Cognitive Models Direct Scanpath Eye Movements: Evidence Obtained by Means of Computer Processing of Perceptual Scanpath Eye Movements **55.6**

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Our experimental question concerns the saccadic eye movements that people continually employ in actively looking in the process of vision. These eye movements can at the very least be considered as tags of experimentally accessible quantities which the scientist may observe to understand the underlying processes of cognition. A much stronger hypothesis is that the eye movements play an essential role in vision, that the eye movements represent cognitive models (either ideals or experientially generated) that are present in our brain and which subjects use to make perceptual hypotheses and test them against the complex world of sensory experience. Again, the experiments to be described below provide strong evidence for the critical role of eye movements as an essential component in cognition and recognition. Previously published scanpath theories in a series of papers by Noton-Stark in 1971 served to justify the essential role of eye movements in cognition but did not have available the quantitative methodology of the current experiments.

The experiments involve display of various pictures, measurement of eye movements, and online digital computer processing. Such use of laboratory digital computers has for us a history going back to our online computer experiments at MIT. Recent developments by Adler and Cahn, and by Magnuski, have extended the Noton-Stark 'slow-down' procedure for obtaining sequential plots of eye movements which required experimenter interaction.

We report in our computer methodology preliminary results which are to be reported in full in a series of papers that are now in preparation.

Markov Conditional Probability Matrices

These matrices represent a quantitative abstraction of the information in the sequential eye movements. The M_0 matrix is a vector representing the unequal probabilities of the eye looking at a particular fixation region of the picture. An entry in the M_1 matrix represents the conditional probability of an eye movement between one fixation region and another. The values of the probability coefficients in the M_1 matrix differ from those calculable from the M_0 matrix and represent part of the sequential structure of the eye movements. This is measured by the Chi-square test. Analogously, an entry in the M_2 matrix represents the conditional probability of two eye movements representing two sequential transitions. An exact probability test is necessary here rather than the Chi-square test. The statistical value quantitates our impression that the scanning pattern has change after recognition. Note also the large 3-2-4 entry in the M_2 matrix again representing sequential structure. The M_2 matrix entries are here the numbers of occurrences of events rather than probabilities to enable ready understanding by the reader.

Artificial Simulations

In order to study the interrelation between the Markov matrix entries and the eye movement traces, it was decided to carry out a series of simulation studies whereby matrices with sample sets of entries would generate artificial eye movements in an artificial scanpath pattern. Figure 5 shows details of such a simulation. For example, in the left frame is a deterministic Markov probability matrix with all values set to zero except for the supra-diagonal ones set equal to 1. Thus, if the eye is in fixation region 5, the probability of going to the sixth fixation region is 1. Thus, the eye would move from 5 to 6. This deterministic matrix clearly generates a cyclic graph. A 'fuzzy' operator has been used so that eye fixation occurs randomly within the fixation region. This contributes to the 'fuzzyness' of the fixation position and to the spread of the superimposed eye movement traces.

The right hand frame of Figure 7 shows a matrix with all coefficients equal to 0.1. If the eye is in fixation region 3, all the next fixation regions are equally probable. The resulting network of eye movements shows a rather diffuse appearance. The center frame, labelled probabilistic, shows the Markov entries in the super diagonal line to be 0.7, in the next diagonal to be 0.3, and to be zero everywhere else. If the eye is in fixation region 8, there is a 0.7 probability of going to 9 and a 0.3 probability of going to 10. If the eye is at fixation region 8, it might have arrived with probability 0.7 from fixation 7 or a probability of 0.3 from fixation 6. This graph has an appearance intermediate between the deter-

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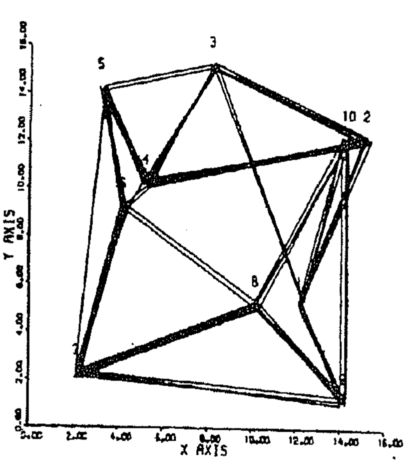
ministic and purely random forms, similar indeed to experiment eye scans.

Discussion

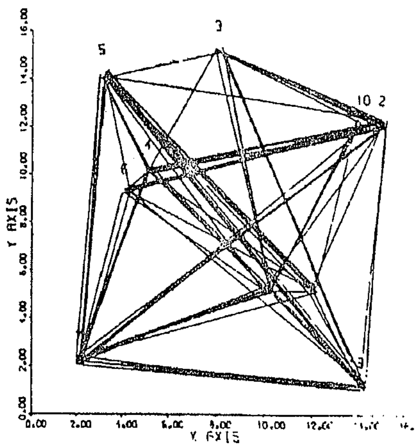
Our present computer-based experimental system objectively determines the collapsed sequence of eye movements as seen, for example, in the lower right frame of Figure 3, the lower left and upper right frame of Figure 4, the middle left and right frames of Figure 5. These represent adequate performance of the instrumentation, the calibration procedure, the linearization procedure, and the completely automatic fixation identification procedure. These sequential strings of eye movements from one fixation point to another represent the basic datum from which all our other analyses depend.

The Markov conditional probability matrices represent an important aspect of our research. Given the fixation regions identification process, we can now construct sequential strings of successive fixation regions and look to various statistical methods for investigating the underlying higher-level cognitive processes that control these eye movements. The first three Markov matrices, M_0, M_1, and M_2, succienctly summarize the structure of the scanpath and other eye movements appearing while a subject looks at a picture. The M_2 matrix and high-order matrices represent the importance of past history of the eye movement sequence in governing the next movement. Simulation of

0	.7	.3	0	0	0	0	0	0	0
0	0	.7	.3	0	0	0	0	0	0
0	0	0	.7	.3	0	0	0	0	0
0	0	0	0	.7	.3	0	0	0	0
0	0	0	0	0	.7	.3	0	0	0
0	0	0	0	0	0	.7	.3	0	0
0	0	0	0	0	0	0	.7	.3	0
0	0	0	0	0	0	0	0	.7	.3
.3	0	0	0	0	0	0	0	0	.7
.7	.3	0	0	0	0	0	0	0	0



.1	.1	.1	.1	.1	.1	.1	.1	.1	.1
.1	.1	.1	.1	.1	.1	.1	.1	.1	.1
.1	.1	.1	.1	.1	.1	.1	.1	.1	.1
.1	.1	.1	.1	1	1	1	.1	1	.1
.1	.1	.1	.1	.1	.1	.1	.1	.1	.1
.1	.1	.1	.1	.1	.1	.1	.1	.1	.1
.1	.1	.1	.1	.1	.1	.1	.1	.1	.1
.1	.1	.1	.1	.1	.1	.1	.1	.1	.1
.1	.1	.1	.1	.1	.1	.1	.1	.1	.1
.1	.1	.1	.1	.1	.1	.1	.1	.1	.1



these matrices is an interesting and helpful application of Monte Carlo methods for obtaining intuition about the non-randomness of sequences of eye movements serving visual perception, visual memory, pattern and cognitive recognition.

SUMMARY

Scanning eye movements were recorded with a computer-based eye monitoring system while subject viewed various figures, including hidden test figures. Software developed by us allowed recording of human eye movement data, correction for instrumental nonlinearities, filtering of noise, automatic fixation identification, and analysis of the sequential pattern of fixations. Fixation sequences made while viewing the same hidden figure both before and after recognition were compared using Markovian models. This technique abstracts alterations in the sequences of fixation corresponding to the change of cognitive state accompanying recognition of the hidden figure.