A short review and primer on cardiovascular signals in human computer interaction applications

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Abstract. The use of psychophysiologic signals in human-computer interaction is a growing field with significant potential for future smart personalised systems. Working in this emerging field requires comprehension of different physiological signals and analysis techniques. Cardiovascular signals such as heart rate variability and blood pressure variability are commonly used in psychophysiology in order to investigate phenomena such as mental workload. In this paper we present a short review of different cardiovascular metrics useful in the context of human-computer interaction.

This paper aims to serve as a primer for the novice, enabling rapid familiarisation with the latest core concepts. We emphasise everyday human-computer interface applications to distinguish from the more common clinical or sports uses of psychophysiology.

This paper is an extract from a comprehensive review of the entire field of ambulatory psychophysiology, with 12 similar chapters, plus application guidelines and systematic review. Any citation to this paper should be made using the following reference:

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1 Introduction

The heart is innervated by both the sympathetic and the parasympathetic branch of the ANS. The sympathetic branch, tied to stress ‘fight-or-flight’ responses, tends to increase heart rate, whereas parasympathetic activity, representing ‘rest-and-digest’ behaviour, decreases it. The rate at which the heart
beats and variations thereof hence reflect the activity of the ANS. Accordingly, various metrics describing the ANS activity can be derived from cardiovascular signals. For instance, heart rate variability metrics derived from the electrocardiogram (ECG) are widely used in psychophysiology (Malik et al., 1996) – for example, to investigate phenomena such as mental workload. The cardiovascular system responds to sympathetic and parasympathetic activation within a few seconds (Berntson, 1997). However, cardiovascular metrics used in psychophysiology are typically analysed on a time scale of minutes (Malik et al., 1996) in the case of short-term heart rate variability metrics. For instance, the Trier Social Stress Test (Kirschbaum et al., 1993) has been used extensively to induce psychosocial stress, and cardiovascular and endocrine responses are well documented (Kudielka et al., 2007). In this connection, one can gain insight from a study by Lackner et al. (2010) investigating the time course of cardiovascular responses in relation to mental stress and orthostatic challenge in the form of passive head tilt-up. There are also longer rhythms evident in cardiovascular metrics, such as circadian patterns in heart rate variability (Huikuri et al., 1994).

The cardiovascular measurement techniques considered here are (i) electrocardiography, (ii) blood pressure measurement, and (iii) photoplethysmography; however, the activity of the heart can also be measured by means of various other techniques, such as ballistocardiography (Lim et al., 2015) or Doppler (Lin et al., 1979).

2 Measurement of cardiovascular signals

Cardiovascular signals can be measured continuously via non-invasive techniques and have been widely utilised in the measurement of mental workload (Aasman et al., 1987). The ECG represents the electrical activity of the heart, and the measurement is carried out with chest electrodes (Malmivuo and Plonsey, 1995). From the ECG it is possible to extract several signals, among them heart rate, or HR (denoting the absolute pace at which the heart beats) and heart rate variability (HRV), which is an umbrella concept for all metrics describing how the rhythm of the heart varies. To record HR and HRV, it is sufficient to record one lead, as only the R-peaks of the ECG waveform are required; for details, refer to Berntson (1997). For instance, affordable sports watches can be used for obtaining a signal suitable for HRV analysis (Gamelin et al., 2006).

Measuring continuous arterial blood pressure (BP) is technically more demanding than ECG measurement and requires more advanced equipment. In addition, long-term measurement of BP is not as unobtrusive as corresponding ECG measurement. Continuous BP can be measured from the finger, via the method of Peñaz (Peñaz, 1973) as implemented in, for example, the Finapres device (Wesseling, 1990) and its ambulatory version, the Portapres.

One can obtain a photoplethysmogram (PPG) either by using methods that require skin contact or remotely. See, for example, Allen (2007) for a review on the measurement of PPG. In transmission PPG, the tissue is between the light source and the receiver, whereas in reflective PPG the light source and the
receiver are next to each other on the surface of the skin, with the light only bouncing through the tissue from the source to the receiver. The PPG is typically obtained from the finger and the pinna by transmission and from the wrist via reflection. The PPG measurement can be performed remotely without skin contact by using imaging techniques to consider changes in the pulse (Sun et al., 2012) (imaging techniques are discussed in Cowley et al. (2016, Section 3.9)). Remote PPG has been used to study, for example, vasoconstrictive responses during mental workload by means of an ordinary webcam (Bousefsaf et al., 2014). Work related to this, by Vassend and Knardahl (2005), has used laser Doppler flowmetry to investigate facial blood flow during cognitive tasks.

The plethysmographic pulse amplitude (PA) depends on the degree of vasoconstriction, which, in turn, is affected by cognitive load (Iani et al., 2004). The pulse transit time (PTT) in the PPG has been found to be correlated with BP (Ma and Zhang, 2005; He et al., 2013). It should be noted that vasoconstrictive effects are not visible in the ear (Awad et al., 2001). The use of reflective PPG has become popular in several consumer sports watches, such as the A360 from Polar Electro (Kempele, Finland); Forerunner 225 from Garmin Ltd (Schaffhausen, Switzerland); Charge from Fitbit, Inc. (San Francisco, CA, USA); Apple Watch from Apple, Inc. (Cupertino, CA, USA); and Microsoft Band from Microsoft, Inc. (Redmond, WA, USA). Reflective PPG is used also in research equipment such as the E4 from Empatica Inc. or various sensors from Shimmer Sensing (Dublin, Ireland).

3 Methods

3.1 Analysis of cardiovascular signals

In using the cardiovascular signals to investigate the activity of the autonomic nervous system, it is the variability of the signal that is of interest. The cardiovascular signals are hence analysed on a beat-by-beat basis. Raw, continuous cardiovascular signals such as the ECG, PPG, or continuous beat-by-beat BP signal must therefore be preprocessed. The goal with the preprocessing is to remove artefacts from the recorded signals through various methods and reliably convert the raw signals into event series, where an event corresponds to some property of one beat of the heart. Accordingly, there are as many events in the event series as there are heart beats in the raw signal. Different cardiovascular signals give rise to different event series. For the ECG, the resulting event series is called an inter-beat interval (IBI) series or an RR series and each event corresponds to the duration between consecutive heart beats, typically measured in milliseconds. The term ‘RR series’ comes from the fact that the R-peak in the ECG waveform is used as the marker for a heart beat and each event is the time from one R-peak to the next R-peak. Similarly, for the PPG the event series is an interpulse interval time series reflecting changes in blood volume in the tissue, which varies with the action of the heart. For the continuous BP signal, it is possible to form, for example, three event series wherein each event in the
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respective series corresponds to the systolic blood pressure (SBP) for each heart beat, the diastolic blood pressure (DBP), or the mean blood pressure (MBP).

Panel a in Figure 1 shows a 100-second sample of ECG data from the Physionet (Goldberger et al., 2000) Fantasia database (Iyengar et al., 1996). R-peaks in the ECG have been identified and are shown in red. The resulting IBI series is presented in Panel b, and Panel c shows a shorter, five-second segment of the ECG signal.

![Figure 1](image)

**Fig. 1.** Example of the formation of an inter-beat interval (IBI) series from an ECG. The R-peaks in the ECG are shown in red. Panel a shows a 100-second ECG signal, and the corresponding IBI series is shown in panel b. Panel c shows a five-second segment of the ECG signal.
The variability of cardiovascular signals is studied by taking into consideration several distinct variability metrics calculated from the event series: HRV from the ECG (Malik et al., 1996; Berntson 1997), blood pressure variability (BPV) from the BP signal (Parati et al., 1995), and pulse rate variability (PRV) from the PPG (Constant et al., 1999). The calculation for these variability metrics constitutes the main part of the analysis of the cardiovascular signals. The variability metrics for the individual signals can be calculated by means of several methods, such as (i) time-domain, (ii) frequency-domain, and (iii) nonlinear methods. It should be noted that, although the cardiovascular signals are of a different nature (e.g., IBIs or SDP values), many of the analysis techniques developed for HRV analysis are applicable also for BP analysis (Tarvainen 2004). We discuss some HRV metrics next. Two examples of time-domain measures are the standard deviation of inter-beat intervals (SDNN), reflecting overall HRV, and the square root of the mean of the squares of the IBIs (RMSSD), reflecting short-term HRV (Malik et al., 1996). The analysis in the frequency domain is based on the power spectrum of the IBI signal, derived by using the Fourier transform, an autoregressive method, or the Lomb–Scargle method (Clifford et al., 2006). In the spectral analysis, the power of the signal is considered primarily in three bands: the very low-frequency (VLF) band (0–0.04 Hz), the low-frequency (LF) band (0.04–0.15 Hz), and the high-frequency (HF) band (0.15–0.40 Hz). The LF band is typically linked to sympathetic activation and the HF band to parasympathetic activation (Malik et al., 1996), and the ratio of power in the LF band to power in the HF band (LF/HF ratio) is used to describe the degree of sympathovagal balance; see Billman (2007) for a discussion addressing issues related to the interpretation of the LF/HF ratio. The nonlinear analysis methods involve use of metrics such as various entropies.

There are relationships among cardiovascular signals; for instance, the correlation between HRV metrics derived from fingertip PPG and from the ECG has, in general, been found to be high (Selvaraj et al., 2008; Lu et al., 2009; Lin et al., 2014), although confounding factors such as respiration should be taken into account (Lee et al., 2010). It ought to be noted that, though HRV and PRV are related, they are not identical (Constant et al., 1999; Lu et al., 2009; Lin et al., 2014). In addition, factors such as ambient light can affect the PPG signal, and the latter signal is less stable than the ECG during physical activity.

For a discussion of the analysis of BPV, see de Boer (1985) and Tarvainen (2004). Blood pressure reactivity can be studied also in terms of baroreflex sensitivity (BRS), which uses a combination of ECG and BP, as illustrated in other works by, for example, Mulder et al. (1990) and Van Roon et al. (2004). The BRS metric describes how rapidly the heart rate responds to changes in blood pressure.
4 Applications

The most interesting phenomenon from the perspective of human–computer interaction is how the various cardiovascular metrics reflect mental workload. It is this aspect of study to which we direct our focus in the primer.

4.1 Heart rate variability

The relationship between mental workload and the ANS response, reflected in HRV, is complex. However, one can state that HRV generally is reduced during mental effort, with the degree of reduction dependent on the level of mental effort \cite{Mulder1993}. It has been shown that average heart rate is one of the most sensitive metrics for distinguishing between low and high levels of mental workload in a computerised task \cite{Henelius2009}. In addition, HRV has been used in occupational settings, a review of which can be found in the work of Togo and Takahashi \cite{Togo2009}.

Garde et al. \cite{Garde2002} used HRV to investigate the difference between two computerised tasks (one using a keyboard, the other using a mouse) and concluded that no difference was evident in terms of mental workload. Differences in HRV metrics were found when the setting featured a physically demanding computer task. In a study \cite{Hjortskov2004} investigating differences in a computerised task with different difficulty levels, the researchers found differences in the HRV LF/HF ratio between the tasks. Hjortskov and colleagues also concluded that HRV is more sensitive than BPV is to mental stress levels. In a recent study, \cite{Taelman2011}, found several HRV metrics (average normal-to-normal interval length, SDNN, RMSSD, pNN50, LF, and HF) to be affected by the extent of mental load.

A study by Cinaz et al. \cite{Cinaz2013} investigated the use of HRV for classifying levels of workload during office work. They found that RMSSD and pNN50 decreased with the degree of workload experienced, while the LF/HF ratio increased.

In an example of particular frequency bands within the HRV spectrum, Nickel and Nachreiner \cite{Nickel2003} investigated the 0.1 Hz component of HRV during the performance of a battery of computerised stress tests. They concluded that this particular frequency component was not sensitive to workload level.

The heart pre-ejection period (PEP) \cite{Backs2000, Miyake2009} and the T-wave amplitude (TWA) \cite{Myrtek1994, Vincent1996} too have been linked to mental stress. See the work of Lien and colleagues \cite{Lien2015} for a study comparing these indices as metrics of sympathetic nervous system activity in ambulatory settings.

Heart rate variability has been studied extensively in connection with measuring the task difficulty or mental workload experienced by pilots \cite{Jorna1993, Roscoe1993, Roscoe1992, Roscoe1993}. In addition, research by Wilson \cite{Wilson2002} investigated various psychophysiological measurements during flight and found that HR was more sensitive than HRV to task difficulty.
4.2 Blood pressure

Measurements of BP, BPV, and BRS have been applied in multiple studies related to mental workload.

For instance, in a study (Stuiver and Mulder, 2014) that considered two simulated tasks (ambulance dispatching and a driving simulator), the researchers found that HR increased during the dispatch task; BRS decreased; and BP showed an initial increase, after which it continued to rise, albeit more slowly. For the driving task, BP initially increased but then fell to near baseline levels. Both BRS and HR decreased during the task. The researchers concluded that there are task-specific differences that lead to different types of autonomic control.

A study carried out by Madden and Savard (1995) utilised a computerised quiz to induce mental stress. It was found that BPV decreased and systolic BP rose as the degree of mental stress increased. Similar results were obtained in another study (Ring et al., 2002), in which mental stress was induced by mental arithmetic, leading to an increase in mean BP.

Finally, a study by Robbe et al. (1987) investigated BRS during mental arithmetic and memory tasks. Its conclusion was that the modulus (the gain between BPV and HRV (Mulder, 1988; Robbe et al., 1987)) decreased during task performance. Additionally, blood pressure was recorded during flight in research conducted by Veltman and Gaillard (1998), and the modulus was found to be a good index for mental effort.

4.3 Photoplethysmography

In addition to the measures discussed above that reflect various aspects of cardiac variability, the autonomic activity can be studied by observing vasoconstriction. As noted above, mental stress is reflected in peripheral vasoconstriction, which is visible in the PPG signals as a decreased pulse amplitude (PA). For instance, Iani et al. (2004) investigated the peripheral arterial tone (measured by means of a pneumatic plethysmograph) during the performance of a computerised memory task. They found that subjects exhibited vasoconstriction during the more demanding memory tasks in their experiment. Similar results were found in an experiment involving simulated flight, wherein vasoconstriction was observed during difficult phases of the simulation (Iani et al., 2007).

Pulse rate variability can also be analysed in a fashion similar to HRV. Yoo and Lee (2011) examined detection of mental stress by using the PPG signal and PRV, while other researchers (Yashima et al., 2006; Kageyama et al., 2007) have explored the use of wavelet analysis for mental stress detection via the PPG signal. Arai et al. (2012) estimated mental stress by considering the LF/HF ratio calculated from the PPG signal, and the resulting extracted mental stress metric was used to control the functioning of a mail program on a smartphone.

5 Conclusions

Cardiovascular signals and the variability metrics extracted from them are used extensively for the determination of mental workload during various types of task
performance. Of the signals considered in this section of the paper, the ECG and PPG signals are easy to measure, and good-quality recordings can be obtained with affordable devices such as sports watches. The recent incorporation of PPG sensors into several wrist-worn devices means that such devices could well be usable for long-term measurements. The use of remote PPG techniques, of various types, that employ ordinary webcams might be highly suitable for computer work. Blood pressure, however, is not well suited to the prolonged measurement of cardiovascular activity at present, on account of the technical requirements. In terms of usability, ECG and PPG measurements are hence currently more suitable for human–computer interaction applications than is BP.

The metrics used for analysing cardiovascular signals are well established, as illustrated, for example, by Malik et al. (1996). Furthermore, other metrics describing variations in cardiovascular signals are being studied, such as the fractal dimension of the HRV signal (Nakamura et al., 1993; Cáceres et al., 2004).

Cardiovascular metrics have been applied extensively for determining and monitoring levels of mental workload. However, it appears that these metrics have not been used thus far for the purpose of adapting user interfaces to the degree of mental workload. This is a new, relatively unexplored area.
Aasman, J., Mulder, G., and Mulder, L. J. Operator effort and the measurement of heart-rate variability. Human Factors: The Journal of the Human Factors and Ergonomics Society, 29(2):161–170, 1987.

Allen, J. Photoplethysmography and its application in clinical physiological measurement. Physiological measurement, 28(3):R1, 2007.

Arai, S., Ohira, K., Thepvilovanapong, N., Tetsutani, N., Tohe, Y., Oyama-Higa, M., and Ohta, Y. A design of software adaptive to estimated user’s mental state using pulse wave analysis. In Networked Sensing Systems (INSS), 2012 Ninth International Conference on, pages 1–4. IEEE, 2012.

Awad, A. A., Ghobashy, M.-A. M., Ouda, W., Stout, R. G., Silverman, D. G., and Shelley, K. H. Different responses of ear and finger pulse oximeter wave form to cold pressor test. Anesthesia & Analgesia, 92(6):1483–1486, 2001.

Backs, R. W., Navidzaede, H. T., and Xu, X. Cardiorespiratory indices of mental workload during simulated air traffic control. In Proceedings of the Human Factors and Ergonomics Society Annual Meeting, volume 44, pages 89–92. SAGE Publications, 2000.

Berntson, G. G. Heart rate variability: Origins, methods and and interpretive caveats. Psychophysiology, 34:623–648, 1997.

Billman, G. E. The LF/HF ratio does not accurately measure cardiac sympathovagal balance. Heart Rate Variability: Clinical Applications and Interaction between HRV and Heart Rate, page 54, 2007.

Bouselfaf, F., Maaoui, C., and Pruski, A. Remote detection of mental workload changes using cardiac parameters assessed with a low-cost webcam. Computers in biology and medicine, 53:154–163, 2014.

Cáceres, J. H., Sibat, H. F., Hong, R., Garcia, L., Sautié, M., and Namugowa, V. Towards the estimation of the fractal dimension of heart rate variability data. Electron J Biomed, 2(1), 2004.

Cinaz, B., Arrrich, B., La Marca, R., and Tröster, G. Monitoring of mental workload levels during an everyday life office-work scenario. Personal and ubiquitous computing, 17(2):229–239, 2013.

Clifford, G. D., Azuaje, F., and McSharry, P. Advanced methods and tools for ECG data analysis. Artech House, Inc., 2006.

Constant, I., Laude, D., Murat, I., and Elghozi, J.-L. Pulse rate variability is not a surrogate for heart rate variability. Clinical Science, 97:391–397, 1999.

Cowley, B., Filetti, M., Lukander, K., Torniainen, J., Henelius, A., Ahonen, L., Barral, O., Kosunen, I., Valtonen, T., Huotilainen, M., Ravaja, N., and Jaccuci, G. The Psychophysiology Primer: a guide to methods and a broad review with a focus on human computer interaction. Foundations and Trends in HCI, 9(3-4):150–307, 2016. doi: 10.1561/1100000065.

de Boer, R. W. Beat-to-beat blood pressure fluctuations and heart rate variability in man: Physiological relationships, analysis, techniques, and a simple model. PhD thesis, University of Amsterdam, 1985.
A review and primer for cardiovascular signals in HCI

Gamelin, F. X., Berthoin, S., Bosquet, L., et al. Validity of the polar s810 heart rate monitor to measure rr intervals at rest. Medicine and science in sports and exercise, 38(5):887, 2006.

Garde, A., Laursen, B., Jørgensen, A., and Jensen, B. Effects of mental and physical demands on heart rate variability during computer work. European journal of applied physiology, 87(4-5):456–461, 2002.

Goldberger, A. L., Amaral, L. A., Glass, L., Hausdorff, J. M., Ivanov, P. C., Mark, R. G., Mietus, J. E., Moody, G. B., Peng, C.-K., and Stanley, H. E. Physiobank, physiotoolkit, and physionet components of a new research resource for complex physiologic signals. Circulation, 101(23):e215–e220, 2000.

He, X., Goubran, R. A., and Liu, X. P. Evaluation of the correlation between blood pressure and pulse transit time. In Medical Measurements and Applications Proceedings (MeMeA), 2013 IEEE International Symposium on, pages 17–20. IEEE, 2013.

Henelius, A., Hirvonen, K., Holm, A., Korpela, J., and Muller, K. Mental workload classification using heart rate metrics. In Engineering in Medicine and Biology Society, 2009. EMBC 2009. Annual International Conference of the IEEE, pages 1836–1839. IEEE, 2009.

Hjortskov, N., Rissén, D., Blangsted, A. K., Fallentin, N., Lundberg, U., and Søgaard, K. The effect of mental stress on heart rate variability and blood pressure during computer work. European journal of applied physiology, 92(1-2):84–89, 2004.

Huikuri, H. V., Niemelä, M., Ojala, S., Rantala, A., Ilkäheimo, M., and Airaksinen, K. Circadian rhythms of frequency domain measures of heart rate variability in healthy subjects and patients with coronary artery disease. effects of arousal and upright posture. Circulation, 90(1):121–126, 1994.

Iani, C., Gopher, D., and Lavie, P. Effects of task difficulty and invested mental effort on peripheral vasoconstriction. Psychophysiology, 41(5):789–798, 2004.

Iani, C., Gopher, D., Grunwald, A., and Lavie, P. Peripheral arterial tone as an on-line measure of load in a simulated flight task. Ergonomics, 50(7):1026–1035, 2007.

Iyengar, N., Peng, C., Morin, R., Goldberger, A. L., and Lipsitz, L. A. Age-related alterations in the fractal scaling of cardiac interbeat interval dynamics. American Journal of Physiology-Regulatory, Integrative and Comparative Physiology, 271(4):R1078–R1084, 1996.

Jorna, P. Heart rate and workload variations in actual and simulated flight. Ergonomics, 36(9):1043–1054, 1993.

Kageyama, Y., Odagaki, M., and Hosaka, H. Wavelet analysis for quantification of mental stress stage by finger-tip photo-plethysmography. In Engineering in Medicine and Biology Society, 2007. EMBS 2007. 29th Annual International Conference of the IEEE, pages 1846–1849. IEEE, 2007.

Kirschbaum, C., Pirke, K.-M., and Hellhammer, D. H. The trier social stress test—a tool for investigating psychobiological stress responses in a laboratory setting. Neuropsychobiology, 28(1-2):76–81, 1993.

Kudielka, B. M., Hellhammer, D. H., Kirschbaum, C., Harmon-Jones, E., and Winkielman, P. Ten years of research with the trier social stress test–revisited.
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Social neuroscience: Integrating biological and psychological explanations of social behavior, pages 56–83, 2007.
Lackner, H. K., Goswani, N., Papousek, I., Roessler, A., Grasser, E. K., Montani, J.-P., Jezova, D., and Hinghofer-Szalkay, H. Time course of cardiovascular responses induced by mental and orthostatic challenges. International Journal of Psychophysiology, 75(1):48–53, 2010.
Lee, C., Shin, H., Min, S., Yun, Y., and Lee, M. A study on comparison ppg variability with heart rate variability in the sitting position during paced respiration. In World Congress on Medical Physics and Biomedical Engineering, September 7-12, 2009, Munich, Germany, pages 1703–1705. Springer, 2010.
Lien, R., Neijts, M., Willemsen, G., and de Geus, E. J. Ambulatory measurement of the ecg t-wave amplitude. Psychophysiology, 52(2):225–237, 2015.
Lim, E., Lee, H.-K., Myoung, H.-S., and Lee, K.-J. Development of a noncontact heart rate monitoring system for sedentary behavior based on an accelerometer attached to a chair. Physiological measurement, 36(3):N61, 2015.
Lin, J. C., Kiernicki, J., Kiernicki, M., and Wollschaeger, P. B. Microwave apexcardiography. Microwave Theory and Techniques, IEEE Transactions on, 27(6):618–620, 1979.
Lin, W.-H., Wu, D., Li, C., Zhang, H., and Zhang, Y.-T. Comparison of heart rate variability from ppg with that from ecg. In The International Conference on Health Informatics, pages 213–215. Springer, 2014.
Lu, G., Yang, F., Taylor, J., and Stein, J. A comparison of photoplethysmography and ecg recording to analyse heart rate variability in healthy subjects. Journal of medical engineering & technology, 33(8):634–641, 2009.
Ma, T. and Zhang, Y. A correlation study on the variabilities in pulse transit time, blood pressure, and heart rate recorded simultaneously from healthy subjects. In Engineering in Medicine and Biology Society, 2005. IEEE-EMBS 2005. 27th Annual International Conference of the, pages 996–999. IEEE, 2005.
Madden, K. and Savard, G. Effects of mental state on heart rate and blood pressure variability in men and women. Clinical Physiology, 15(6):557–569, 1995.
Malik, M., Bigger, J. T., Camm, A. J., Kleiger, R. E., Malliani, A., Moss, A. J., and Schwartz, P. J. Heart rate variability standards of measurement, physiological interpretation, and clinical use. European heart journal, 17(3):354–381, 1996.
Malmivuo, J. and Plonsey, R. Bioelectromagnetism: Principles and applications of bioelectric and biomagnetic fields. Oxford university press, 1995.
Miyake, S., Yamada, S., Shoji, T., Takae, Y., Kuge, N., and Yamamura, T. Physiological responses to workload change. a test/retest examination. Applied ergonomics, 40(6):987–996, 2009.
Mulder, B., Veldman, H., van der Veen, F., van Roon, A., Rüddel, H., Schächinger, H., and Mulder, B. On the effects of mental task performance on heart rate, blood pressure and its variability measures. Blood Pressure and Heart Rate Variability: Computer Analysis, Modelling and Clinical Applications, 4:153, 1993.
A review and primer for cardiovascular signals in HCI

Mulder, L. Assessment of cardiovascular reactivity by means of spectral analysis. *Biological Psychology*, 1988.

Mulder, L., Veldman, J., Rüddel, H., Robbe, H., and Mulder, G. On the usefulness of finger blood-pressure measurements for studies on mental workload. *Homeostasis in health and disease: International journal devoted to integrative brain functions and homeostatic systems*, 33(1-2):47–60, 1990.

Myrtek, M., Deutschmann-Janicke, E., Strohmaier, H., Zimmermann, W., Lawrence, S., Brügger, G., and Müller, W. Physical, mental, emotional, and subjective workload components in train drivers. *Ergonomics*, 37(7):1195–1203, 1994.

Nakamura, Y., Yamamoto, Y., and Muraoka, I. Autonomic control of heart rate during physical exercise and fractal dimension of heart rate variability. *Journal of Applied Physiology*, 74:875–875, 1993.

Nickel, P. and Nachreiner, F. Sensitivity and diagnosticity of the 0.1-Hz component of heart rate variability as an indicator of mental workload. *Human Factors: The Journal of the Human Factors and Ergonomics Society*, 45(4): 575–590, 2003.

Parati, G., Saul, J. P., Di Rienzo, M., and Mancia, G. Spectral analysis of blood pressure and heart rate variability in evaluating cardiovascular regulation. *Hypertension*, 25(6):1276–1286, 1995.

Peñáz, J. Photoelectric measurement of blood pressure, volume and flow in the finger. In *Digest of the 10th international conference on medical and biological engineering*, volume 104. International Federation for Medical and Biological Engineering, Publishers New York, 1973.

Ring, C., Burns, V. E., and Carroll, D. Shifting hemodynamics of blood pressure control during prolonged mental stress. *Psychophysiology*, 39(5):585–590, 2002.

Robbe, H., Mulder, L., Rüddel, H., Langewitz, W., Veldman, J., and Mulder, G. Assessment of baroreceptor reflex sensitivity by means of spectral analysis. *Hypertension*, 10(5):538–543, 1987.

Roscoe, A. H. Assessing pilot workload. Why measure heart rate, HRV and respiration? *Biological psychology*, 34(2):259–287, 1992.

Roscoe, A. H. Heart rate as a psychophysiological measure for in-flight workload assessment. *Ergonomics*, 1993.

Selvaraj, N., Jaryal, A., Santhosh, J., Deepak, K. K., and Anand, S. Assessment of heart rate variability derived from finger-tip photoplethysmography as compared to electrocardiography. *Journal of medical engineering & technology*, 32(6):479–484, 2008.

Stuiver, A. and Mulder, B. Cardiovascular state changes in simulated work environments. *Frontiers in neuroscience*, 8, 2014.

Sun, Y., Papin, C., Azorin-Peris, V., Kalawsky, R., Greenwald, S., and Hu, S. Use of ambient light in remote photoplethysmographic systems: Comparison between a high-performance camera and a low-cost webcam. *Journal of biomedical optics*, 17(3):0370051–03700510, 2012.

Taelman, J., Vandeput, S., Vlemmix, E., Spaepen, A., and Van Huffel, S. Instantaneous changes in heart rate regulation due to mental load in simulated office work. *European Journal of Applied Physiology*, 111(7):1497–1505, 2011.
A review and primer for cardiovascular signals in HCI

Tarvainen, M. *Estimation methods for nonstationary biosignals*. PhD thesis, Kuopion yliopisto, 2004.

Togo, F. and Takahashi, M. Heart rate variability in occupational health—a systematic review. *Industrial health*, 47(6):589–602, 2009.

Van Roon, A. M., Mulder, L. J., Althaus, M., and Mulder, G. Introducing a baroreflex model for studying cardiovascular effects of mental workload. *Psychophysiology*, 41(6):961–981, 2004.

Vassend, O. and Knardahl, S. Personality, affective response, and facial blood flow during brief cognitive tasks. *International journal of psychophysiology*, 55(3):265–278, 2005.

Veltman, J. and Gaillard, A. Physiological workload reactions to increasing levels of task difficulty. *Ergonomics*, 41(5):656–669, 1998.

Vincent, A., Craik, F. I., and Furedy, J. J. Relations among memory performance, mental workload and cardiovascular responses. *International Journal of Psychophysiology*, 23(3):181–198, 1996.

Wesseling, K. Finapres, continuous noninvasive finger arterial pressure based on the method of penaz. In *Blood pressure measurements*, pages 161–172. Springer, 1990.

Wilson, G. F. An analysis of mental workload in pilots during flight using multiple psychophysiological measures. *The International Journal of Aviation Psychology*, 12(1):3–18, 2002.

Yashima, K., Sasaki, T., Kageyama, Y., Odagaki, M., and Hosaka, H. Application of wavelet analysis to the plethysmogram for the evaluation of mental stress. In *Engineering in Medicine and Biology Society, 2005. IEEE-EMBS 2005. 27th Annual International Conference of the*, pages 2781–2784. IEEE, 2006.

Yoo, K.-s. and Lee, W.-H. Mental stress assessment based on pulse photoplethysmography. In *Consumer Electronics (ISCE), 2011 IEEE 15th International Symposium on*, pages 323–326. IEEE, 2011.