

Committee Report

Publication Guidelines for Heart Rate Studies in Man

J. RICHARD JENNINGS (Chair), *University of Pittsburgh*; W. KEITH BERG, *University of Florida*;
J. STANFORD HUTCHESON, PAUL OBRIST, *University of North Carolina*; STEPHEN PORGES,
University of Illinois, AND GRAHAM TURPIN, *University of London*

ABSTRACT

Publication guidelines are provided for the collection, quantification, and analysis of heart rate data.

DESCRIPTORS: Heart rate, Interbeat interval, Heart period, Experimental design, Statistical analysis.

Heart rate variability.

Purpose

These guidelines are for the preparation of manuscripts describing research in which heart rate is a dependent measure. The editorial board will use the guidelines to establish standards for the description and analysis of data. Fixed standards are not intended; instances will occur when the guidelines are not applicable. The guidelines are the consensus of the authors as positively influenced by the guidance of the Editor, David Shapiro, and the comments of fellow psychophysiologicalists during the Twentieth Annual Meeting of the Society in Vancouver, British Columbia.¹

Data Collection

Volunteers

Some information should be included in heart rate studies in addition to that generally provided in research reports. The experimenter should be aware of drug use or heart disease among experimental volunteers. These factors may significantly alter heart rate level and responsivity. Variation among individuals in heart rate can also result from degree of physical fitness and age—children have

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Address requests for reprints to: J. R. Jennings, University of Pittsburgh, Department of Psychiatry, 3811 O'Hara Street, Pittsburgh, Pennsylvania 15261.

higher heart rate than adults and their heart rate may change more with breathing (sinus arrhythmia). Physical exertion immediately prior to an experiment can cause individual differences that dissipate during the course of a session. Furthermore, common stimulants such as coffee and tobacco have clear cardiovascular effects. In general, any factor influencing cardiovascular function should be reported. If possible and consistent with the experimental design, these factors should be controlled by eliminating volunteers or balancing across experimental conditions. Experimental sessions can generally be arranged to prevent direct effects of common agents—coffee, tobacco, alcohol. Lengthy abstinence procedures are frequently inappropriate. Such procedures, if adhered to, may lead to withdrawal symptoms equally injurious to experimental control. The study of patients on medication poses a particular problem of experimental control, human ethics, and interpretation. Specific guidelines on this problem cannot be drawn.

Environmental-Stimulus Conditions

Heart rate is sensitive to environmental change; therefore, studies should be performed in an environment in which change is minimal (except for the experimental manipulation). The volunteer should be separated as completely as possible from the recording equipment, e.g. polygraph, tape recorder. Body movements can both disturb heart rate electrodes and physiologically induce heart rate change. Postural adjustments also influence breath-

ing patterns which in turn can alter heart rate. Comfortable positioning of the volunteer minimizes these unwanted changes in heart rate. Environmental and stimulus conditions should always be reported although the detail required will vary with the research question posed. Investigations of discrete sensory stimuli should show particular care in describing the stimulus parameters. In particular, the rise time of auditory stimuli has been found to be a critical parameter eliciting heart rate change. (Putnam, Graham, & Sigafus, 1975, discuss calibration of earphone transmitted sound.)

Transduction

These criteria deal with the measurement of heart rate, not with the electrocardiogram (EKG). The rate measure requires only the reliable identification of a particular point on the electrocardiogram, e.g. the peak of the R wave. Amplitudes of specific features of the EKG are sometimes used in medical applications. Such measures, e.g. T-wave amplitude and ST elevation, require significantly more methodological care than rate measures. We will discuss only heart rate, although we recognize that psychophysiologicals are increasingly interested in other aspects of the EKG.

Electrodes and paste used should be specified. These are not major variables in the measurement of heart rate, and as such require little further comment.

Electrode placement should be specified in anatomical terms. Placement is critical for medical use of the EKG, but not of prime importance in the measurement of heart rate. Arm-leg leads are frequently employed. Many have used chest placements, e.g. sternum to left lateral margin of the chest, in order to minimize movement artifact. When a standard medical placement is used, e.g. lead 2, AVR, both anatomical and medical designation may be noted (see American Heart Association standards, 1975).

Heart rate has frequently been measured using a photoplethysmograph placed on the finger or other extremity. This is an adequate procedure if pulse counts over a period of a minute or longer are the dependent variable assessed. The plethysmographic procedure is less acceptable for beat-by-beat or second-by-second measures of heart rate. Ease of use and noninvasiveness of the plethysmograph should be weighed against two factors. First, detection of a standard point, e.g. peak, on the plethysmographic output is usually more difficult than detecting a standard point, e.g. R-wave peak, on the EKG. Second, propagation of the pulse is influenced by peripheral vascular change. Thus, using the plethysmographic technique two beats with

equal R to R wave times (that is with identical heart rate) will appear different if one is accompanied by significant vasoconstriction.

Data collection should include whenever possible measures of respiration and vascular activity. Respiratory maneuvers have clear effects on heart rate (e.g. Sroufe, 1971; Levenson, 1979). Less dramatic respiratory changes may be important aspects of an experimentally induced physiological response pattern. Ideally, respiration should be measured and quantified with the same accuracy and care as heart rate. Minimally, respiration should be monitored so that consistent respiratory maneuvers induced by experimental events are identified. Rate, depth, and regularity of breathing are all important parameters. Psychophysiologicals commonly measure heart rate as an index of the activity of cardiac autonomic nerves. Blood pressure and flow changes in the peripheral vasculature can, however, affect heart rate independently of neural effects on the heart. Monitoring of both the cardio and vascular parts of the system can thus be important for adequate interpretation.

Finally, details of the instrumentation used to record the EKG and any accompanying physiological signals should be given. In particular, amplifier time constants and filter characteristics should be specified.

Quantification

The electrical waveform of the EKG must be processed to derive a measure of heart rate or inter-beat interval. Two methods are in common use for this purpose, cardiometer and computer scoring.

Some confusion is associated with the use of a cardiometer as an intermediate data reduction device. A cardiometer serves to translate a time measurement into a voltage measurement. Obviously, a time interval cannot be measured until it ends. Furthermore, such a measurement cannot be converted to a voltage measure until the end of the interval. It is in this sense that a cardiometer "lags" a beat behind the heart. Stated differently, the typical cardiometer maintains a voltage proportional to the length of the previous interbeat interval for the time of the current interbeat interval. Reading the cardiometer output at the initiation of each beat yields readings close in time to the end of the measured (previous) beat. A second concern is the conversion of a cardiometer record to digital data using computer techniques. Hand reading on a beat-to-beat basis of cardiometer output presents few technical problems although chart calibration and reader error information should be reported. Electronic

computers make it feasible, however, to treat a cardiometer record as a time varying waveform which can be sampled and translated into digital voltage readings. Sampling could, for example, be either at a fixed rate in the range of heart rate or at a high rate permitting subsequent digital "smoothing" of the resulting numbers. The first procedure is likely to overrepresent slower heart beats and under-represent faster ones. The second procedure smooths a naturally discontinuous measure and as such creates artificial rates. Both procedures may be justified in certain instances, but must be carefully considered.

Computer scoring of heart rate without using a cardiometer also poses a few minor questions. Typically, computer scoring is accomplished by "triggering" on the R wave, and then using a computer clock to measure the time between R waves. Ideally, the R wave triggering should occur on the same point of the R wave for every beat. This is not necessarily the case with a Schmitt trigger², but can be achieved with peak or slope detection circuits (e.g. Shimizu, 1978). Such circuitry is particularly important if experimental events are timed relative to the R wave, i.e. cardiac cycle experiments. Thus, descriptions of experimental methods should include location on the EKG and method of triggering. A second point is the resolution obtained. Investigators should know the resolution possible with the computer clock and associated data word; that is, whether time is measured with millisecond accuracy or tens of millisecond accuracy.

Regardless of method of quantification and data collection, errors (artifacts) will occur. Beats will be missed and extra "triggers" will produce artificially short "beats." These errors will significantly alter statistical analyses and must be detected and corrected (see Tukey, 1977). Techniques of correction include summing short "beats," subdividing missed "beats," and coding errors as "missing data" to be subsequently replaced by appropriate statistical estimates. Data are usually hand edited but editing computer programs are acceptable if combined with careful checking of their results. Cheung (1981) discusses computer editing and presents one editing technique. Edited data cannot replace real data, and is only a last resort. Care in electrode applica-

tion and signal processing is much more important than sophisticated editing. Data sets with high proportions of errors should be considered for complete deletion. Editing procedures should be completely reported whenever the data have required any more than minimal adjustment. This is an even more critical requirement for: a) studies of heart rate variability—a dependent measure directly influenced by the editing procedure, and b) experiments comparing groups or conditions that may reasonably differ in frequency of artifactual data, e.g. shock vs no shock, hyperactive vs less active children.

Definition of Dependent Measure and Variable

The question, "Is heart rate or interbeat interval (also termed heart period) the more appropriate measure?" has been discussed thoroughly in the literature. The number of papers should not obscure the recognition that in most cases the choice of measure has only small effects on the results. Graham (1978a and 1978b) has argued that heart rate per second and interbeat interval per beat are the only measures correctly estimating common parameters such as the arithmetic mean. Graham's point is extremely important given the assumption most commonly made by investigators: the heart rate estimate (rate or interbeat interval) is considered an event sampled randomly from an ensemble of estimates, each estimate with an equal probability of occurrence. Under these conditions incorrect estimates of the arithmetic mean will occur if heart rate per beat or interbeat interval per second are calculated. (If however, the heart rate estimates are viewed as a time series; time is randomly distributed rather than the cardiac event. Therefore, the probability of sampling a given cardiac event is not equal (except when there is a constant heart rate), but a function of the duration of the cardiac event. Longer interbeat intervals are more likely to be sampled at random times than shorter interbeat intervals. For the purpose of time series analyses Porges has proposed a weighted interbeat interval measure (Porges, Bohrer, Cheung, Drasgow, McCabe, & Keren, 1980). This measure is independent of the duration of the sampling interval and does not attempt to estimate the arithmetic mean.)

The choice of whether measures are expressed beat-by-beat or second-by-second has to be determined by the experimental question asked. One practical concern is raised by heart rate measured between two temporally fixed experimental events, e.g. in the foreperiod of a reaction time task. In a fixed period of time, for example 10 seconds, one volunteer may have 12 beats and another 8 due to a difference in mean heart rate. Averaging across volun-

²A Schmitt trigger is an electronic circuit that produces an output signal whenever an input voltage exceeds a preset level. The R wave peak frequently varies over beats in its absolute voltage value. Triggering at a preset level means that timing will be initiated, e.g. one half of the distance to the peak on some beats and two thirds of the distance on other beats. This induces a variability in timing of a few milliseconds. AC coupling of the EKG signal will reduce this variability to some extent.

teers to examine a beat-by-beat time series in the 10-sec interval poses a problem. This problem is not presented if second-by-second measures are employed. Note that complete use of data requires the computation of rate or interbeat interval for fractional beats created by events such as stimulus occurrence or the start or end of a sampling interval.

Once a dependent measure is chosen, the investigator should identify the dependent variable of primary interest. Three major classes of heart rate dependent variables can be identified: sustained heart rate, heart rate variability, and event-related heart rate. These classes can be influenced by different variables and are generally suited to different methodological and measurement approaches. All refer to responses to research situations.

A sustained heart rate response is typically a consistent change in average heart rate due to an ongoing situation—e.g. heart rate speeding while participating in an auto race. A sustained change in heart rate would generally last more than 30 sec and be less clearly time-locked to an eliciting event than an event-related response. Sustained heart rate may also be distinguished from tonic or resting heart rate. Tonic or resting heart rate would be observed in "control" periods prior to the situation of interest, e.g. heart rate before and after the auto race. For certain purposes, pulse counts over time would be an adequate measure of sustained heart rate although averaging beat-by-beat information will generally provide more precise estimates.

A heart rate variability response is typically a situationally-induced change in how variable successive beats are in heart rate or interbeat intervals. Heart rate variability is thus also related to the covariance between beats over time. Typically, heart rate variability is assessed over intervals of 30 sec or more and is related to an imposed condition, such as a continuous performance task. Variability may also be assessed as a characteristic of an individual. In such an application, tonic or resting heart rate variability may be of primary interest.

An event-related heart rate response is exemplified by a stimulus-induced change lasting a few seconds. Observation of such a response requires the measurement of individual heart beats. Typically, a phasic response would last less than 30 sec and show a latency from the eliciting event of less than 10 sec.

Some problems are associated with the description of the multiple beats defining an event-related response. The event-related response is generally assessed by event-related averaging. Beat-by-beat or second-by-second data are averaged across trials and a consistent response is expected to emerge from this process as "noise" cancels. Averaging a

portion of data in which a response is not expected, for example, a period prior to stimulus presentation, is an advised check on this procedure. Graphical presentation is desirable for either individual or group averages showing the beat-by-beat or second-by-second response of interest and the control average. Graphic presentation can become confusing when the occurrence of a stimulus must be defined relative to the heart rate time series. Consider the case of a tone stimulus presented on the R wave. The tone occurs on the third R wave following the end of the intertrial interval. When the heart rate results are plotted, should the stimulus be shown at beat 2 or beat 3? Remember that heart rate can only be measured for a completed beat of the heart. The question may be clarified by adopting a standard terminology. Beat 0 can be defined as the first R wave after the end of the intertrial interval. (If using second-by-second measures, second 0 is the end of the intertrial interval.) Using this terminology, Beat 1 completes the first interbeat interval and the stimulus should be shown at Beat 2. The first interbeat interval after the stimulus is then that plotted at Beat 3. (Using second-by-second measures, the stimulus should be shown at the average time of occurrence, i.e. at the time of Beat 2.) A similar logic should be followed when the stimulus is not time-locked to the R wave. The investigator must be aware of which R waves were on either side of stimulus presentation. This ordinal location must be maintained in graphic presentation as well as in data tabulation.

Analysis

The analysis of heart rate can be difficult, and issues well beyond the scope of the current standards arise. Guidelines are given with some references to discussion of problems. Research reports should present the rationale for using a particular data analytic technique. Any assumptions of the method which are subject to reasonable question should be noted. Editors and readers should be able to judge independently whether the analytic approach to the data was reasonable and unbiased. If an analysis of variance technique is employed, this criterion requires that the factors and their type (e.g. repeated measure, nested) be completely described. A useful discussion of analysis techniques is found in Richards (1980) and a discussion including other issues as well in Siddle and Turpin (1980). These papers as well as these guidelines address specific issues and cannot substitute for a general background in statistics and design.

Analysis of a sustained heart rate response is generally straightforward. If pulse counts or aver-

age heart rate are the dependent measure, then means and variance across measurement units are readily presented and analyzed. If beat-by-beat information is obtained, the investigator should consider a full description of the mean, variance, and covariance of the obtained time series. Research variables may influence any one or all of these parameters. Such a consideration clearly relates to all the dependent variables: event-related heart rate, sustained heart rate and heart rate variability. Statistical measures of variability have been recently discussed by Heslegrave, Ogilvie, and Furedy (1979). These investigators recommend the use of a successive difference mean square; however, problems with this statistic also occur (Wastell, 1981). The description of covariance and patterns of covariance may also be worthwhile although complex (see Levey, 1980).

Powerful time series statistics are available to describe the temporal regularity of heart rate and its relationship to other time-varying physiological signals such as respiration or blood pressure. These statistics, e.g. spectral and cross-spectral analysis, require the sampling of data at equal time intervals and the use of statistics with equal expected values irrespective of time. These techniques cannot be dealt with in these criteria, but are discussed in Porges et al. (1980) and Porges, Bohrer, Keren, Cheung, Franks, and Drasgow (1981). A related, but conceptually different, approach is presented by Jones, Crowell, Nakagawa, and Kapuniai (1971).

The analysis of event-related heart rate responses is complex and it is particularly dangerous to apply a statistical technique to such data without understanding both the technique and the general structure of the heart rate data. Some simple recommendations may be of assistance. A general data analytic scheme should be developed prior to examining the data, but it should not be applied blindly. Examination of obtained distributions and individual beat-by-beat responses must guide the analytic strategy. This initial data exploration should answer questions such as whether base levels appear to be related to degree of change; and whether base levels differ between experimental groups or variables. The results of such an examination should be reported briefly. If regression techniques designed to remove the influence of basal levels are judged necessary, care must be taken to ensure that the assumptions of these techniques are met (Winer, 1971). Care must also be taken when using difference scores relative to some baseline. The baseline must be chosen so that it does not bias the score toward revealing acceleration or deceleration (see Graham & Jackson, 1970). Furthermore, the baseline should accurately reflect both the mean

level and variability of the prestimulus activity. Provided that there are no consistent prestimulus heart rate fluctuations (due, for example, to temporal conditioning or some inadvertent cue), the single beat or second prior to stimulus onset has an expected value which meets these conditions. Statistical tests of several beats or seconds in the immediate prestimulus period can provide explicit information on whether these conditions are met. When they are met, the single interval has an advantage over using the mean of several prestimulus intervals in that it has the same expected reliability and temporal relationship to adjacent intervals as does any single poststimulus point. When the conditions are not met, use of a prestimulus average or multiple beats including the observed fluctuation may be preferable.

The widespread use of analysis of variance suggests a few added points. Results for analysis of variance factors may express effects on average heart rate even though the investigator set out to study an event-related response. For example, if an analysis of variance is performed with heart beat as a factor and tone intensity as a factor, the main effect of beats and the beats by tone intensity effect indicate event-related effects but the main effect of tone intensity indicates change in average heart rate. The tone intensity main effect is based on tone intensity means created by averaging across heart beats. The investigator should examine these means. If the analysis included both pre and post stimulus beats (seconds) note that the main effect does not reflect an event-related response (see Wilson, 1967, 1974). Care must be taken in both analysis of variance and the multivariate generalization of this technique to include a balanced representation of variables expected to change and those expected to remain constant. For example, either technique is insensitive to an experimental change at beat 10 if beats 1 to 9 forming a preperiod are included as variables in the design. Repeated measures designs are frequently employed in the analysis of event-related responses. Violations of the assumptions of this design are almost certain with heart rate data and the epsilon corrected or conservatively adjusted degrees of freedom should be applied to adjust for violation of the assumptions (Jennings & Wood, 1976; Keselman & Rogan, 1980). Orthogonal polynomials used in conjunction with analysis of variance are designed to test the fit of a mathematical function to a set of means. The function used must be justified on *a priori* grounds if this technique is to be used for hypothesis testing.

In summary, guidelines have been presented which should facilitate the accurate assessment of heart rate as a dependent measure. The primary

aim of any data representation is, however, to accurately answer the question posed by the research. The guidelines should assist in this goal: but as im-

plied previously, blind application of fixed guidelines cannot substitute for a clear concept of the relationship of data to the question asked of them.

REFERENCES

- American Heart Association. Report of the Committee on Electrocardiography. Recommendations for Standardization of Leads and of Specifications for Instruments in Electrocardiography and Vectocardiography. *Circulation*, 1975, 52, 11-31.
- Cheung, M. N. Detection of and recovery from errors in cardiac interbeat intervals. *Psychophysiology*, 1981, 18, 341-346.
- Graham, F. K. Normality of distributions and homogeneity of variance of heart rate and heart period samples. *Psychophysiology*, 1978, 15, 487-491. (a)
- Graham, F. K. Constraints on measuring heart rate and period sequentially through real and cardiac time. *Psychophysiology*, 1978, 15, 492-495. (b)
- Graham, F. K., & Jackson, J. C. Arousal systems and infant heart rate responses. In L. P. Lipsitt & H. W. Reese (Eds.), *Advances in child development and behavior* (Vol. 5). New York: Academic Press, 1970. Pp. 59-117.
- Heslegrave, R. J., Ogilvie, J. C., & Furedy, J. J. Measuring baseline-treatment differences in heart rate variability: Variance versus successive difference mean square and beats per minute versus interbeat intervals. *Psychophysiology*, 1979, 16, 151-157.
- Jennings, J. R., & Wood, C. C. The ϵ -adjustment procedure for repeated-measures analyses of variance. *Psychophysiology*, 1976, 13, 277-278.
- Jones, R. H., Crowell, D. H., Nakagawa, J. K., & Kapuniiai, L. E. An adaptive method for testing for change in digitized cardiometer data. *IEEE Transactions on Bio-Medical Engineering*, 1971, 18, 360-365.
- Keselman, H. J., & Rogan, J. C. Repeated measures F tests and psychophysiological research: Controlling the number of false positives. *Psychophysiology*, 1980, 17, 499-503.
- Levenson, R. W. Cardiac-respiratory-somatic relationships and feedback effects in a multiple session heart rate control experiment. *Psychophysiology*, 1979, 16, 367-373.
- Levey, A. B. Measurement units in psychophysiology. In I. Martin & P. H. Venables (Eds.), *Techniques in psychophysiology*. Chichester: Wiley, 1980. Pp. 597-628.
- Porges, S. W., Bohrer, R. E., Cheung, M. N., Drasgow, F., McCabe, P. M., & Keren, G. A new time-series statistic for detecting rhythmic co-occurrence in the frequency domain: The weighted coherence and its application to psychophysiological research. *Psychological Bulletin*, 1980, 88, 580-587.
- Porges, S. W., Bohrer, R. E., Keren, G., Cheung, M., Franks, J., & Drasgow, F. The influence of methylphenidate on spontaneous autonomic activity and behavior in children diagnosed as hyperactive. *Psychophysiology*, 1981, 18, 42-48.
- Putnam, L. E., Graham, F. K., & Sigafus, D. L. Calibration of earphone-transmitted sounds. *Psychophysiology*, 1975, 12, 106-109.
- Richards, J. E. The statistical analysis of heart rate: A review emphasizing infancy data. *Psychophysiology*, 1980, 17, 153-166.
- Shimizu, H. Reliable and precise identification of R-waves in the EKG with a simple peak detector. *Psychophysiology*, 1978, 15, 499-501.
- Siddle, D. A. T., & Turpin, G. (Eds.). Measurement, quantification, and analysis of cardiac activity. In I. Martin & P. H. Venables (Eds.), *Techniques in psychophysiology*. Chichester: Wiley, 1980. Pp. 139-246.
- Sroufe, L. A. Effects of depth and rate of breathing on heart rate and heart rate variability. *Psychophysiology*, 1971, 8, 648-655.
- Tukey, J. W. *Exploratory data analysis*. Reading, MA: Addison-Wesley, 1977.
- Wastell, D. G. Measuring heart rate variability: Some comments on the successive difference mean square statistic. *Psychophysiology*, 1981, 18, 88-90.
- Wilson, R. S. Analysis of autonomic reaction patterns. *Psychophysiology*, 1967, 4, 125-142.
- Wilson, R. S. CARDIVAR: The statistical analysis of heart rate data. *Psychophysiology*, 1974, 11, 76-85.
- Winer, B. J. *Statistical principles in experimental design*. New York: McGraw-Hill, 1971.