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Heart Rate Variability for Evaluating Vigilant Attention in Partial Chronic Sleep Restriction

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Study Objectives: Examine the use of spectral heart rate variability (HRV) metrics in measuring sleepiness under chronic partial sleep restriction, and identify underlying relationships between HRV, Karolinska Sleepiness Scale ratings (KSS), and performance on the Psychomotor Vigilance Task (PVT).
Design: Controlled laboratory study.
Setting: Experimental laboratory of the Brain Work Research Centre of the Finnish Institute of Occupational Health, Helsinki, Finland.
Participants: Twenty-three healthy young males (mean age ± SD = 23.77 ± 2.29).
Interventions: A sleep restriction group (N = 15) was subjected to chronic partial sleep restriction with 4 h sleep for 5 nights. A control group (N = 8) had 8 h sleep on all nights.
Measurements and Results: Based on a search over all HRV frequency bands in the range [0.00, 0.40] Hz, the band [0.01, 0.08] Hz showed the highest correlation for HRV–PVT (0.60, 95% confidence interval [0.49, 0.69]) and HRV–KSS (0.33, 95% confidence interval [0.16, 0.46]) for the sleep restriction group; no correlation was found for the control group. We studied the fraction of variance in PVT explained by HRV and a 3-component alertness model, containing circadian and homeostatic processes coupled with sleep inertia, respectively. HRV alone explained 33% of PVT variance.
Conclusions: The findings suggest that HRV spectral power reflects vigilant attention in subjects exposed to partial chronic sleep restriction.
Keywords: HRV, PVT, KSS, partial chronic sleep restriction, vigilant attention
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INTRODUCTION

Sleepiness impairs cognitive functioning and increases the likelihood of human error, leading to serious unwanted consequences such as traffic and workplace accidents.[1-3] From a safety perspective, there is hence a considerable interest to be able to objectively and unobtrusively monitor the level of sleepiness.

Currently, measures of sleepiness are mainly based on (1) physiologic metrics related to brain activity such as electroencephalography (EEG) and measures of eye and eyelid movements such as electrooculography (EOG), (2) neurobehavioral metrics of vigilant attention such as the psychomotor vigilance task (PVT), and (3) self-reported sleepiness such as the Karolinska sleepiness scale (KSS).

Although the relationship between EEG and KSS has been established,[4] EEG and EOG metrics are rather sensitive to movement artifacts and are not always suitable for use in naturalistic working conditions due to, e.g., discomfort and conspicuous placement of electrodes. Novel techniques strive to remedy this situation for EEG measurements.[5] Neurobehavioral and self-reported metrics interfere with task performance and cannot be measured in real-time. On the other hand, heart rate variability (HRV), known to reflect sympathetic and parasympathetic activity,[6] is feasible to measure also in persons engaged in tasks such as driving or controlling a production process. HRV has been used to assess workload, stress, recovery, and cardiovascular health,[7] and affordable devices for measuring HRV are readily available and can be worn invisibly under clothing. HRV metrics could therefore be very well suited for measuring sleepiness in naturalistic working conditions.

The use of heart rate variability (HRV) metrics in the measurement of sleepiness is hence an important and novel area but has been investigated only in a few studies; e.g., during task performance, in short-term sleep restriction, in total sleep deprivation, and during driving.[8-13] Interestingly, a correlation between HRV spectral power in the [0.02, 0.08] Hz band and PVT has recently been found by Chua et al. in 40 h of total sleep deprivation.[10] The use of spectral HRV metrics in measuring sleepiness in chronic partial sleep restriction has, however, not previously been studied.

The buildup of sleep pressure due to chronic partial sleep restriction is common in real-life working situations, e.g., hectic work with long working hours. It is therefore important to be able to accurately measure sleepiness in such settings.

Thus, the aim of this study is to investigate the use of spectral HRV metrics in the measurement of sleepiness in chronic partial sleep restriction: we examine computationally the association between spectral HRV metrics and neurobehavioral metrics of vigilant attention (PVT) and subjective sleepiness measures (KSS).

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METHODS

Protocol

The data analyzed in this study and the study protocol have been described in detail by Haavisto et al.[14] The study was approved by the Ethics Committee of the Hospital District

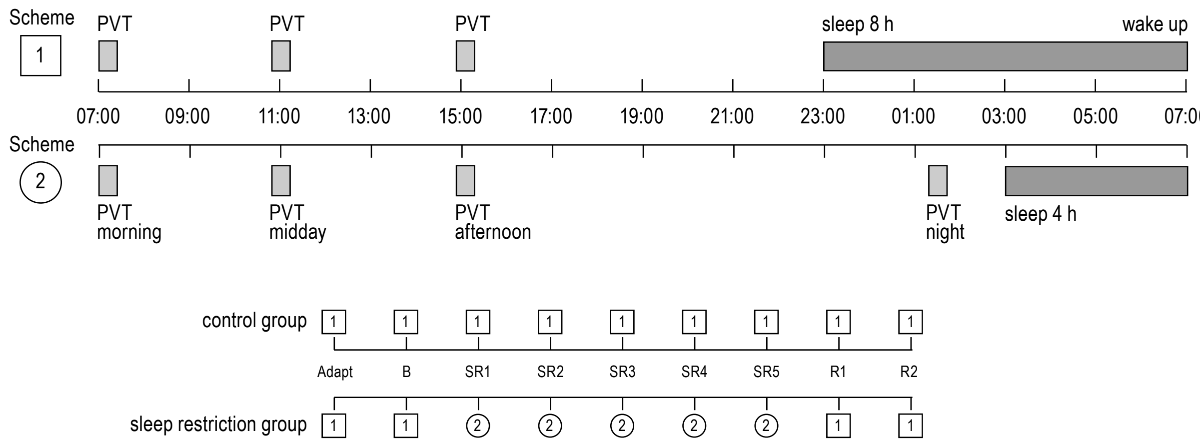

Figure 1—The protocol used for the study. The control group with no sleep restriction (8 h sleep) adheres to scheme 1 on all days in the laboratory, while the sleep restriction group follows scheme 2 on the 5 sleep restriction days (4 h sleep). In each scheme, the day begins at 07:00 in the morning as the subjects wake up. Adapt, adaptation; B, baseline; SR, sleep restriction; R, recovery.

of Helsinki and Uusimaa. In brief, the study protocol was as follows. The subjects arrived in the laboratory on the evening prior to the adaptation day. The stay in the sleep laboratory lasted 9 days. The subjects in the control group adhered to scheme 1 in Figure 1, with 8 h of nightly sleep during their entire stay in the laboratory. The subjects in the sleep restriction group followed scheme 1 during the adaptation and baseline days (days A and B) and during the recovery days (R1 and R2). During the 5 sleep restriction days (SR1 to SR5), the subjects in the sleep restriction group followed scheme 2 with nightly sleep restricted to 4 h (03:00 to 07:00).

Subjects

Twenty-three healthy males (mean age ± SD = 23.8 ± 2.3 years) participated in the study after giving informed consent. The subjects were randomly assigned into 2 groups—one sleep restriction group (N = 15) undergoing sleep restriction and a control group allowed to sleep normally. The subjects were screened to exclude subjects with extreme circadian types, sleep disorders, psychiatric illness, chronic or recent acute medical conditions, history of alcohol or substance abuse, having crossed time zones 4 weeks prior to the study, habitual napping, and shift and/or night work. Inclusion criteria included 7–9 h habitual sleep and sleep need, regular lifestyles with habitual bedtime before 24:00, and wake time after 06:00.

Measurement of Vigilant Attention

The PVT[15] measuring vigilant attention was presented on a computer and the subjects responded using the keyboard. The subjects performed the 10-min PVT 4 times daily (morning, midday, afternoon, and night) during the sleep restriction days and 3 times daily (morning, midday, and afternoon) during the baseline and recovery days. The times for the PVT sessions were scheduled as follows: morning at 07:15, midday at 11:00, afternoon at 15:00 and night at 01:30. Lapses in the PVT are defined as responses with reaction times > 500 ms. It has been shown that the performance on the PVT is sensitive to the effects of sleep loss.[16]

Measurement of Subjective Sleepiness

The subjects' subjective sleepiness was determined using the Karolinska Sleepiness Scale (KSS).[17] The subjects rated their sleepiness on the 9-point KSS scale shown on a PC prior to the performance of each PVT and immediately after each PVT. The average value of these responses was used as an indicator of subjective sleepiness at the time of the PVT.

Physiological Measurements

The electrocardiogram (ECG) was recorded using a single lead, with one electrode placed below the right clavicle and the other electrode on the lower left ribcage in approximately the V5 position in the standard 12-lead ECG system. The signals were recorded at 200 Hz using an Embla A10 polysomnograph (Medcare, Reykjavík, Iceland). The ECG data used in this study were recorded during the performance of the PVT.

Signal Processing

The signal processing was performed in Matlab.[18] The R-peaks, used to form the interbeat interval (IBI) series, were detected from the ECG using an adaptive algorithm. The spectral analysis of HRV was performed using the Lomb-Scargle periodogram.[19] The frequencies in the spectral analysis spanned the range (0.00, 0.40) Hz, which includes the very low frequency (VLF: [0.00, 0.04] Hz), low frequency (LF: [0.04, 0.15] Hz) and high frequency (HF: [0.15, 0.40] Hz) bands typically used in HRV analysis.[20] All available data recorded during the 10-min PVT sessions was used in the spectral analysis. The IBI series was not detrended prior to spectral analysis, and the Lomb-Scargle periodogram was not normalized. The data were analyzed in one segment, and the logarithm of the power spectral values was used in the analyses.

Statistical Analysis

The statistical analyses were done in R,[21] using custom code. Only data from days SR1 to SR5, corresponding to the sleep restriction days for the sleep restriction group, were used in the analyses. All data series were z-transformed to zero mean and unit variance on the subject level for all analyses.

Confidence Intervals

Interpretation of statistical results requires knowledge of the accuracy of the estimated characteristic. Bootstrap confidence intervals (CIs) are well suited for small sample sizes and provide a robust, nonparametric, method for the assessment of the uncertainty of the statistical estimate such as the correlation coefficient.[22]

Confidence intervals for correlation coefficients were evaluated using the bias-corrected and accelerated (BC*a*) bootstrap method,[23] by sampling over correlation coefficients from individual subjects. The sampling is performed with replacement over the subjects in order to account for both inter- and intra-subject variability. The bootstrap sampling was performed separately for the subjects within the sleep restriction and control groups. In the estimation of CIs, 5000 bootstrap samples were used.

Calculation of Correlation

The correlation between HRV spectral power and the measures of vigilant attention (PVT lapses) or subjective sleepiness (KSS ratings) was calculated using Pearson correlation coefficients. In the calculation of the correlation, the HRV spectral power and value of the PVT or KSS measures on different days (either on the level of individual subjects or on the group level) were considered as time series. The calculation was performed using all available paired data points of HRV spectral power and the PVT or KSS measures. Correlation coefficients were calculated individually for each subject, after which they were averaged. The average correlation and the confidence intervals are unaffected by the z-transformation, since the Pearson correlation coefficient is invariant under translation and scaling.

The percentages of missing data points for the sleep restriction group were as follows; HRV: 5.61, PVT: 1.05, and KSS: 3.51. For the control group, the percentages of missing data points were as follows: HRV: 2.86, PVT: 0.95, and KSS: 0.95.

Group-Level Comparisons

The group level differences of HRV, PVT, and KSS on the morning, midday, and afternoon measurement sessions during the sleep restriction days were tested using a permutation test. The data were first averaged on the subject level across the 3 measurement sessions for both groups, after which a permutation test was performed, randomly permuting the group labels $N = 10000$ times. The Holm-Bonferroni correction for multiple testing was used to adjust the obtained P-values. The obtained P-values were compared at the 5% level.

Modeling Vigilant Attention and Subjective Sleepiness

When studying the correlation between variables, it is important to investigate the mechanisms by which the variables are related in order to understand the underlying causes to an observed correlation. We examined what components of alertness were shared between (1) HRV power and PVT lapses, and (2) HRV power and KSS responses. This can be accomplished by computationally modeling HRV, KSS, and PVT and investigating how the variance is shared between the variables.

Human alertness is regulated by several processes, described by, e.g., the 3-process model presented by Åkerstedt and Folkard.[24] In this model, alertness is modeled as consisting of a circadian process, a homeostatic process, and sleep inertia. The circadian process describes the variation of alertness with the time of day. The sleep inertia models the short-lasting state of reduced alertness after waking up. The homeostatic process describes the buildup of sleep pressure due to prolonged lack of sleep.

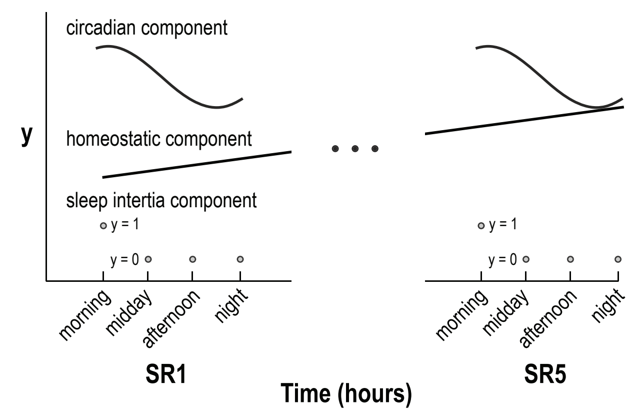

Figure 2—The components of the three-process model. SR, sleep restriction.

To study the interconnections between the variable pairs HRV–PVT and HRV–KSS, we constructed a simple 3-component alertness model. The 3 components in this model are (1) the circadian process, (2) sleep inertia, and (3) a homeostatic component. The amount of data points available in the study did not permit a more complex model. The circadian process is modeled as a cosine wave and represents the daily variation of alertness with time of day. Sleep inertia is represented by a binary variable, being one in the morning and zero otherwise; the short-term effect of sleep inertia dissipates within 2 to 4 h after awakening.[25] The homeostatic component was modeled as a linearly increasing function of time, modeling the buildup of sleep pressure due to insufficient homeostatic recovery during the short 4-h sleep periods. A visual representation of the 3 components is shown in Figure 2. More formally, HRV power, KSS responses, and PVT lapses are estimated by linear models defined by:

$$\mathrm{HRV}[t, \varphi] = a_0 + a_1 I[t] + a_2 C[t, \varphi] + a_3 H[t] \quad (1)$$

$$\mathrm{KSS}[t, \varphi] = b_0 + b_1 I[t] + b_2 C[t, \varphi] + b_3 H[t] \quad (2)$$

$$\mathrm{PVT}[t, \varphi] = c_0 + c_1 I[t] + c_2 C[t, \varphi] + c_3 H[t] \quad (3)$$

respectively, where the time t is given as decimal hours. $I[t]$ represents sleep inertia which equals one for the morning measurements and is zero otherwise.

The function $C[t, \varphi] = \cos(2\pi t/24 + \varphi)$ represents the circadian rhythm with a 24-h period and phase φ. The sleep pressure is defined as $H[t] = t$. The parameters a_0, b_0 and c_0 are intercepts.

For each variable in the analysis, a vector was formed with all the z-transformed data from all subjects. The models were then fit using ordinary weighted least squares linear regression, after which amounts of variance shared between the variables were

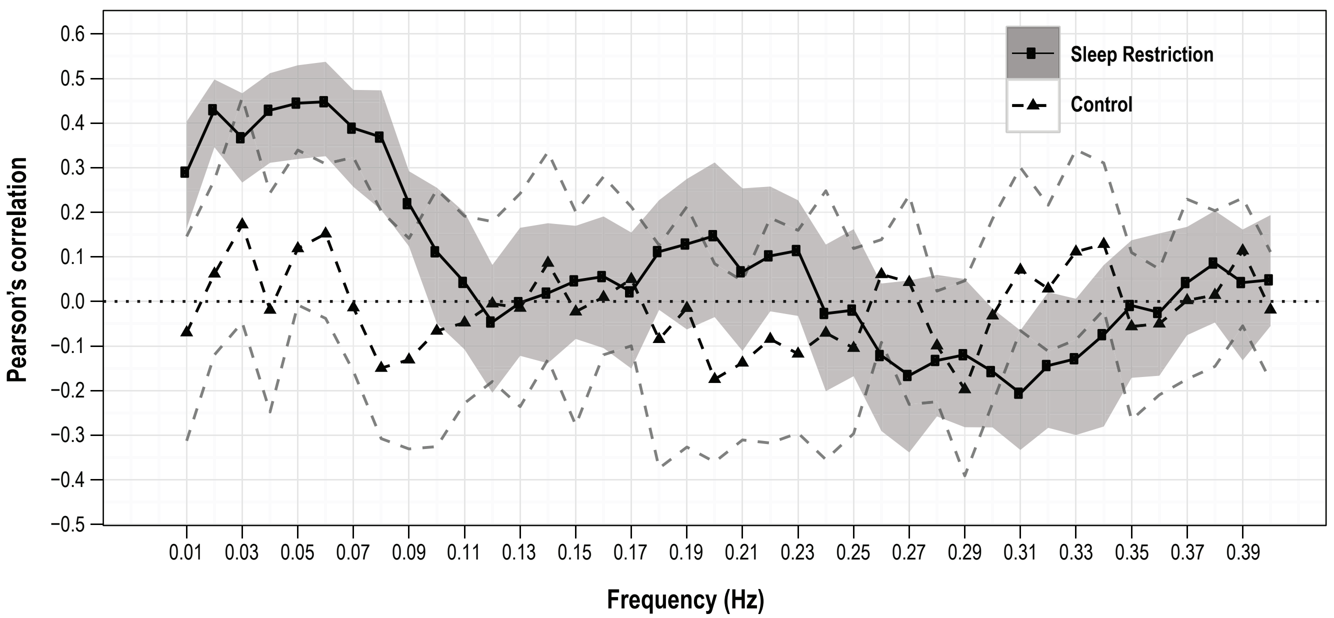

Figure 3—The correlation between HRV power and PVT lapses in 0.01 Hz frequency bands between 0.00 Hz and 0.40 Hz for the sleep restriction group (solid line) and control group (dashed line). 95% bootstrap confidence intervals are drawn shaded for the sleep restriction group and shown with dashed lines for the control group.

evaluated. Weights were used in the fitting process to ensure that each subject contributed an equal amount of variance to the model, thus controlling for the effects of missing data.

Bootstrap sampling was used to obtain 95% confidence intervals for the shared variances and for the model parameters. In short, subjects were randomly sampled with replacement and their data used to form vectors as described above. These vectors were used in the evaluation of model parameters.

Variance Partitioning

The performance of a regression model is commonly measured using the coefficient of determination, called the R^2 statistic. The R^2 statistic represents the fraction of variance of the dependent variable that is explained by the regression model. The R^2 statistic equals the squared Pearson correlation coefficient between the independent and the dependent variable, if the model is an ordinary least squares linear regression, as above, and the independent variable is one-dimensional.

If the dependent variable is modeled by several regression models with unique independent variables, the variance of the dependent variable can be partitioned into the fractions explained by the different combinations of independent variables. The partitioning of the variance can be presented graphically using Venn diagrams, where each variable is depicted as an oval. The area of an oval represents the total variance of a particular variable, and the variance shared between variables is represented by the intersecting areas between ellipses.[26,27]

RESULTS

Optimal HRV Frequency Band

In order to examine if HRV spectral power can be used in the measurement of sleepiness, we first had to establish the HRV frequency band that is most correlated with the sleepiness variable (PVT or KSS), i.e., we studied the correlation between the variable pairs HRV–PVT and HRV–KSS.

To establish a general profile of the correlation between HRV power and the sleepiness variable, we first calculated the correlation between HRV power and the sleepiness variable separately in 0.01 Hz wide bands between 0.00 Hz and 0.40 Hz.

The average correlations between HRV and PVT are shown in Figure 3 with 95% CIs. In the sleep restriction group, the bands up to 0.08 Hz showed a moderately strong positive correlation between HRV and PVT. The correlation rapidly dropped at around 0.10 Hz and stayed low above this frequency. Above 0.09 Hz, the CIs also included zero for the majority of the frequencies. For the control group, the average correlation was very low for all frequency bands, with zero consistently included in the CIs.

The average correlations for the pair HRV–KSS are shown in Figure 4. The highest correlations were found in the [0.01, 0.08] Hz region for the sleep restriction group, which was the same region as was found for the correlation between HRV and PVT. However, the correlation in this region was weaker for HRV–KSS than for HRV–PVT. Zero was included in the majority of the CIs for the control group.

Although the correlations between HRV power in narrow 0.01 Hz bands and the sleepiness variables are indicative of the general performance of HRV as a measure of sleepiness, it is not possible to directly draw conclusions regarding the average correlations for wider frequency bands. To determine which HRV frequency bands show the highest correlation with the sleepiness variables, we calculated the correlation between HRV and the sleepiness variables for all possible combinations of HRV frequency bands between 0.00 Hz and 0.40 Hz in 0.01 Hz discrete steps. The correlations for all bands are visualised in Figure S1 (supplemental material).

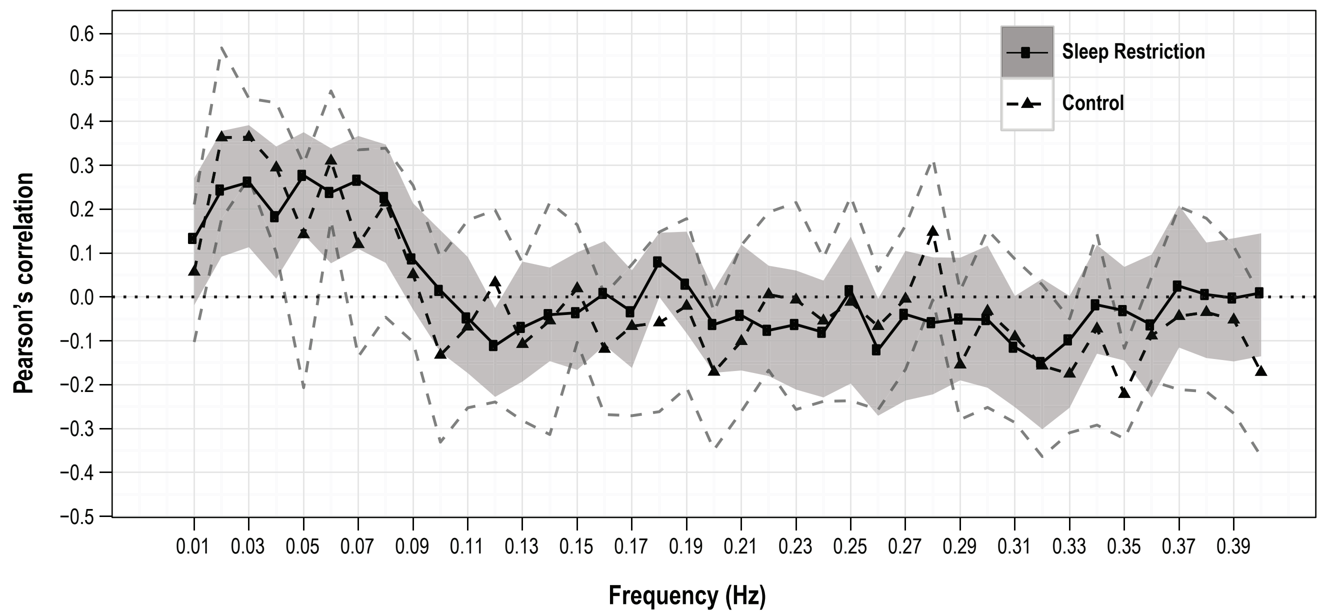

Figure 4—The correlation between HRV power and KSS ratings in 0.01 Hz frequency bands between 0.00 Hz and 0.40 Hz for the sleep restriction group (solid line) and control group (dashed line). 95% bootstrap confidence intervals are drawn shaded for the sleep restriction group and shown with dashed lines for the control group.

The 5 bands with a bandwidth ≥ 0.05 Hz with the highest correlations between HRV and PVT are presented in Table 1, with 95% CIs formed by bootstrap sampling. The table also shows the correlations between HRV–KSS in the same bands for comparison. The criterion of a minimum bandwidth ≥ 0.05 Hz was used to ensure that the results were not due to sporadic fluctuations in very narrow frequency band. All 5 bands with highest correlation between HRV and the sleepiness variables were below the upper frequency of the traditional HRV LF band (0.15 Hz). The correlation between the HRV LF/HF ratio and the sleepiness variables are also shown in the table.

Table 1—Pearson correlations, 95% bootstrap confidence intervals (in parentheses) and bandwidths for the bands, with a bandwidth of at least 0.05 Hz, for the ten bands with the highest correlations between HRV power and PVT lapses, and between HRV power and KSS ratings.

Band (Hz)	Bandwidth (Hz)	Correlation HRV–PVT	Correlation HRV–KSS
[0.01, 0.08]	0.07	0.60 (0.49, 0.69)	0.33 (0.19, 0.46)
[0.01, 0.07]	0.06	0.59 (0.49, 0.68)	0.32 (0.18, 0.45)
[0.01, 0.09]	0.08	0.58 (0.45, 0.67)	0.31 (0.16, 0.44)
[0.00, 0.08]	0.08	0.57 (0.47, 0.67)	0.30 (0.16, 0.43)
[0.02, 0.08]	0.06	0.57 (0.44, 0.68)	0.33 (0.16, 0.46)
VLF: [0.00, 0.04]	0.04	0.49 (0.40, 0.61)	0.26 (0.13, 0.39)
LF: [0.04, 0.15]	0.11	0.35 (0.16, 0.49)	0.11 (−0.04, 0.23)
HF: [0.15, 0.40]	0.25	0.00 (-0.17, 0.15)	−0.07 (−0.22, 0.02)
LF/HF ratio	–	0.38 (0.25, 0.48)	0.21 (0.04, 0.36)

The standard VLF, LF, and HF bands of HRV and the LF/HF ratio are provided for reference.

The search over all frequency bands for both sleepiness variables interestingly showed that the HRV frequency band with the highest correlation for HRV–PVT and HRV–KSS was the same, namely the band [0.01, 0.08] Hz. This band showed the highest average correlation of 0.60 (95% CI: [0.49, 0.69]) for HRV–PVT and 0.34 (95% CI: [0.19, 0.46]) for HRV–KSS. The correlation between HRV and PVT is thus almost twice that of the correlation between HRV and KSS.

In the HRV frequency bands commonly used in, e.g., psychophysiology, the correlation between HRV–PVT in the VLF band was moderately large. The LF band exhibited wide CIs and an overall low correlation for HRV–PVT, while the CI for HRV–KSS in the LF band included zero. No significant correlation was found for the traditional HF band for either variable pair.

For both of the variable pairs HRV–PVT and HRV-KSS, the correlation in the [0.01, 0.08] Hz band was within error limits the same as for the band [0.02, 0.08] Hz previously found to have the highest correlation between HRV and PVT in total sleep deprivation by Chua et al.[10] We hence used the band [0.02, 0.08] Hz for the HRV metrics in the remaining part of this study to facilitate easy comparison of results.

Time Courses of HRV Power, PVT Lapses, and KSS Ratings

The HRV power in the [0.02, 0.08] Hz band during the PVT sessions is shown in Figure 5. The average number of PVT lapses and the average KSS ratings with CIs are shown in Figures 6 and 7, respectively. The comparison between the sleep restriction and control groups reported here was performed using permutation testing, as described above.

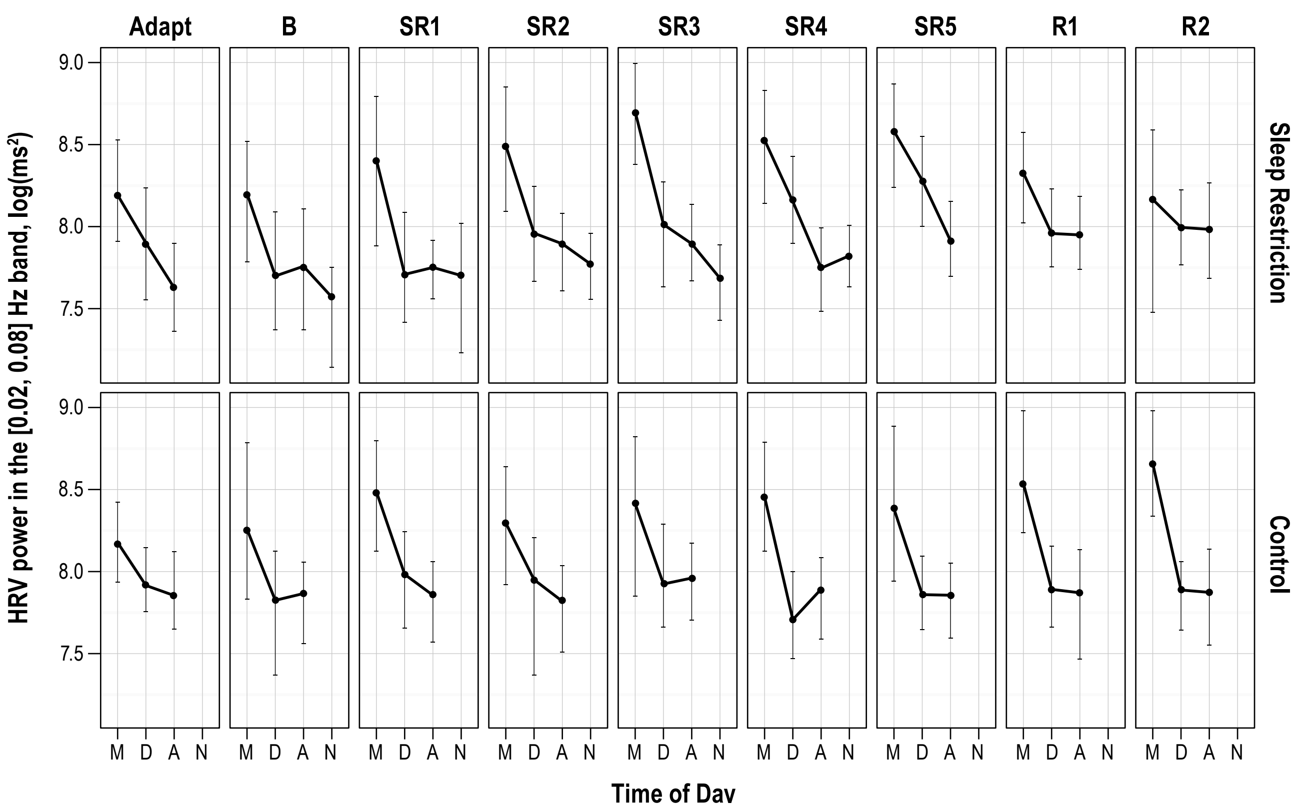

Figure 5—Average HRV power in the [0.02, 0.08] Hz frequency band during the PVT sessions on each day. 95% bootstrap confidence intervals are marked using vertical bars. Adapt, adaptation; B, baseline; SR, sleep restriction; R, recovery; M, morning; D, midday; A, afternoon; N, night.

The HRV profiles were similar across both the sleep restriction and control groups, with the highest values in the morning and the lowest in the night. The average power was similar within error limits during the different measurements for both the sleep restriction and control groups. No P-values from the permutation test were significant for the HRV profiles.

The average number of PVT lapses for the sleep restriction and control groups during the measurement sessions are shown in Figure 6. The average number of lapses was similar for both the sleep restriction and control groups during the adaptation and baseline days and during the recovery days. During days SR1–SR5, the sleep restriction group showed an increased number of PVT lapses, especially during the morning sessions, compared to the other days and compared to the control group. In general, the number of lapses was highest in the morning for the sleep restriction group, and progressively decreased towards the night. The P-values from the permutation test showed significant differences between the sleep restriction and control groups during the morning sessions (P = 0.03) and during the midday sessions (P = 0.04), but not during the afternoon sessions.

The subjects' average KSS ratings are shown in Figure 7. The profiles of KSS ratings remained similar throughout the study for the control group, as expected in the constant protocol. In the sleep restriction group, there was an increasing trend in the average KSS ratings during days SR1–SR5, compared to the adaptation and baseline days, and compared to the control group. Lower KSS ratings were observed on the recovery days, when the subjects again were allowed to sleep for 8 h. Subjects in both the sleep restriction and control groups in general rated their sleepiness to be greater in the morning immediately after waking up, corresponding to sleep inertia. The permutation test showed no differences between the sleep restriction and control groups during the different measurement sessions.

Group Level Correlation between HRV, PVT, and KSS

The correlation coefficients between the variable pairs HRV–PVT and HRV- KSS were calculated for the individual subjects during the 5 sleep restriction days. The average correlation coefficients with 95% CIs are presented in Table 2, together with the 2-sided Mann-Whitney U test for difference between the sleep restriction and control groups. The greatest average correlation was observed for HRV–PVT in the sleep restriction group. For the control group the respective correlation was consistent with zero. The average correlation for the sleep restriction and control groups was within error limits the same for the variable pairs HRV–KSS and PVT–KSS. The variable pair HRV–PVT was hence the only pair for which a significant difference between the sleep restriction and control groups was observed. The CIs for the average correlation in the two groups do not overlap.

The correlation coefficients between HRV power in the band [0.02, 0.08] Hz and PVT for individual subjects in the sleep restriction and control group are shown in Figure 8. The correlations were consistent on the individual level within the groups.

The partitioning of variance between the variables HRV power in the band [0.02, 0.08] Hz, PVT lapses, and KSS responses is shown in the Venn diagram in Figure 9A. The

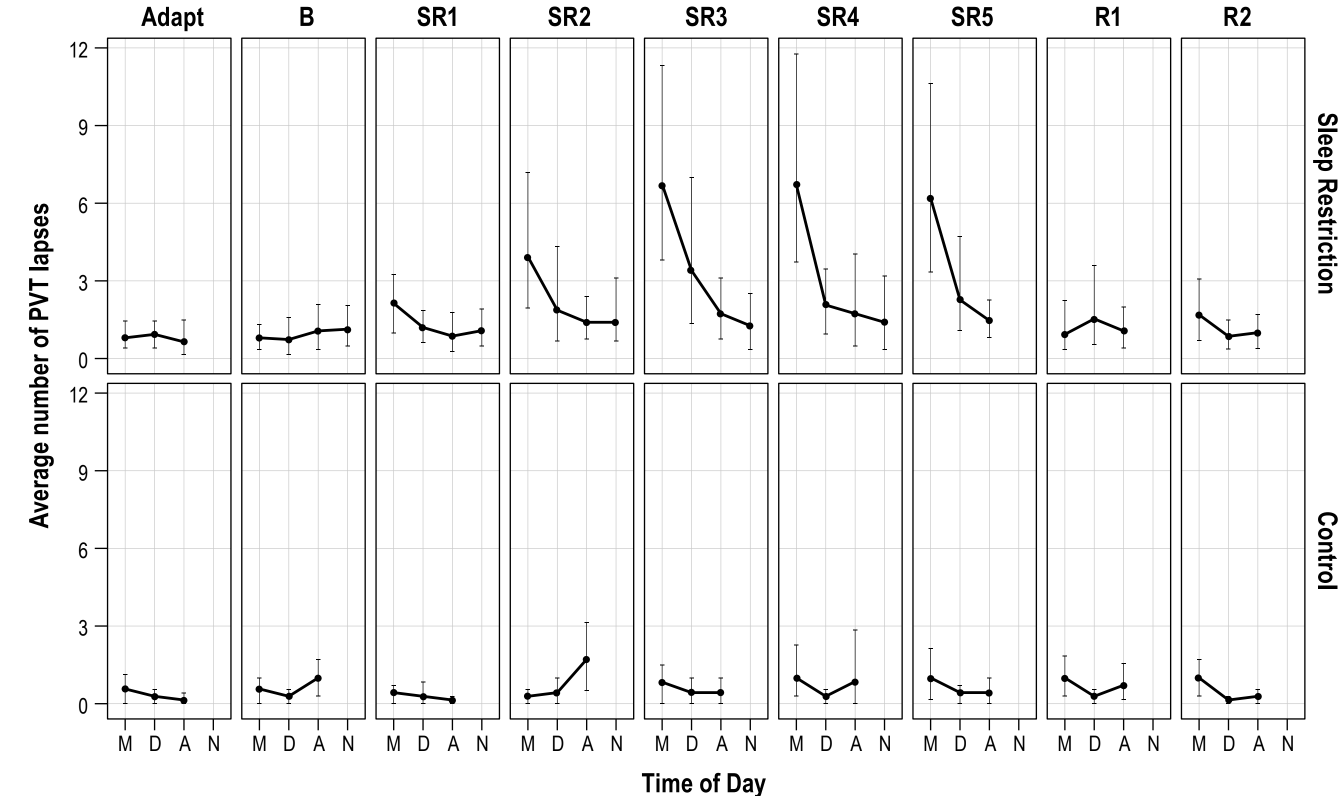

Figure 6—The average number of PVT lapses for each measurement session on each day. 95% bootstrap confidence intervals are marked using vertical bars. Adapt, adaptation; B, baseline; SR, sleep restriction; R, recovery; M, morning; D, midday; A, afternoon; N, night.

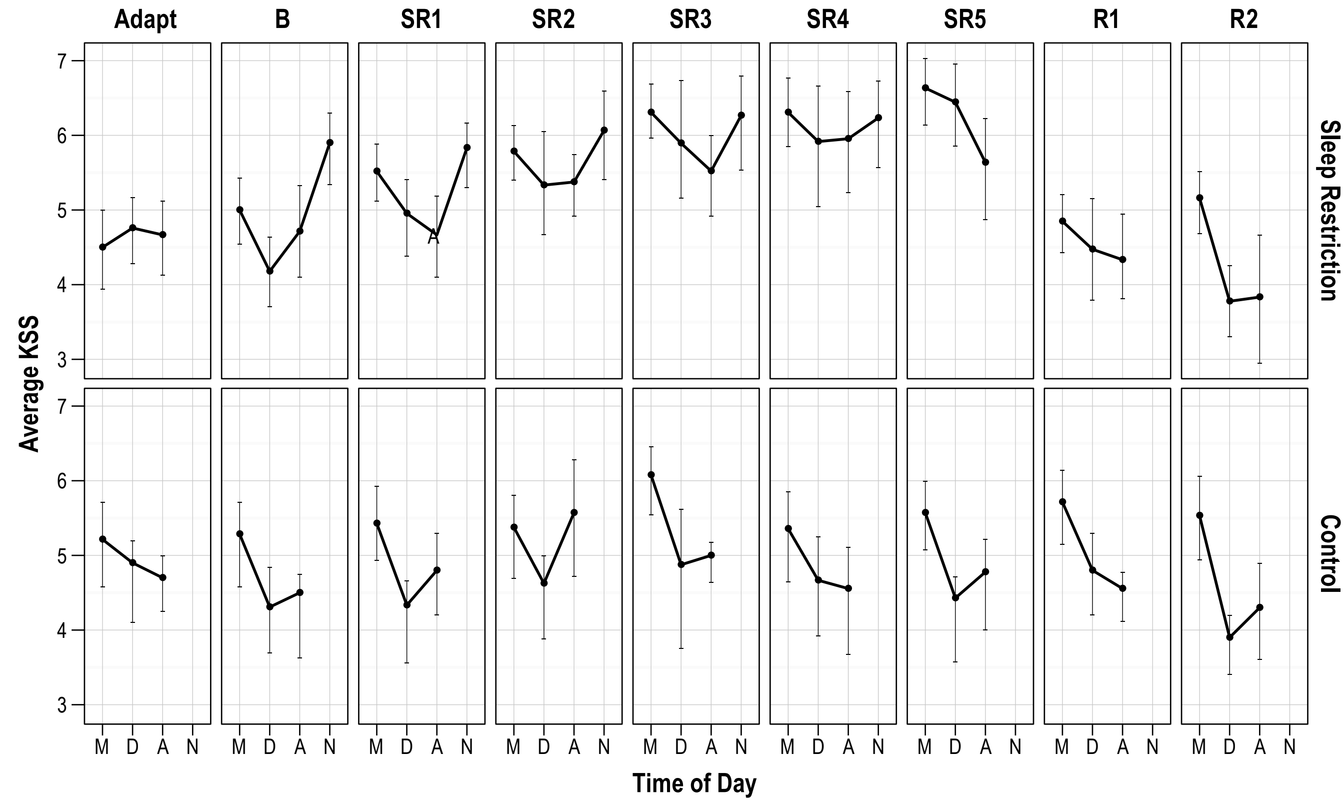

Figure 7—The average KSS ratings for each measurement session on each day. 95% bootstrap confidence intervals are marked using vertical bars. Adapt, adaptation; B, baseline; SR, sleep restriction; R, recovery; M, morning; D, midday; A, afternoon; N, night.

variance partitioning shows, that HRV and PVT share 25% of variance, while KSS shares only 11% of the variance with HRV. All 3 variables share only 8% of their variance. A total of 86% of the variance in KSS remains unexplained.

Modeling Sleepiness

The modeling of the relationship among HRV, PVT, and KSS was performed as described above. The model parameters for HRV power in the [0.02, 0.08] Hz band, PVT lapses, and KSS values (for comparison) are shown in Table 3. The partitioning of variance from modeling HRV–PVT is presented as a Venn diagram in Figure 9B.

The modeling of the relationship between HRV and PVT showed, that there are 4 components contributing to the variation in PVT values: (1) the variance uniquely shared between HRV and PVT (15%), (2) the variance uniquely shared between the model and PVT (8%), (3) the variance common to the model, HRV and PVT (18%), and (4) the variance PVT shares with HRV and the model (15+18+8 = 41%).

Hence, HRV power explains 33% of the total variation in PVT, of which 18% is shared with the model. The 3-component model uniquely shares only 8% of variance with the PVT and hence adds little extra information beyond that covered by HRV.

To investigate the importance of the 3 individual components in the alertness model when modeling HRV, PVT, and KSS, the coefficient of determination was calculated separately using one component at a time. The results are shown in Table 4. The sleep inertia and circadian components are the most important model parameters for both HRV and PVT. The homeostatic component is of little importance and could be left out when modeling HRV and PVT without loss of much information. The fact that the homeostatic component is not essential implies that the model represents a circadian cycle with a period of 24 h.

Table 2—Average correlation coefficients and 95% bootstrap confidence intervals (CI) using the BC*a* method, and the P-value for the two-sided Mann-Whitney U test for difference in medians of the two groups.

Variable Pair	Control Group Mean (95% CI)	Sleep Restriction Group Mean (95% CI)	P-value
HRV–PVT	0.02 (−0.14, 0.42)	0.57 (0.44, 0.68)	0.01
HRV–KSS	0.39 (0.24, 0.49)	0.33 (0.16, 0.46)	0.84
PVT–KSS	0.30 (0.14, 0.46)	0.31 (0.17, 0.45)	1.00

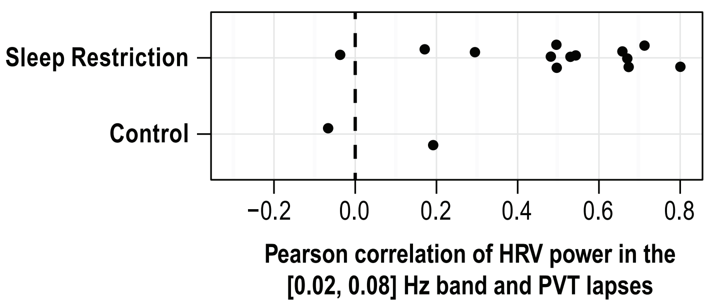

Figure 8—The correlation coefficients for individual subjects between HRV power in the [0.02, 0.08] Hz frequency band and PVT lapses for the sleep restriction and control groups during the sleep restriction days.

DISCUSSION

In this study, we investigated the use of HRV metrics as an indicator of vigilant attention and subjective sleepiness by exploring the association between HRV spectral power, PVT lapses, and KSS responses.

Our results showed that the magnitude of the correlation between HRV and PVT or KSS varied depending on the HRV frequency band. The highest correlation

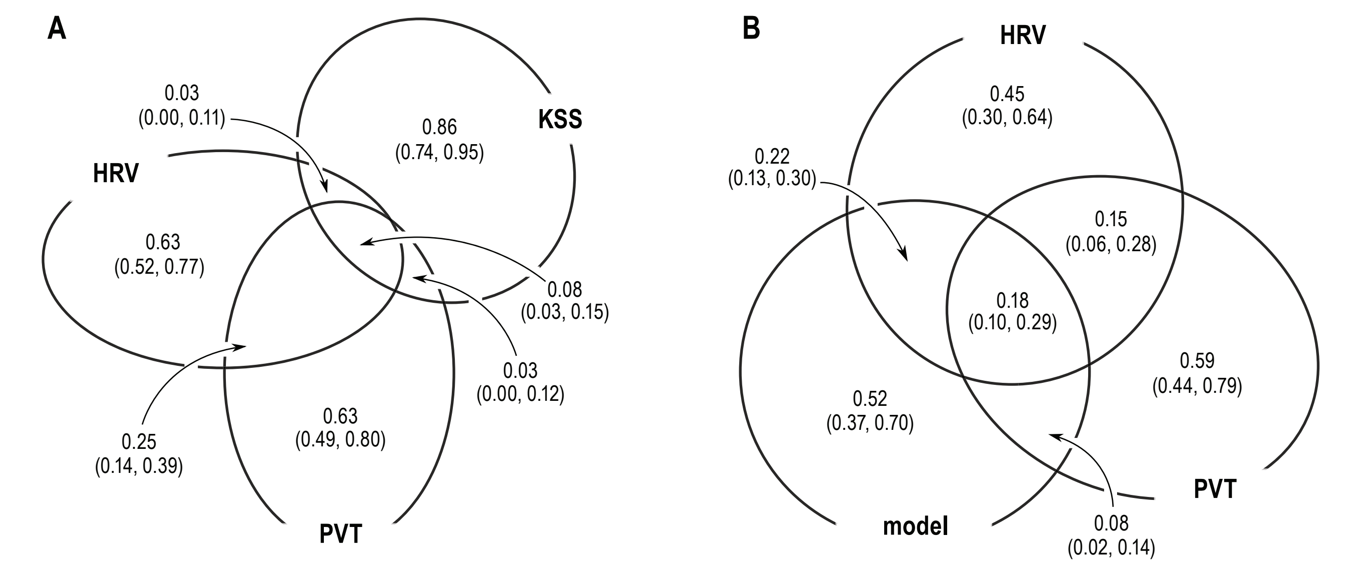

Figure 9—**(A)** The partitioning of total variance when investigating the relationship between HRV power, PVT lapses, and KSS ratings. **(B)** The partitioning of total variance when investigating the relationship between HRV power, PVT lapses, and the alertness model. 95% bootstrap confidence intervals are in parentheses.

between HRV power and PVT lapses (0.60) was found in the band [0.01, 0.08] Hz. This frequency band also showed the highest correlation (0.34) between HRV and KSS. The correlation between HRV and PVT was only present for subjects in the sleep restriction group.

Modeling of the association between HRV power and PVT lapses using the three-component alertness model showed that HRV power explained 33% of the variance in PVT lapses, of which 18% was shared with the alertness model. KSS showed minor association with HRV or PVT.

Based on these results, we conclude that HRV is indicative of vigilant attention measured by PVT in conditions involving some degree of sleep restriction, and that the frequency band [0.01, 0.08] Hz is of special interest when measuring vigilant attention.

Table 3—Estimates and 95% bootstrap confidence intervals (in parentheses) for the model parameters of HRV spectral power in the band [0.02, 0.08] Hz, PVT lapses, and KSS ratings.

	HRV	PVT	KSS
Intercept	−0.65 (−0.81, −0.46)	−0.57 (−0.76, −0.23)	−0.54 (−0.77, −0.20)
Inertia	1.07 (0.66, 1.41)	0.98 (0.50, 1.31)	−0.02 (−0.48, 0.44)
Homeostatic	0.03 (0.01, 0.05)	0.03 (0.00, 0.05)	0.06 (0.03, 0.08)
Circadian	0.44 (0.24, 0.67)	0.22 (0.06, 0.46)	0.50 (0.34, 0.69)
φ	2.29 (2.08, 2.73)	2.20 (1.74, 3.02)	1.24 (0.66, 1.62)

Table 4—Coefficients of determination of the individual components of the alertness model for HRV spectral power in the band [0.02, 0.08] Hz, PVT lapses, and KSS ratings.

	Inertia	Homeostatic	Circadian
HRV	33.82 (17.50, 49.06)	0.47 (0.00, 3.48)	27.99 (16.14, 39.04)
PVT	23.97 (12.18, 37.78)	1.53 (0.03, 5.87)	16.69 (8.42, 25.17)
KSS	3.01 (0.05, 13.69)	7.66 (1.62, 18.84)	9.92 (4.30, 16.13)

Values shown are in percent. Values in parentheses are 95% bootstrap confidence intervals, using the BC*a* method.

Correlations among HRV Power, PVT, and KSS

The exhaustive search over all HRV frequency bands revealed that the frequency band [0.01, 0.08] Hz showed the highest correlation with PVT lapses (0.60, 95% CI: [0.49, 0.69]). The same frequency band also showed the highest correlation between HRV and KSS (0.34, 95% CI: [0.19, 0.46]). The correlation for HRV–PVT was thus almost twice that of HRV–KSS. Generally, the correlations involving KSS were weak.

On the group level, only the variable pair HRV–PVT exhibited a significant difference in correlations between the sleep restriction and control groups. The observed correlation was significant only in the sleep restriction group subjected to partial chronic sleep restriction for the duration of a work week. The correlation between HRV power and PVT lapses was consistent on the individual level and attributable to sleepiness.

The correlation between the traditional VLF band was moderate 0.50 (95% CI: [0.39, 0.61]), but the CIs were wider than those of the ten best-performing bands. The correlation in the LF band was low and the HF band did not correlate with PVT lapses. The results hence imply that specific frequency bands should be used when evaluating vigilant attention using HRV power, instead of the traditional frequency bands used to study sympathetic and parasympathetic balance.

The correlations between HRV power and PVT lapses for the sleep restriction group in the present study agree with the results of Chua et al. under total sleep restriction.[10] In the study of Chua et al., the [0.02, 0.08] Hz frequency band showed a correlation of 0.68, comparable to 0.57 obtained in the present study. Also, the shape of the curve for the sleep restriction group showing the correlation between PVT lapses and bandpower in 0.01 Hz bands (Figure 3) in the present study is similar to the corresponding curve (Figure 2C) in Chua et al.[10]

Furthermore, the agreement between the association of HRV power and PVT lapses in studies using partial chronic or total sleep restriction provides important insight into the reproducibility of the results in different settings. The partial chronic sleep restriction of five consecutive nights used in the present study attempted to model a modern hectic work week. This setting provided an interesting possibility to evaluate the association between HRV spectral power, vigilant attention, and subjective sleepiness in a realistic setting common to everyday life.

It is also most interesting that the same HRV frequency band showed the highest correlation in the present study between both HRV–PVT and HRV–KSS, although the analysis also revealed that KSS is only weakly associated with both HRV and PVT. In fact, eight of the ten best-performing bands for HRV–PVT and HRV–KSS were jointly shared, though not in the same order. Our results, together with the study of Chua et al. thus suggest that the frequency band [0.01, 0.08] Hz indeed reflects some characteristic of vigilant attention. The present study indicates that the type of sleepiness measured by HRV power is more associated with vigilant attention measured by the PVT than by subjective sleepiness measured by the KSS. It is possible that this is due to the condition of partial chronic sleep restriction, which could impair the ability to reliably self-assess the current level of vigilance.

It has previously been shown that the PVT and subjective sleepiness ratings perform differently in conditions of partial chronic sleep restriction. In the study by van Dongen et al., the number of PVT lapses increased over 14 days of sleep restriction, while ratings on the Stanford Sleepiness Scale increased first, but plateaued out after a few days.[28] Zhou et al. also found that sleep restriction did not have similar effects on neurobehavioral and subjective alertness measures.[29]

Shift work is known to disturb sleep and affect alertness.[30] In the study by Åkerstedt et al., it was found that the sleep duration of workers with work start times between 03:00 and 04:30 was less than five hours.[31] The alertness of these workers was also reduced compared to workers starting work at 08:00. Also, Sallinen et al. reported that the mean sleep duration for shift-working train drivers and train traffic controllers was on average 4.6 h and 5.7 h for traffic controllers and train drivers, respectively, between consecutive night shifts.[30] The subjects in the sleep restriction group in the present study were allowed 4 h of nightly sleep, which is comparable to sleep amounts of shift-workers with early start times. On the population level, 14% of the American population sleep less than 6 h during workdays.[32] A longitudinal study of sleep trends in the Finnish population from 1972 to 2006 revealed that approximately 10% of the population below 30 years of age, and more than 10% of the population aged 30–65 years sleep 6 hours or less per night.[33] In a study by van Dongen et al., it was found that nightly sleep periods of 4 h and 6 h resulted in performance deficits compared to 8 h sleep periods.[28] In future studies investigating the relationship between HRV power and measures of vigilant attention it would hence be interesting to include, e.g., 6–7 h of nightly sleep in chronic partial sleep restriction settings.

The Connection between HRV Power and PVT Lapses

We used a simple three-component alertness model to gain insight into the relationship between HRV spectral power and PVT lapses in the sleep restriction group. The modeling allowed us to partition the variance explained by HRV power and the alertness model and hence provided information on the origins of the correlation.

The modeling showed that both HRV and PVT contain processes that cannot be adequately explained by a simple circadian model, as 59 % of the total variation in the PVT values is left unexplained by the HRV power and the three-component model. Based on the partitioning of variance, HRV power accounts for the majority of the variance of PVT, while the unique contribution of the three-component model used in this study is small.

The most important model coefficients were found to be the circadian and sleep inertia components. It has been shown that the circadian pattern of the HRV frequency bands follows a cycle where the HF power component is reduced upon awakening and the LF power component increased.[34] This behavior was also observed in the time courses of HRV spectral power in the present study, where the circadian pattern of HRV was similar for both the sleep restriction and control groups. The HRV power peaked in the morning and gradually decreased during the day.

The increase in the average number of PVT lapses in the sleep restriction group in the morning session on the sleep restriction days can be explained by sleep inertia following awakening,[35] which was the dominant feature in the morning PVT sessions. The control group did not exhibit sleep inertia in the same degree as the sleep restriction group. The results regarding PVT lapses are in line with those of Mollicone et al., who showed that PVT performance worsened in a time-of-day and sleep dose-dependent manner as the number of sleep restriction days increased.[36] In their study, performance deficits were most visible in the morning, whereas the performance was stable in the afternoon and early evening despite chronic sleep restriction. In the study by Cohen et al., it was shown that PVT performance deteriorated both due to acute and chronic sleep loss.[37] Although sleep opportunities restored PVT performance for the first few hours following sleep, chronic sleep loss at the same time increased the rate of PVT performance deterioration. PVT performance was good during the circadian day and bad during the circadian night.

A possible explanation for the association observed between HRV power and vigilant attention measured by PVT is that the endogenous circadian rhythm affects both HRV power and vigilant attention, as was observed by Chua et al.[10] Hence, measurement of HRV spectral power carries information about the current phase of the endogenous circadian rhythm, which in turn reflects vigilant attention in sleep restricted subjects, as observed, e.g., in the study by Cohen et al.[37]

If the goal is to identify degradation of vigilant attention due to the effects of sleep loss, the measurement of HRV spectral power could provide information regarding the endogenous circadian rhythm of an individual that would be useful in predicting vigilant attention. For instance, a person's vigilant attention could be impaired already at noon, if this time corresponds to the person's circadian night. Such information would be extremely valuable in professions involving shift work or long working hours in safety-critical professions. Furthermore, HRV spectral power can be measured on-line, which is important in many circumstances.

Use of HRV Power for Sleepiness Measurement

The results of the present study indicate that spectral HRV power could be used to draw conclusions regarding vigilant attention in real-world settings in the future. There are, however, several issues to be considered before that. One of the issues is that our results suggest that baseline levels of HRV power are needed to assess the current level of vigilant attention. In addition, as evidenced by our data, the sensitivity of HRV spectral power does not adequately distinguish between slight decrements in vigilant attention during the course of an ordinary day for a person having slept a full 8-hour night. Hence, prior knowledge of the degree of sleep restriction is also needed, which might limit the use of this method.

Directions of Future Research

The fact that only a rather small and homogeneous group of young healthy males was studied limits the generalizability of the results. In the future, it is important to extend the results by studying also, e.g., females and older age groups. When doing so, particular issues and risks of adverse health effects that might be caused by the study and especially concern these groups need to be taken into account. The female hormonal profile differs from men, and must thus be taken into account in the planning of the study and in the interpretation of results. Aging itself increases the presence of medical conditions that can be worsened by sleep restriction. More thorough medical health screening and monitoring is thus needed when studying older age groups.

It should also be noted that in addition to direct effects of physical activity on HRV measures, it has also been shown that HRV is affected by factors such as alcohol intake.[38] Some questions have also been raised regarding the test-retest reliability of short-term HRV metrics.[39] The present study established that HRV power is potentially usable as a metric of vigilant attention in partial chronic sleep restriction settings due to the fact that HRV power reflects the circadian rhythm. In the future, field measurements and investigations of the reproducibility of the results in naturalistic settings are needed.

CONCLUSIONS

Our results show that changes in HRV power reflect vigilant attention as measured by the PVT, under partial chronic sleep restriction. Our alertness model show that most of the association between HRV power and PVT lapses is attributable to the common variance shared between HRV, PVT, and the components of alertness, with the circadian and sleep inertia components as the most important model parameters. The use of HRV power for monitoring of vigilant attention is an interesting and important novel topic: our results open up new possibilities for online monitoring of sleepiness in occupational settings involving sleep restriction.

DISCLOSURE STATEMENT

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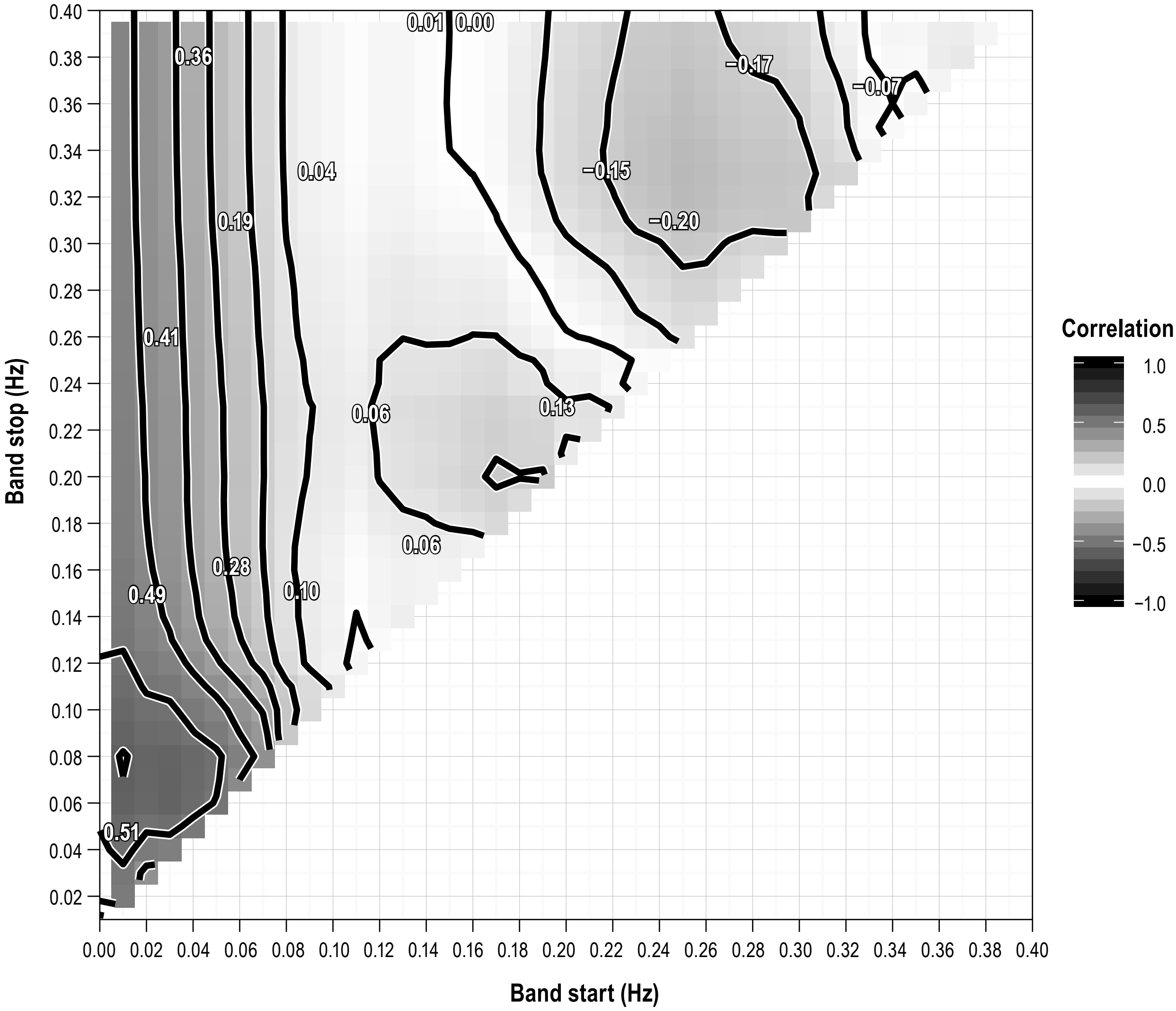

Figure S1—Correlation between HRV bandpower and PVT lapses for all possible frequency bands in 0.01 Hz discrete steps between 0.00 Hz and 0.40 Hz. The correlation $c_{i,j}$ between the sleepiness variable and the power in the HRV frequency band $[f_i, f_j]$ is given by the i^{th} row and j^{th} column in the matrix [0.00, 0.40] × [0.00, 0.40]. This matrix is here visualized as a contour plot. The same pattern as seen for the sleep restriction group in 0.01 Hz bands in Figure 3 is visible here; the correlation was positive and moderately strong positive for frequency bands located approximately below 0.10 Hz. Above this frequency, the correlations were weak and negative.