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Journal of Psychosomatic Research 69 (2010) 151 – 159

Journal of Psychosomatic Research

# The fruits of ones labor: Effort–reward imbalance but not job strain is related to heart rate variability across the day in 35–44-year-old workers☆

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Received 7 November 2008; received in revised form 25 February 2010; accepted 2 March 2010

## Abstract

**Objective:** Previous research has suggested that the association between work stress and heart disease is more pronounced in young than in old employees. Similar age specificity may apply to the relation between work stress and heart rate variability (HRV), but data on this issue is sparse. We aimed to assess the age-specificity of the work stress-HRV association in greater detail. **Methods:** We used cross-sectional data from an occupational cohort ($n$=591) from Germany. Work stress was assessed using the job content and the effort-reward-imbalance (ERI) questionnaires. HRV was recorded over 24 h and was divided into three periods of the day (work time, leisure time, sleep time). Partial correlation coefficients (PCCs) were calculated for four age groups (17–34, 35–44, 45–54, and 55–65 years). Further, multilevel growth curve models (GCM) were run to examine whether age may modify potential work stress-HRV associations in a non-linear fashion. **Results:** Job strain and HRV were unrelated in either analytical approach and this association was not modified by age. In contrast, using PCCs ERI was only related to HRV during work (PCC=−0.231, $P$<.01) and leisure time (PCC=−0.195, $P$<.05) in employees aged 35–44. Multilevel GCM models confirmed this finding. **Conclusion:** The inverse association between work stress as measured by ERI and HRV appears to be most pronounced in workers aged 35–44. These findings may partly be explained by age-dependent HRV declines, age-related differences in career attitudes or increased susceptibility among those aged 35–44 due to facing multiple different stressors at the same time.


*Keywords:* Age-specificity; Heart rate variability; Stress; Workload; Workplace

## Introduction

An extensive body of evidence suggests that stressful work conditions are a risk factor for cardiovascular disease (CVD) and cardiovascular mortality [1,2]. The association between work stress and CVD could in part be mediated by a reduced vagal tone [3,4]. Heart rate variability (HRV) is considered a proxy measure of vagal activity and represents one of the core parameters to characterize individuals' physiological stress responses.

A number of occupational observational studies have examined stressful work characteristics in relation to HRV. Some of these studies reported the expected inverse association between work stress and HRV [4–6], but others did not [7,8]. A recent Finnish study found that work stress might be associated with a lowered HRV in women, but not in men [9].

One factor that may account for the inconsistency in the literature is the operationalization of work stress. There are

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0022-3999/10/$ – see front matter 
doi:10.1016/j.jpsychores.2010.03.004

two predominant models of work stress. One, developed by Karasek et al., is a task-level control model based on the idea of job demands and job control [10]. Job demands refer to the quantity of work and the associated time demands as well as the mental demands of the work. Job control refers to decision latitude, and the possibility of creativity and growth associated with the work. The other model, developed by Siegrist [11], by adding a more personal component, places work in a broader sociological context and is based on the balance between efforts and rewards. Thus, the stressful aspects of work captured by these two models are different and these two models are thought to be complementary [12]. To our knowledge, very few if any studies have examined these two models simultaneously with respect to physiological mechanisms.

In addition, it is of major interest to identify occupational sub groups that are particularly likely to show reduced HRV in response to mental work site stressors. Members of such vulnerable groups might be at increased risk of coronary heart disease [13,14] and might benefit from appropriate primary prevention resources. It has been observed that the association between occupational stress and heart disease is more pronounced in younger than in older employees [6,15]. Accordingly, it might be expected that similar age specificity applies to the association between psychosocial work stress and HRV. To our best knowledge, data on this issue from occupational cohorts is very limited [6]. In previous studies on work stress and CVD, younger employees were defined as aged below 50 or below 55 years [6,15]. The working population aged below 50 might, however, be very heterogeneous with regard to career goals and aspirations and with regard to their selection due to health (e.g., workers aged 49 are more likely to quit work for health reasons than apprentices aged 15). Such heterogeneity warrants examining the association between work stress and HRV as a function of age in greater detail.

Recent findings from our study group support the notion of age-specific associations between work stress and physiological outcomes [16]: We found that work stress was a powerful predictor of progenitor cell counts only in those aged >36–46 years. No associations were however found in those aged 18–≤36 years or in those aged >46 years [16]. These results suggest that age may modify the relationship between work stress and physiological outcomes in a nonlinear fashion. The same may hold true for the association between work stress and HRV. Thus, we hypothesize that the association between work stress and HRV is affected by age in a curve-linear fashion with the most pronounced association being possibly observed in middle-age adults.

Applying both the demand-control model and the effort-reward-imbalance (ERI) model as measures of work stress, we aimed to examine the age-specificity of the association between work stress and HRV. We specifically aimed to be able to detect non-linearity of the work stress-HRV association across age using advanced statistical modeling techniques.

## Methods

### *Study population*

The study population consisted of employees from an airplane manufacturer located at multiple manufacturing sites in Southern Germany. This occupational cohort was initiated in 2000 with additional recruitment and follow-up in 2002, 2003/2004 and 2007. For this analysis, we used cross-sectional data from September 2003 and February 2004, because HRV data was available only for the sample recruited during this period of time. In 2003/2004, questionnaire data were collected on psychosocial stress and medical examinations were carried out.

This study was based on an open cohort approach meaning that follow-up assessments were not limited to the baseline population of 2000, but that this cohort was replenished with additional participants or volunteering employees at follow-up that had not participated at baseline. A total of 657 individuals participated in medical examinations in 2003/2004 including a 24-h electrocardiogram (ECG) recording. We excluded individuals from this analysis if they had missing 24-h HRV data or other ECG recording failures. The final sample comprised 520 men and 71 women. The study was approved by the institutional review board. All participants gave written informed consent.

### *Measurements*

#### *Psychosocial work stress*

We employed two scales to assess psychosocial work conditions. First, we used a 16-item German translation of the job content questionnaire by Karasek et al. [17], which measures job demands and job control with eight items each. Job strain was operationalized as the job demands sum score divided by the job control sum score. The second scale was the 17-item effort–reward imbalance questionnaire [11], which assesses effort by six items and reward by eleven items. The sum scores of the effort and reward scales can be combined into an effort-reward imbalance ratio (ERI) by using a correction factor that accounts for the uneven numbers of items [11]. We used the following equation: ERI ratio=sum score effort scale/(sum score reward scale*6/11). The Pearson correlation coefficient for the job strain score and the ERI score was 0.48 ($P$<.01).

#### *Heart rate variability*

HRV was recorded as beat-to-beat intervals using a Mini-Vitaport ECG logger (Becker Medical Systems, Karlsruhe, Germany), sampling at a rate of 400 Hz. Study participants were instrumented with the ambulatory ECG recorders between 9 and 12 a.m. until the next morning. After instrumentation with the ambulatory ECG recorder, individuals proceeded with their daily work until 3:30 p.m. and then continued with their usual leisure and sleep activities. The next morning between 7:15 and 8:00 a.m., the ECG monitors were disconnected. Raw ECG data were processed according to the Task Force Guidelines [18]. Beat-to-beat intervals were calculated as the time between successive R-spikes. Beat-to-beat intervals that corresponded to a heart rate below 30 or above 200 as well as interbeat changes of over 30% were excluded. The root mean square of successive differences (RMSSD), which is considered a time-domain based index corresponding to parasympathetic neural regulation of the heart, was used as HRV measure. The RMSSD is less affected by breathing and is therefore a suitable outcome measure in ambulatory studies [19].

In order to investigate the association between psychosocial work conditions and HRV in greater detail, the 24-h recording period was subdivided into the following three broad periods of the day: work time, leisure time and sleep time. Work time was operationalized as 8 a.m. to 3:30 p.m. Leisure time was defined as the time between 4 pm and the self-reported time of going to bed. Sleep time was defined as the interval from 30 min after self-reported going to bed until 30 min prior to awakening. Sleep time was further verified from the ECG loggers inbuilt accelerometer.

### *Statistical analyses*

We adopted a two-stage analytical strategy. As a first step, we estimated correlation coefficients for the association between work stress measures and HRV measured over the course of the day stratified by age categories. Such correlation measures estimated for different age categories provide rather intuitive evidence of assumable shifts in the work stress-HRV relation over the workday and across the age span. The categorization of age groups was based on German labor market regulations: the earliest age of apprenticeship in Germany is 15 years and the statutory retirement age was 65 years in 2003/2004. This age span was initially divided in five equally wide age categories, that is, 15–24, 25–34, 35–44, 45–54, and 55–65 years. As the youngest worker included in the study was aged 17, the youngest age group was labeled 17–24 years. Furthermore, as this youngest age group comprised few individuals ($n$=55), it was collapsed with the neighboring category resulting in the following strata: 17–34 ($n$=159), 35–44 ($n$=158), 45–54 ($n$=183), and 55–65 years ($n$=81). The partial correlation coefficients (PCCs) were controlled for the following variables due to potential or documented associations with HRV and work stress: sex, physical activity per kilogram of body weight (continuous), number of cigarettes smoked (continuous), alcohol consumption (g/day, continuous), sleep quality (a continuous score based on a translation of the 4-item Jenkins sleep quality scales [20]), position (senior manager, foremen, qualified workers, unskilled workers, trainees). Furthermore, the PCCs for job strain score were controlled for ERI scores and those for ERI scores were controlled for job strain scores.

In the second analytical step we adopted a more in-depth statistical approach and ran hierarchical linear (multilevel) regression analysis [21]. In repeated measures designs, such as inherent in the HRV data used in our study, the multilevel structure is given by repeated observations nested within the individual. Multilevel analyses are able to decompose the sample variance of repeated-measures of HRV at work time, leisure time and sleep time into components of interindividual variation of HRV levels and intraindividual change of HRV across the workday. This statistical approach was chosen to estimate the work stress effect on the workday fluctuation of HRV levels. Following this rationale, we modeled the intraindividual workday fluctuation in terms of the daily drop in HRV during work and leisure time compared with sleep time. Sleep time HRV served as “baseline measurement” and was thus conceptualized to reflect the individual’s HRV level when the organism is at rest and under minimal exposure to work stressors. Further, we modeled curvilinear effects of age (used as continuous variable) as a predictor of level and change in HRV and as a modifier of work stress effects. Doing so, we ran conventional linear growth curve models (GCM) [22]. The estimated GCM slope can be interpreted as the individual rate of HRV drop across the day relative to the sleep time (see Appendix 1 for details). The GCM employs the work stress measure (ERI or job strain) and age (age and age-squared) as between-subject predictors, both centered to the respective sample mean. Further, the same confounders were included as in the PCC computations. All two- and three-way interactions between the work stress predictors, age (age and age-squared), and time of HRV measurement were included in the model: the work stress×slope interaction indicates the impact of work stress on daily HRV drop while the age×slope interaction indicates age effects on daily HRV drop. The interaction term “work stress×age” reflects to what extent age modifies a potential work stress impact on sleeptime HRV. Finally, the age×work stress×slope interaction indicated the modifying effect of age on the work stress effects on daily HRV drop. Multilevel analyses were conducted using SAS version 9.1. (SAS Institute, Cary, NC, USA) (proc mixed with the restricted maximum likelihood estimation algorithm).

## Results

Table 1 provides the characteristics of the study population stratified by the four age groups. The study population was predominately male. The proportion of women was considerably higher in the youngest age group than in the other age categories. Most employees were categorized as qualified workers and the position in the company generally increased with increasing age. Except for smoking rates, which were highest in the youngest workers and declined with age, the youngest workers appeared to have more favorable health profiles than all older workers: about one third of the youngest employees and roughly half of all older workers reported moderate to high alcohol

Table 1
Characteristics of the study population stratified by age ($n$=581)

| Characteristics | Age groups (years) 17–34 | 35–44 | 45–54 | 55–65 |
|---|---|---|---|---|
| *n* | 159 | 158 | 183 | 81 |
| Age, mean (S.D.) | 26.34 (4.98) | 39.87 (3.08) | 49.67 (2.87) | 56.49 (1.9) |
| Sex, *n* (%) | | | | |
| Male | 123 (77.4) | 144 (91.1) | 170 (92.9) | 75 (92.6) |
| Female | 36 (22.6) | 14 (8.9) | 13 (7.1) | 6 (7.4) |
| Position, *n* (%) | | | | |
| Senior manager | 0 | 6 (3.8) | 9 (4.9) | 8 (9.9) |
| Foremen | 6 (3.8) | 25 (15.8) | 26 (14.2) | 15 (18.5) |
| Qualified workers | 126 (79.2) | 124 (78.5) | 142 (77.6) | 54 (66.7) |
| Unskilled workers | 4 (2.5) | 2 (1.3) | 3 (1.6) | 4 (4.9) |
| Trainees | 22 (13.8) | 1 (0.6) | 0 | 0 |
| Smoking, *n* (%) | | | | |
| No | 106 (66.7) | 110 (69.6) | 139 (76.0) | 69 (85.2) |
| Yes | 53 (33.3) | 48 (30.4) | 40 (21.9) | 12 (14.8) |
| Self reported alcohol intake [a], *n* (%) | | | | |
| Abstinent or low | 110 (69.2) | 78 (49.4) | 72 (39.3) | 35 (43.2) |
| Moderate to high | 49 (30.8) | 79 (50.0) | 105 (57.4) | 43 (53.1) |
| Estimated physical activity per kg body weight [b], mean (S.D.) | 4.80 (4.35) | 3.76 (5.55) | 3.89 (3.88) | 4.08 (8.26) |
| Jenkins's sleep quality index [c], mean (S.D.) | 4.96 (3.54) | 5.57 (4.35) | 5.98 (4.17) | 5.81 (4.47) |
| RMSSD [d] during work time, mean (S.D.) | 37.92 (14.52) | 36.37 (13.71) | 33.77 (13.21) | 31.47 (12.75) |
| RMSSD during leisure time, mean (S.D.) | 41.94 (16.13) | 35.94 (13.18) | 33.37 (13.00) | 30.99 (12.22) |
| RMSSD during sleep time, mean (S.D.) | 60.51 (26.00) | 46.07 (18.80) | 36.80 (16.60) | 35.56 (16.98) |

Due to missing values numbers per column might not add up to 159, 158, 183 and 81, respectively.

[a] Alcohol intake was classified below (abstinent or low) or above (moderate to high) based on the median split (11.2 g/day).

[b] Calculated as metabolic equivalents, estimated from self-reported activities.

[c] Four-item scale with a possible range from 4 to 24 points. Higher scores indicate poorer sleep quality.

[d] RMSSD = root square differences of successive heart beats in milliseconds.

consumption. Likewise, levels of physical activity were highest and sleep quality was best in the youngest workers and similar in all older groups.

The RMSSD declined with age during all periods of the day (see Table 1 and Fig. 1). This was particularly true for the RMSSD during sleep, which decreased significantly

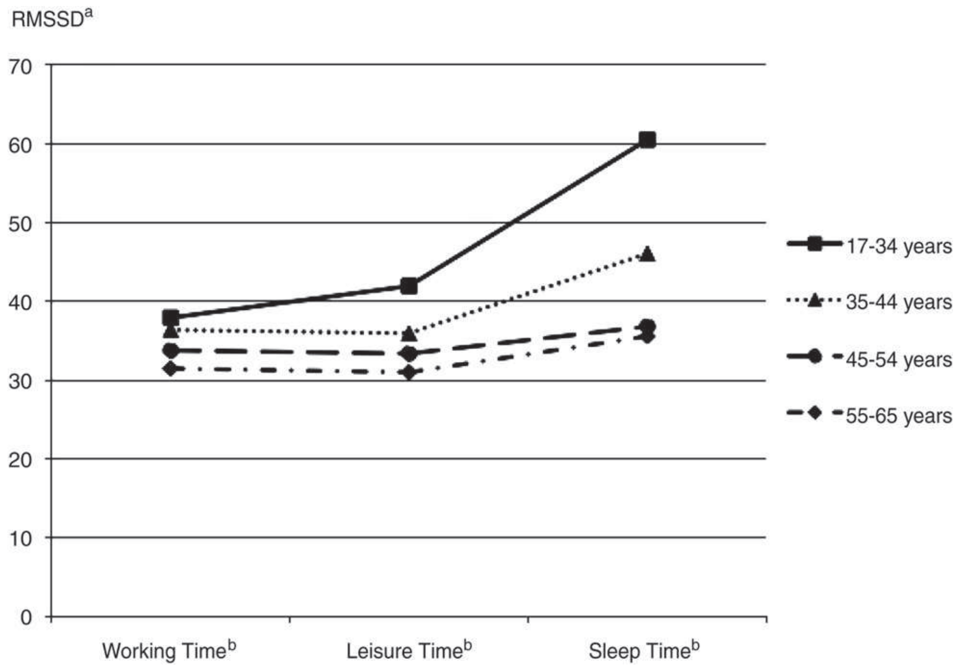


Fig. 1. Mean RMSSD by period of the day and age group. [a]RMSSD=root square differences of successive heart beats in milliseconds. [b]Work time=8 a.m.–3:30 p.m.; leisure time=4 p.m. until self-reported time of going to bed; sleep=the interval from 30 min after self-reported going to bed until 30 min prior to awakening.

from age 17–34 to age 35–44 ($P$<.0001) and from age 35–44 to age 45–54 ($P$<.0001), but not from age 45–54 to age 55–65. The youngest age group also had significantly greater leisure time RMSSD than the other age groups ($P$<.006). Furthermore, within the age group of 17–34 years, the RMSSD increased significantly from work time to leisure time ($P$<.0001), from work time to sleep time ($P$<.0001), and from leisure time to sleep time ($P$<.0001). In the age categories of 35–44 years, 45–54 years, and 55–65 years, the RMSSD increased significantly only from leisure time to sleep time ($P$<.01), and from work time to sleep time ($P$<.0001), but not from work time to leisure time (see Fig. 1). These comparisons remained significant when corrected for multiple comparisons [23].

PCCs for work stress measures and HRV stratified by age groups and HRV measurement periods are provided in Table 2. Job strain and HRV were unrelated in any age group at any period of the day, with all correlations being negligible in terms of effect size [24]. For ERI, no association was observed with sleep time HRV for any age group. This finding supports the notion that the organism is a rest at night with HRV being relatively unaffected by work stress that has been experienced during the working day. However, ERI showed a significant inverse correlation with work time HRV (PCC=−0.231, $P$=.0047) and with leisure time HRV (PCC=−0.195, $P$=.0175) in workers aged 35–44 years, but not in the other age groups. These correlations remained significant when corrected for the number of tests done within each age group for ERI. Thus, age seems to affect the ERI–daytime HRV association in a nonlinear fashion.

Re-examining these associations by multilevel analyses, we found no job strain effects on the intercept and slope of

Table 2
Partial correlation coefficients (PCC) for work stress indices and RMSSD [a] during different recording periods of the day stratified by age

| Work stress index | Age groups | RMSSD during work time PCC [b] | P | RMSSD during leisure time PCC [b] | P | RMSSD during sleep time PCC [b] | P |
|---|---|---|---|---|---|---|---|
| Job strain | 17–34 | 0.073 | .38 | 0.036 | .67 | 0.078 | .35 |
| | 35–44 | 0.025 | .76 | −0.002 | .98 | −0.040 | .63 |
| | 45–54 | 0.003 | .97 | 0.00 | 1.00 | −0.018 | .82 |
| | 55–65 | −0.047 | .71 | −0.023 | .85 | −0.086 | .49 |
| ERI [c] | 17–34 | −0.078 | .35 | 0.006 | .94 | −0.047 | .58 |
| | 35–44 | −0.231 | <.01 | −0.195 | <.05 | −0.074 | .37 |
| | 45–54 | 0.096 | .23 | 0.10 | .21 | 0.090 | .26 |
| | 55–65 | −0.079 | .53 | −0.066 | .59 | −0.093 | .46 |

[a] RMSSD = root square differences of successive heart beats in milliseconds.
[b] Mutually adjusted for job strain (continuous) and effort-to-reward-imbalance (continuous) and sex, physical activity per kg body weight (continuous), number of cigarettes smoked (continuous), alcohol consumption (g/day, continuous), Jenkins sleep quality scale (continuous), and position (senior manager, foremen, qualified workers, unskilled workers, trainees).
[c] Effort-to-reward-imbalance.

Table 3
Multi-level growth curve model [a] for effort-to-reward-imbalance (ERI) and age as predictors of RMSSD [b]

| Variable | Coefficient Estimate | df | t | P |
|---|---|---|---|---|
| Intercept | 47.687 | 535 | 11.70 | <.0001 |
| Slope | −4.035 | 544 | −7.20 | <.0001 |
| ERI | 2.753 | 549 | 0.68 | .4942 |
| Age | −0.795 | 549 | −9.96 | <.0001 |
| Age$^2$ | 0.008 | 549 | 1.23 | .2192 |
| ERI×Slope | −4.074 | 549 | −2.13 | .0335 |
| Age×Slope | 0.298 | 549 | 7.83 | <.0001 |
| Age$^2$×Slope | −0.009 | 549 | −2.61 | .0094 |
| Age×ERI | −0.125 | 549 | −0.46 | .6439 |
| Age$^2$×ERI | −0.036 | 549 | −1.50 | .1336 |
| Age×ERI×Slope | 0.180 | 549 | 1.36 | .1757 |
| Age$^2$×ERI×Slope | 0.025 | 549 | 2.19 | .0292 |

[a] Adjusted for job strain (continuous), sex, physical activity per kg body weight (continuous), number of cigarettes smoked (continuous), alcohol consumption (g/day, continuous), Jenkins sleep quality scale (continuous), and position (senior manager, foremen, qualified workers, unskilled workers, trainees).
[b] RMSSD = root square differences of successive heart beats in milliseconds.

HRV (data not shown). By contrast, ERI showed significant interactions with the HRV slope (see Table 3), these being ERI×slope and ERI×age-squared×slope. The ERI×slope interaction coefficient suggests that ERI affects the daily drop in HRV. The three-way interaction indicates a quadratic "acceleration" of this impact with age departing from its sample mean. This observation suggests that ERI's impact on HRV is modified by age in a non-linear fashion. These complex patterns of associations are visualized in Fig. 2. Fig. 2 shows the relationship between age (on the abscissa) and the ERI×slope interaction (on the ordinate), that is, the curve shows the effect of ERI on the change in RMSSD (difference daytime-nighttime) at a given age, according to the multilevel model effects. Note again that a negative slope (i.e. change) value means daily drop of RMSSD and a negative value of the slope×ERI interaction (curve running below the zero line) indicates that the higher the ERI, the steeper this daily drop. For example, at the mean value of age and under the mean value of ERI, the results predict a change in RMSSD of −4.035, according to the coefficient estimates in Table 2 (with ERI and age mean centred for this analysis). An ERI value raised one unit above the mean predicts a RMSSD change of −4.035−4.074=−8.110 for the mean aged. Thus, Fig. 2 suggests that higher ERI promotes substantial daily drop of RSMMD among middle-aged workers, whereas the ERI impact on this daily drop attenuates towards both ends of the age range. Note that the zero line indicates no ERI impact on the daily drop and that the high positive values at both ends of the curve should be interpreted with caution, as the curvature is largely determined by the majority of cases in between the ends of the age range. Furthermore, the prolongation of the curve towards the ends may overestimate the characteristic location of the youngest and oldest cases. Thus, the slope×ERI×age$^2$

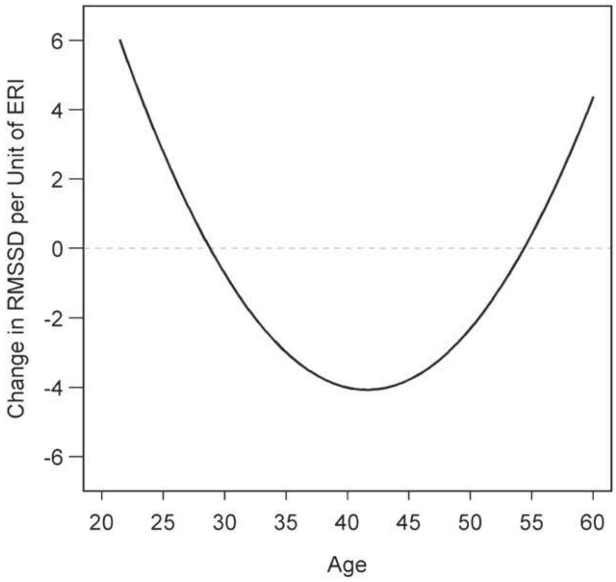


Fig. 2. Change in RMSSD per unit of ERI as a curvilinear function of age. Change=Daytime RMSSD−nighttime RMSSD. RMSSD=root square differences of successive heart beats in milliseconds.

interaction effect comports with the negative PCCs between ERI and work and leisure time HRV found in those aged 35–44; that is, in that middle-aged individuals with higher ERI showed larger reductions of HRV across the day, such that daily HRV was inversely related with ERI. Overall, our multilevel results confirm that ERI may exert the strongest effects on the daily drop of HRV in middle-aged adults.

## Discussion

In this study, we examined the association between work stress (measured as either job strain or ERI) and HRV with a particular focus on the potential age-specificity of this association. We observed no relationship between job strain and HRV. In contrast, the association between ERI and HRV was most pronounced in workers aged 35–44 years, but weaker in younger or older workers.

The job-demand-control model and the ERI model are widely accepted models, which have been employed frequently to characterize psychosocial work conditions. However, the number of observational occupational studies examining these models in relation to HRV is limited and findings are mixed. In a Dutch study of female nurses, no association was detected between job strain, job demands and HRV [8]. This is contrasted by reports of inverse associations in a predominantly male Dutch population [5], a US study of men [3], and by a recent report from the large Whitehall II study, which could draw on HRV data from a gender-mixed population of more than 3,000 civil servants for analyses [6]. With regard to the ERI, Vrijkotte et al. observed that those with high imbalance tended to have lower HRV based on a sample of 109 Dutch middle-aged white-collar workers [4]. However, this trend was not statistically significant. In contrast, based on data from another Dutch study of 70 workers, a positive association between ERI and HRV was found later in the work day [25]. A Finnish study of 863 women and men found that high ERI was associated with a reduced vagal tone in women, but no associations were found in men [9]. Thus, it appears that studies of work stress and HRV tend to show different associations when using the ERI model compared to the job-demand-control model. Our results may help to clarify this inconclusive body of evidence on the relation between job strain, ERI and HRV.

In the present study, we utilized both the job-demand-control model and the ERI model of work stress and found different associations for each model. Obtaining differing associations was not completely unexpected. It has been noted that the ERI model may be more associated with autonomic nervous system arousal than the job-demand-control model [26,27]. Specifically, it has been postulated that the emotional distress associated with the lack of reciprocity in the core social role of work that characterizes high effort and low rewards may have its effects outside of conscious awareness and with a particular tendency to manifest as physiological responses [11,26,27]. Thus, the present results further clarify the differential associations of the two dominant work stress models.

Our aim to evaluate whether the relation between work stress and HRV is modified by age groups was based on observations from previous studies reporting a more pronounced association between work stress and coronary heart disease (CHD) or myocardial infarction (MI) in employees younger than 50 years [6] or younger than 55 years [15]. In another study, Kivimäki et al. found a positive association between job strain and ischemic disease in workers aged 55 and below, but observed that this association was considerably attenuated when older employees (aged>55–65) were included [28]. The authors concluded that the inclusion of older employees in analyses might partly explain the mixed findings from earlier studies on job strain and cardiovascular disease [28]. Reduced HRV has been suggested as one of the underlying mechanisms explaining how work stress increases the risk of CHD [6]. Thus, a more pronounced association between work stress and HRV might also be expected in younger than in older employees. Our study confirmed this expectation. However, more specifically, we observed the association between work stress and HRV to be strongest in middle-aged workers (approximately 35–44 years) and to be weaker in younger and older workers. The Whitehall II study [6] is to our knowledge the only previous study that examined the potential age-specificity of work stress and HRV. Whereas these researchers reported an inverse association between work stress (as characterized by the demand-control model) and HRV, they found no interaction between age and work stress in relation to HRV [6].

What could explain our finding that the inverse association between ERI and HRV is possibly confined to middle-aged workers (approximately 35–44 years)? It has been observed that HRV and autonomic function decline with age in healthy adults [29,30]. As mentioned above, also in our cohort we observed considerably lower HRV in older workers than in younger workers. In healthy individuals, HRV shows a circadian variation, which is characterized by significant increases during the nighttime. The increase of HRV during the night may be blunted by acute stress or conditions such as chronic alcoholism [31,32]. In our study, we observed similar blunting of this increase in workers aged ≥45 compared to younger adults. The age-associated reduction of HRV in employees aged ≥45 might limit their capacity of further HRV reductions in response to stressors. This may partly explain the lack of association between work stress and day-time HRV in this age group. Age-related HRV declines can however not explain why we found no association between ERI and RMSSD in younger workers (<35 years). An alternative explanation of the observation that ERI and RMSSD are only associated in those middle-aged years may relate to the differing career perspectives across age strata. One might speculate that employees perceive as an unwritten rule that significant career advancements should be achieved by about 45 years. Beyond 50 years of age, many employees may wish to sign early retirement contracts that allow them to leave the company before 60. This may be particularly true for those workers aged ≥50 that label themselves as “older workers” [33]. It is conceivable that violations of reciprocity exert context-specific effects, i.e., someone looking forward to early retirement might be less vulnerable compared to someone seeking promotion and salary increases.

A third explanation pertains to characteristics that are inherently related to the German study setting: In Germany, the average age at first marriage is 33 years for men and 30 years for women. Within married partnerships, the first child is usually born within the first few years following marriage (for instance, 72% of the first children are born within 3 years after marriage) [34]. Furthermore, in particular, university graduates enter the German labor market at a comparatively late age. The labor force participation rate in Germany does not reach its peak before the age of 35 years in men and before the age of about 45 years in women [34]. Thus, German adults aged between 30 and 40 years may face both major personal and occupational challenges at the same time. Everything needs to be done and achieved within this crucial decade in Germany: getting married, having children, making first savings for retirement, and distinguishing oneself in the work setting to advance the career [35]. One might speculate that this possibly highly stressful period might increase this age groups’ susceptibility to work stress. This susceptibility might contribute to the development of physiological dysregulation (e.g., impaired vagal tone) in response to work stress. In line with this hypothesis, the large INTERHEART study has highlighted that not only stress at work, but also other sources of stress (e.g., financial stress and stress at home) as well as stressful life events are positively related to MI [36].

A number of limitations of our study need to be noted. We drew on cross-sectional data, which does not allow inferring causality from observed associations. The vast majority of study participants were male and findings can therefore not be generalized to female populations. Although we could adjust for many important confounders in our statistical analyses, residual or unmeasured confounding can never be excluded as an explanation. Like in any empirical study, chance findings cannot be ruled out. Further, more detailed analyses of autonomic regulation would be desirable. However, we chose the optimal method available to us for ecologically valid real-life situations. Finally, we did not specifically assess stress outside of the work context and can therefore not examine whether the age groups specified in our study differ with regard to stress from other sources than the work environment.

Our study has several strengths. First, we could draw on a large occupational sample. Second, our occupational cohort comprised employees with differing socioeconomic backgrounds rather than being limited to one particular professional group. Third, we could account for many important confounders in the statistical analyses. Fourth, HRV was recorded over 24 h. This allowed us to differentiate between work time, leisure time and sleep time and to investigate the relationship between work stress and HRV in greater detail. Finally, we used state-of-the-art statistical techniques (multilevel growth curve models) to examine the work stress-HRV associations and its age specificity.

In conclusion, we found effort–reward imbalance and vagal control to be inversely associated in middle-aged workers (aged approximately 35–44), but not in younger or older workers. These findings may partly be explained by age-related declines of autonomic function, age-differences in career aspirations, or increased susceptibility to work stress among those aged 35–44 due to facing multiple stressors from various sources simultaneously. Our results add to the specification of an occupational group that is particularly likely to show a reduced vagal tone in response to work site stressors and might thus be of increased risk for work stress-related heart disease. Future studies of the relationship between work stress and HRV as a function of age are needed in order to reveal whether our findings can be replicated.

## Acknowledgments

We are grateful to Brigitte Kabiczek and Max Weber for data collection. This study was supported by the Federal Institute of Technology, Zurich, Switzerland, and the European Aeronautic Defence and Space Company (EADS), Germany. The contribution of the last two (senior) authors was equal.

## Appendix

The growth curve model used for analysis can be specified in formal terms as follows. The *Level 1 (within-subject) model* is:

$$RMSSD_{it}=b_{0i}+b_{1i}t+e_{it},$$

where $RMSSD_{it}$ denotes the RMSSD-value of individual $i$ at time $t$; $t$ denotes the time of measurement, scaled 2, 1, 0 for work time, leisure time, sleep time respectively; $b_{0i}$ and $b_{1i}$ are random regression coefficients, namely the intercept and slope of the linear trajectory for individual $i$; and $e_{it}$ denotes the residual term for individual $i$ at time $t$. The *Level 2 (between-subject) model* is:

$$b_{0i} = a_{00} + a_{01}S_i + a_{02}A_i + a_{03}A_i^2 + a_{04}S_i \times A_i + a_{05}S_i \times A_i^2 + a_{06}C_i + u_0,$$
$$b_{1i} = a_{10} + a_{11}S_i + a_{12}A_i + a_{13}A_i^2 + a_{14}S_i \times A_i + a_{15}S_i \times A_i^2 + u_1,$$

where $S_i$ denotes the stress-value measured for individual i; $A_i$ denotes the age of individual $i$; $C_i$ denotes an additional control variable; $a_{00}...a_{15}$ are fixed regression coefficients and $u_0$ and $u_1$ are Level 2 random components. Note that $C_i$ has been included here as "placeholder" for all the control variables included in the model to keep the expression short. Substituting the level 1 equation coefficients by the level 2 model expressions yields the *mixed regression model* as follows:

$$\begin{aligned}RMSSD_{it}=&a_{00}+a_{10}t+a_{01}S_i+a_{02}A_i+a_{03}A_i^2+a_{06}C_i+a_{11}S_i\\&\times t+a_{12}A_i \times t+a_{13}A_i^2 \times t+a_{04}S_i \times A_i+a_{05}S_i\\&\times A_i^2+a_{14}S_i \times A_i \times t+a_{15}S_i \times A_i^2 \times t+u_0+u_1\\&\times t+e_{it}\end{aligned}$$

In this analysis model, the $a$-coefficients are fixed regression effects, to be interpreted as in "conventional" regression analysis. Thus, the coefficients of interaction terms involving t denote the impact of the respective Level 2 predictor on the individual slope (i.e., the rate of change across the three measurement occasions). The basic difference between the two regression approaches consists in the estimation of variance of three random components, namely $u_0$ (unexplained interindividual variation of the intercept), $u_1$ (unexplained interindividual variation of the slope), and $e_{it}$ (residual variance, variance of deviations of the RMSSD-scores from the individual linear trajectory).

## References

[1] Belkic KL, Landsbergis PA, Schnall PL, Baker D. Is job strain a major source of cardiovascular disease risk? Scand J Work Environ Health 2004;30:85–128.
[2] Elovainio M, Leino-Arjas P, Vahtera J, Kivimaki M. Justice at work and cardiovascular mortality: a prospective cohort study. J Psychosom Res 2006;61:271–4.
[3] Collins SM, Karasek RA, Costas K. Job strain and autonomic indices of cardiovascular disease risk. Am J Ind Med 2005;48:182–93.
[4] Vrijkotte TG, van Doornen LJ, de Geus EJ. Effects of work stress on ambulatory blood pressure, heart rate, and heart rate variability. Hypertension 2000;35:880–6.
[5] van Amelsvoort LG, Schouten EG, Maan AC, Swenne CA, Kok FJ. Occupational determinants of heart rate variability. Int Arch Occup Environ Health 2000;73:255–62.
[6] Chandola T, Britton A, Brunner E, Hemingway H, Malik M, Kumari M, et al. Work stress and coronary heart disease: what are the mechanisms? Eur Heart J 2008;29:640–8.
[7] Kageyama T, Nishikido N, Kobayashi T, Kurokawa Y, Kaneko T, Kabuto M. Self-reported sleep quality, job stress, and daytime autonomic activities assessed in terms of short-term heart rate variability among male white-collar workers. Ind Health 1998;36:263–72.
[8] Riese H, Van Doornen LJ, Houtman IL, De Geus EJ. Job strain in relation to ambulatory blood pressure, heart rate, and heart rate variability among female nurses. Scand J Work Environ Health 2004;30:477–85.
[9] Hintsanen M, Elovainio M, Puttonen S, Kivimaki M, Koskinen T, Raitakari OT, et al. Effort-reward imbalance, heart rate, and heart rate variability: the Cardiovascular Risk in Young Finns Study. Int J Behav Med 2007;14:202–12.
[10] Karasek R, Theorell T. Healthy work: stress, reproductivitiy, and the reconstruction of working life. New York: Basic Books, 1990.
[11] Siegrist J, Starke D, Chandola T, Godin I, Marmot M, Niedhammer I, et al. The measurement of effort-reward imbalance at work: European comparisons. Soc Sci Med 2004;58:1483–99.
[12] Tsutsumi A, Kawakami N. A review of empirical studies on the model of effort-reward imbalance at work: reducing occupational stress by implementing a new theory. Soc Sci Med 2004;59:2335–59.
[13] Tsuji H, Larson MG, Venditti FJ, Manders ES, Evans JC, Feldman CL, et al. Impact of reduced heart rate variability on risk for cardiac events. The Framingham Heart Study. Circulation 1996;94:2850–5.
[14] Dekker JM, Crow RS, Folsom AR, Hannan PJ, Liao D, Swenne CA, et al. Low heart rate variability in a 2-minute rhythm strip predicts risk of coronary heart disease and mortality from several causes: the ARIC Study. Atherosclerosis Risk In Communities. Circulation 2000;102:1239–44.
[15] Theorell T, Tsutsumi A, Hallquist J, Reuterwall C, Hogstedt C, Fredlund P, et al. Decision latitude, job strain, and myocardial infarction: a study of working men in Stockholm. The SHEEP Study Group. Stockholm Heart epidemiology Program. Am J Public Health 1998;88:382–8.
[16] Fischer JC, Kudielka BM, von Kanel R, Siegrist J, Thayer JF, Fischer JE. Bone-marrow derived progenitor cells are associated with psychosocial determinants of health after controlling for classical biological and behavioral cardiovascular risk factors. Brain Behav Immun 2009;23:419–26.
[17] Karasek R, Brisson C, Kawakami N, Houtman I, Bongers P, Amick B. The Job Content Questionnaire (JCQ): an instrument for internationally comparative assessments of psychosocial job characteristics. J Occup Health Psychol 1998;3:322–55.
[18] Task Force of the European Society of Cardiology and the North American Society of Pacing and Electrophysiology. Heart rate variability. Standards of measurement, physiological interpretation, and clinical use. Task Force of the European Society of Cardiology and the North American Society of Pacing and Electrophysiology. Eur Heart J 1996;17:354–81.
[19] Penttila J, Helminen A, Jartti T, Kuusela T, Huikuri HV, Tulppo MP, et al. Time domain, geometrical and frequency domain analysis of cardiac vagal outflow: effects of various respiratory patterns. Clin Physiol 2001;21:365–76.
[20] Jenkins CD, Stanton BA, Niemcryk SJ, Rose RM. A scale for the estimation of sleep problems in clinical research. J Clin Epidemiol 1988;41:313–21.
[21] Hox J. Multilevel analysis. Mahwah (NJ): Erlbaum, 2002.
[22] Stoel RD. Issues in growth curve modeling. Amsterdam: TT-Publikaties, 2003.

[23] Simes RJ. An improved Bonferroni procedure for multiple tests of significance. Biometrika 1986;73:751–4.
[24] Cohen J. Statistical power analysis for the behavioral sciences. Hillsdale (NJ): Erlbaum, 1988.
[25] Hanson EK, Godaert GL, Maas CJ, Meijman TF. Vagal cardiac control throughout the day: the relative importance of effort-reward imbalance and within-day measurements of mood, demand and satisfaction. Biol Psychol 2001;56:23–44.
[26] Siegrist J. Adverse health effects of high-effort/low-reward conditions. J Occup Health Psychol 1996;1:27–41.
[27] Peter R, Siegrist J, Hallqvist J, Reuterwall C, Theorell T. Psychosocial work environment and myocardial infarction: improving risk estimation by combining two complementary job stress models in the SHEEP Study. J Epidemiol Community Health 2002;56:294–300.
[28] Kivimäki M, Theorell T, Westerlund H, Vahtera J, Alfredsson L. Job strain and ischaemic disease: does the inclusion of older employees in the cohort dilute the association? The WOLF Stockholm Study. J Epidemiol Community Health 2008;62:372–4.
[29] Piccirillo G, Fimognari FL, Viola E, Marigliano V. Age-adjusted normal confidence intervals for heart rate variability in healthy subjects during head-up tilt. Int J Cardiol 1995;50:117–24.
[30] Umetani K, Singer DH, McCraty R, Atkinson M. Twenty-four hour time domain heart rate variability and heart rate: relations to age and gender over nine decades. J Am Coll Cardiol 1998;31:593–601.
[31] Hall M, Vasko R, Buysse D, Ombao H, Chen Q, Cashmere JD, et al. Acute stress affects heart rate variability during sleep. Psychosom Med 2004;66:56–62.
[32] Irwin MR, Valladares EM, Motivala S, Thayer JF, Ehlers CL. Association between nocturnal vagal tone and sleep depth, sleep quality, and fatigue in alcohol dependence. Psychosom Med 2006;68:159–66.
[33] Desmette D, Gaillard M. When a “worker” becomes an “older worker”: the effects of age-related social identity on attitudes towards retirement and work. Career Dev Int 2008;13:168–85.
[34] Federal Statistical Office. Statistical yearbook 2007 for the Federal Republic of Germany. Wiesbaden: Federal Statistical Office, 2007.
[35] Deutsche Welle. Study: Men in Germany Are Scared to Start Families. http://www.dw-world.de/dw/article/0,2144,2071657,00.html (November 7, 2008).
[36] Rosengren A, Hawken S, Ounpuu S, Sliwa K, Zubaid M, Almahmeed WA, et al. Association of psychosocial risk factors with risk of acute myocardial infarction in 11119 cases and 13648 controls from 52 countries (the INTERHEART study): case-control study. Lancet 2004;364:953–62.