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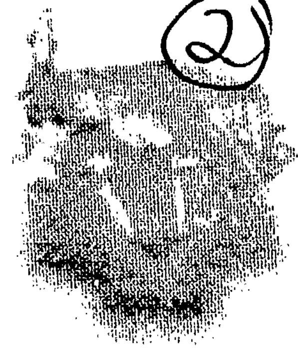
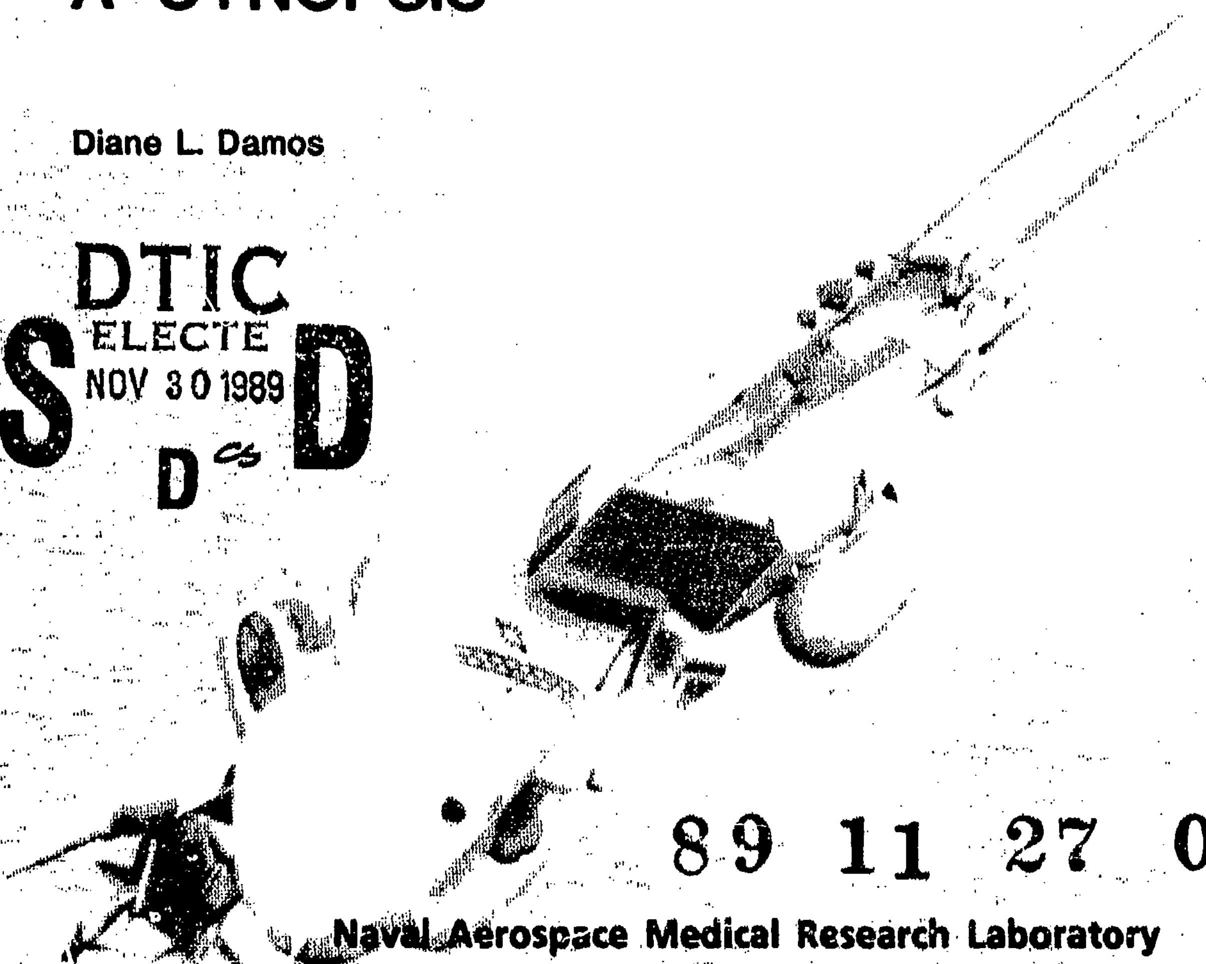


# IDENTIFYING THE CIRCADIAN CYCLE IN HUMAN INFORMATION PROCESSING DATA USING PERIODICITY ANALYSIS: A SYNOPSIS

Diane L. Damos





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# IDENTIFYING THE CIRCADIAN CYCLE IN HUMAN INFORMATION PROCESSING DATA USING PERIODICITY ANALYSIS: A SYNOPSIS


## ABSTRACT

Data from human information processing tasks frequently cannot satisfy the assumptions of many common periodicity techniques. This memorandum identifies appropriate techniques for data that cannot meet all of the assumptions of the more familiar ones.



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## INTRODUCTION

Historically, most studies examining the magnitude of the circadian effect on human information processing analyzed their data either by interpreting graphs or conducting analyses of variance (ANOVAs). Today, a disproportionate number of these studies still analyze their data using these methods rather than using some type of periodicity analysis (techniques that identify specific cycles in the data), which would be more informative. This puzzling state of affairs occurs because most studies of human information processing cannot meet the assumptions of many periodicity techniques. This memorandum describes some of the available techniques and the assumptions that must be met to use each technique. Problems in satisfying these assumptions are also discussed for repeated-measures assesments of information processing tasks.

## PERIODICITY ANALYSES

Several different mathematical techniques can identify periodicities in data. The techniques described below are appropriate when the investigator is only interested in certain specific periodicities, such as the circadian cycle. In other words, the investigator is not asking "What periodicities are present?" but rather "Do the data show evidence of an x-hour cycle?" where x can be any value.

The selection of an analytical technique depends in part on satisfying its assumptions. These assumptions may be grouped into three major categories: 1) the regularity of the data sampling, 2) the behavior of the component periodicities (stationary vs. nonstationary), and 3) the independence of the observations. The strictest combination of assumptions is that the data are equally spaced, the component periodicities are stationary, and the observations are independent. Typically, data from information processing tasks cannot satisfy one or more of these assumptions and, consequently, must be analyzed using other techniques, such as ANOVA. The remainder of this memorandum discusses analytical techniques as a function of the assumptions that must be satisfied.

## EQUISPACED DATA, STATIONARY COMPONENT PERIODICITIES, AND INDEPENDENCE OF OBSERVATIONS

A variety of mathematical techniques--including Fourier analysis, autocorrelation, power spectrum analysis, and periodic (trigonometric) regression analysis (1,2)--are available to analyze equispaced data that have stationary periodicities and independent errors of observation. In addition to identifying the periodicities present in the data, Fourier analysis and periodic regression analysis provide phase information that allows the time of peak performance to be determined. These techniques also allow the investigator to calculate both the change in performance over a fixed period of time and the best-fitting equation (see 2 for several excellent examples). Common statistical tests can be performed on the results of all of these analyses. For example, the results of an autocorrelation analysis can be tested to determine if the putative oscillations observed at a given frequency are statistically significant (1).

The major drawback of these techniques is that the data must be obtained at equally spaced intervals. Presently, many physiological variables can be monitored continuously. Information processing data cannot be obtained, however, at equally spaced intervals without depriving the subject of sleep or waking the subject during the sleep cycle. Because the sampling frequency is determined primarily by the period of the cycle to be detected (see the Other Periodicity Analysis Problems Section), investigators studying the circadian cycle usually must either wake the subject for testing or prevent the subject from sleeping.

Some investigators (i.e., 3) claim that subjects reach baseline levels of performance on information processing tasks a few minutes after being awakened. This claim is not universally accepted. Few investigators question the effect of sleep deprivation on performance although short periods (a few hours) of deprivation may not have a statistically significant effect on performance. From a strictly practical point of view, either method may be used to obtain data at equally spaced intervals if the investigator has some assurance that the method will not significantly distort the data. If the subject needs an impractical amount of time after awakening to regain baseline performance levels or if short periods of sleep deprivation affect performance, the data may be collected at unequal intervals using the appropriate techniques.

## UNEQUALLY SPACED DATA, STATIONARY PERIODICITIES, AND INDEPENDENCE OF OBSERVATIONS

Trigonometric regression is the most well known technique that can be used to analyze data collected at unequally spaced intervals. The data are assumed to be independent and to reflect stationary cycles. Fourier analysis can also be performed for data collected at unequally spaced intervals (2) although it quickly becomes cumbersome and does not appear to be used often in chronobiology. Easy-to-follow examples of trigonometric regression analysis for data collected at unequal, as well as equal, intervals are available (4).

## EQUALLY SPACED DATA, NONSTATIONARY PERIODICITIES, AND INDEPENDENCE OF OBSERVATIONS

Arguably, the most serious assumption concerning the assessment of the circadian cycle in human information processing data concerns the period of the cycle; the period is assumed to be stationary during the experiment. Usually, the investigator can safely assume that the component periodicities do not vary during the course of the experiment, that is, the frequency of each of the component periodicities is constant. This assumption has been challenged recently (5) for investigations of sustained operations, cumulative sleep deprivation, jet lag, and shift work. Frazier et al. (6) provide an excellent example of a large-magnitude change in periodicity in a highly controlled study of sustained operations. If the assumption of stationary periodicities is unwarranted, complex demodulation is the only time-series technique commonly available that can analyze nonstationary periodicities. This technique is restricted to "semistationary time series with slowly changing phase or amplitude or both" (5, p. 627).

Basically, complex demodulation first detrends the data, removing changes in the mean performance that occur over time (5). Then, it analyzes the rhythmic components of the data. Estimates of the instantaneous power and instantaneous phase are available at each sampling point for each frequency examined. (This is in contrast to Fourier analysis, which provides one estimate of phase and one estimate of power for the entire time series.) By comparing the instantaneous power and phase across sampling points, the investigator can determine the extent to which the component periodicities changed during the experiment. Complex demodulation also provides estimates of the percentage of variance accounted for by each frequency being examined. Thus, the investigator can determine what percentage of the variance in the data was accounted for by trends in mean performance, the circadian (24-h) cycle, a 12-h cycle, an 8-h cycle, et cetera. Complex demodulation is relatively new and is still being developed. It should, therefore, be viewed with some caution.

## UNEQUALLY SPACED DATA, NONSTATIONARY PERIODICITIES, AND INDEPENDENCE OF OBSERVATIONS

Currently, this situation cannot be analyzed using any commonly available technique. Sing et al. (7) have attempted to develop a version of complex demodulation that can use unequally spaced data. To date, this version has not been widely accepted because of its complexity. Nevertheless, advances in complex demodulation may allow the analysis of unequally spaced data with nonstationary periodicities at some time in the future.

## NONINDEPENDENCE OF OBSERVATIONS

Regardless of the spacing of the data points, all the analysis techniques mentioned above assume that the observations are independent. This assumption is clearly untenable in the majority of situations where each subject in an experiment is measured repeatedly on an information processing task; in these situations, intertrial correlations usually exceed 0.50 and may exceed 0.90. The problem mathematically then becomes how to take these intercorrelations into account.[1]

Unfortunately, analyzing such data, especially when they are collected at unequal intervals, is difficult. Nonstationary periodicities only worsen the problem. Currently, no analysis technique appears to be available for such data. Instead, such data are often analyzed by calculating the best fitting equation to one subset of the data and then cross-validating the fit on the second subset (P. Naitoh, Naval Health Research Center, San Diego, CA, personal communication, September 8, 1988). Although primitive, this technique may provide sufficient information about the presence of periodicities for the investigator's purposes.

## OTHER PERIODICITY ANALYSIS PROBLEMS

Two other data analysis problems should be discussed. The first concerns the amount of data to be collected. The well-known Nyquist sampling theorem states that a signal must be sampled at a frequency of 2x

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[1] Much repeated-measures human performance data are analyzed using analysis of variance (ANOVA) rather than a time series technique. In such experiments, the assumption of independence of errors of observation is also not tenable. To compensate for the violation of this assumption, criteria concerning the homogeneity of the variance-covariance matrix must be met.

to detect a periodicity with a frequency of x (8). That is, an investigator must sample twice as fast as the fastest frequency to be detected. Thus, to detect a circadian effect, an investigator theoretically must sample the variables of interest only twice during a 24-h period. Most investigators, however, assess performance at least four times during a 24-h period because of problems, such as the shifting cycle length, and the variance of human data.

A second related problem concerns the number of cycles (replications) to be sampled. For economic reasons, an investigator collects the minimum amount of data necessary to detect the periodicities in the dependent variable. At least five cycles may be necessary to permit a good estimate of an underlying periodicity (9). Estimates of a periodicity can be obtained using fewer than five cycles, but such estimates may be relatively inaccurate.

## DISCUSSION

As noted in the introduction, many investigators apparently have been reluctant to use periodicity analysis on human information processing data. One possible explanation for this reluctance is that the assumptions and the requirements underlying some of the analyses cannot be met. The need for equally spaced intervals may be the most easily satisfied requirement. The assumption concerning independence of observations may be the most difficult to meet unless the investigator forgoes a repeated-measures design. The assumption concerning cycles of constant periods has only recently been challenged, and investigators have not yet identified the situations in which the "circadian" cycle shortens or lengthens significantly. Thus, for the immediate future, many investigators will continue to rely on graphs and ANOVAs to detect the presence of the circadian cycle in information processing data. As new periodicity techniques with less restrictive assumptions become available, investigators may shift the emphasis of their work from detecting differences in performance at various testing times to a more detailed examination of periodicities in the data.

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