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Heart Rate Variability, the Autonomic Nervous System, and Neuroeconomic Experiments

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Measuring the activity of the autonomic nervous system may yield insights into individual stress levels. One small, nonintrusive instrument for collecting such data is a high-resolution heart rate monitor that allows measurement of heart rate variability (HRV). This complements brain-scanning methods and increases the number of participants that can be studied simultaneously. Combining HRV data with recorded data on the decisions made in experimental games throws light on how different individuals react in (economic) decision-making situations. This article therefore introduces the HRV measurement method and, using data from an ultimatum bargaining experiment in a laboratory environment, illustrates its application in experimental economic research.

Keywords: neural basis of economic decisions, autonomic nervous system, neuroeconomics, heart rate variability

Although experimental research in both economics and neuroeconomics aims to better understand human decision making in economic situations, the former focuses on identifying regularities in human decision behavior, whereas the latter studies the neural basis for decisions. In fact, one key aim of neuroeconomics is to explore the unobservable aspects of decision making in order to understand concepts that economic analysis has traditionally ignored (e.g., emotions) and assess the importance of different theories on behavioral anomalies like reciprocity, risk aversion, or altruism (Camerer, Bhatt, & Hsu, 2007). Thus, as Laibson (2007) pointed out, neuroeconomics provides a biological microfoundation of neurochemical mechanisms, including brain systems, heart rate, skin resistance, genes, neurons, and neurotransmitters. At the same time, because advances in imaging techniques allow precise spatial localization of brain activities during the decision-making process (see, e.g., Glimcher & Rustichini, 2004; Sanfey, Rilling, Aronson, Nystrom, & Cohen, 2003; Zak, 2004), an increasing number of studies are using brain activity as a basis for economic theory. Hence, Camerer and Loewenstein (2004) have argued that although there is still "undoubtedly a large leap from precise neural activity to big decisions like planning for retirement or buying a car," data from such studies "could resolve years or decades of debate that are difficult to resolve with other sorts of experiments" (p. 38).

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Most particularly, the high-resolution data generated by methods like functional MRI come at a cost: The sheer magnitude of the technology precludes simultaneous observation of a large number of participants and imposes limitations on the experimental design. This article therefore introduces an additional tool that mitigates this problem—the measurement of heart rate variability (HRV) using portable devices. Not only does this technology have the comparative advantage of small size and nonintrusivity (see Figure 1), which allows experimenters to observe a large set of participants and their interactions in both the lab and the field, but its highly accurate recording functionality allows true and precise derivation of HRV parameters. Hence, because it enables data collection in a range of settings and interpersonal contexts in conjunction with traditional experimental tools, this method offers an exciting new approach for investigating decision-making processes.

It remains to be asked, however, whether HRV measurements can provide new insights in economic experimentation. Studies by both Crone, Somsen, van Beek, and van der Molen (2004) and Crone, Bunge, de Klerk, and van der Molen (2005) have shown that heart rate is indeed affected during decision-making processes that involve payoff-relevant feedback. They have also shown that the heart rates of anxious participants react more strongly to such situations than do the heart rates of less anxious participants, a relation also established by Koelsch et al. (2007) in their identification of emotional personality based on heart rate data from electrocardiograms (ECG). Further support for this measurement's usefulness has been provided by neuroeconomic and neuroscientific research. For example, using experimental games such as the ultimatum bargaining game, neuroeconomic studies have identified the anterior insula, the dorsolateral prefrontal cortex (DLPFC), and the anterior cingulate cortex (ACC) as the brain areas activated during decision making (Rilling, King-Casas, & Sanfey, 2008; Sanfey, Loewenstein, McClure, & Cohen, 2006). Neuroscientific studies also have shown that these three areas are associated with the autonomic state of the cardiovascular system. For instance, Critchley et al. (2003), by regressing HRV measurements on the activity of several brain regions during simple cognitive and motor tasks, showed not only that activity in the anterior insula and ACC is a significant explanatory variable for sympathetic (low-frequency, LF) and parasympathetic (high-frequency, HF) activity, but that it is significantly correlated with HRV. Later experimental work by Critchley et al. (2005), in which participants were shown different emotional facial expressions, also established a link between HRV and activity not only in the anterior insula and ACC but also in the DLPFC. These findings may indicate that, as implied by earlier neuroeconomic research, HRV data can be used to measure participant reactions in economic experiments.

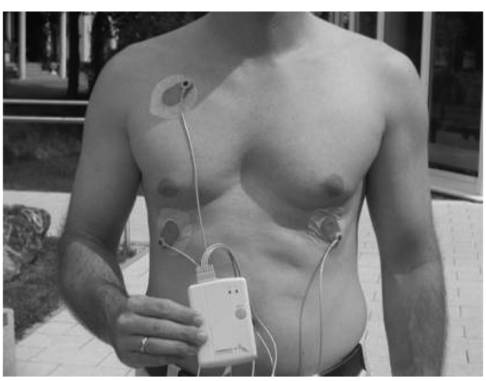

Figure 1. Size of the electrocardiogram recording device and application of the electrodes to the chest. (*Source*: AUTONOM TALENT, Austria).

Building on this assumption, we show how HRV measurement can provide a nonintrusive but useful form of physiological monitoring that allows a wide variety of laboratory experiments on economic decisions. After first reviewing the relevant research on deriving psychological indicators from HRV data, we describe our experimental design and use the resulting data to illustrate the observable relationship between HRV and economic decision making.

Relevant HRV Literature

Although in the literature the term *HRV* is used for different measurements and techniques that allow interpretation of heart rate variation data, HRV analysis is generally used to identify several medical predispositions (Malik et al., 1996), as well as psychological, emotional, and mental activities (Crone et al., 2004, 2005;

Koelsch et al., 2007; Yang et al., 2007). For example, the HRV method is used to obtain information on the activity of two major parts of the autonomic nervous system (ANS), the sympathetic and parasympathetic systems. The first (the fight-or-flight response) affects the heart rate indirectly through the sympathetic nerves and by releasing cell-stimulating hormones (mainly adrenaline) into the blood stream. The second (which is responsible for rest and relaxation) influences the heart directly through the vagal nerve's connection to specific "pacemaker" cells (Levy & Martin, 1979). Because changes in heart rate induced by the sympathetic system occur over a considerably longer time (maximum effect after more than 5 s) than those induced by the parasympathetic system (maximum effect after less than 5 s; Levy, Martin, Iano, & Zieske, 1970), these timing difference can be used to identify the extent of sympathetic and parasympathetic activity.

In experimental environments that control (avoidance of) physical activity, eating, and drinking, the HRV method can generate indicators of the participants' psychological state (Berntson & Cacioppo, 2008) based on correlations between changes in the balance between the sympathetic and parasympathetic systems and mental (rather than motor) activity in the anterior insula, DLPFC, and ACC. Indeed, as several studies have shown, participants react to mental stress with either increased sympathetic or decreased parasympathetic activity (Berntson et al., 1994). Hence, the ratio of activity in the low-frequency band to that in the high-frequency band (i.e., the LF/HF ratio), shown to remain stable in laboratory testing of different mental tasks (Seong, Lee, Shin, Kim, & Yoon, 2004), may serve as a useful indicator of mental stress.

Method

HRV Measurement

In our experiment, we recorded the ECG measures using a small portable recorder (Holter Medilog Digital ECG Recorder AR4) with a high sampling rate of 128 Hz (see Figure 1), a device that also records respiration rates and has a built in QRS (heartbeat) detection algorithm. Although several techniques exist for estimating HRV and activity in different parts of the ANS systems from ECG data, all approaches must deal with two issues: (a) that the sympathetic and vagal system are active alongside several other prominent systems, including those that regulate respiration, temperature, and blood pressure (Hainsworth, 2008); and (b) that there is a large degree of heterogeneity in heart rates and individuals' heart rate reactions. Fortunately, there is a viable solution: using time–frequency analysis of the (interpolated) heart rate signal, we can identify the level of activity (power) at different velocities of change (frequencies). The most commonly used method for obtaining this information is the smoothed pseudo-Wigner–Ville distribution (SPWVD), a wavelet transformation (Bianchi et al., 1993; Seong et al., 2004; Wiklund, Akay, & Niklasson, 1997).

This technique, which until now has been used primarily in medical research, has identified several interesting factors, including the fact that activity in the sympathetic system is reflected mainly in high spectral power in the low-frequency band (LF [0.033–0.15 Hz]), whereas the parasympathetic system (and respiration) is characterized by high spectral power in the high-frequency band (HF [0.15–0.4 Hz]; Malik, 2008). Research also has linked high spectral power in ultra-low- (ULF, [0–0.016 Hz]) and very-low- (VLF [0.016–0.033 Hz]) frequency bands to day–night variation and temperature regulation (for more detail on frequency bands, see Malliani, Pagani, Lombardi, & Cerutti, 1991; Pagani et al., 1986; Pomeranz et al., 1985; Sayers, 1973).

Research Design

To assess whether, in economic laboratory experiments, the HRV method can explain participant behavior and whether physiological reaction to social situations carries over to individual behavior, we used the standard economic experiment of the ultimatum bargaining game (see Gueth, Schmittberger, & Schwarze, 1982; Roth, 1995). In this game, in which two players negotiate the division of a certain sum of money, the first player, the proposer, offers a split that the second player, the responder, can either accept or reject. If the offer is rejected, neither player receives anything. The primary goal of this experiment, which was computer based and implemented using z-Tree (Fischbacher, 2007), was to identify protocols and techniques that would allow application of the HRV measurement method in large-scale economic experiments. The experimental protocol was reviewed by the Queensland University of Technology Faculty Research Ethics Advisory Board, which found it in compliance with the National Statement on Ethical Conduct in Human Research.

Participants

The median age of the 156 (89 men, 67 women) participants, recruited primarily from first-year economics units through a faculty-wide invitation e-mail and in-lecture announcements, was 20 years (M = 21.18 years, SD = 4.44). These voluntary participants, none of whom had had previous experience with such research, were informed that the experiment would include measurement of their heart rates and that they could not eat or drink anything except water 90 min prior to a session.

Experimental Procedure

A total of 13 sessions, with six proposers and six responders in each, were held in the afternoon to minimize the effect of daytime variation on heart rate. To ensure that the two groups (proposers and responders) would not meet during the first part of the experiment, the randomly assigned participants reported to two different locations. On arrival, they received initial instructions on how to use the HRV monitors and help applying the electrodes. To calibrate the devices, they climbed two sets of stairs up to the computer labs (STAIRS in Figure 2). Here, the main experimental instructions were displayed on computer screens and were also read aloud to the participants by a native English speaker. Before proceeding to the bargaining stage, the participants had to answer a set of control questions to ensure that they had a solid understanding of the game structure. A total of nine rounds of the ultimatum bargaining game were played in which proposers were randomly matched with one responder in every round (ULT). The assignation method was designed to ensure that no repetition in matching occurred in the first six rounds, but that in the last three rounds participants were matched randomly and had no indication with whom they were playing (we also controlled for learning effects by introducing period dummy variables).

Each proposer received 360 cents (AUD) to split. At the end of each round, both participants received a statement containing all the information about this round and their individual payoffs. To identify the potential effects of social interaction on the behavioral variables, groups of two proposers and two responders met in person for 5 min after the sixth round in the majority of the sessions or after the ninth round in three control sessions. In this key experimental communication phase (COMM), the participants were allowed to talk freely about anything except the experiment. Once the main experiment was finished, further participant information was gathered using a standard risk-preferences elicitation tool (RISK; see Holt & Laury, 2002, for details) and a final demographic questionnaire (QUESTIONNAIRE).

Data Analysis

These experimental stages are summarized in Figure 2, which also gives the HRV parameters derived from measuring one individual participant and the activity of different frequencies over time (time–frequency distribution). As the figure clearly shows, the different experimental stages are easily distinguishable based on the associated HRV pattern.

To identify whether the stress level during the communication phase was in any way correlated with the economic decisions made during the bargaining game, we conducted several regressions (using Stata, Version 10.1) to explore the relation between participants' HRV and their economic decision making (see Table 1). Here, the dependent variable was the amount of the offer as a percentage of the total amount to be distributed, and the key independent variable was the level of mental stress (measured by the LF/HF ratio) during the communication phase.

We obtained the LF/HF ratio by applying a standard SPWVD transformation using the cubic interpolated heart rate signal (5 Hz) and 512 frequency bins (each ~0.001 Hz wide) in Matlab (Version 2009a). After estimating the parameters using a moving time window of 27 s and a frequency window of 101 points (bins), we tested the robustness of these values using short-term fast Fourier transformation and autoregressive estimation techniques. Having cho-

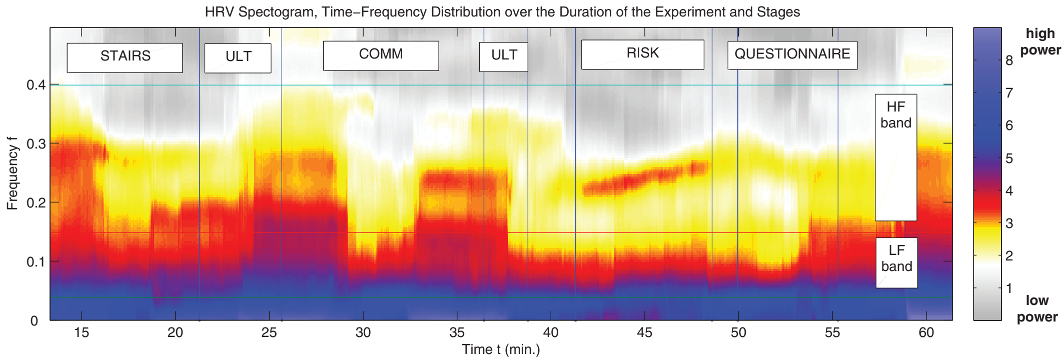

Figure 2. Spectrogram of heart rate variability frequency band activity for a participant in the bargaining experiment. LF = low frequency; HF = high frequency; STAIRS = participants climbed two sets of stairs to calibrate the monitor; ULT = rounds of the ultimatum game; COMM = communication phase; RISK = information gathering with a standard risk-preferences elicitation tool; QUESTIONNAIRE = demographics questionnaire.

sen our primary analytical method for its ability to provide the best time and frequency resolution (Seong et al., 2004), we then split the resulting time–frequency distribution into two frequency bands and used their average values to build the desired ratio.

Specifications (1) and (2) in Table 1 include all nine observations for each proposer ($n = 66$) in the sample ($n = 9 \times 66 = 594$), which allowed the introduction of period and session fixed effects (dummy variables) into our overall data analysis. One key challenge in measuring heart rate variability is that individual heterogeneity may matter. For example, according to the literature, the HRV measure declines with age, and women seemingly have a higher high-frequency power (indicating higher parasympathetic tone) and lower low-frequency power (suggesting lower sympathetic activity) than men. Multivariate analyses should therefore test for the impact of basic age and gender demographics; for example, by including an age and a gender variable (female = 1) as in our Specification (2). We also believe that our use of a relatively homogeneous group of student participants helped control for such effects, especially as the literature has reported an inverse correlation between educational attainment and heart rate (Britton & Hemingway, 2008). Nonetheless, the relation between psychological processes and autonomic control is complex, making it a challenge to fully control for all potential factors (for a discussion on the standardization of HRV measurement, see Malik et al., 1996; for the confounding psychological factors in particular, see Berntson & Cacioppo, 2008). In Specifications (3) to (5), we tested the robustness of the previous results focusing on the first, last, and average offer.

Results

Overall, the results—reported in Table 1 as standardized beta coefficients to facilitate assessment of the relative impact of different parameters—do indeed indicate that stress levels during the social interactions (as measured by average LF/HF ratio) correlate with higher offers from proposers before and after the communication phase (statistically significant at the 1% level in most cases). This finding may also indicate that HRV data in general could be used to better control for heterogeneous participant characteristics that are inaccessible in traditional economic experiments and thus account for interpersonal differences.

We admit, however, that implementing a measurement tool to obtain HRV is not free of technical problems: Irregularities can be caused by participants' medical conditions or by dislodged electrodes. In fact, such irregularities in ECG recording forced us to drop the HRV measurements for 26 (16.7%) of the participants in our bargaining experiment. Nonetheless, such occurrences can be reduced by testing the heart rate monitor application using an infrared

Table 1
Regression of Proposers' Stress Levels During the Communication Phase on Offers Made During the Ultimatum Bargaining Game

Variable	Single offers (1)	Single offers + demographics (2)	First offer (3)	Last offer (4)	Average offer (5)
Stress (LF/HF) during communication	.334** (7.83)	.353** (7.81)	.266* (2.08)	.393** (3.16)	.469** (3.95)
Dummy after communication	−.063 (−0.76)	−.063 (−0.76)		.030 (0.25)	
Gender		.062 (1.32)	−.053 (−0.41)	.136 (1.07)	.074 (0.61)
Age		−.008 (−0.19)	.095 (0.75)	.037 (0.30)	.048 (0.41)
Period dummies	Yes	Yes	No	No	No
Session dummies	Yes	Yes	No	No	No
R^2	.15	.15	.08	.15	.20
F	4.549**	4.242**	1.749	2.595*	5.250**
Prob > F	.000	.000	.166	.045	.003
Number of observations	594	594	66	66	66

Note. LF = low frequency; HF = high frequency. The results are reported as beta coefficients with robust standard errors; *t* statistics are given in parentheses. The df for the model and the residuals are (in order of specification): (22,571), (24,569), (3,62), (4,61), and (3,62).
* Significant at the .05 level. ** Significant at the .01 level.

data association interface. Likewise, in the computer-based part of the experiment, network traffic issues caused some variations in the time data for events, thereby producing time records that gave only an indication of when the event actually happened (e.g., when the information screen was actually visible to the participant). Subsequently, however, we were able to reduce such problems as the same event being recorded for different participants by isolating the laboratory network from the university network and assigning it its own subnet. Doing so reduced the length of recording discrepancies from an average 2.423 s in the ultimatum bargaining experiment to 0.00626 s in a later experiment (reported elsewhere).

Most important, neither of these problems affected the results reported here. First, the exclusion of participants because of equipment failure did not impair the statistical method because the failure was exogenous and in no way correlated with individual characteristics. The random selection process therefore remained intact. Second, the timing of the communication phase was identified based on the average recorded time for all participants, thereby reducing any inaccuracy within a 5-min period to less than 3 s (1%), which is negligible for the statistical model used.

Discussion

In this article, we have argued for the potential use of HRV measurements in economic experiments based on neuroscientific findings that brain areas activated during economic decision correlate with HRV parameters. Research has also shown that in controlled environments, the ANS's control over HRV can be used to identify individual stress levels (LF/HF ratio). Measuring HRV, therefore, not only generates several indexes for autonomic arousal but provides an opportunity to observe additional individual variables that are inaccessible in traditional economic experiments or behavioral economic studies.

To illustrate this point, we provided an experimental example in which HRV measures did indeed correlate with individual bargaining behavior. It should be noted, however, that HRV, being affected by changes in physical state and driven by a wide range of mental states that rely on different neural substrates, does not provide access to a specific mental state. Rather, the laboratory experiment approach outlined here enabled us to control and isolate HRV changes caused by physical states (e.g., identical temperature conditions, limited physical activity during the experiment) and thus allowed the development of a reference point based on dedicated phases of controlled physical activity.

There are several interesting avenues for further research. Such technology may be useful for testing the correlation between HRV measurements and other stress responses like the amount of cortisol present in the bloodstream or commonly used self-reported stress scales. In light of previous findings that individual heterogeneity (e.g., demographics, education) has an impact on HRV measures, the use in such laboratory experiments of a relatively homogeneous group of participants (e.g., students) may prove advantageous. Because the complex relation between psychological processes and autonomic control implies the importance of controlling for additional factors such as stress and psychological condition, there is a need to identify additional factors that drive HRV measures. Postexperimental questionnaires may offer a valuable tool for such inquiry. More important, we believe that the HRV approach is helpful for understanding group phenomena when social interactions are crucial. Most particularly, because current brain scanning technology does not allow nonintrusive observation of groups of participants interacting simultaneously and naturally, HRV measurements using small portable recorders may usefully complement research that employs other high-resolution technologies.

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