Fractal Time Series Analysis of Human Heartbeat Intervals in a Change Blindness Task

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Fractal analysis is a set of techniques used in the study of complex systems to understand patterns of variability that are often observed in non-linear and natural systems. These techniques have been successfully applied to the study of human physiology, such as gait, heart rate variability, and respiration (West, 2004). Understanding variability in physiological measures may provide insight into human performance, individual workload, and stress. As an exploration of the possible contributions of fractal analysis to human performance, heart rate data from an existing research study was re-analyzed using methods common in fractal analysis of time series data. Results indicate that variability was measurably different based on experimental manipulations, illustrating the potential utility of fractal analytic methods in understanding human performance. Researchers are encouraged to explore these methods for their own research.

Although a relatively new addition to the sciences, the study of non-linear dynamical systems (formerly known as chaos theory) has yielded interesting findings in a variety of scientific disciplines (an easily accessible overview of this body of work can be found in Gleick, 1998). As the study of complex systems progressed, Mandelbrot (e.g., 1983) introduced fractal geometry, a new type of mathematics used to describe the unique nature of non-linear systems. One of the more prolific findings has been that many natural systems have data that is fractal in structure (Newman, 2005). Fractal data sets are those that obey a power law distribution and have a persistent pattern that is independent of the scale of observation (Mandelbrot, 1983).

The application of these new methods to non-linear systems has yielded a variety of interesting findings in the short time they have been studied (Newman, 2005). While the bulk of scientific contributions in the area have been in the earth and physical sciences, some relationships have emerged in the area of human physiology – examples include the variability observed in heart rate and walking gait (West & Griffin, 2004).

Many existing data sets may already lend themselves to reanalysis using fractal methods, allowing further exploration without significant design and data collection costs. The requirements of frequency analysis of time series data are relatively easy to meet, in that the time series must be from one measurement source (i.e., one subject) and data collection resolution must be high enough to produce a minimum of 300 data points for inclusion in the analysis (a comprehensive overview of time series analysis can be found in Malamud & Turcotte, 1999).

Interestingly, study of the fractal structure of the human heartbeat has yielded important diagnostic information related to heart health. Analysis of inter-beat interval (IBI) data using frequency analysis reveals that a frequency pattern known as “pink noise” (or “1/f noise”) is typically observed in a healthy heartbeat (when fitted to a power law this ratio is expressed as an exponent of 1). Research indicates that differences in the frequency response patterns of an IBI time series can signal the development of a serious heart malfunction, such as cardiopulmonary arrest or myocardial infarction, in the near future (an overview of frequency analysis of IBI data can be found in McSharry & Malamud, 2005).

Measures of heart rate variability have previously been used as indices of cognitive workload and stress (see, e.g., O'Donnell & Eggemeier, 1986, for a review). Researchers utilizing these measures typically compare mean interbeat variability across conditions for evidence of differences attributable to experimental manipulations. Overall, decrements in heart rate variability have been observed in association with increases in mental workload (Kalsbeek, 1971; Kalsbeek & Ettema, 1963).

Since fractal analysis of IBI has been demonstrated to be diagnostic in hospital patients, it is possible that the fractal dynamics of a heartbeat time series may also provide a sensitive index of workload and stress, and yield new insights into human performance. Of particular interest is the possibility that fractal indicators of workload may be more sensitive than averaged measures when comparing across individuals due to the computational process required for analysis. This process essentially normalizes the data, thereby reducing individual differences often associated with physiological measures, which should result in increased sensitivity (Malamud & Turcotte, 1999).

Several goals were established for the present exploratory study. The first was to test if a significant fractal structure could be observed in IBI data from an existing data set, and to determine if differences in the fractal properties of that data could be attributed to experimental manipulations. The second goal was to compare the results of the fractal analysis to a standard measure of workload as an index of convergent validity. Demonstrating similar statistical results using each of these measures will help to establish the utility of fractal analysis for understanding workload.

Methods

Participants

Three men and seven women between the ages of 18 and 30 (M = 22.7 years, SE = 1.33) served as paid participants in this study. Participants completed the experiment in groups of two, yielding a total of five groups.

Experimental Design

Data for the current study were drawn from a change detection experiment by Knott et al. (2007). In their study, participants were required to monitor an array of geometric shapes for small shifts in spatial location. Participants completed the experiment individually and in a dyadic "team" condition.

Though the original featured a more complex experimental design, data included in the current study was drawn from a subset of variables manipulated by Knott et al. (2007). Specifically, data in the current study was derived exclusively from the team condition and was organized around two of the original factors: set size (6 or 48 icons) and communication condition (permitted, restricted). Both of these were within-groups variables. The set size factor determined the number of shapes participants were required to monitor. The communication factor specified if participants were allowed to communicate with their teammate during task performance.

Stimuli & Apparatus

A flicker task display was created using custom JAVA scripts. Each display consisted of an even number of randomly distributed red, blue, and green squares at 1° visual angle. A trial consisted of four images presented in the order and duration shown in Figure 1: display A (750 ms), mask (250 ms), either display A, or A' with one square changed in position (750 ms), mask (250 ms). This sequence repeated until the participant responded by key press to indicate whether or not a change had occurred. If a change was detected, then participants also indicated by mouse click which square changed in position. Pentium 4 desktop computers were used to present two identical displays to participant dyads on 18" NEC Multisync LCD 1800 flat screen monitors.

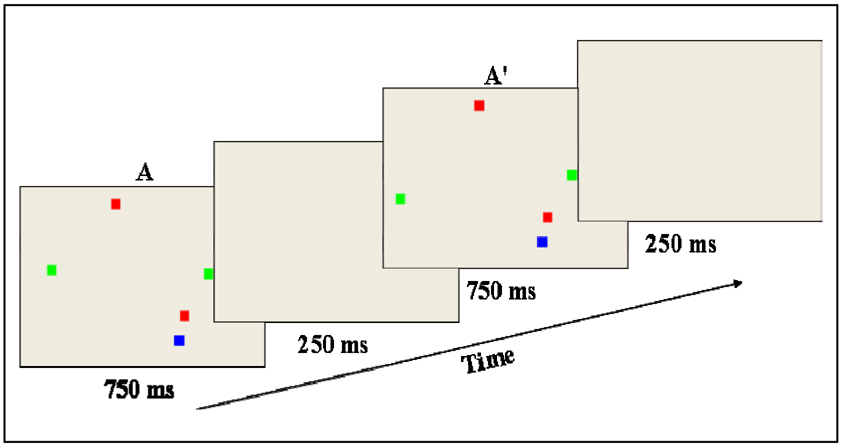

Figure 1. The figure denotes the flicker task with a change in the set size 6 condition. In this trial, the leftmost square moved closer to the screen edge on the third frame. This figure is from Knott, Nelson, McCroskey & Miller (in press) and is reprinted with permission from the authors.

Heart rate information was collected using UFI EZ-IBI software and equipment which recorded the interval between R-wave peaks at a rate of 1000Hz. This system required three surface electrodes to be attached to the participant to detect the electrocardiogram (ECG) signal. Electrodes were attached to the sternum, the left side of the body below the 5th rib (approximately 6 inches from the armpit), and to the right wrist (as a ground). The skin below the electrodes was prepared by applying NuPrep ECG skin abrasion gel to the site, gently wiping the skin with gauze, and then cleaning the site with alcohol prior to application of the electrodes. Heart rate data was recorded to Microsoft Access, and was exported into Microsoft Excel for subsequent analysis. A time series for one participant is displayed in Figure 2.

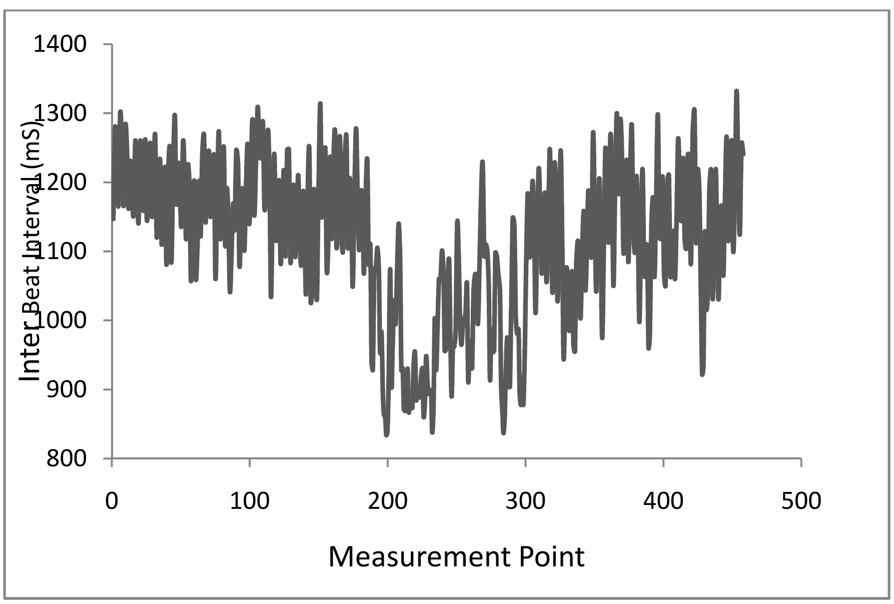

Figure 2. Inter-beat interval (IBI) time series for one participant in the communication-restricted condition, with a set size of 48 icons. IBI is measured in milliseconds. Values on the abscissa correspond to the serial count of measurements recorded during this block of trials.

Procedure

Teams completed 36 trials in each experimental condition, for a total of 144 trials in each experimental session. Both set size and communication condition were blocked factors; set size was blocked within communication condition. All teams completed trials in the communication-restricted condition followed by trials in the communication-permitted condition to ensure that participants could not carry over team-level strategies between conditions.

Following the conclusion of each trial block, participants completed the NASA Task Load Index (TLX; Hart & Staveland, 1988), a standard measure of cognitive workload which is widely used in human performance research (Wickens & Hollands, 2000). The TLX was employed in this experiment to provide a global index of mental workload associated with task performance, and to establish convergent validity with the fractal analytic technique employed in the current study.

Results

Fractal Analysis

Data from each block of trials was imported into Autosignal, version 1.6, and analyzed using the power spectral density method, described as follows. First, a Fourier transform for unevenly spaced data (i.e., the Lomb Periodogram method; McSherry & Malamud, 2005) was performed. Output from this analysis was then imported into Microsoft Excel, and trimmed such that the largest data point included in each data set was equal to or less than half the length of that data set.

The trimmed data was then plotted on log x/log y axes and two best fitting power lines were plotted with their equations displayed. The exponent value of the line for the frequency values from -.3 to -.4 Hz was recorded for subsequent analysis. This frequency range was selected because a visible “break” in the slope of the data which occurred at -.4Hz, indicating that frequency values less than -.4Hz were white noise and did not have a significant fractal structure (this pattern of frequency structure has also been observed by Voss, Schulz, Schroeder, Baumert, Caminal, 2009). The output from a power spectral density analysis for one participant is depicted in Figure 2.

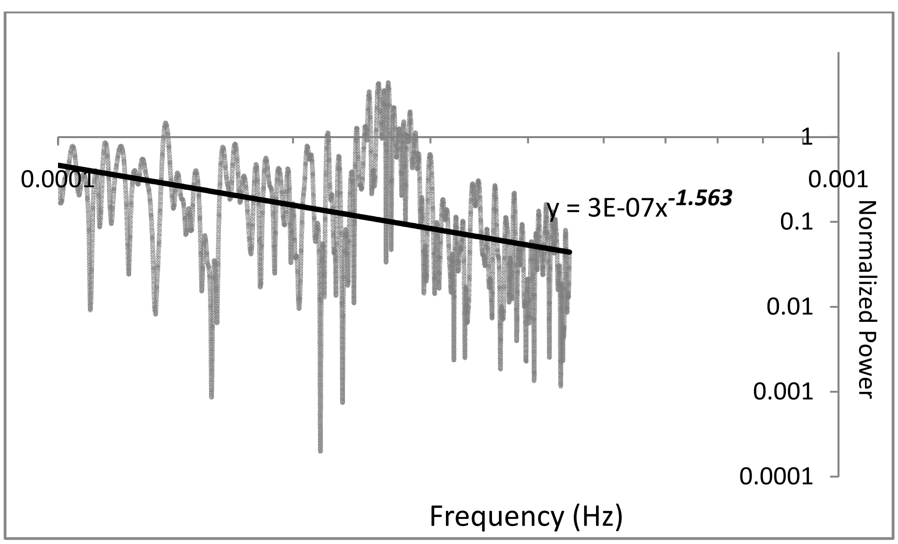

Figure 3. Power spectral density plot of the time series data of Figure 2, fitted to log-x log-y axes. A power function has been fitted to the data and the exponent is displayed for the equation.

Statistical analysis

The observed fractal exponents ranged from -.935 (the most variable) to -3.289 (the most ordered). Exponents for each participant were compiled and the resulting data were analyzed by means of a 2 (set size) × 2 (communication condition) repeated measures analysis of variance (ANOVA). The goal of this analysis was to determine if differences in fractal exponents could be attributed to the experimental factors. A statistically significant difference between conditions in this analysis would indicate that experimental manipulations were associated with a shift in heart rate variability (i.e., from less to more ordered).

Results of the analysis indicated a statistically significant main effect for communication condition, $F(1, 9) = 10.47$, $p < .05$. No other sources of variance in the analysis were significant ($p > .05$). Participants' IBI was significantly more structured in the communication-restricted condition (mean exponent = -2.26, $SE = .19$) compared to the communication-permitted condition (mean exponent = -1.79, $SE = .14$).

Mental workload

To test the effects of the experimental conditions on participants' evaluation of task workload, participants' mean global TLX workload ratings in each condition were calculated. These ratings were then tested for statistically significant differences between conditions by means of a 2 (set size) × 2 (communication condition) repeated measures analysis of variance (ANOVA). The results of this analysis indicated statistically significant main effects for communication condition, $F(1, 9) = 7.86$, $p < .05$, and for set size, $F(1, 9) = 12.95$, $p < .05$, but their interaction was non-significant ($p > .05$). Participants rated their workload as higher in the communication restricted condition ($M = 37.87$, $SE = 4.88$) compared to the communication permitted condition ($M = 28.75$, $SE = 5.08$). In addition, participants rated their workload as higher in the set size 48 condition (M = 37.87, SE = 4.85) compared to the set size 6 condition ($M = 28.75$, $SE = 4.90$).

Discussion

The results suggest that in an experimental setting, differences in fractal properties can be observed in heart rate variability that correspond to experimental manipulations when using frequency analysis techniques. Furthermore, fractal exponents can be observed in existing data sets that fit the necessary requirements for the analytic techniques. In the current analysis there was a statistically significant difference present between subjects who were in communication during the block of trials and those that had restricted communication. It is noteworthy that this result does not match the analysis of heart rate data conducted by Knott et al (in press). The results of the previous analysis suggested a statistically significant increase in heart rate between set size (heart rate was faster when the set size was 48 icons when compared to 6).

In interpreting the significance of the current findings, one must be even more cautious than normal. Although existing data sets can meet the necessary criterion for time series analyses, problems may arise. In this case, a necessary implementation with the order of conditions used by Knott et al (2007) created a confound for the current analysis. Specifically, communication restricted conditions were always collected before communication allowed conditions. This was important to prevent carryover effects of strategy, but it is difficult to distinguish if the observed fractal changes are due to the effect of communication condition, are a measure of fatigue, or some other effect of order. Another perplexing finding is that subjective workload was reported as higher when communication was restricted. Although order confounds this finding as well, it suggests that the increase in the fractal exponent is not related to an increase in subjective workload, and in fact the reverse may be true, although future research should address this relationship.

Regardless of the origin of the changes, the present analysis suggests that power spectral density analyses of fractal structure may be sensitive to experimental manipulations in a laboratory setting. Given their abundance in natural systems, it is likely that increased study of fractals will bring new findings for human performance research, particularly in physiological measures of workload and fatigue. Further research in this area should focus on designing experiments with fractal analysis techniques in mind, as well as further exploring the corresponding changes in fractal structure of heart beat intervals based on experimental manipulations of workload and fatigue.

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