Spatial Pattern of Eye Fixations and Evidence of Ultradian Rhythms in Aircraft Pilots

Francesco Di Nocera; Ronald Ranvaud; Vittorio Pasquali

INTRODUCTION: Eye fixations can be distributed in three ways: randomly, in clusters, and regularly. However, there is always a continuum among these types, because these spatial patterns are the result of a process evolving over time. The focus of the present work was to study the changes over time observed in the Nearest Neighbor Index (NNI), an index derived from the spatial distribution of eye fixations that has been reported to be sensitive to variations in mental workload. Of particular interest are periodic changes in the ultradian timescale (an ultradian rhythm is a recurrent period or cycle repeated throughout a 24-h circadian day).

METHODS: Data from a previously reported experiment were further analyzed using temporal spectral analysis, which is one of the most commonly used techniques for studying measurements collected at regularly spaced intervals of time.

RESULTS: An ultradian rhythm with a periodicity between 2 and 15 min was found, which is compatible with results obtained by analyzing reaction times in prolonged vigilance tasks.

DISCUSSION: The identification of a periodicity in the allocation of mental resources should be considered in the design of automation support that is dynamically matched to mental workload.

KEYWORDS: mental workload, eye tracking, pilots, times series, fixations.

Di Nocera F, Ranvaud R, Pasquali V. *Spatial pattern of eye fixations and evidence of ultradian rhythms in aircraft pilots.* Aerosp Med Hum Perform. 2015; 86(7):647–651.

Recent evidence strongly suggests that the spatial distribution of eye fixations is sensitive to variations in mental workload.[6–8] Spread out fixations appear to be associated with mental workload when task load depends on temporal demand, whereas fixation clustering seems to be associated with mental workload when task load depends on visuo-spatial demand.[2,5] These tendencies have been found in different task settings (from simple arcade games to flight simulation), in different populations (students and aircraft pilots), and have been quantified using a spatial statistics index called Nearest Neighbor Index (NNI). The index was also found to be correlated with other known workload indicators such as NASA Task Load Index (NASA-TLX) ratings and the P300 amplitude.[1]

It is intriguing that the distribution of eye fixations may be used to implement a real-time measure of mental workload and thus as a trigger for automated systems. One of the most important features of this indicator is that it may be computed over relatively small epochs (e.g., 1-min), thus allowing the analysis in real time of the progression of mental load of any individual.[10] Of course, this is of critical importance for implementing adaptive systems based on the assessment of operator functional state.[9] Also, this index can be computed with fixations belonging to the whole scene and does not need a priori definition of regions of interest. This can make a great difference when dynamic scenarios are of interest.

Given what has been reported above, this approach seems promising even though more work is needed in order to fully understand the relationship between fixation dispersion and mental load. For example, notwithstanding the potential of the technique and the consistency of the results, the functional significance of the index is unclear. One possible interpretation is that the distribution of fixations might be the outcome of an adaptive inspection strategy. Such a strategy should be effective in optimizing the individual's promptness to incoming

From the Department of Psychology, Sapienza University of Rome, Rome, Italy.

This manuscript was received for review in January 2015. It was accepted for publication in April 2015.

Address correspondence to: Francesco Di Nocera, Ph.D., Department of Psychology, Sapienza University of Rome, Via dei Marsi 78, 00185 Rome, Italy; francesco.dinocera@uniroma1.it.

DOI: 10.3357/AMHP.4275.2015

information, which is particularly important when temporal task load is high. Fixation clustering, instead, may serve as an effective strategy in other situations, such as when visual exploration is challenged by a secondary task demanding resources from the same (visuospatial) pool. Several studies[11] have reported fixation clustering under such a type of load. As reported elsewhere,[5] the fact that spatial imagery tasks lead to fixation clustering is not surprising: it is a common experience to "lock our eyes" on a point when we are mentally visualizing something. Clearly, the understanding of spatial patterns and their relationship to mental workload need to include the study of the time-course of eye fixations.

The relationship between fixation patterns and mental workload in the research program reported above was primarily carried out using a spatial dispersion index known as NNI. The index provides a single value that is indicative of the type of spatial distribution of the data with which it is computed. Readers interested in the statistical details may refer to the original article by Clark and Evans.[3] In short, the index compares mean distance between pairs of (nearest) neighbors in the data to that expected on the basis of chance (random distribution). The actual mean distances can be smaller (points are clustered; NNI < 1), larger (points are regularly distributed; NNI > 1), or not different from the expected distances (points are randomly distributed; NNI $\sim$1). However, the classification of point patterns as clustered, regular, or random is only made for convenience: it is a snapshot in time and there is always a continuum among these categories, because a spatial pattern is the result of a process continuously evolving over time. With that in mind, NNI can be used (actually, should be used) to test hypotheses about the time course of resource allocation (i.e., mental workload). The focus of the present work is the quantitative time evolution of NNI as a task is carried out. To this purpose, data from a previous experiment[6] were further analyzed using spectral analysis, which is appropriately and commonly used in studying measurements collected at regularly spaced intervals of time.

METHODS

Subjects

There were 10 instrument flight rules licensed pilots belonging to the Italian Police (all men; mean age = 41.10 yr, SD = 4.82), all members of a special unit employed in critical law enforcement missions, who volunteered for this study. Participants had 594 to 2570 h of flight experience (mean = 1681, SD = 757). All participating pilots received training with the simulation software prior to experimentation. The Department of Psychology's Institutional Review Board approved the study protocol in advance. Each subject provided written informed consent before participating.

Equipment

Microsoft Flight Simulator 2004 was used to provide participants with the task environment in this study. The deck was that of the Beechcraft Baron 58, which is similar to the Partenavia P68 Observer aircraft actually used by Italian police pilots. The input device was a Trust (Dordrecht, The Netherlands) GM-2600 joystick. Pilots were vectored by a simulated air traffic control workstation, with an experimenter using the Microsoft Flight Simulator Navigator. A Tobii ET17 (Danderyd, Sweden) eye-tracking system was used for recording ocular activity. Sampling frequency was 30 Hz.

Procedure

Participants sat in a dark and sound-attenuated room, underwent a calibration procedure for the eye-tracker, and received instructions for the execution of the task. Participants were asked to fly from Pratica di Mare (41°39′34″ N 12°26′43″ E) to Ciampino (41°47′58″ N 12°35′42″ E) without the use of autopilot, GPS, or radio communication controls. An instrumental landing system procedure was used in the final phase. The total flight duration was about 38 min.

Statistical Analysis

Given the dynamic nature of the task, the flight segments were not perfectly aligned (e.g., a pilot could start the descent phase before or after another pilot) and the total flight duration was slightly different among pilots. Consequently, ocular data were aligned at the beginning of each of five phases: departure, climb, cruise, descent, and landing. The NNI was computed over 1-min epochs for each pilot. Missing values in the series due to phase alignment were substituted with the mean between the preceding and the successive epochs. A total of 38 points was obtained for each pilot. On visual inspection, individual time series showed an oscillating pattern that was also reflected by the average time series (**Fig. 1**).

In order to have a clearer picture of underlying periodicity, power spectra were computed for each pilot's series. Spectral analysis time series were smoothed (3-point moving average) and the linear trend was removed before analysis. Power spectra were computed for each pilot by discrete Fourier transform. Smoothed estimation of the spectra were obtained by a Parzen window. A one-sample Kolmogorov-Smirnov test was used to check the random component of the spectra (white noise). In spectra significantly different from white noise, peaks above 2.33 SD ($P < 0.01$) were considered significant.[4]

RESULTS

Fig. 2 shows the power spectra for each pilot. Visual inspection of individual spectrograms showed the presence of significant peaks with periods $<$ 9 min (high frequency), in the 10-19 min range (medium frequency), and $>$ 20 min (low frequency). We do not exclude that the low frequency oscillations observed in some pilots could be attributed to the fact that recordings were short, so that increasing the observations may increase data significance. In particular, pilots #3 and #10 showed peaks in the high frequency range, pilots #5, #7, #8, and #9 in the medium frequency range, and pilots #1, #2, #4, and #6 in the low

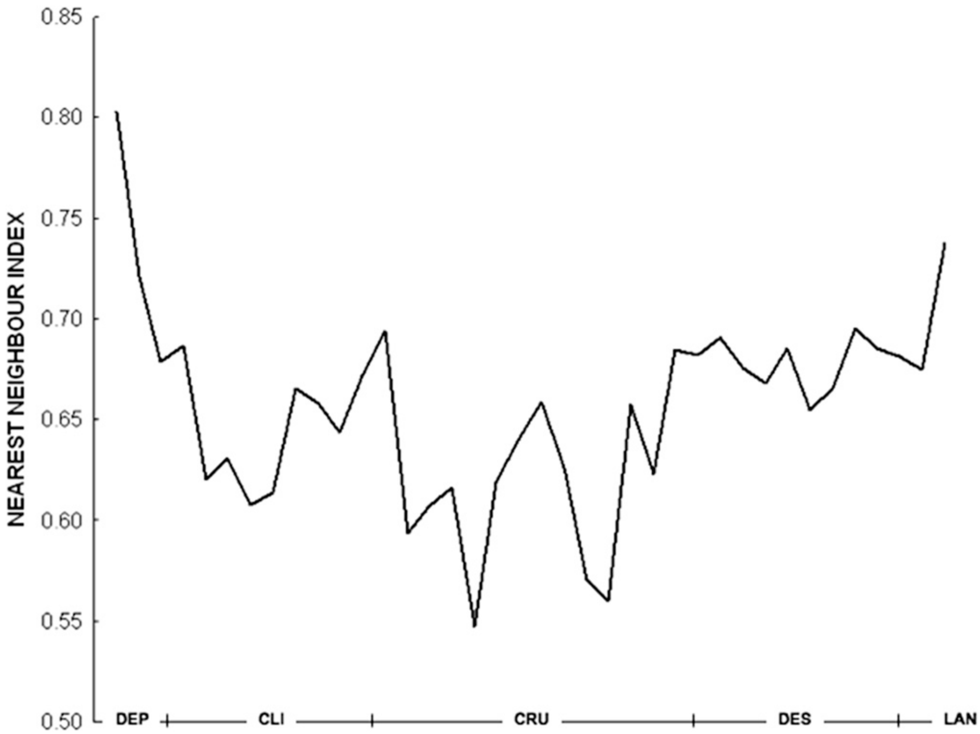

Fig. 1. Time series of the Nearest Neighbor Index (all pilots averaged). Flight segments are indicated as DEParture, CLImb, CRUise, DEScend, and LANding.

frequency range. A Kruskal-Wallis ANOVA showed significant difference in two of the three groups (medium $\chi^2 = 7.0$, df $= 2$, $P < 0.05$; low $\chi^2 = 8.0$, df $= 2$, $P < 0.05$; high $\chi^2 = 3.0$, df $= 2$, $P > 0.05$).

In order to address the differences found between the subgroups of pilots showing different periodicity, two ANOVA designs by Subgroup (high- vs. medium- and low-frequency) were carried out using pilots' visual exploration extension (in terms of a convex hull defined by the outermost fixations) and expertise (in terms of pilots' flight hours) as dependent variables, respectively. This attempt was made even if the subgroups were very small ($N = 4$, $N = 4$, and $N = 2$, respectively). No significant effect was found in either case ($P > 0.05$).

DISCUSSION

The re-analysis carried out in the present paper indicated the presence of ultradian rhythms (an ultradian rhythm is a recurrent period or cycle repeated throughout a 24-h circadian day) with periodicity $6 < t < 17$ min. This range of ultradian rhythms in mental functions, with individual differences, is consistent with reports by other authors,[4,12] who analyzed reaction times in prolonged vigilance tasks and uncovered the presence of cycles alternating relatively good and poor performance, tending to last about 4 min or somewhat longer. It must be said, however, that experiments designed to study ultradian rhythms usually last for hours and make use of much longer series than the ones described here. The main limit of the present account is the fact that only 38 values (one per each minute of flight) were available. In less than 1 min, often there are not enough fixations to compute NNI reliably, so that it is not feasible to increase the number of values used in the spectral analysis of the data at hand. As a rule of thumb, 50 points are often considered as the threshold sample size. In the future, having a large database of studies, it will be possible to progress from such anecdotal considerations and obtain more specific information on the sample size needed to confidently compute the index from ocular data.

The spectra (graphs 1 to 10 in Fig. 2) seem to support the idea of a cyclic pattern in the NNI. At this stage it is impossible to address the basic mechanisms involved in the generation of this effect. However, the results provided in this paper suggest a fluctuation in attentional resources. As reported by Di Nocera and colleagues,[6] from a logical standpoint we could think of three possible strategies for resources allocation: 1) on-demand, 2) continuous, and 3) cyclical. The first would be a strategy based on minimizing the expenditure of resources when they are not needed and allocating them only when required. That, of course, strongly reduces the promptness of the individual to react quickly to a sudden challenge. The second strategy would involve continuous expenditure of attentional resources in order to put the individual permanently in the best condition to always react appropriately. This is clearly unsustainable, considering that mental resources are limited in nature. The third, instead, considers the possibility of cyclic allocation of attentional resources, which is a parsimonious strategy, so that a certain degree of promptness is always available to the individual, albeit cyclically varying in intensity. Such a cyclic "rise and fall" would then allow individuals to best take advantage of the level of mental resources at their disposal as a starting point for voluntary resources management in responding to external challenges.

The evidence obtained from this reanalysis (namely, the three periodicity groups) may have important applications in several domains, including aviation. Indeed, the identification of a periodicity in the allocation of mental resources should be considered in the design of automation support that is dynamically matched to mental workload. Moreover, the fact that this periodicity is different for groups of

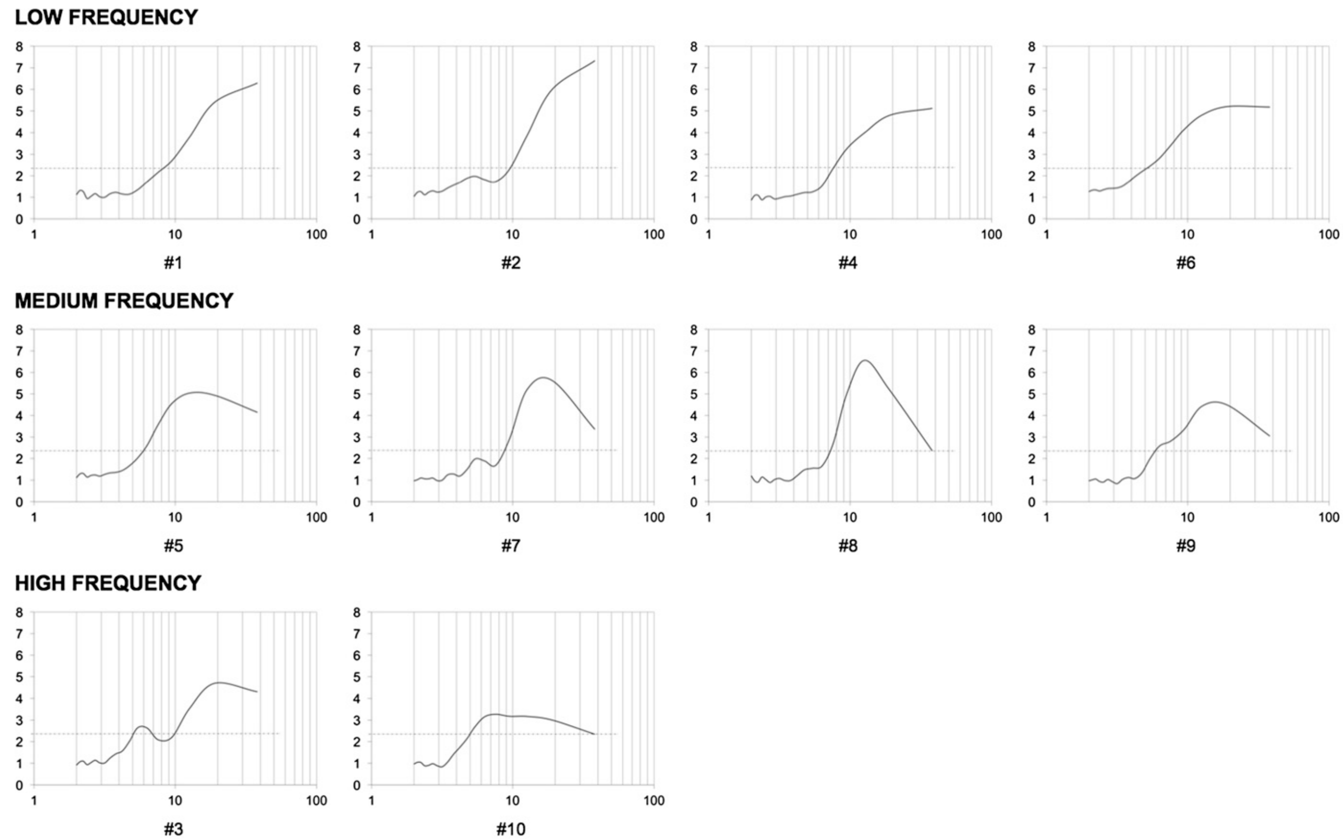

Fig. 2. Power spectra computed for each pilot by Discrete Fourier Transform. Periods (in minutes) are shown on a logarithmic scale.

individuals represents valuable information that may be used for devising specific training programs. Future research should provide an explanation for these individual differences that, with the limitations of the present study, could not be ascribed either to flight experience or to the pilots' eye movement strategies.

The goal of the original study by Di Nocera and colleagues[5] was limited to testing the potential of the NNI for assessing mental workload in complex operational settings. Future studies should be devised in order to specifically address the oscillatory pattern examined here and comparing it with that observed in prolonged vigilance tasks.[4] That could be accomplished, for example, by adding a secondary reaction-time task in order to understand whether cyclical patterns in eye movements and performance data are comparable or not.

ACKNOWLEDGMENTS

Authors and affiliations: Francesco Di Nocera, Ph.D., and Vittorio Pasquali, Ph.D., Department of Psychology, Sapienza University of Rome, Rome, Italy, and Ronald Ranvaud, Ph.D., Universidade de São Paulo, Instituto de Ciências Biomédicas, Depatamento de Fisiologia e Biofísica, Cidade Universitária "Armando de Salles Oliveira", São Paulo, Brazil.

REFERENCES

1. Camilli M, Terenzi M, Di Nocera F. Concurrent validity of an ocular measure of mental workload. In: de Waard D, Hockey B, Nickel P, Brookhuis K, editors. Human factors issues in complex system performance. Maastricht (The Netherlands): Shaker Publishing; 2007: 117–129.
2. Camilli M, Terenzi M, Di Nocera F. Effects of temporal and spatial demands on the distribution of eye fixations. Proceedings of the Human Factors and Ergonomics Society Annual Meeting; September 22-26, 2008; New York, NY. Santa Monica (CA): HFES; 2008; 52(18):1248-1251.
3. Clark PJ, Evans FC. Distance to nearest neighbor as a measure of spatial relationships in populations. Ecology. 1954; 35(4):445–453.
4. Conte S, Ferlazzo F, Renzi P. Ultradian rhythms of reaction times in performance in vigilance tasks. Biol Psychol. 1995; 39(2-3):159–172.
5. Di Nocera F, Camilli M, Terenzi M. A random glance at the flight deck: pilot's scanning strategies and the real-time assessment of mental workload. Journal of Cognitive Engineering and Decision Making. 2007; 1(3):271–285.
6. Di Nocera F, Bolia RS. PERT networks as a method for analyzing the visual scanning strategies of aircraft pilots. In: Proceedings of the 14th International Symposium on Aviation Psychology; April 23-26, 2007; Dayton, OH. Dayton (OH): Wright State University; 2007:165-169.
7. Dillard MB, Warm JS, Funke GJ, Funke ME, Finomore VS, et al. The Sustained Attention to Response Task (SART) does not promote mindlessness during vigilance performance. Hum Factors. 2014; 56(8):1364–1379.
8. Fidopiastis CM, Drexler J, Barber D, Cosenzo K, Barnes M, et al. Impact of automation and task load on unmanned system operator's eye movement patterns. In: Schmorrow DD, Estabrooke IV, Grootjen M,

editors. Foundations of augmented cognition. Neuroergonomics and operational neuroscience. Heidelberg (Germany): Springer; 2009:229–238.

9. Hockey GRJ, Gaillard AWK, Burov O, editors. Operator functional state: the assessment and prediction of human performance degradation in complex tasks. Amsterdam (The Netherlands): IOS Press; 2003.
10. Proietti Colonna S, Capobianco C, Mastrangelo S, Di Nocera F. Implementing dynamic changes in automation support using ocular-based metrics of mental workload: a laboratory study. In: de Waard D, Sauer J, Röttger S, Kluge A, Manzey D, et al., editors. Proceedings of the Human Factors and Ergonomics Society Europe Chapter 2014 Annual Conference; Lisbon, Portugal. Groningen (Netherlands): HFES Europe Chapter; 2014. Available from: http://hfes-europe.org/human-factors-high-reliability-industries-2/.
11. Recarte MA, Nunes LM. Effects of verbal and spatial-imagery task on eye fixations while driving. J Exp Psychol Appl. 2000; 6(1):31–43.
12. Smith KJ, Valentino DA, Arruda JE. Rhythmic oscillations in the performance of a sustained attention task. J Clin Exp Neuropsychol. 2003; 25(4):561–570.