An open-source LabVIEW application toolkit for phasic heart rate analysis in psychophysiological research

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The cardiovascular system has been extensively measured in a variety of research and clinical domains. Despite technological and methodological advances in cardiovascular science, the analysis and evaluation of phasic changes in heart rate persists as a way to assess numerous psychological concomitants. Some researchers, however, have pointed to constraints on data analysis when evaluating cardiac activity indexed by heart rate or heart period. Thus, an off-line application toolkit for heart rate analysis is presented. The program, written with National Instruments' LabVIEW, incorporates a variety of tools for off-line extraction and analysis of heart rate data. Current methods and issues concerning heart rate analysis are highlighted, and how the toolkit provides a flexible environment to ameliorate common problems that typically lead to trial rejection is discussed. Source code for this program may be downloaded from the Psychonomic Society Web archive at www.psychonomic.org/archive/.

Accurate and reliable assessment of cardiovascular function is critical in a wide range of research and clinical domains (Brownley, Hurwitz, & Schneiderman, 2000). In particular, noninvasive techniques such as impedance cardiography and transthoracic echocardiography have advanced the fields of exercise physiology and psychophysiology alike. The use of spectrally derived indices of autonomic nervous system activity is also becoming widespread (Task Force of the European Society of Cardiology and the North American Society of Pacing and Electrophysiology, 1996). In addition to these methods, the assessment of phasic changes in heart rate (HR) remains a fundamental tool in addressing a host of research questions. To cite just three examples, heart rate is often used as an index of hedonic valence or emotional pleasantness during affective picture processing (Bradley, Codispoti, Cuthbert, & Lang, 2001; Cuthbert, Bradley, & Lang, 1996), as an index of emotional expression in response to film stimuli (Palomba, Sarlo, Angrilli, Mini, & Stegagno, 2000), and as an index of orienting and attention (Öhman, Hamm, & Hugdahl, 2000).

Several researchers, however, have identified varied constraints on data analysis when evaluating cardiac activity indexed by heart rate or heart period (Berntson, Cacioppo, & Quigley, 1993; Graham, 1978; Siddle & Turpin, 1980). Heart rate typically corresponds to the number of beats per minute (BPM), whereas heart period, commonly

termed *R-R interval* or *interbeat interval* (IBI), corresponds to the time it takes to complete one beat. In particular, Graham (1978) has illustrated that the estimates derived from either of these indices will be biased if the subsets that constitute the estimate do not conform to equal divisions of the measure of interest. Hence, to express HR in real time, the subsets estimating rate must be equal in real time. For example, if one desires to evaluate HR in beats per minute in half-second intervals, it must be fractionated for each derived heart period instance on the basis of the weight of the current IBI (Graham, 1978). This process is completed by computing weighted averages across the bin length of interest. As is illustrated in Figure 1, IBIs are computed into a rate-per-half-second format.

Given a bin length of 500 msec, the first IBI value (i.e., 652 msec at 92.02 BPM) is parsed into two bins, with the first bin consisting of 500 msec of HR at 92.02 BPM and the remaining 152 msec of IBI time being allocated to the subsequent bin. Next, because the second bin contains 152 msec of data remaining from the previous IBI, only 348 msec from the subsequent IBI are needed for a complete bin. For the second bin, a weighted average computation is performed by proportionally weighting each BPM value to the IBI time allotted to the bin.

Prior to scoring cardiac activity, extracting IBIs or the R-R interval from the cardiac waveform is a priority. A common strategy is to ascertain this information on line, using either a Schmitt trigger or employing a software threshold-detection algorithm. However, depending on one's experimental constraints and/or task requirements, artifacts may be introduced in the cardiac waveform. Thus, on-line extraction may lead to many lost or incorrectly scored trials. Since both extraction and analysis

The most current version of the HRAP program can be downloaded from <http://www.sourceforge.net/projects/lviewhranalysis>. The National Instruments LabVIEW player can be downloaded from <http://www.ni.com>. Correspondence concerning this article should be addressed to A. R. Duley, 25 Florida Gym, P. O. Box 118207, Gainesville, FL 32618 (e-mail: aduley@ufl.edu).

Figure 1. The procedure to compute weighted averages of each IBI into a specified bin length (500 msec in this example).

are relatively cumbersome, the purpose of this article is to outline a flexible application written in National Instruments' LabVIEW (Austin, TX). The program allows users to easily extract IBIs to the nearest millisecond, compute HR weighted averages across a user-specified bin length, and export data into a tab-delimited output file. In addition, the program has tools for handling IBI extraction problems that can arise from subject movement, noisy data, masking effects of the R-R interval by the relaxation of the ventricles (T-wave), or data collection such that the HR waveform is inverted.

ABOUT LABVIEW

Laboratory Virtual Instrumentation Engineering Workbench, or LabVIEW, is a multifunction programming environment that allows users to graphically develop applications with structured dataflow diagramming. The concept of graphical development is not native to LabVIEW. Several related dataflow programming tools employ graphical development, such as Prograph (Halifax, NS), SimuLink (Natick, MA), and Visual Engineering Environment (Agilent Technologies, Palo Alto, CA). In this programming paradigm, code is orchestrated as a collection of nodes connected by wires, in which the execution of the program is governed by the flow of data from one node to another, easily allowing parallel execution of code. In LabVIEW, users interact with a front panel and a diagram. As controls, or indicators, are added to the graphical user interface (GUI), a corresponding component is added to a diagram. Because of the similarity between LabVIEW GUI components and controls on traditional instrumentation, LabVIEW programs are formally referred to as *virtual instruments* (VIs). In addition, LabVIEW is primarily a compiled language similar to that of C/C++, and applications can be ported to a variety of platforms, such as Mac OS, Windows, Sun, and Linux.

Program Description

The HR analysis program, dubbed HRAP, is a menu-driven application that allows for off-line analysis of HR data (see Figure 2 for a screenshot). In its current version, each ASCII file must correspond to a trial or condition, although, users may retain any file-naming convention they choose. Once the files are selected for analysis, the

program will display the HR waveform in a graphing window. Users can also select from a variety of waveform processing operations such as signal decimation, smoothing, windowing (e.g., Hanning, Hamming, Blackman, Kaiser-Bessel), and filtering (e.g., Butterworth, Chebyshev, Bessel, Equi-Ripple) if desired. HRAP allows users to print the cardiac waveform, view various waveform statistics, and save filtered, decimated, or smoothed data. Because many of the interface elements are native LabVIEW GUI components, users have a great deal of flexibility in customizing many of the properties of the interface elements. The program will retain these properties, which are saved in a configuration file that is automatically initialized the next time the program is loaded.

IBI extraction and waveform operations. Three primary methods are used to extract IBIs from the cardiac waveform. The first two use only a single value as a threshold level to detect the R-wave peaks. The Line Threshold method allows users to specify a single threshold level by moving a horizontal slider that corresponds to a threshold line to a position that crosses each of the R-waves for the entire trial. In certain cases in which the HR waveform is inverted or the R-wave peak is small or inconsistent across the trial, the user also can specify the threshold orientation from the default *peaks* to *valleys*. Once switched, the user can detect negative-going peaks. The second method, called Point Threshold, allows users to view the threshold demarcation level represented by single points superimposed on each peak. This method is desirable when it is difficult to visually determine whether the threshold level, represented by a single line, crosses each R-wave peak. In our initial testing, some users preferred this threshold view over the line view. For both of these methods, the threshold level is automatically set on the basis of a user-defined percentage of peak maximum, although the upper and lower bounds for the slider can be changed.

The third method to extract IBIs differs from the first two in that the user adds markers to the graph and positions them over the R-wave peaks. Thus, this method allows for multiple threshold values and is particularly desirable for extracting IBIs from noisy data that may vary about a baseline or in which the repolarization of the T-wave makes it impossible to use a single threshold line. This method can also be used to extract components from the HR waveform other than the R-R interval. The

Figure 2. Screenshot of the main interface screen for the HRAP program.

necessity for this method of extraction is illustrated in Figure 3.

As is shown in the top panel, a single threshold value cannot be used when segments of the HR waveform,

other than the R-wave peaks, cross the threshold line (solid). For that reason, as is illustrated in the bottom panel, multiple vertical markers (dotted) are applied to differentiate each R-wave peak.

Figure 3. The screenshot in the top panel illustrates why it is necessary to use multiple threshold lines for trials in which a single threshold value is insufficient. In the top panel, a single line cannot cross each R-wave peak without also capturing the T-wave. Therefore, a second extraction method (bottom panel) allows users to place vertical lines to demarcate each R-wave peak.

Weighted average computation and change scores. Once the IBIs for the current trial have been extracted, the program automatically computes HR in BPM according to the following procedure (see Figure 4 for a diagrammed view and Figure 5 for the code view).

First, IBIs are converted into BPM values by taking the reciprocal of the IBI and multiplying it by 60; thus, an IBI of 0.95 would yield a BPM value of 63.16. Subsequently, depending on the user-specified bin length, the BPM values for each IBI instant are computed for each bin until all

Figure 4. The program's data flow from IBI extraction to change score computation.

Figure 5. LabVIEW source code for each stage of processing.

IBI data have been processed. Next, weighted averages are computed for each bin by multiplying the IBI's respective BPM value and dividing it by the user-specified bin length. This process ultimately leads to a series of bins containing BPM values weighted proportionally to the fraction of time occupied by each. Following this step, change scores

from baseline are calculated, which allows for analysis of phasic changes in HR for the trial. For any trial, users may save the current data to a master data sheet for later export as a tab-delimited ASCII file.

Open-source initiative. The underlying objective of any open-source effort is to allow a community of de-

velopers to refine and modify code, yielding more rapid and efficient software production. In psychophysiological research, the cost of proprietary software often limits the use of a measure that might otherwise strengthen a specific design or methodology. Turnkey software packages are usually less desirable for researchers who seek greater flexibility in adapting to changing techniques, methodology instrumentation, or simply switching from one operating platform to another. There are, however, alternatives for researchers who seek freeware, shareware, or other low-cost alternatives (see, e.g., Angrilli, 1995; Cook, 1997). Still, the ability of the scientific community to participate in the development and evolution of the tools used in research cannot be overstated.

CONCLUSION

HR is one of the most extensively used variables in psychophysiological research. Despite technological and methodological advances in cardiovascular science, it is still commonplace for researchers to evaluate phasic HR change. The program described here, written with National Instruments' LabVIEW, incorporates a variety of tools for off-line analysis, meeting constraints on data analysis when evaluating cardiac activity indexed by HR or heart period. The program is also being put forth as an open-source effort that will allow the scientific community to customize and enhance HRAP to meet its research needs.

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ARCHIVED MATERIALS

The following materials associated with this article may be accessed through the Psychonomic Society's Norms, Stimuli, and Data archive, <http://www.psychonomic.org/archive/>.

To access these files or links, search the archive for this article using the journal (*Behavior Research Methods, Instruments, & Computers*), the first author's name (Duley) and the publication year (2004). The downloadable archive, Duley-BRMIC-2004.zip, contains two files:

FILE: duley2004hrap_source.zip.

DESCRIPTION: Compressed .zip archive that includes the HRAP program (Build 3.0) source files developed by Duley et al. (2004). These files are contained in a single LabVIEW Version 7.0 library file (.llb).

FILE: duley2004hrap_Win.zip.

DESCRIPTION: Contains the HRAP program developed by Duley et al., (2004) for end users. The compressed .zip archive includes the HRAP program, an application installer for Microsoft Windows targets, and the LabVIEW runtime engine. Instructions on how to use the HRAP program in .pdf format, in addition to several example files, are also included.

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(Manuscript received June 2, 2003;
revision accepted for publication June 21, 2004.)