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Vagal cardiac control throughout the day: the relative importance of effort–reward imbalance and within-day measurements of mood, demand and satisfaction

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Abstract

The effects of variables derived from a work stress theory (the effort–reward imbalance theory) on the power in the high frequency (HF_HRV) band of heart rate (0.14–0.40 Hz) throughout a work day, were determined using multilevel analysis. Explanatory variables were analysed at two levels: at the lowest level (within-day level), the effects of positive mood, negative mood, demand, satisfaction, demand-satisfaction ratio, and time of day were assessed. At the highest level (the subject level), the effects of sleep quality, effort, reward, effort–reward imbalance, need for control, type of work (profession), negative affectivity, gender and smoking on HF_HRV were assessed. Need for control has a negative effect on HF_HRV after controlling for time of day effects, i.e. subjects with a high need for control have a lower vagal control of the heart. In the long run, these subjects may be considered to

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be at increased health risk, because they have less of the health protective effects of vagal tone. The interaction between effort–reward imbalance and time of day has a positive effect on HF_HRV, i.e. the cardiac vagal control of subjects with a high effort–reward imbalance increases as the day progresses. It is discussed that this probably reflects reduced effort allocation, ensuing from disengagement from the work demands.

Keywords: Vagal cardiac control; Effort–reward imbalance; Ambulatory; Heart rate variability; Ecological momentary assessments; Mood

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1. Introduction

The relation of psychosocial factors in work, either objectively assessed or measured by subjective judgements, with cardiovascular reactions and complaints has been amply demonstrated (Karasek, 1979; Hackman and Oldham, 1980; Cooper and Payne, 1991; Marmot, 1994; Siegrist, 1996a). However, less is known about the physiological mechanisms allegedly responsible for this relationship. A theory that may explain certain aspects of these mechanisms has been proposed by Siegrist (1996b). This theory, known as the effort–reward imbalance theory, suggests that a high effort, a low reward and a high need for control first lead to changes in physiological and psychological responses and eventually to the development of cardiovascular disease. However, sufficient evidence, especially for the relation with physiology, is still needed. The present paper will focus on this issue, by assessing the effects of effort–reward imbalance (ERI) — both as a trait and as a state — as well as need for control on vagal autonomic control (as is indicated by high frequency heart rate variability (HF_HRV)). Furthermore, the effects of within-day measurements of negative mood, positive mood, time of day and other potential determinants (sleep quality, negative affectivity, smoking, gender and profession) on HF_HRV are assessed.

The effort–reward imbalance theory is based on the premise that an imbalance between effort and reward leads to psychophysiological changes referred to as ‘emotional distress’ and an ‘activation of the autonomic nervous system’. Furthermore, the consequences of effort–reward imbalance are amplified by a high need for control (i.e. a strong tendency to engage in work activities). Thus, three major constructs are distinguished in the effort–reward imbalance theory that may codetermine psychological and physiological responses: the invested effort, reward received and an individual’s need for control. Siegrist and Peter (1994) argue that the risk for cardiovascular disease is mainly due to a chronic activation of the autonomic nervous system, and that the risk increases if individuals respond to effort–reward imbalance with a high need for control (after controlling for traditional risk factors).

To date, effort, reward and need for control have been associated with a decreased task elicited blood pressure reactivity in the laboratory (Siegrist, 1996b), but not yet with cardiovascular dynamics throughout an actual working day. Hypotheses about the relation between effort, reward, need for control and cardiovascular changes have to be based on an extension of the theoretical framework. Increased mental effort induces a decrease in vagal tone (Aasman et al., 1987). Low vagal control of heart rate has been shown to be related to coronary artery disease (Martin et al., 1987) and increased mortality (Kleiger et al., 1987). In a recent consensus paper it is confirmed that HF_HRV clearly represents vagal influence: a low HF_HRV is associated with a low vagal cardiac control (Berntson et al., 1997). The meaning of the low frequency (LF) heart rate variability (< 0.14 Hz) is more debated, most probably reflecting a mix of sympathetic and parasympathetic influences. According to Sloan et al., (1994) high LF/HF_HRV ratio is also associated with the relative dominance of sympathetic nervous system activity.

Putting these elements together, we expect subjects high on effort or on need for control (involving expenditure of mental effort) to have a lower vagal tone. The status of reward relative to autonomic drive is unclear; its effects will be tested as well. Imbalance of effort and reward may lead to either decrease or increase in vagal tone. The former response is expected in individuals, that perceive the environmental demands as a challenge, and still engage in work related activities. The latter response is expected in individuals that cope with the demands by disengagement from work related activities and/or switch to less effort demanding strategies. These responses are in line with the hypothesis that the motivational drive of individuals interacts with environmental demands, and co-determines the psychological and physiological responses (Hockey, 1997). In the effort–reward imbalance theory, need for control reflects the motivational aspects of an individual. Consequently, individuals with a high need for control as well as a high effort–reward imbalance are expected to have a lower parasympathetic drive than individuals with the opposite. The hypothesised interaction is tested in the present paper.

According to the effort–reward imbalance theory, effort, reward and need for control are stable trait-like constructs, implicitly assuming that these psychological characteristics are continuously and evenly present over longer periods of time. Expanding on the theoretical framework, it may also be argued that ongoing within-day assessments of these variables (referred to as 'demand', and 'satisfaction') also should affect heart rate variability throughout the work day. In line with the effort–reward imbalance theory, in which an imbalance ratio was expected to have a stronger predictive value, the ratio between demand and satisfaction ('the actual demand–satisfaction ratio') was also determined, anticipating an effect on heart rate variability. By testing all three variables (demand, satisfaction and the demand-satisfaction ratio) simultaneously, it was aimed to determine which of the effects was the strongest.

Other factors than the ones derived from the ERI theory have been shown to affect physiological functioning: the psychological trait of negative affectivity (Parkes, 1994), but also sleep quality, smoking, profession, gender (Grossman and Kollai, 1993; Egloff et al., 1995; Meijman, 1997; Shapiro et al., 1997), and negative and positive mood (Gellman et al., 1990; Schwartz et al., 1994; Shapiro et al., 1997) have been shown to have an effect on physiological changes throughout the day. The relative contribution of these factors to HF_HRV will be estimated as well.

Finally, some studies have also shown that time of day may interact with aspects of work (e.g. night shifts, long working hours) (Akerstedt, 1988, 1991), thereby influencing performance but also physiological state (Campbell, 1992). Another study has shown time of day to affect heart rate variability (Malliani et al., 1991). Therefore, it is hypothesised that time of day will interact with the constructs for the effort–reward imbalance theory, and have an effect on heart rate variability. Specifically, it was explored whether subjects differing in ERI show another HF_HRV pattern over the day, and whether this is affected by need for control.

2. Method

2.1. Subjects

From an initial sample of 104 subjects, 77 agreed to participate in the study. Four subjects were removed from the analysis of heart rate data, because they used anti-hypertensive medication, and another three were removed due to equipment failure. The final sample consisted of 70 workers from two different professions: health professionals (mean age = 40.0, S.D. = 4.6; 18 male, 15 female) and office clerks (mean age = 33.1, S.D. = 9.3; 21 male 16 female). The age and proportion of male subjects did not differ significantly between the occupations. The work tasks of both professions were usually performed sitting down and had a low physical component. A large part of the day was spent answering telephone calls, communicating with clients or typing data into a computer. The majority of the health professionals were nurses working at a '911' emergency line, and at a drug rehabilitation centre in Amsterdam (The Netherlands). The office clerks worked at the call centre of a large Telecommunication Company in The Netherlands. All subjects reported the confrontation with clients (e.g. emergency telephone calls, drug addicts and dissatisfied customers) as rather stressful. Based on the similarities between the groups it may be concluded that the entire sample is homogeneous. However, to ensure this, the variable 'profession' was added to the analysis.

2.2. Procedure

Two days before the ambulatory measurement of heart rate, subjects were asked to fill out questionnaires in order to measure effort, reward, need for control and negative affectivity. Subjects were also questioned on their medical history (hypertension etc.), smoking habits and profession. These variables were measured once in contrast to the variables demand, satisfaction, positive and negative mood that were measured several times a day using a diary implemented in a palm top computer. The diaries were filled in for 7 consecutive days. For the present purpose, only the diary ratings on the day of ambulatory measurements were used for analysis. Sleep quality was measured at the beginning of the day, using a special 'morning diary' generated by the palm top computer. After the questionnaires were filled in, the use of the portable diaries was explained.

On the day of the ambulatory heart rate measurements, subjects were equipped with the ambulatory apparatus during the first hour of work (8:00–9:00 h). Subjects then engaged in normal work activities during the day. At the end of the work day (16:30 h) the ambulatory physiological measurements of the health professionals were concluded. Although the measurements of some health professionals started later than 20:00 h and ended later than 16:30 h, no physiological measurements were performed at home. This was in contrast to the office clerks who had to continue ambulatory physiological measurements at home till 21:30 h. This means that the data obtained after 16:30 h is mainly based on the measurements obtained from the office clerks. They were instructed how to disconnect the measuring device at home. The devices were returned to the investigator the next day. In both groups, diary measurements started at 20:00 h and continued till 22:30 h (see within-day diary measurements).

At the end of all measurements subjects were debriefed in order to determine any confounding factors during measurement.

2.3. Measures

2.3.1. Effort, reward and need for control

The revised Dutch Effort–Reward Imbalance Questionnaire (Hanson et al., 2000a) was used to determine effort, reward and need for control. Effort referred to demanding aspects of the work environment, and was determined by six items (e.g. ‘I have constant time pressure due to a heavy work load’). Reward was measured by items referring to esteem by colleagues and superiors (esteem reward, six items), monetary gratification (one item), and status control (five items). Need for control referred to work related behaviour and commitment (e.g. ‘I don’t let others do my work’) and was measured by nine items. The reliability (Chronbach’s alpha) of effort, reward and need for control range between 0.70 and 0.81 (Hanson et al., 2000b). The mean values and standard deviation of effort, status control, esteem reward and monetary gratification are 10.9 (3.0), 19.9 (3.6), 17.5 (3.1), 3.6 (0.8), respectively (Hanson et al., 2000a).

2.3.2. Trait negative affect

Negative affect was measured using a Dutch translation (Doosje and Godaert, 1994) of the Well-being questionnaire (Bradley and Lewis, 1990). The questionnaire consisted of four subscales: anxiety, depression, energy and positive well being. A factor analysis performed on the anxiety and depression subscales resulted in a new subscale (seven items) called negative affect. The items used to measure negative affect refer to feelings of depression (e.g. ‘I have crying spells or feel like it’) and anxiety (e.g. ‘I feel nervous and anxious’). Both depression and anxiety are associated with negative affect (Watson and Clark, 1984; McCrae, 1990). Each item was rated on a 4-point numeric scale (with the labels ‘never’ and ‘always’ on the extremes). The range of the scores was 21. A psychometric analysis performed on the scale revealed a satisfactory internal consistency (Cronbach’s $\alpha = 0.86$) (Doosje and Godaert, 1994). In the present study an alpha of 0.82 ($n = 77$) was obtained.

2.3.3. Momentary demand, satisfaction, positive and negative mood

Items of the demand, satisfaction and mood scales were programmed in a portable Hewlett Packard 100 LX computer. The palmtop computer was implemented with software to conduct measurements according to the principles of Ecological Momentary Assessment (EMA) or by using the Experience Sampling Method (ESM) (Csikszentmihalyi and Larson, 1987; Delespaul, 1995). EMA (or ESM) is a method used to assess fluctuating psychological states such as mood, location, activities, thoughts and perceived stress in a subjects natural environment, contingent on an auditive signal (beep). The occurrence of the beep is programmed by the investigator. In the present study, the palm top computer was programmed to beep several times at semi-random intervals throughout the day. This method of data collection has several advantages of which the reduction of retrospective bias and the detection of small fluctuations of a subjects state are the most important (see Delespaul, 1995; Hanson, 2000 for an extensive review).

The diaries of the subjects from each profession had slightly different beep intervals and number of beeps. The diaries of the health professionals beeped six times a day and the diaries of the office clerks beeped ten times a day. For both professions the first beep could be expected after 20:00 h and the last beep before 22:30 h.

The subjects were instructed to complete the diary immediately after each beep by pressing an event maker button on the EGC-recorder. If the diary was not filled in directly after the beep, the subjects were prompted again after 15 min. Subjects were also given the possibility to skip 1 beep per day at their own convenience (sometimes beeps are inconvenient, e.g. during an important meeting). This option was expected to enhance compliance. Theoretically, a maximum of 568 beeps (6 beeps × 33 subjects) + (10 beeps × 37 subjects) could have been generated, however 472 beeps were generated, due to equipment failures (software and hardware) and the exclusion of beeps that occurred during equipment installation and recovery.

The EMA diary was used to measure momentary demand, satisfaction and negative mood. The diary contained three questions about the perceived demands: (1) 'Since the last beep I was interrupted a lot': yes/no); (2) 'Since the last beep I was under time pressure': yes/no); and (3) 'Since the last beep I experienced physical demands': yes/no). Two questions referred to perceived satisfaction: (1) 'Since the last beep my actions were worth the trouble': yes/no); and (2) 'Since the last beep my input was acknowledged': yes/no). For each item, the level of distress associated with it was obtained. Distress was rated on a scale running from 1 ('Not at all distressed') to 4 ('very distressed'). The scores for the total demand scale were obtained by summing the answers of the three items together with the scores on the yes/no items, leading to a minimum of three points and a maximum of 15. The scores for the total satisfaction scale were obtained by adding the answers of the two items together, leading to a minimum of two points and a maximum of 10. Finally, a score for the momentary demand-satisfaction ratio was obtained by dividing the scores on demand by the scores on satisfaction.

The subjects were asked to rate their momentary negative mood using four mood adjectives. The scores on negative mood (e.g. 'I feel sad') were obtained using a numerical scale (ranging from 1 ‘not at all’ to 7 “very much’). The items used to rate negative mood were a selection of 4 out of 5 variables used by Smyth et al. (9): sad, angry, unhappy and worried. The minimum score for negative mood was 4 and the maximum score was 28 (range = 24). In this study we found an internal consistency (Cronbach’s alpha) of 0.80, 0.76 and 0.85 for, respectively negative mood, demand and satisfaction. Positive mood was also determined by a numeric scale (1–7). The items were: happy, playful, energetic and pleased (internal consistency = 0.87).

2.3.4. Sleep quality

At 20:00 h the diary prompted the subjects to fill out a sleep quality questionnaire. This questionnaire, the Groningen Sleep Quality Scale (14 items), was used to measure subjective sleep quality during the preceding night (Meijman et al., 1990; Mulder-Hajonides and Van den Hoofdakker, 1990). The scale covers various complaints about sleep such as: sleep quality in the previous night, insufficient sleep, difficulty falling asleep etc. Higher scores on the scale indicate a lower sleep quality. A score between 2 and 4 is considered normal in a healthy population. The internal consistency (Cronbach’s alpha) was 0.85 on the first day and 0.87 on the second.

2.4. Continuous ambulatory measurements

Ambulatory data consisting of ECG R-top interval times (or ‘inter-beat-intervals’ (IBIs)) and an index of the subjects body movement, was collected using two recording devices. The VITAPORT-I system was used to collect data from the health professionals, and the VU-AMD was used to collect data from the office clerks.

2.4.1. VITAPORT-I

The VITAPORT-I is a portable event data recorder (8 × 13 × 3.2 cm and 300 g) capable of registering several external analogue signals at varying sampling frequencies (see Jain (1995) for an extensive description). For the present purpose only ECG R-top intervals (IBIs), vertical acceleration (movement) and an external marker signal were registered. Each signal is read through a separate channel, pre-processed and stored on a 1 Mb RAM card. Data pre-processing enables efficient storage of data.

IBIs were determined using a built-in R-top detection algorithm based on a principle described by Vary (1980). First the raw ECG was scanned at a frequency of 400 Hz, then after R-top detection, the inter-beat-interval times were stored at a frequency of 4 Hz. To measure ECG, three Ag/AgCl electrodes (AMI type 1650-005 Medtronic) were placed as follows: one electrode was placed 4 cm above the jugular notch of the sternum, the other was placed at the apex of the heart over the ninth rib, and the ground electrode placed above the right iliac crest.

Body movement was derived from a IC-3031 uni-axial 3 g Piezo-resistive accelerometer placed on the subjects leg (outer thigh). Vertical accelerations caused by a subject's walking were registered and identified as body movement. Null-acceleration (0 g, caused by a quiet leg in horizontal position) was identified as a subject sitting down. Vertical accelerations were scanned at 50 Hz and stored at a frequency of 2 Hz.

A subject was instructed to press an event marker button after palm top diary beeps. Events were scanned at 4 Hz and stored at 2 Hz.

2.4.2. VU-AMD

The VU-AMD (Free University-Ambulatory Monitoring Device) is a device ($3.2 \times 6.5 \times 12$ cm and 225 g) specifically designed to measure ECG, respiration, impedance cardiograms (ICG) and vertical acceleration allowing for R-top detection, derivation of pre-ejection periods and body movement (Geus and Doornen, 1996). In the present study the device was used to determine IBIs, body movement and occurrences of external events (palm top beeps).

To obtain R-top interval times, the bipolar ECG signal (see Section 2.4.1 for electrode placement) was relayed into a differential amplifier with 1 Mohm impedance and through a band pass filter of 17 Hz. R-tops were detected using a level detector with automatic adjustment (Thakor et al., 1983). To store R-top interval times, the device was switched to 'beat-to-beat' registration mode by pressing the event marker button. The temporal distance between all successive R-peaks (in ms) are then stored as IBIs in the internal RAM memory.

Body movement was derived from a built-in vertical accelerometer. The output of the accelerometer is amplified, rectified sampled and reset each 5 s. Motility values are determined by averaging these samples over periods of 30 s.

2.5. Data processing

2.5.1. Selection of beep periods

At each palm top beep, subjects had to fill in a diary from which positive mood, negative mood, demand and satisfaction was determined. The time of the beep (time of day) was automatically registered by the palm-top computer. Beeps are introduced as an event, around which a period was selected for the calculation of high frequency (HF_HRV) power of the spectral analysis of IBIs. The periods were determined based on the following criteria: (1) A minimum period length of 3.5 min was selected (to enable fast Fourier transform (spectral analysis), and decrease the risks of non-stationary signals; (2) these periods were maximally 15 min before or after the diary beep (at longer intervals, the relation of demand, satisfaction, mood and the cardiovascular variables, are expected to weaken, possibly leading to a bias); (3) subjects should be seated during the selected period. Pilot testing had shown that subjects sitting quietly in a chair had a vertical acceleration lower than 30 g/s (according to the VU-AMS) or between -0.05 and $+0.05$ g (according to VITAPORT-I). Short bursts of 30–50 g/s were allowed, since testing showed that slight shocks of an arm against the VU-AMD could cause a sudden short increase in motility values.

Finally, the selected periods were double checked with diary information ('Since the last beep I didn't walk and was seated (1) 10, (2) 20, (3) 30, (4) 40, or (5) 50 min before diary entry') to ensure that subjects were sitting down.

A total of 294 out of 428 periods (= 68.7%) met the above mentioned criteria. Most missing data was due to body movement or because they fell outside the 15 min interval before and after the beep. The missing values are randomly distributed throughout the day. It should be noted that the observations of HF_HRV in the evening are predominantly based on the office clerk subpopulation ($n = 37$).

2.5.2. Artefact correction

Incorrect R-top detection due to supraventricular extra systoles or extra triggers, may lead to too long or too short interval times. Using a software program, (CARSPAN, Mulder et al., 1993) these artefacts were detected and corrected. Artefact detection was carried out using a 50 s time window that was moved stepwise through the time series of IBI's. The detection algorithm was set to classify an IBI as a long or short interval if the IBI fell outside a range of mean IBI (over 50 s) ± 4 S.D. The detected artefacts were then visually inspected, and artefact type was confirmed. Where possible, long artefacts were automatically corrected by linear interpolation. Short artefacts were automatically corrected by adding them to the next IBI. Artefacts not corrected by the software program were manually corrected. Long intervals that fell within the range of mean IBI (over 50 s) ± 150 ms were not corrected because deviations this size may be considered local trend effects and as such will have no appreciable effect on the frequency spectrum (Mulder, 1988).

2.5.3. Calculation of HF_HRV

After artefact detection and correction, the R-top interval times were fed into the spectral analysis module of the CARSPAN software. This program uses a sparse discrete Fourier transformation (Rompelman, 1985) that can calculate a power frequency spectrum from 0.01 to 0.50 Hz. This method may be seen as a direct Fourier transform of heart rate data in the frequency domain, based on the so called Integral Pulse Frequency Modulator Model (IPFM; Hyndman and Mohn, 1975). According to this model, fluctuations in heart rate are caused by the continuous modulation of the sinus arrhythmic node. In this concept the modulation signal can be seen as a pulse frequency generator, rather than an interval generator. Thus, HF_HRV is seen as a frequency modulated signal rather than an interval modulated signal. The spectral values calculated by CARSPAN are normalised at the mean and expressed in dimensionless 'squared modulation index'-units (Dellen et al., 1985). Because of this transformation, the dependency between the spectral values and mean IBI is resolved (Mulder, 1988). For further analysis, the integrated power density spectra in the high frequency band (HF_HRV, 0.14–0.40 Hz) of each selected period was calculated. The resulting data is considered an index of variability as well as vagal autonomic control of the heart (Berntson et al., 1997).

2.6. Statistical analysis: random coefficient model

The data collected in the present study has a hierarchical structure. The variables that are measured several times a day (such as heart rate variability) are nested within subjects. Other variables such as sleep quality and trait negative affect (see Table 1 for the entire list) are measured only once and are referred to as units at a higher level or 'subject-level'. The variables measured several times a day are referred to as lower level units or 'beep level' measurements. The nesting of beep-level variables within the subject-level has important consequences. Beep-level measurements within a single subject tend to be more alike than beep-level measurements that are chosen at random from the entire population.

Jaccard and Wan (1993) describe some sources of bias, when ignoring data hierarchies: aggregation, averaging, sampling-error, and individual differences in the overall mean value of the dependent variable. According to these authors, an aggregation bias may occur when heterogeneous sub-units are combined into a single unit and the combined unit analysis yield conclusions that are misleading about the sub-units. Averaging causes bias because the richness of the data is lost. Effects may only be visible under certain circumstances (e.g. at home but not at work). By averaging, this diversity of information is lost. A sampling error may occur if the number of observations that are used to determine a specific effect is not taken into account. Some traditional approaches (e.g. a least squares approach) treat the data as if there were an equal number of observations for each level of the independent variables, and derive estimates of effects accordingly. Individual differ-

Table 1
Measurement levels and variables

Variable	Beep level (within-days)	Subject level (between subjects)
Time	*	
Momentary negative mood	*	
Momentary positive mood	*	
Momentary demand-satisfaction ratio (MD-SR)	*	
Momentary demand	*	
Momentary satisfaction	*	
High frequency heart rate variability (HF_HRV)	*	
Sleep quality		*
Smoking		*
Gender		*
Profession		*
Negative affect		*
Effort		*
Reward		*
Effort-reward imbalance (ERI)		*
Need for control		*

ences in the overall mean value of the dependent variable may inflate error terms and reduce the power of the statistical tests. Strategies used to avoid this problem like centering or stacked subject approaches introduce other problems (e.g. aggregation bias, or incorrect adjustment for the error degrees of freedom).

The existence of such data hierarchies cannot be ignored when searching for the determinants of heart rate variability. Measurements of heart rate variability at a specific time of day or after a specific event (e.g. just after waking up, or the occurrence of a stressful event) are more similar to each other than measurements later in the day. Thus time of day or the occurrence of a stressful event (both beep level variables) should be tested as potential determinants of heart rate variability. In other cases, effects on heart rate variability may arise for reasons less strongly associated with the characteristics of day. For example, the characteristics of the subjects such as the perception of high effort and low reward (or need for control) may also affect heart rate variability. Thus determinants of heart rate variability can be found at two levels, the within-day (or beep) level and the subject-level. In specific cases, there may even be an interaction between subject-level variables and within-day variables. For example, because a high effort–reward imbalance is associated with high work stress, subjects with a high ERI may encounter more stressful events throughout the day. Ignoring the potential existence of relationships at the subject-level or the within-day level (or an interaction between the two) increases the risk of overlooking the importance of psychological traits, time of day effects or the occurrence of important events. This may render invalid many of the traditional statistical analysis techniques used for studying and exposing embedded data relationships (e.g. time series, structural equations, event history analysis, and repeated measures analysis of variance).

Researchers have long recognised the so-called ‘unit of analysis’ problem (i.e. ignoring hierarchical structures), and the introduction of bias using common analytic strategies. However, they were difficult to solve because powerful general-purpose tools were unavailable. Special purpose software, for example for the analysis of genetic data, has been available longer but this was restricted to ‘variance components’ models and was not suitable for handling general linear models. Several authors have tackled the software issue using a random coefficient model or multilevel analysis (Bryk and Raudenbusch, 1992; Goldstein, 1995), rather than a traditional method (such as analysis of variance or regression analysis). In addition to preventing the above mentioned biases, a random coefficient model also adequately addresses problems caused by varying time points in time and missing cases.

In the present study, we tested the adequacy of distinguishing two levels of analysis (the beep and subject level) by determining whether enough variance of HF_HRV was present at each level. This is achieved by testing an ‘empty model’ (i.e. without any explanatory variables included), referred to as model 1. Using a model that distinguishes two levels, the effects of time of day (model 2) and the remaining beep level variables on HF_HRV were tested (model 3). Finally, possible interaction effects were tested (model 4). The following interactions were of interest: ERI × need for control, effort × time[1], reward × time, and ERI × time. For reasons of simplicity, only the significant effects are shown in the table (Table 2).

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[1] The interactions with $time^2$ and $time^3$ were also determined (see Section 3).

Table 2
Mean, standard deviation (SD), range and Standard Error of mean (SE Mean) for the Momentary Demand-Satisfaction Ratio (MD-SR), Effort-Reward Imbalance (ERI), need for control, trait negative affect, momentary negative mood, and sleep quality

	N		Mean	SD	Range		SE Mean	Percentiles		
	Valid	Missing			Valid	Observed		25	50	75
Momentary negative mood	428	44	6.64	3.67	4–28	4–23	0.18	4.0	5.0	8.0
Momentary positive mood	428	44	18.91	4.91	4–28	4–28	0.24	16.0	20.0	23.0
Momentary demand-satisfaction ratio (MD-SR)	421	51	2.45	1.48	0.2–7.5	0.38–7.5	0.07	1.5	2.5	3.5
Momentary demand	423	49	5.57	2.67	3–15	3–15	0.13	3.0	5.0	7.0
Momentary satisfaction	426	46	2.75	1.39	2–10	2–8	0.06	2.0	2.0	4.0
Sleep quality	63	7	3.59	2.74	0–14	0–13	0.43	1.0	3.0	5.0
Negative affect	70	0	3.30	3.08	0–21	0–11	0.40	1.0	2.0	5.0
Effort	70	0	10.18	2.58	6–24	6–16	0.34	8.0	10.0	12.0
Reward	70	0	42.05	5.37	12–48	24–48	0.70	40.0	43.0	45.0
Status control	70	0	20.81	3.36	6–24	12–24	0.44	18.0	22.0	24.0
Esteem reward	70	0	17.58	2.36	5–20	10–20	0.31	17.0	18.0	19.0
Monetary gratification	70	0	3.49	0.86	1–4	1–4	0.11	3.0	3.0	4.0
Effort-Reward Imbalance (ERI)	70	0	0.50	0.16	0.25–4	0.25–1.0	0.02	0.38	0.47	0.61
Need for control	70	0	3.65	3.50	0–9	0–9	0.46	1.0	3.0	7.0

All estimates of the regression coefficients were obtained using the program MLn (Woodhouse et al., 1996). The significance of the fixed effects was determined by dividing the estimate by its standard error, and the significance of the covariances and variances were determined by the likelihood ratio test (Bryk and Raudenbusch, 1992).

3. Results

3.1. Descriptive statistics

Mean, Standard Error of Mean (S.E. Mean) and their quartile scores can be found in Table 2. Mean and S.E. Mean for within-day variables derived by aggregating the scores at each beep over subjects and days. The mean effort–reward Imbalance (ERI) ratio (0.50) shows that the present sample was not highly stressed. The average ERI score of a normal working population is 0.54 (derived from Hanson et al., 2000b). According to a criterion provided by the theory, only subjects with an ERI ratio lower than one are at risk of developing cardiovascular disease. The average sleep quality is 3.59, which is normal for a healthy working population.

In the present study, a total of 472 beeps were generated, of which 428 were answered for the items positive and negative mood (eight diaries were skipped by the user, 27 were forgotten, and nine were invalid), leading to a compliance rate of 90.7%. The valid cases and missing values for the other variables are given in Table 2.

3.2. Testing the adequacy of a 2-level model (model 1)

First, a logarithmic transformation was performed on HF_HRV (Ln HF_HRV) data to correct for skewness. This transformation resulted in a normally distributed HF_HRV curve throughout the day (skewness $= -0.37$, min $= 9.50$, max $= 15.99$). Then, the amount of variance at each level (the beep level and subject level) was assessed, by constructing an intercept only model (model 1, Table 3). The intra-level-2 correlation (Goldstein, 1995) shows that 60% $(0.876/(0.583+0.876))$ of the variance is at the subject level and 40% $(0.583/(0.583+0.876)$ at the beep level. The amount of variance at each level is significant, justifying a 2-level model. The results show that the differences between subjects are larger than the differences within the day (60:40%). However, the variance within-days is still quite large.

3.3. Time of day effects (model 2) on HF_HRV

The effect of time of day on HF_HRV was assessed (model 2) estimating a curve to reflect the changes in HF_HRV throughout the day. To achieve this three time variables were calculated: 'time' 'time^{2}' and 'time^{3}' and entered in the model (model 2). All time variables had a significant effect on HF_HRV. As is shown in Table 2 (model 2), the HF_HRV curve can be described by a third degree polynomial.

Table 3
Fixed and random effects on Ln HF_HRV[a]

Fixed effects	Estimate+(S.E.)			
	Model 1[b]	Model 2[c]	Model 3[d]	Model 4[e]
Intercept	12.780 (0.158) *	12.360 (0.367) *	12.860 (0.380) *	13.750 (0.617) *
Time		0.383 (0.189) *	0.419 (0.188) *	0.257 (0.192).
Time^2		−0.074 (0.030) *	−0.079 (0.030) *	−0.071 (0.030) *
Time^3		0.004 (0.001) *	0.004 (0.001) *	0.004 (0.001) *
Need for control			−0.163 (0.045) *	−0.161 (0.045) *
ERI				−1.615 (0.948).
ERI × Time				0.227 (0.080) *
Random effects	Variance			
Subject level				
Var (intercept)	0.876	0.937	0.696	0.695
Beep level				
Var (intercept)	0.583	0.543	0.539	0.512
Δ deviance	–	−8.28	−11.69	−8.01

[a] For all models: n beeps = 294, 70 subjects.

* $P<0.05$. The deviance of each model with respect to the previous model was calculated (Δ deviance).

[b] Model 1, An intercept only model, for estimating variance at the subject and beep levels.

[c] Model 2, The fixed and random effects of time of day ('time', 'time^2', 'time^3') on HF_HRV were assessed. Only the fixed effects were significant.

[d] Model 3, The fixed and random effects of all variables on HF_HRV were tested. Only the fixed effects of 'time', 'time^2', 'time^3' (in hours after 8.00 a.m.) and 'need for control' were significant. When tested separately, the effect of 'profession' was also significant, this effect disappeared when all variables were tested simultaneously.

[e] Model 4, The fixed effects of two interaction variables on HF_HRV were tested separately: 'effort-reward imbalance × need for control', and 'effort–reward imbalance × time'. Only the latter interaction effect was significant.

$$\text{Estimated HF\_HRV} = 12.36 + (0.383 \times \text{time}) + (-0.074 \times \text{time}^2) + (0.004 \times \text{time}^3).$$

The fit of a higher degree polynomials (fourth etc.) was not significantly better than the fit of the third degree polynomial, therefore it was concluded that the HF_HRV changes throughout the day are best described by a third degree polynomial. Both the observed and the estimated HF_HRV values are plotted in Fig. 1. The estimated values closely follow the observed values, although the 'after lunch dip' (at ± 1.20 p.m.) in the observed values was not reflected by the estimated values. The decrease in variance (Δ0.040) at the beep level shows that the time of day effect explains 7% of the variance (0.040/0.583).

A random term for each time variable (time, time^2 and time^3) was introduced into the model, to test whether there were differences between subjects regarding the effect of time of day. None of the effects of the random terms were significant, indicating no time of day differences between subjects.

3.4. Effects of remaining explanatory variables on HF_HRV (model 3)

The fixed and random effects of the following beep level variables on HF_HRV were tested: negative mood, positive mood, the actual demand–satisfaction ratio, demand and satisfaction. None of these effects were significant. The effects of the following subject level variables were also tested: sleep quality, smoking, gender, profession, negative affectivity, effort, reward, need for control, and ERI. When tested separately, both profession and need for control had a significant negative effect on HF_HRV (estimate = − 0.966, S.E. = 0.329; estimate = − 0.163, S.E. = 0.045, respectively). More specifically, the HF_HRV of the health professionals was 0.966 lower than the HF_HRV of office clerks. An increase in need for control by 1 unit (minimal score = 1, maximal score = 9) is associated with a decrease in HF_HRV of 0.163. When tested simultaneously, only the effect of need for control remained significant (see Table 2, model 3). An increase in need for control mood by 1 unit (e.g. from 4 to 5 on a scale ranging from 0 to 9) is associated with a 0.163 HF_HRV decrease (see model 4, Table 3). The average need for control is 3.65, thus the HF_HRV decrease associated with need for control is 0.60. The averaged HF_HRV is 12.75 (Ln power in arbitrary units). Thus, need for control is associated with is a 4.7% HF_HRV decrease below the average HF_HRV. For

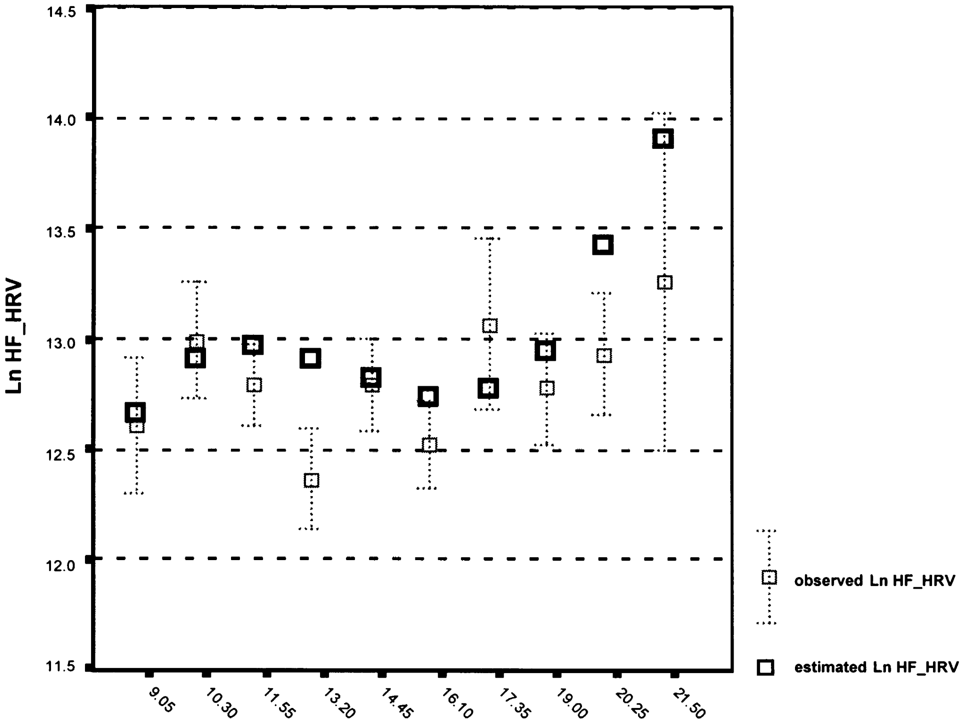

Fig. 1. Estimated and observed Ln HF_HRV throughout the day.

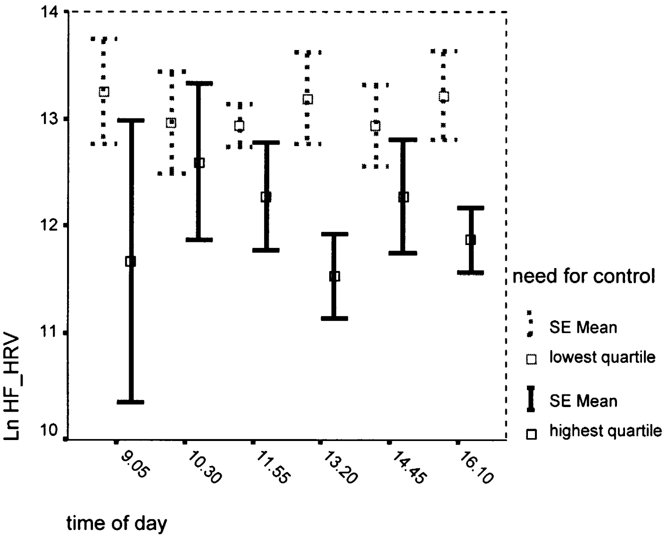

Fig. 2. HF_HRV throughout the day for the first and fourth quartiles of need for control.

illustrative purposes, the means and S.E. Mean calculated within-days for the highest and lowest quartile of need for control are given in Fig. 2. The figure only includes the observations from 9.05 a.m. to 4.10 p.m. since the scores in the evening are predominantly based on the office clerk subpopulation.

3.5. Testing for interaction effects (model 4)

Finally, the following interaction effects on HF_HRV were tested: (1) between ERI and need for control; (2) between effort and time; (3) between reward and time; and (4) between ERI and time. The interaction between effort and time[1] was significant, indicating that a 1 unit increase in 'ERI × time' is associated with a 0.227 HF_HRV increase. Adding the interaction effect to the model, the total model explains 21% variance at the subject level ((0.876–0.695)/0.876) (see Table 2 model 4).

4. Discussion

Most importantly, we found that a higher need for control is associated with lower HF_HRV. According to the effort–reward imbalance theory, a high effort–reward imbalance is associated with vigorous striving and an increased 'autonomic activation', an effect supposedly enhanced by need for control. In the present study, we found support for one aspect of this hypothesis: a higher need for control is associated with more vagal withdrawal. As lower heart rate variability (indicating a lower vagal tone) is associated with cardiac events (Liao et al., 1997) and other negative health outcomes (Stansfeld et al., 1998), subjects high in need of control in the long run might be more at risk. The present data indeed show that in these subjects low vagal control is constantly present, at least during waking hours. Extending this type of recordings through the night and more elaborated assessment of cardiac functioning or subclinical cardiac events such as transient ischemia, will further illuminate in how far this pervasive effort spending coping style compromises cardiovascular status.

In contrast to the expectations, effort, reward, ERI, demand, and satisfaction, did not have significant fixed or random effects on HF_HRV. This suggests that the 'simple' effects of neither perception of the work environment nor the actual experience of demand or satisfaction were associated with HF_HRV. This also applies to effort–reward imbalance, although such an association is a central assumption in the theory of Siegrist. Still, HF_HRV, at specific times of the day, is affected by effort–reward imbalance: subjects high in effort–reward imbalance have a higher vagal tone later in the day. Because a higher vagal tone is associated with lower mental effort, we interpret that later in the day, these subjects spend less mental effort to perform their duties. In the Section 1 this was referred to as disengagement or change to less effort demanding strategies. In other terms: subjectively experienced effort–reward imbalance seems to be accompanied by less investments in terms of mental effort as the day progresses, at least as reflected by vagal status. Analysing cardiovascular concomitants may clarify (the costs of) the dynamic interaction of motivational drives and environmental demands. Future research should expand on this, introducing more detailed assessment of mental effort, related subjective motivational states and performance measures.

As previously discussed, the imbalance between effort and reward was only reflected in the diurnal curve of HF_HRV, suggesting a disengagement from the work demands later in the day. No main effect of ERI could be found, possibly caused by under sampling. Table 2 shows that the S.E. Mean of effort–reward Imbalance is low (0.02), indicating low variance. This is mainly due to reward which has a potential range of 12–48, whilst only 24-48 is observed. This affects the ERI ratio, that does not exceed the value 1, although in theory the value 4 can be obtained (see Table 2). The low observed variance may be a result of a rewarding work environment (i.e. the population may not be excessively stressed) leading to high reward scores, or the result of an insensitive ERI questionnaire. Interviews and observations prior to the research indicated that the population did experience high work demands, and could be considered stressed. The validity and reliability of the ERI questionnaire was tested elsewhere (Hanson et al., 2000a). The mean values and standard deviations of the reward subscales in the present study, are comparable to those reported in a larger population ($n = 770$). This increases the confidence in the scales used to measure effort and reward. To further address the issue of under sampling, future studies should include subjects with low reward scores to enable generalizability of the conclusion (that ERI is not associated with cardiovascular changes) to a larger population. Some evidence for this was given in a study performed by (Vrijkotte et al., 1999). They found that not ERI, but need for control was associated with metabolic and hemostatic cardiovascular functioning, which is similar to our observation.

It is conceivable that with progressing age or stress, the mental effort disengagement will not suffice to prevent deleterious effects of perceived disharmony between give and get. Although the interaction 'effort–reward imbalance × need for control' was not significant in this study, the combination with a high need of control in the long run may make people especially vulnerable to the negative health effects of a low vagal tone. It is intriguing to link these observations and speculations to the risk factors and the development of burnout: highly striving individuals finally not fulfilling their aspirations (Schaufeli and Buunck, 1996). The similarity of 'exhaustion', the primary component of burnout to 'vital exhaustion' as related to myocardial infarction (Goodkin and Appels, 1997) may turn out to be less than superficial.

To date, relatively little is known about the relationship between autonomic cardiac control and mood. Sloan et al. (Sloan et al., 1994) combined a number of items reflecting negative mood (unhappy, irritable, tense and pressured), and assessed it's relation with cardiac control. This variable (which they referred to as 'stress') was related to a higher LF/HF_HRV ratio (an index of increased sympathetic predominance in cardiac sympathovagal balance). In contrast to these results, the present study shows that neither negative nor positive mood are related to HF_HRV. A possible explanation for this finding is that in natural settings, HF_HRV may be subject to control by other factors (such as physical activities) that override the influence of mood, although HF_HRV was only determined when the subject was seated for at least 5 min, to minimise the effects of physical activity. However, the influence of previous intensive physical activity (e.g. especially if the effects last longer than 5 min) can not be totally ruled out. Another possible explanation for the absence of a relationship between mood and autonomic activity may be provided by the actual items used to reflect mood. The mood variable used by Sloan et al. did not solely consist of mood items, but also contained items reflecting time pressure and tension. This suggests that the interaction between pressure, tension and negative mood items may affect autonomic activity rather than mood per se. Future studies should continue these efforts to identify the exact items related to autonomic cardiac function. This can be achieved by assessing the effects of a wider range of variables. For example, a study performed by Schwartz et al., (1994) has shown that anger increases ambulatory blood pressure and that feelings of being rushed increases ambulatory heart rate. It should be tested if these variables also affect HF_HRV as is also suggested by Brosschot and Thayer (1998).

This study has focused on effects of effort and reward on the HF_HRV band, for reasons explained in the Section 1. Findings with other work related variables and a different choice of dependent measures should be attended to as well. For instance Meijman (1997) has shown that the power in the middle frequency range of heart rate (0.07–0.14 Hz) is associated with mental effort as well as fatigue. Future studies, could very well include these variables and, for instance, identify how time of day and fatigue may affect heart rate variability.

The primary aim of this study was the effect of work related factors on HF_HRV. However, interesting spin-off for the general field of psychobiology should be mentioned as well. Confirming and expanding on the findings of Malliani et al., 1991), the ambulatory measurements of HF_HRV in the present study are affected by the time of the day. The graphical representation of HF_HRV (see Fig. 1) shows that HF_HRV is low in the morning (9:00 h), and in the afternoon (13:00–16:00 h) and increases towards the end of the evening (21:30 h). As HF_HRV reflects parasympathetic cardiac control, we see two peaks in vagal withdrawal throughout the day: in the morning (at the beginning of the workday), and after lunch. The increase in vagal activity towards the end of the evening may reflect decreasing demands and/or the occurrence of recovery processes. Conclusions about observations in the evening (after 16:10 h) should be drawn with some caution, since they are predominantly based on data derived from the office clerk subpopulation. Factors such as gender and smoking did not have a significant effect on ambulatory HF_HRV.

5. Conclusions

The importance of ongoing psychophysiological measurements is now gaining recognition (Hockey, 1997). The relationships between patterns of work strain and their consequences for the individual are essentially dynamic, requiring dynamic assessments and analyses to reflect these processes. In the present study, the variance in ambulatory HF_HRV could partly be explained by variables at the beep (time of day) and the subject level (need for control) as well as by interaction of time of the day and subjects' characteristics (ERI × time). This strongly points to the necessity to add ambulatory assessments to the more traditional trait like approaches in order to understand the dynamic psychobiological adaptation or maladaptation (vagal cardiac regulation) to the work environment while actually at work. The present study also proved the feasibility of this approach, without noticeable disturbance of the ongoing work assignments or of the work environment.

The amount of explained variance may not be overwhelming (model 4 explains 21% at beep level i.e. some 12% of total variance). However, in contrast to other, momentary effects under artificial conditions (e.g. laboratory) reported in the literature, the effects in this study are present during prolonged periods of time and in a natural setting, enhancing potential clinical relevance.

The negative impact of 'need for control' — considered as a generalised coping strategy — invites to envisage the usefulness of interventions. Intervention programs for burnout (see Schaufeli and Enzmann, 1998) include an evaluation of, and adaptive changes in the way people cope with job demands. The intended accompanying positive changes in autonomic drive directly affect 'the heart of the matter'.

Finally, the results of this study point to the challenging issue of 'chronopsychobiological' effects: changes in biological regulation over the day are influenced by individual psychological differences, in the present case by a perceived imbalance between give and get in the work situation. Taken together, we consider that the present results add to the understanding of mechanisms by which work related factors may in the long-term contribute to cardiovascular health or disease.

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