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PERT NETWORKS AS A METHOD FOR ANALYZING THE VISUAL SCANNING STRATEGIES OF AIRCRAFT PILOTS

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In a Program Evaluation and Review Technique (PERT) network, no process can begin executing until all processes that immediately precede it have completed their activity. PERT networks have been used in psychology to investigate the structure of cognitive processes, and may be applied also to the analysis of eye-movements in order to gather detailed information on the processes underlying the ocular activity. This may be particularly useful to understand phenomena for which specific hypothesis have been made. The primary aim of this paper is to show the potential of this approach as a visualization technique, and to devise a research agenda for future applications of PERT networks as a method for investigating the time course of visual scanning.

Introduction

The scanpath is a sequence of eye movements that is executed when viewing a scene. Its analysis is a technique often used in Human Factors / Ergonomics (HF/E) research, and several authors (e.g. Diez et al., 2001; Itoh et al., 1990) have employed this method for gathering information about the scanning strategies of pilots. Often these studies have analyzed the ocular activity within specific Areas Of Interest (AOI), each one including a tool inspected by pilots during a simulated flight. Although the scanpath is usually used to obtain qualitative information, it can also be used in conjunction with advanced computing techniques. For example, by using a simple geostatistical index based on the distance between "nearest neighbors," researchers (Di Nocera *et al.*, 2006; in press) have found that fixation dispersion is associated with high workload, while fixation grouping is indicative of low workload. These patterns have been found in different tasks settings (e.g., simple video games and flight simulation) and in different populations (e.g., students and pilots). Moreover, the index is correlated to other known workload indicators such as the NASA-TLX and the P300 amplitude (Camilli *et al*., submitted).

One of the most important features of this indicator is the possibility to compute it over relatively small epochs (e.g., 1-minute), thus allowing the analysis of the progression of mental workload. Of course, this is of critical importance for implementing biologically-based adaptive systems. Also, this index can be computed over a distribution of fixations belonging to the whole scene and does not require a priori definition of regions of interest. This can make a great difference for dynamic scenarios (e.g. driving and air traffic control).

However, notwithstanding the potential of the technique and the consistency of the results, the functional significance of the index remains unclear.

Nearest Neighbor Index

As reported above, the relation between the pattern of fixations and mental workload has been primarily investigated using a spatial dispersion index known as Nearest Neighbor Index (NNI). This index provides a single value that is indicative of the type of distribution on which it has been computed. Readers interested in the statistical details may refer to the original article by Clark and Evans (1954). In short, the mean distance between pairs of nearest neighbors is compared to that expected on the basis of chance. The actual mean distances can be smaller (points are aggregated; NNI < 1), larger (points are regularly dispersed; NNI > 1), or not different from the expected distances (points are randomly dispersed; NNI $= 1$). However, the separation between random, clustered, and regular point patterns is only made for convenience: it is a snapshot in time. There is always a continuum along which these types exist, because a spatial pattern is the result of a process evolving over time. This is particularly evident for patterns of eye fixations. With that in mind, the NNI should be used to test hypothesis about the time course of the process itself.

In its application as an index of mental load, one of the most critical aspects of the NNI is that it provides results that contrast directly with other indices (e.g., scanpath entropy), and with the commonly accepted consideration that, when workload is high, fixation groupings should be observed instead.

Although the dispersion of fixations has been interpreted as the outcome of an adaptive inspection strategy aimed at optimizing the individual's promptness to incoming information, there is also another hypothesis that might explain the inconsistency of the results obtained using the NNI as opposed to other measures. Indeed, all of the experiments that have reported the relation between the distribution of fixations and mental workload have used manipulations of the temporal characteristics of the task:

1) the Asteroids game (Di Nocera *et al.*, 2006) was modified to prevent the use of the weapon in the high task load condition. This clearly led participants to frequently monitor the trajectory of the asteroids in order to avoid collision;
2) flight simulation (Di Nocera *et al.*, in press) showed more dispersed patterns during the take-off and landing phases. Those phases are the most demanding and the pilots were busy monitoring several instruments in a short period of time;
3) the Tetris game (Camilli *et al.*, submitted) implemented three difficulty conditions obtained by varying the speed of the falling blocks. Participants showed more dispersed patterns as speed increased.

Clearly, what appears to make the difference is the temporal demand aspect of mental workload. However, other studies have reported fixations concentration when task load was high (e.g. Recarte & Nunes, 2000). Remarkably, these results were obtained when the visual exploration was challenged by a secondary task demanding resources from the same (visuospatial) pool. Consequently, the fact that spatial imagery tasks lead to a fixation grouping is not surprising: it is a common experience to "lock our eyes" over a point when we are mentally visualizing something.

Considering these differences, it may be hypothesized that two processes respectively contribute to dispersion and grouping: temporal demand and visuospatial demand. To evaluate these claims, data from a previous experiment (Di Nocera *et al.*, in press) were further analyzed. Particularly, the aim of the present study was to link the differences in the NNI (variable levels of dispersion/grouping) to visual scanning strategies.

PERT Networks

Eye movement data may be represented as a graph. A graph is a diagram showing a relationship between variables. A directed graph or digraph G is an ordered pair $G = (V, A)$ with V, a set of vertices or nodes, and A, a set of ordered pairs of vertices, called directed edges, arcs, or arrows. Techniques referred to as Program Evaluation and Review Technique (PERT) and the critical path method make use of activity digraphs (Chartrand, 1977), in which the set of ordered pairs includes bidirectional pairs. In a PERT network, no process can begin executing until all processes that immediately precede it have completed their activity. When the durations of the processes arranged in a network vary from trial to trial, the network is called stochastic. Stochastic PERT networks have been used in psychology to investigate the structure of cognitive processes (see Fisher & Goldstein, 1983), and may also be applied to the analysis of eye-movements in order to gather detailed information on the processes underlying the ocular activity.

Analysis

In order to understand the plausibility of our hypothesis, we analyzed ocular data collected from ten professional pilots during a simulated flight using PERT networks as a visualization method.

The following picture shows the development of the NNI across flight segments. Consistently with the literature on mental workload in aviation, the measure showed the lowest values during cruise and highest values during departure/climb and descend/landing.

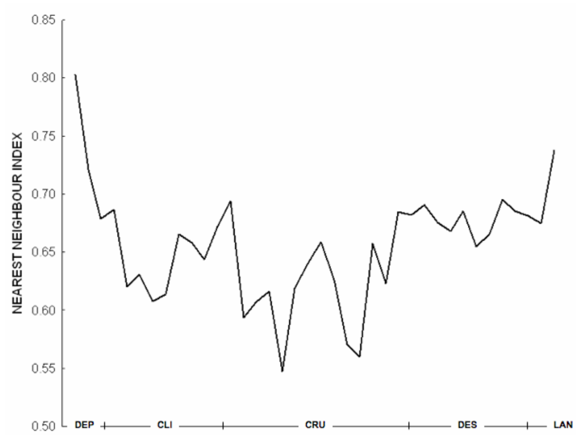

Figure 1. Time series of the Nearest Neighbor Index (all pilots averaged). Flight segments are indicated as DEParture, CLImb, CRUise, DEScend, LANding.

For the purpose of the present analysis only the first minute of departure was taken into consideration (what contributed to the first point in the time series showed in figure 1). The general idea was to investigate the individual differences in the dispersion of fixations. Indeed, pilots showed differential NNI values along the whole flight, but the first minute (associated with the highest NNI values) was considered as a good starting point for this exploratory analysis.

Data were analyzed using the ASTEF package (http://www.astef.info), allowing fixations analysis and management as well as easy computation of the NNI.

The following graphs show exploration patterns for each pilot. Numbers refer to flight deck instruments (see Appendix).

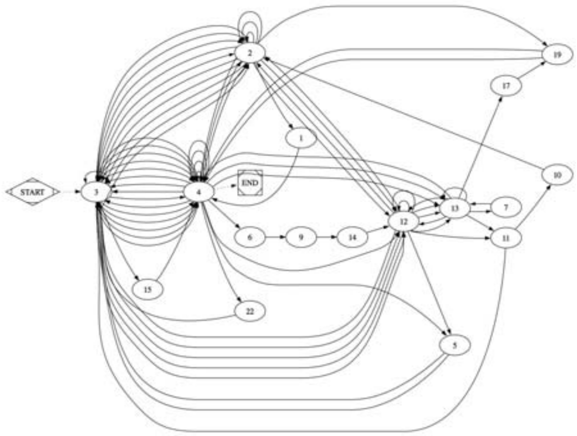

Figure 2. Ocular activity digraph for pilot #1. NNI = .94 (first minute of take-off).

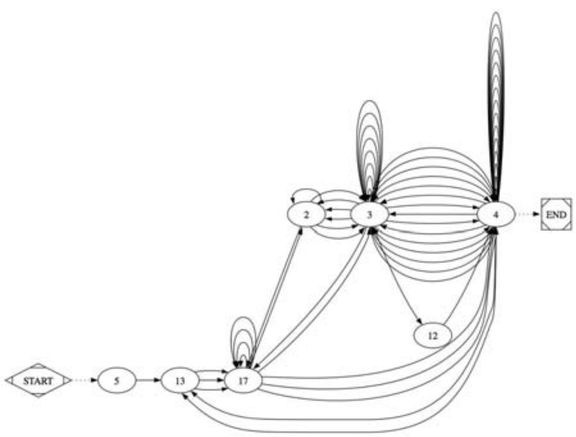

Figure 3. Ocular activity digraph for pilot #2. NNI = .89 (first minute of take-off).

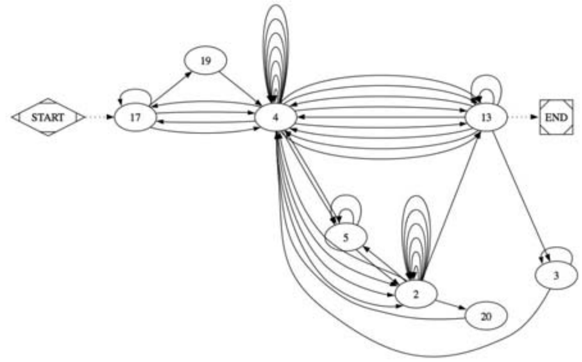

Figure 4. Ocular activity digraph for pilot #3. NNI = .56 (first minute of take-off).

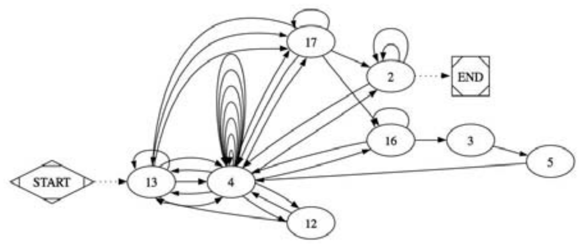

Figure 5. Ocular activity digraph for pilot #4. NNI = .89 (first minute of take-off).

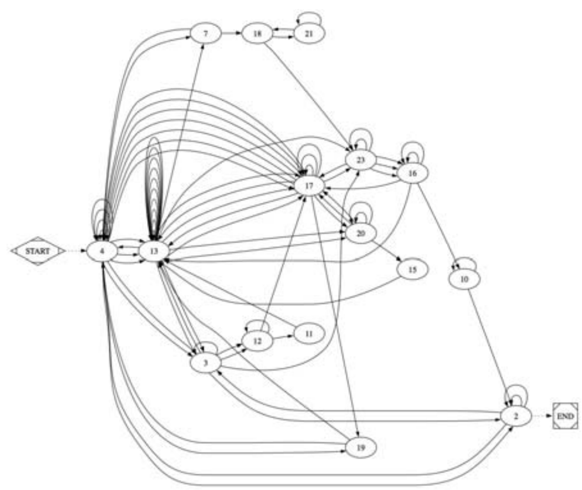

Figure 6. Ocular activity digraph for pilot #5. NNI = .96 (first minute of take-off).

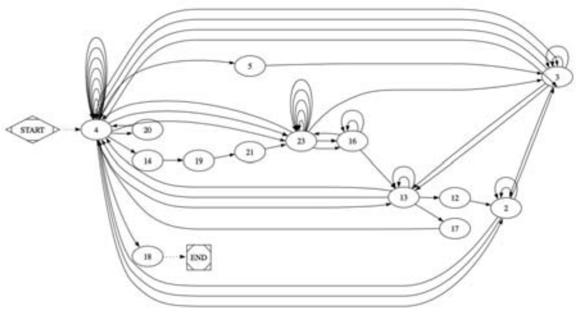

Figure 7. Ocular activity digraph for pilot #6. NNI = .92 (first minute of take-off).

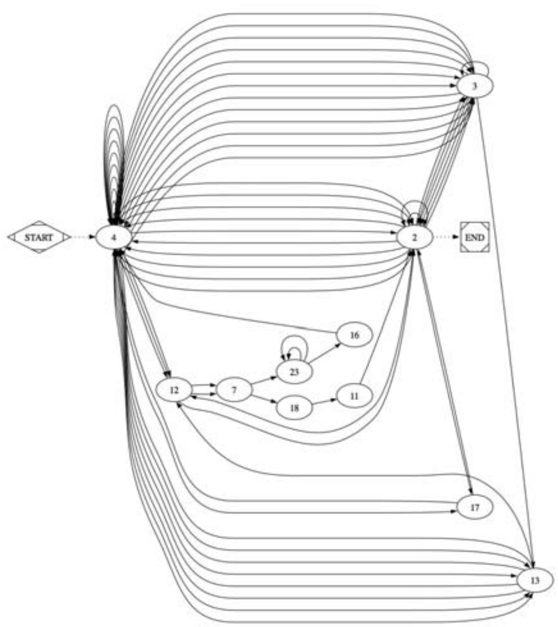

Figure 8. Ocular activity digraph for pilot #7. NNI = .78 (first minute of take-off).

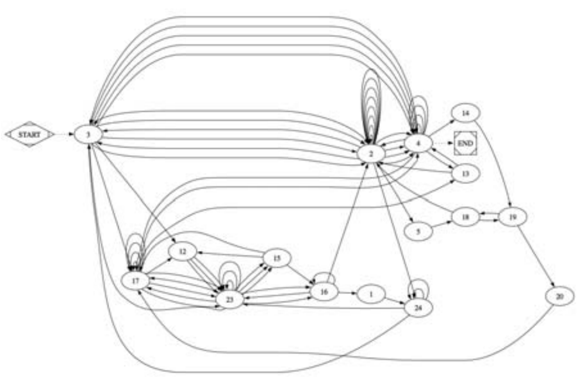

Figure 9. Ocular activity digraph for pilot #8. NNI = .79 (first minute of the take-off).

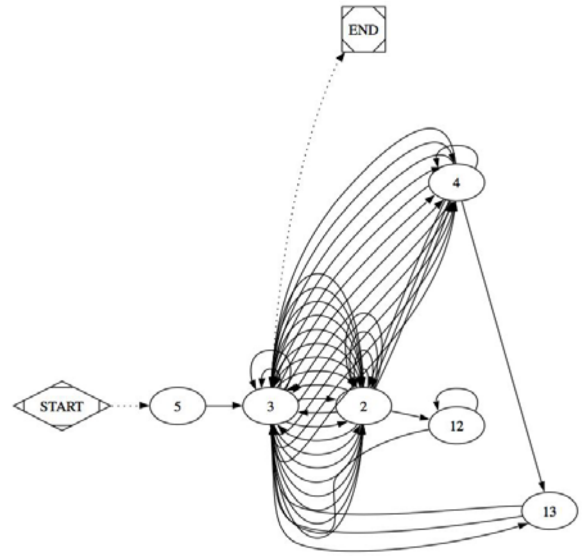

Figure 10. Ocular activity digraph for pilot #9. NNI = .68 (first minute of take-off).

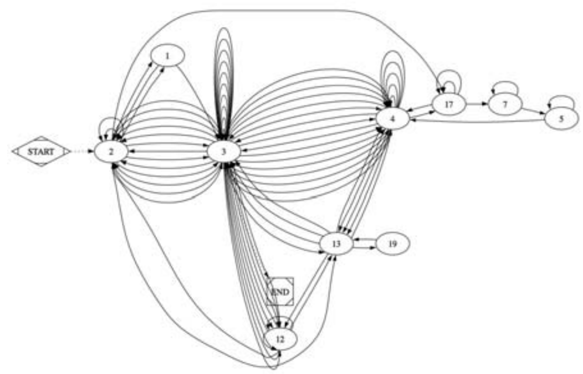

Figure 11. Ocular activity digraph for pilot #10. NNI = .63 (first minute of take-off).

Discussion and Conclusions

The aim of this study was to explore the possibility that individual differences observed in the NNI computed over eye fixations might be due to the effects of two separate processes: one involving the ocular strategy related to temporal demands and the other involving the ocular strategy related to the visuospatial demands of a task. To this aim, we have represented the visual scanning behavior of ten professional pilots as digraphs. Figures (2 to 11) clearly show that pilots whose NNI was low (roughly below .80) frequently monitored speed-, altitude-, and attitude-indicators. Those instruments, more than others, involve some type of visuo-spatial imagery and are used by pilots to mentally represent the current position of the aircraft.

This effect is quite constant, and only pilot #1 was inconsistent with this pattern as he showed both high NNI (.94) and the speed-altitude-attitude exploration strategy.

Pilots whose NNI was high (roughly over .80) frequently monitored many instruments. Graphs show that they looked around much more than the other pilots.

Of course, those are only qualitative considerations and should be supported by more formal (i.e. analytical) considerations. Results of this first exploratory study suggest that it will be useful in the future to add temporal properties to the spatial patterns we have taken into consideration. Indeed, stochastic PERT networks offer the possibility break down a mental operation into its underlying elements, thus understanding how the processes we have hypothesized contribute to fixation durations.

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Appendix: flight deck instruments

1. Clock
2. Speed Indicator
3. Attitude Indicator
4. Altitude Indicator
5. Manifold Pressure
6. Engine Speed (RPM)
7. Fuel Flow
8. Marker
9. Distance Measure Equipment
10. VOR & ADF
11. Turn Coordinator
12. Horizontal Situation Indicator
13. Vertical Speed
14. Engines Temperature
15. Oil Temperature and Pressure
16. Starter and Lights
17. Flaps
18. Trim
19. Lights
20. Shift
21. Battery