scanning abstract images are similar as for realistic images. Therefore, it can be concluded that abstract paintings are viewed via a similar active perceptual process, utilizing cognitive schemas to drive scanpath active-looking eye movements.

Reduced local scanning for sophisticated subjects viewing abstract art

A second important result is the relative paucity of local scanning when sophisticated and professional subjects viewed abstract art. Indeed, our most experienced viewer, a professional painter, showed the highest global/local indices for all images. This is what critics mean with 'painterly' viewing or appreciation of art. Evidently, global viewing is the preferred strategy for the professional subject that tries to evaluate both the visual content and the artfulness of the picture.

What is local scanning? Even though Noton and Stark [35, 36] and Stark and Ellis [38] showed that peripheral information can be excluded as the immediate control for the scanpath, their results related to local scanpaths. Groner *et al.* [18], Groner and Menz [17] and also Finke [14] support their top–down, cognitive model scanpath theory for a global scanpath, but argue in favour of an *immediate* peripheral bottom–up control of *local* scanning, although evidence for the latter is not conclusive at the present time. Jeannerod [24] has argued for an exchange between local and global scanning in free exploration, as e.g. in our 'easy' task. Evidently, the sophisticated and professional viewer avoids this type of immediate bottom–up control in favour of the top–down controlled global scanpath. Our paradigm of viewing abstract images probably enforced this ability that was not present in the naive, unexperienced viewers.

Similar global/local indices for abstract and realistic art in naive subjects

Our naive subjects had equal global/local ratios for both realistic and abstract images. These ratios were similar to that of sophisticated subjects viewing realistic images [51].

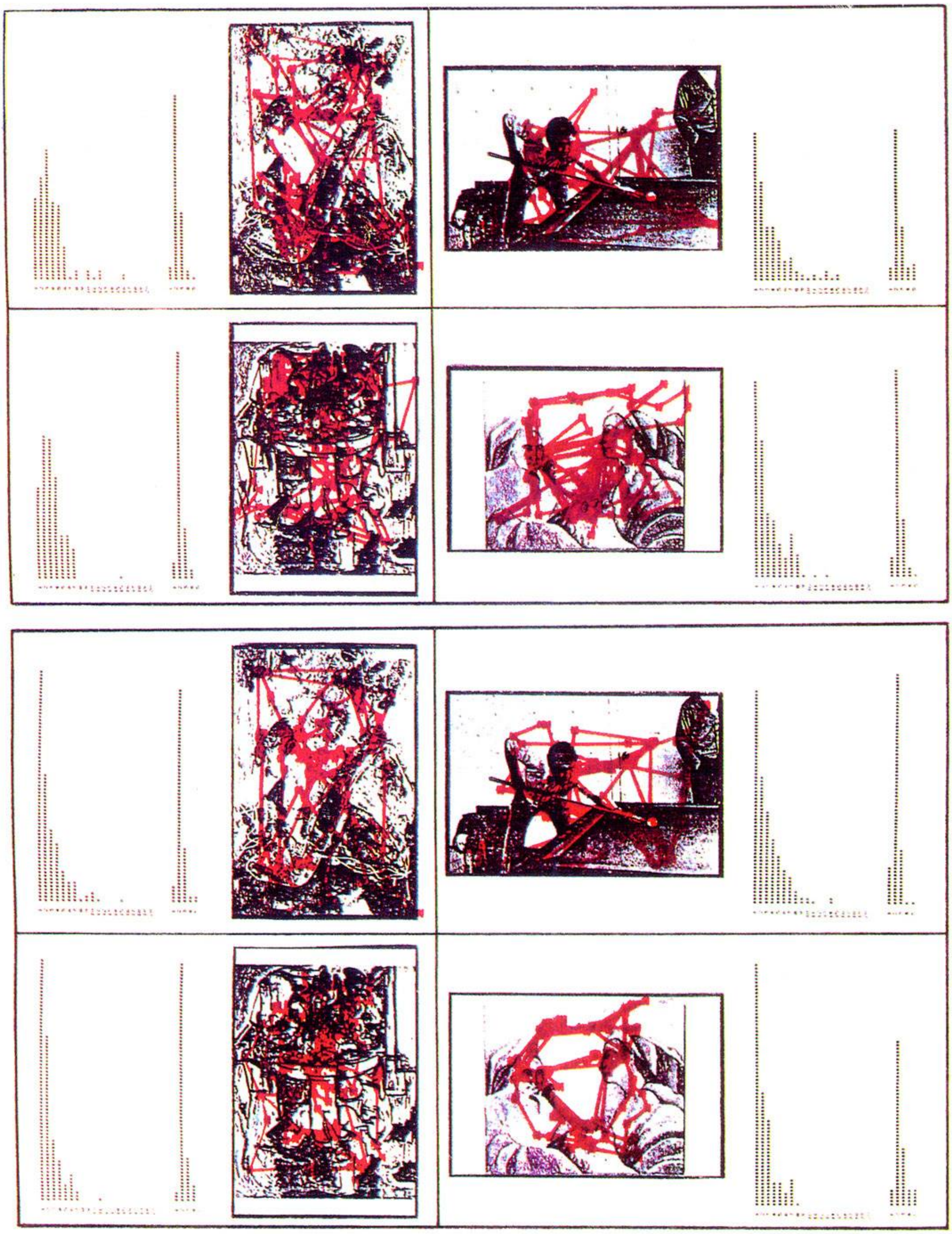
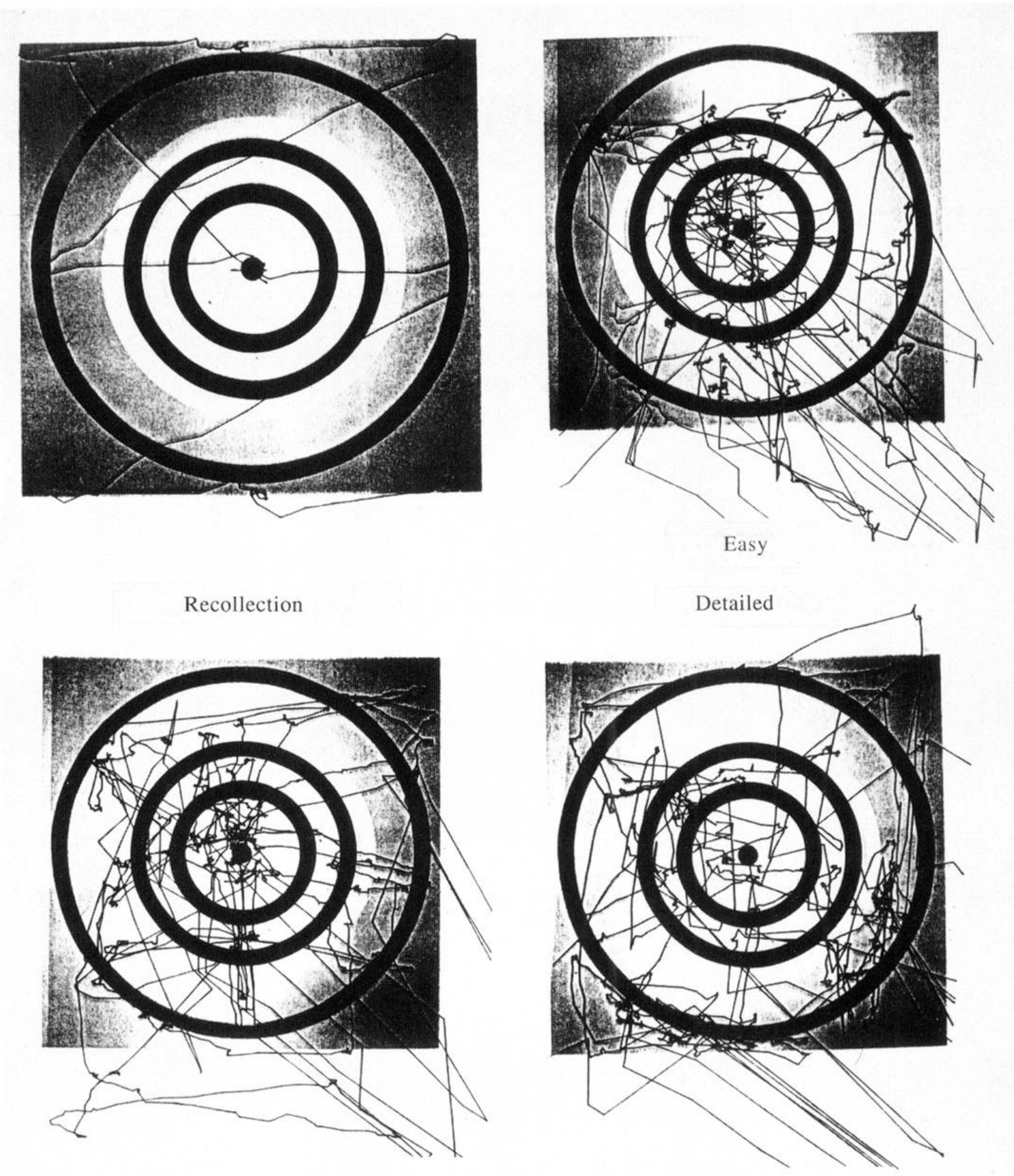


Fig. 4. Comparison of professional and naive subject. Same paradigm and pictures as in Fig. 2. Plots of probability density of eye movement size and fixation duration are appended to each picture on outer panels with size of saccades left and fixation duration right. Note: Fixation durations did *not* indicate correlations with experimental parameters. However, size histograms showed highly peaked, monotonic distributions for naive subject shown on lower half of figure, indicating large numbers of small saccades, i.e. a small global/local (g/l) index. Conversely, histograms of eye movement size of a professional subject, showed wider distribution with peaks at mid-sized saccades and reliance on larger saccades to overview the paintings, i.e. a large g/l index. This effect is most strongly exemplified for abstract paintings (upper left pair).



Professional painter

Fig. 5. Picture (5) (Ken Noland) viewed by a professional painter (ME) showed characteristically high individual global/local ratio of exploratory saccadic eye movements and few blink artifacts with 'detailed' as well as 'recollection' condition. With 'easy looking' both local eye movements and blink artifacts were high. Upper left part: calibration.

Whether the local scanpath is driven immediately by peripheral, bottom–up information or by small-scale cognitive models is unknown.

Locher and Nodine [29] have argued for immediate bottom–up control, e.g. in symmetry "that catches the eye"; whereas Mackworth and Morandi [30] showed evidence for top–down active selection of informative details through gaze. In any case, this detailed looking is apparently common for realistic images, and the naive subjects carry this behaviour on to abstract images. It is noteworthy that even with realistic images the naive subjects show a tendency to prefer local whereas the sophisticated and professional viewers showed more global scanpath trajectories.

Task effect on scanpaths

The third result of this study was the hidden task effect on the eye movements of our subjects. We were encouraged to look for changes in scanpath patterns as a function of task, because Buswell [9] reported longer fixations after reading comments on the picture viewed and Yarbus [48] showed clear pattern differences with differently instructed tasks (see especially Fig. 109, p. 174). Buswell [9] had suggested that eye movement patterns can be changed with the same subject looking at the same image. Yarbus [48] and later Stark and Ellis [38], have demonstrated positive evidence for this hypothesis. The latter authors used ambiguous figures, and the subject's scanpath changed its form; this depended on which of the ambiguous figures was in the viewer's active cognitive state at that moment. In our paradigm, we have the same subjects looking at the same picture but showing different amounts of perceptual cognitive effort corresponding to task instructions. In this experimental paradigm only statistical analysis of variance enabled us to differentiate this task effect. Other than Molnar [32] we did not find a correlation between task, grade of abstraction of the images *and* fixation duration of eye movements: neither in professional and sophisticated subjects nor in naive subjects.

Recent experiments by Brandt and Stark [8] studied the question raised by Hebb [19] in his theoretical analysis of imagery: Do the eyes scan an internally visualized image in much the same way as they look at an external scene or object? Most earlier studies, particularly with visualization of a given stable stimulus, failed to show that eye movements during visualization reflected the visual content of the image (Antrobus [1]; Zikmund [52]). Only indirect studies of eye movement rates, through reconstructions of the eye movement paths (Marks [31]; Finke [14]), and psychophysical methods (Jacobs [23]) could demonstrate a correlation. Brandt and Stark [8] compared sequences of eye movements of subjects looking at the real visual stimulus and then at their mental image. Comparing these two conditions using objective string-editing analyses and Markov matrices they were able to demonstrate firm evidence for scanpath sequences of their subjects' eye movements, that reflected the content of the visualized image.

Sorting experiment of the raw eye movement and blink data

In two different trials, we presented raw eye movement/blink data not overplotted on the pictures to two different classes, containing 10 and eight bioengineering students, respectively. We asked these students to guess which eye movement patterns were obtained from each of the three tasks: easy looking (E), recollection (R), detailed viewing (D). In both trials, the students were very successful in separating easy looking on the one hand from recollection and detailed looking on the other hand, with a chi square yielding a $P<0.001$ [46]. Of course, it is not certain what information in the raw eye movement and blink *xy*-plots the students used to differentiate these task groups. However, since the blink rate separated these (see next paragraph) and since enhanced global viewing of professional subjects showed up only in the abstract images with the additional knowledge of the statistical g/l analysis, it appeared most likely that indeed the students used the blink rate data to differentiate between the tasks. Interestingly, the students, with their pattern-recognition abilities when asked to classify the instructed tasks indeed were able to distinguish between the easy task and the other two tasks.

Task effect on blink rate

It has been known that visual effort reduces blink rate [26]. Here, we find that increased central nervous system (CNS) activity of a very abstract cognitive model sort, also produces the same inverse relationship between increased effort, i.e. the *detailed* viewing task, and decreased blink rate. Evidently, the task instruction for easy viewing required less effort as measured by blink rate than did the recall or detailed tasks. It has been known for some time that visual effort reduces blink rate [12, 43]. This has been noted with blurring [26, 47] of video display screens and with glare on these screens, both of which cause increased visual effort. The same effect has been observed for increased output demand, such as increasing the speed of a reading-aloud task [44]. Our present experiment extends these experiments, since the cognitive-model, perceptual aspects of viewing pictures must surely be considered a much higher level central nervous system effect than those previously studied with blink rate. Thus, we find that increased central nervous system activity of a very abstract, cognitive-model sort also produces the same inverse relationship between increased effort and decreased blink rate.

Correlation of our findings with aesthetic theories and artists' views

The two main findings of our study were: Cognitive models control active viewing of abstract paintings, and local scanning is reduced when sophisticated subjects view abstract art. Earlier approaches to aesthetic theory assumed bottom–up 'abstractive' viewing [2, 5, 28]. Hegel [20] considered an 'abstract' form as someting that could be reduced to mathematical configurations and proportions. For him the beauty of abstract shapes and of the abstract entity of perceptible matter became lifeless through the process of abstraction. More recently the top–down active perceptual process, the Anschauung of Kant [39] has prevailed in artists' and critics' view of painting. Beginning with impressionism the basic new concept of non-classical modern painting is that the trace of the brush does not any more give a clue to the conceptual understanding of forms. Thus, the viewer is forced to generate his own images of recollection and to project them on to the picture's surface, such that the painting is "evoked through the mind's eye" [16]. Kandinsky [25] was perhaps calling for suppression of the local scanpath when he stated: "The properly trained eye should be able at the same time to distinguish the *surface as such* and *disregard* it, when it changes to an *imaginary space*."

In recent research on perceptual displays [13] it has been argued that a depth distortion effect is counterbalanced by a surface effect. The secret of space in painting is that the artist has only the surface, but at the same time he is forced to "leave and transcend" the surface [27], such that vision happens as a creative activity of the mind.

Neurophysiological aspects

Fourment *et al.* [15] recording from intracerebral occipital electrodes in man have shown that the amplitude of cortical occipital waves related to free eye movements was increased during scanning of complex scenes. This electrical activity started at the end of the eye movement with their latency increasing with size of the movement and with complexity of the scene. Fourment *et al.* [15] concluded that such systematic variations probably depend on extra-visual and oculomotor mechanisms such as attention and curiosity of the subject. It relates to our result that the sophisticated and professional subjects showed very high g/l indices as a sign of their tendency towards large eye movements and more global scanpath especially in abstract images.

This is probably what Berlyne [7] had in mind, when he argued in favour of complexity in abstract artwork that was preferred by most of his experimental subjects. As he in an earlier work [6] stated, the visual *and* cognitive complexity that is perceived by the subject determines the choice of the relevant oculomotor behaviour. However, when the specific complexity of the picture is not perceived, because the subject is unsophisticated and naive looking at abstract images as in our paradigm, the choice of the top–down like control of eye movements is limited to the same strategy as in realistic images.

CONCLUSIONS

The eye movement experiments reported here of subjects looking at abstract paintings have shown that abstract images are viewed by the same top–down, perceptual–cognitive processes that drive active looking or scanpaths in viewing ordinary realistic paintings, scenes and objects.

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REFERENCES

1. Antrobus, J. Eye movements accompanying daydreaming. Visual imagery and thought suppression. *J. Abnorm. Soc. Psychol.* **69,** 244–252, 1964.
2. Arnheim, R. *Art and Visual Perception*, pp. 68–69. University of California Press, Berkeley. 1954.
3. Bahill, A. T. and Stark, L. Neurological control of horizontal and vertical components of oblique saccadic eye movements. *Math. Biosci.* **27,** 287–298, 1975.
4. Bahill, A. T. and Stark, L. Oblique saccadic eye movements: Independence of horizontal and vertical channels. *Arch. Ophthalmol.* **95,** 1258–1261, 1977.
5. Bense, M. *Aesthetica*, pp. 163–164. Agis Verlag, Baden-Baden, 1965.
6. Berlyne, D. E. The influence of complexity and novelty in visual figures on orienting responses. *J. exp. Psychol.* **55,** 289–296, 1958.
7. Berlyne, D. E. and McDonnel, P. Effects of complexity and prechoice stimulation on exploratory choice. *Percept. Psychophys.* **10,** 241–246, 1971.
8. Brandt, S. and Stark, L. Experimental evidence for scanpath eye movements during visual imagery. *IEEE Biomed. Engin. Proc.* 11*th Ann., Seattle*, pp. A317–318, 1989.
9. Buswell, G. T. *How People Look at Pictures*. University of Chicago Press, Chicago, 1935.
10. Carpenter, R. H. S. *Movements of the Eyes*. Pion Publ., London, 1988.
11. Ditchburn, R. W. and Ginsborg, B. L. Involuntary eye movements during fixation. *J. Physiol.* (*Lond.*) **119,** 1–17, 1953.
12. Drew, G. C. Variations in reflex blink rate during visual motor tasks. *Q. J. exp. Psychol.* **3,** 73–81, 1951.
13. Ellis, S. R. Pictorial communication: Pictures and the synthetic universe. In *Pictorial Communication in Virtual and Real Environments*, S. R. Ellis, M. K. Kaiser and A. C. Grunwald (Editors), pp. 22–41. Taylor & Francis, London, 1991.

14. Finke, R. A. Directional scanning of remembered visual patterns. *J. exp. Psychol.* **9,** 398–410, 1983.
15. Fourment, A., Calvet, J. and Bancaud, J. Electrocorticography of waves associated with eye movements in man during wakefulness. *Electroencephalogr. clin. Neurophysiol.* **40,** 457–469, 1976.
16. Gombrich, E. H. *Art and Illusion: A Study in the Psychology of Pictorial Representation*, pp. 242–244. Phaidon Press, London, 1977.
17. Groner, R. and Menz, C. The effects of stimulus characteristics, task requirements, and individual differences on scanning patterns. In *Eye Movements and Human Information Processing*, R. Groner, D. McConkie and C. Menz (Editors). North-Holland, Amsterdam, 1985.
18. Groner, R., Walder, F. and Groner, M. Looking at faces: Local versus global aspects of scanpaths. In *Theoretical and Applied Aspects of Scanpaths*, A. G. Gale and F. Johnson, pp. 58–59. North Holland, Amsterdam, 1984.
19. Hebb, D. O. Concerning imagery. *Psychol. Rev.* **75,** 466–477, 1968.
20. Hegel, G. W. F. *Vorlesungen ueber die Aesthetik 1835*. Kroener, Stuttgart, 1953.
21. Helmholtz, H. von and Southall, J. P. C. *Physiological Optics*. Dover Publ., New York, transl. from orig. German version published in 1866, 1962.
22. Hochberg, J. In the mind's eye. In *Contemporary Theory and Research in Visual Perception*, R. N. Haber (Editor), pp. 309–312. Holt, Rinehart & Winston, New York, 1968.
23. Jacobs, L. Are the eye movements of dreaming sleep related to visual images of the dreams? *Psychophysiol.* **9,** 393–401, 1972.
24. Jeannerod, M., Gerin, P. and Pernier, J. Deplacements et fixation du regard dans l'exploration libre d'une scene visuelle. *Vision Res.* **8,** 81–97, 1968.
25. Kandinsky, W. *Von Punkt zu Linie und Fläche*. Bauhaus Verlag, Dresden, 1926.
26. Kim, W. S., Zangemeister, W. H. and Stark, L. No fatigue effect on blink rate. *Proc. 20th Ann. Conf. Manual Control*, pp. 337–343. NASA Ames Res. Center, Moffett Field California, 1984.
27. Klee, P. *Paedagogisches Skizzenbuch, Bauhausbücher 2*, W. Gropius and L. Moholy-Nagy (Editor). Langen, Müchen, 1925.
28. Langer, S. K. Abstraction in science and abstraction in art. In *Structure, Method and Meaning—Philosophy in a New Key*. Plenum Press, New York, 1951.
29. Locher, P. J. and Nodine, C. F. Symmetry catches the eye. In *From Physiology to Cognition*, J. K. O'Reagan and A. Levy-Schoen (Editors). North-Holland, Amsterdam, 1977.
30. Mackworth, N. H. and Morandi, A. Y. The gaze selects informative details within pictures. *Percept. Psychophys.* **2,** 547–552, 1967.
31. Marks, D. Visual imagery differences and eye movements in the recall of pictures. *Percept. Psychophys.* **14,** 407–412, 1973.
32. Molnar, F. About the role of visual exploration in aesthetics. In *Advances in Intrinsic Motivation and Aesthetics*, I. Day (Editor). Plenum Press, New York, 1981.
33. Myers, G. Sherman, K. and Stark, L. Eye moniotor: Microcomputer-based instrument uses an internal model to track the eye. *Computer* **24,** 14–21, 1991.
34. Nachmias, J. Two-dimensional motion of the retinal image during monocular fixation. *J. Opt. Soc. Am.* **49,** 901–908, 1961.
35. Noton, D. and Stark, L. Scanpaths in eye movements during pattern perception. *Science* **171,** 308–311, 1971.
36. Noton, D. and Stark, L. Eye movements and visual perception. *Scient. Am.* **244,** 34–53, 1971.
37. Sachs, L. *Applied Statistics*, pp. 612–657. Springer, Berlin, 1991.
38. Stark, L. and Ellis, S. Scanpaths revisited: Cognitive models in active looking. In *Eye Movements, Cognition and Visual Perception*, B. Fisher, C. Monty and M. Sanders (Editors), pp. 193–226. Laurence Erlbaum, Hillsdale, New Jersey, 1981.
39. Stark, L., Vossius, G. and Young, L. R. Predictive control of eye tracking movements. *IEEE Trans. Hum. Fac. Electron. HFE-3*: 52–67, 1962.
40. Stark, L., Zangemeister, W. H., Hannaford, B. and Kunze, K. Use of models of brainstem reflexes. In *Clinical Problems of Brainstem Disorders*, K. Kunze, W. H. Zangemeister and A. Arlt (Editors), pp. 178–189. Thieme, Stuttgart, 1986.
41. Steinman, R. M., Cunitz, R. J., Timberlake, G. T. and Herman, M. Voluntary control of microsaccades during maintained monocular fixation. *Science* **155,** 1577–1579, 1967.
42. Steinman, R. M., Hadad, G. M., Skavenski, A. A. and Wyman, D. Miniature eye movements. *Science* **181,** 810–819, 1973.
43. Stern, J. A. and Skelly, J. J. The eye blink and workload considerations. *Proc. 23rd Ann. Meeting of Human Factors Soc.*, pp. 941–944. Santa Monica, California, 1984.
44. Sun, F., Morita, M. and Stark, L. Comparitive patterns of reading eye movements in Chinese and English. *Percept. Psychophys.* **37,** 501–506, 1985.
45. Viviani, P., Berthoz, A. and Tracey, D. The curvature of oblique saccades. *Vision Res.* **17,** 661–664, 1977.
46. Winer, B. J. *Statistical Principles in Experimental Design*. McGraw-Hill, London, 1971.

47. Wu, S. S., Stark, L., Veretto, F., Grenawalt, W., Kim, W. and Zangemeister, W. H. Blink rate as a measure of effort in visual task performance. Proc. Conf. on Work Display Units Stockholm. *Ergonomics* **7,** 10–18, 1986.
48. Yarbus, A. L. *Eye Movements and Vision*, Chap. 27. Plenum Press, New York, 1967.
49. Zangemeister, W. H., Oechsner, U. and Freksa, C. Short term adaptation of search- and scan-path in patients with visual field defects. *Optom. Vis. Sci.*, in press.
50. Zangemeister, W. H. and Schoepf, D. Correlation of coordinated gaze strategies to the status of adaptation in patients with hemianopic visual field defects. *Ann. N.Y. Acad. Sci.* **682,** 404–409, 1993.
51. Zangemeister, W. H., Sherman, K. and Stark, L. Eye movements and abstract images. In *ECEM5*, R. Schmid and D. Zambarbieri (Editors), pp. 165–172. University of Pavia Press, Pavia, 1989.
52. Zikmund, V. Oculomotor activity during visual imagery of a moving stimulus pattern. *Studia Psychol.* **8,** 254–273, 1966.