Circadian Components in Energy and Tension and Their Relation to Physiological Activation and Performance

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ABSTRACT

The purpose of the study was to examine validity of R. Thayer’s activation model regarding 24 h variations of two subjective dimensions of activation (Energy and Tension), and their 24 h relations with indices of physiological activation and performance efficiency. The participants of the study (n = 28 females) spent 26 h under controlled laboratory conditions. Self-ratings of subjective activation and measurements of oral temperature, electrodermal activity, and performance on a visual vigilance task were done every 4 h. Twenty-four-hour variations were examined by means of repeated measures analyses of variance and by group mean cosinor analyses before and after controlling for the data trends. Self-ratings on both dimensions of subjective activation showed significant 24 h variation. Energy showed both nonrhythmic and endogenously determined circadian variation, while 24 h variation of tension was dominantly nonrhythmic and most probably determined by exogenous factors. Significant 24 h covariation was found between energy and body temperature. A negative correlation between 24 h variation of energy and tension was also found. Considering low and intermediate levels of subjective activation established over the 24 h in this study, the
association of the two dimensions of subjective activation did not prove to be consistent with the assumptions of Thayer’s model.

**Key Words:** Circadian rhythm; Subjective activation; Temperature; Electrodermal lability; Vigilance task.

**INTRODUCTION**

In 1967 Robert Thayer started developing a two-dimensional activation model based on the self-report measures of activation states. He considered activation to be a result of integration of physiological and psychological processes generated in an organism and self-reported activation to be superior to any single physiological measure of activation. Thayer (1967, 1989) devised a scale called the Activation-Deactivation Adjective Check List or AD ACL for measuring nondirectional general bodily activation conceptualized similarly to that in Duffy (1972).

In Thayer’s studies the results obtained using the AD ACL grouped around two factors, called energy and tension, which constituted two main dimensions of his model (Thayer, 1967, 1986, 1989). According to the model, energy can vary from subjective feelings of energy and vigor to feelings of tiredness and sleepiness, while tension can vary from feelings of tension and jitteriness to calmness and placidness. In Thayer’s view energy most probably underlies the sleep-wake cycle and general physical activity, while tension mediates danger-related activities.

Thayer’s model (1978, 1989) assumes that energy and tension are not independent from one other. The nature of their relationship varies on different parts of an assumed continuum of energy expenditure. At low to moderate levels of energy expenditure, the dimensions are positively correlated. At high levels of energy expenditure, the correlation between them is negative, i.e., an increase in one activation dimension will produce a decrease in the other. For example, feeling extremely energetic and vigorous would reduce feelings of tension.

Thayer (1989) stated that energy showed spontaneous circadian variations, relatively independent of environmental influences. However, his statement was predominantly based on the results of studies conducted in natural settings during the participants’ normal waking period. They showed that energy was low upon waking, rose to peak around noon (Thayer, 1978) or early afternoon hours (Clements et al., 1976; Thayer et al., 1988), and then again fell to low values in the evening (Clements et al., 1976; Thayer, 1978; Thayer et al., 1988). The results of laboratory studies, which covered the entire 24 h period, showed pronounced 24 h variation of energy, but with a later peak around 16:00 h (Foret et al., 1998; Manenica, 1987; Proroković, 1996). According to Thayer (1989), tension showed less-pronounced 24 h variation and more situational specificity. Some authors failed to detect any 24 h change in that dimension (Bohlin and Kjellberg, 1973; Manenica, 1987). In most studies tension showed weaker correlations with physiological variables and task performance measures than energy (Bohlin and Kjellberg, 1973; Thayer, 1967, 1968, 1978). The only opposite findings were reported by Proroković (1996).
Existing results of laboratory studies consistently show 24 h variation of energy (e.g., Åkerstedt et al., 1977; Foret et al., 1998; Fröberg, 1977; Manenica, 1987; Proroković, 1996) and indicate the circadian rhythm of that activation dimension. However, the parameters of its rhythm have not yet been estimated. The results of the 24 h variation of tension are conflicting and inconclusive (Bohlin and Kjellberg, 1973; Manenica, 1987; Proroković, 1996; Thayer, 1967, 1978), and it is not clear whether 24 h variation of tension has a circadian component at all. The nature of the relationship between energy and tension during the 24 h is also unclear. Furthermore, there are no experimental data on the 24 h relation between subjective dimensions of energy and tension and indices of physiological activation and performance efficiency.

The aim of this study was to explore 24 h variation in energy, tension, indices of physiological activation, and performance efficiency in a controlled laboratory setting. Such a setting is supposed to eliminate or control masking factors and enable detection of the circadian component in the variation of those variables, which is of particular importance regarding the variable tension.

A study aiming at detecting the circadian rhythmic component in the overt variations of psychological variables, i.e., performance, subjective activation, and mood, are complicated by special measurement issues. Time-of-day variations in psychological variables are thought to be generated by the interaction of homeostatic process (time since awake) and the circadian rhythmic process (Carrier and Monk, 2000). In addition, the practice effect and factors such as motivation of the subject, perception of the task, and distraction by some nontask events are known to influence performance efficiency (Monk et al., 1985). These factors, with the exception of the practice effect, can also interact in generating variation of subjective activation and mood. There are further problems of taking measurements during the span of normal sleep, resulting in sleep fragmentation or sleep deprivation and prolonged time since awake. Therefore, an approach has to be adopted to separate rhythmic processes from homeostatic and other nonrhythmic processes. This study attempted to distinguish variations due to endogenous circadian factors from those linked to exogenous factors using a mathematical approach, i.e., mathematical removal of linear data trends. In order to obtain nighttime performance and subjective activation readings, and minimize deteriorating effect of sleep deprivation, a technique of awaking subjects before measurements was used (Vidaček et al., 1988).

The studies that examine circadian variation of subjective activation rarely use questionnaires or checklists (Adan and Guardia, 1993), since the repeated and extensive self-ratings can easily become tiring to participants. However, when examining activation states and their 24 h variation, per se, the use of a more sophisticated list of activation descriptors is required. The Short Form of the AD ACL (Thayer, 1968) was used in this study, which is detailed enough to be reliable, and short enough not to become tiresome in repeated self-ratings.

Body temperature and electrodermal activity were chosen as the measures of physiological activation in this study. Body temperature is the most common indicator of circadian variation in physiological activation, and electrodermal activity (EDA) has been the most extensively used indicator of arousal in psychophysiological research (Boucsein, 1992). Various EDA parameters are
indicative of the activity of the sympathetic division of the autonomous nervous system. Tonic EDA parameters, i.e., level of skin conductance or resistance and frequency of nonspecific electrodermal responses, are used as indicators of general arousal (Boucsein, 1992). Surprisingly, chronobiological studies have not shown much interest in EDA. Some studies have assessed temporal variation in EDA over few testing times or only during the waking period (Bull, 1972; Hot et al., 1999; Kerkhof et al., 1981; Venables and Mitchell, 1996; Wilson, 1990), but only two studies analyzed EDA parameters over the 24 h (Vidaček et al., 1988; Radosvić-Vidaček, 1996). In the study of Vidaček and coworkers (1988), a significant time-of-day effect was found for skin conductance level during the performance of a visual vigilance task, and no difference was observed in mean acrophase either between morning and evening “types” or between introverts and extraverts. In the study of Radosvić-Vidaček (1996) cosinor analysis showed significant circadian rhythms for tonic level of skin conductance and frequency of specific electrodermal responses to signals in a vigilance task.

A vigilance task was chosen for measuring performance in this study since it represents a monotonous task particularly sensitive to changes in alertness (Blake, 1967; Harrison and Horne, 2000; Hoddes et al., 1973). The long and difficult version of the task was chosen to enable analysis of both quantitative (reaction time) and qualitative (errors) aspects of the 24 h variation in performance (Adan, 1993).

METHODS

Study Subjects

The participants of the study were selected from the population of psychology students at the University of Zagreb. The students participated in the experiment as a part of their study requirements. They were selected on the basis of their score in the Student Morningness-Eveningness Questionnaire—SMEQ (Šverko et al., 1979), whose psychometric properties were extensively explored in the population of psychology students (Košćec et al., 2001; Šverko and Fabulić, 1985). Only the intermediate “types,” whose scores were in the range of $M \pm 1$ S.D., were chosen to participate. It was assumed that otherwise the differences in the phase position between the morning and evening types could flatten the amplitude of group rhythms.

Out of those students who volunteered to participate, SMEQ results of 35 females and 4 males were within the expected range. Due to the small number of potential male participants, only female students were offered participation. Some 7 female students dropped out during recruitment procedure because of medical reasons or because they decided to quit after getting acquainted with the experimental procedure. Therefore, a total of 28 female students, who self-rated themselves as healthy, participated in the study. Their age ranged from 19 to 24 yrs ($M = 20.8$, S.D. = 1.4). Although 12 women reported to be smokers, none foresaw difficulty in restraining from cigarettes for 26 h when queried during an initial training session. During the course of the experiment, the smokers were occasionally
asked if they experienced difficulties in abstaining from smoking. None complained or left the study, for that or any other reason. Later comparisons of the self-reported activation of smokers and nonsmokers throughout the 26 h failed to reveal significant difference between the two groups.

Considering the gender structure of the sample, it was necessary to control for the phase of the menstrual cycle on the day of the examination. The experimental data on differences in self-rated mood and performance on different phases of the menstrual cycle are still inconclusive (e.g., Collins et al., 1985, Compton and Cohen Levine, 1997, Wright and Badia, 1999). A relative consensus has been reached only considering the occurrence of negative moods and somatic complaints in the menstrual phase (Patkai, 1985). Changes of the circadian rhythm of body temperature during the menstrual cycle have been reported; during the luteal phase an increase in mesor, a slight dampening of amplitude, and no change in acrophase have been observed (Lee, 1988; Wright and Badia, 1999).

In this study, the students could participate in the experiment in any phase of the menstrual cycle except for the menstrual phase. The phase of the menstrual cycle was arbitrarily estimated on the basis of the information about the duration of the cycle and the date of the last menses. On the day of the study, 10 women were estimated to be in the follicular phase, two in the ovulatory phase, and 8 in the luteal phase. Of the remaining 8 participants, 7 were taking oral contraceptives and 1 could not provide the date of the last menses. Later comparisons of the data obtained from participants studied in the follicular and luteal phase or on oral contraceptives revealed no significant differences between the groups in the 24 h variation of any of the studied variables.

**Study Procedure**

Seven participants took part in the study during July and August, and the rest from the end of September to mid-December. Subjects spent 26 h in the psychological laboratory under constant artificial lighting conditions, and with ambient temperature varying between 24 and 26°C, depending on season.

Each participant first came to the laboratory to get acquainted with the laboratory conditions, tasks, and experimenters 2–4 days before the commencement of study. The data on their medical condition, special dietary requirements, other habits, and engagements were collected in a structured interview in order to screen out subjects whose medical conditions did not permit participation (e.g., antiepileptic therapy) and to efficiently schedule the experiment (e.g., according to the menstrual cycle phase). Each subject participated in a training session during which all the variables were assessed in the same manner as in the experiment.

The study was organized and conducted in a way to comply with good practice principles enunciated in Touitou et al. (2004). The participants received thorough oral and written instructions about the experimental procedure and conditions. The written instructions represented the constitutional portion of an informed consent, which the prospective subjects took home and returned signed on the day of the experiment. It was also clearly explained that they could, without any consequences,
withdraw from the experiment at any point, if they felt they could no longer participate for any reason. Throughout the course of the experiment an on-call medical doctor was always present in the department.

On the day of the experiment, subjects came to the laboratory at 07:00 h. The seven measurements were taken every 4 h starting at 07:50 h on day 1 and ending at 07:50 h on day 2 the following morning. Between measurements participants remained in the laboratory reading, studying, listening to the music, or napping. Half an hour before each measurement, subjects were checked and awoken if napping. The subjects received three nourishing, but light, meals at 09:15, 14:00, and 21:15 h. Participants were not allowed to have any snacks between meals. Beverages containing alcohol, caffeine, and vitamin C also were not allowed. Smokers abstained from smoking during the course of the experiment. Each measurement session started with the assessment of oral temperature, and was followed by the measurement of electrodermal activity, self-rating of subjective activation, performance of the visual vigilance task, second self-rating of subjective activation, and determination of peak expiratory flow (PEF, an index of airways patency). The measurements taken after the vigilance task are not presented here. Each complete measurement session lasted 75 min.

Study Variables

Measures of Subjective Activation

Subjective activation was measured with the Short Form of Activation-Deactivation Adjective Check List—AD ACL (Thayer, 1968). It consists of 20 descriptors of activation states, which group around four primary factors (Energy, Wakefulness, Tension, and Calmness) and two secondary order dimensions (Energy and Tension). Each descriptor in the scale is self-rated on a four-point scale with the following points: 1 (“definitely do not feel”), 2 (“somewhat feel”), 3 (“feel quite a bit”), and 4 (“definitely feel”). The AD ACL was translated into Croatian and psychometric properties and cross-cultural equivalence of the scale were established (Košćec and Radošević-Vidaček, 2001). The translated AD ACL had the same factor structure as Thayer’s original one, and the Croatian descriptors loaded on the same four primary and two secondary components as expected. The only exception was the adjective quiet that under Thayer’s model comprised the tension dimension but in the Croatian translated version loaded on the energy dimension.

In this study the AD ACL was scored for the two dimensions of energy and tension, with energy being described by 11 and tension by 9 adjectives (Košćec and Radošević-Vidaček, 2001). The adjectives describing energy were active, energetic, vigorous, full of pep, lively, wide-awake, wakeful, sleepy, drowsy, tired, and quiet. The adjectives describing tension were still, placid, calm, at rest, tense, intense, clutched up, fearful, and jittery. E-Prime® computer software (Schneider et al., 2002) was used to present the scale on the computer screen. Total time needed for the ratings of the complete scale varied from 30 s to 2.30 min, depending on subject and time of day.
Measures of Physiological Activation

Body temperature was measured orally by a mercury thermometer (Zeal, \(+35/_{\circ}\text{C} + 39/_{\circ}\text{C} \times 0.1/_{\circ}\text{C}\)) for 10 min. During the measurement, subjects sat comfortably in an armchair. They were instructed not do drink anything in order to preserve normal mouth temperature 20 min before the measurement.

Electrodermal activity (EDA) was measured for 15 min while subjects sat comfortably in an armchair. Subjects were instructed not to move their head, body, or limbs, and to relax with their eyes open. The EDA was measured using the exosomatic technique. A constant current of 10 \(\mu\text{A}\) was applied through the Beckman Type Polygraph fitted with preamplifier 481B, amplifier 482AM8, and couplers 9842 and 9853A. The paper speed was 5 mm/s. The disc Beckman Ag-AgCl electrodes with the contact surface of 0.8 cm\(^2\), filled with the contact paste for registering EDA (TD-246, Med Associates), were used. The electrodes were attached to the participant’s medial phalanges of the second and third finger of the nondominant hand with adhesive collars and were additionally secured with a hypoallergenic adhesive tape. Before placing the electrodes, participants washed their hands with soap, and the electrode area was additionally cleaned with ethanol. The electrodes were placed on participant’s fingers at least 50 min before the first measurement and checked 20 min before each measurement session. In two cases the electrodes had to be replaced due to mechanical malfunction.

The frequency of nonspecific electrodermal responses was chosen as a tonic parameter of electrodermal activity indicating general arousal. Any change in skin resistance equal or more than 636 \(\Omega\) (pen deflection of 3 mm) was registered as a response, and the frequency of nonspecific electrodermal responses (NS.EDR freq) was counted per minute.

Measures of Performance

For the purpose of this study, a visual vigilance task was designed with the E-Prime\(^\text{®}\) computer software (Schneider et al., 2000). Three versions of the task were originally designed and tested on a separate group of 14 participants. The first two versions were not sensitive enough to allow for the analyses of both performance accuracy and speed and were therefore disregarded. The final version of the task, as used in this study, was selected as the most appropriate regarding difficulty.

The presentation of the task and the instructions were computer-based. The duration of the task was 42 min. It consisted of 1260 stimuli that were combinations of three digits and two letters (e.g., 724CA). There were 30 combinations of three odd digits and two vowels (e.g., 379AE) that represented signals to which participant had to respond. The participant’s task was to press the spacebar key as quickly as possible whenever a signal appeared on the screen. The interstimulus interval was 1993 ms and the presentation of each stimulus lasted 243 ms. The average reaction time to signals (in ms) and average number of errors (omissions and commissions combined) per measurement were used as measures of performance efficiency.

It is well known that in the last measurement of an experiment, participants show an increase in performance and mood ratings due to increased motivation to complete
their participation in the experiment. Considering the psychological variables that were examined in this study, a seventh measurement at 07:50 h the second day was introduced to control for the last measurement effect. Thus, the data of only the initial six measurement sessions between 07:50 and 03:50 h were analyzed.

RESULTS

Kolmogorov-Smirnov testing showed the distribution of the results of each measurement session did not significantly differ from normal for any of the variables \((p > 0.01)\). The average time-of-day change in each variable is presented in Figure 1.

Testing for Time of Day Effect and Linear Trend

The data of the six measurement sessions were first subjected to repeated measures analyses of variance to determine time-of-day variation. The Greenhouse-Geisser epsilon was used for correcting the degrees of freedom, since Mauchley’s test of sphericity showed that the sphericity assumption was violated in all the variables. The analyses revealed a significant time-of-day effect for all the variables, except the NS.EDR freq (Table 1).

The significant \(F\)-ratios do not imply changes in the observed variables are in any way systematic, let alone rhythmic. Twenty-four-hour changes in biological and psychological functions can be due to both exogenous and endogenous factors, which could produce systematic changes of different shape. Linear changes would indicate influences of homeostatic process or exogenous influences, such as practice effects or fatigue, for example. The subsequent analyses of the observed data revealed a significant linear trend in the variables of energy, tension, signal reaction time, and number of performance errors (Table 1).

Testing for the Circadian Component

Cosinor analyses were conducted on each variable to explore for an endogenous rhythmic component of the 24 h variation. First, single cosinor analyses were conducted using the COSINA computer program (Monk and Fort, 1983). The data were fitted with a 24 h cosine curve to determine rhythmicity by means of the zero-amplitude test (\(F\)-test of variance explained by the cosine vs. straight line approximation) and to derive the rhythm parameters of mesor (a 24 h time series mean), amplitude (one-half the peak to trough variation), and acrophase (peak time of rhythm references to local midnight). The results of the single cosinor analyses were further subjected to group cosinor analyses (Nelson et al., 1979) that were adjusted to the SPSS computer program (Radošević-Vidaček, 1996). The results of the group cosinor analyses and the estimated 24 h rhythm parameters for variables with implied rhythmicity are presented in Table 1. Results of the zero-amplitude test revealed that the fitted 24 h cosine curve approximated the data of energy, tension, temperature, and vigilance task errors more closely than did a straight line.
We also tested whether significant rhythmic changes persisted after the observed linear trend was statistically removed from the data of energy, tension, and number of errors on the vigilance task. Cosinor analyses of these data (after removal of the linear trend in the variables) showed significant rhythmic variation only in energy, with somewhat lower amplitude and later acrophase (Table 1).

Figure 1. Mean 24 h change of energy, tension, oral temperature, number of nonspecific electrodermal responses (NS.EDR), signal reaction time, and number of errors.
Table 1. Results of repeated-measures ANOVA, testing for the linear trend, and cosinor analyses prior to and after removal of linear trend with estimated rhythm parameters.

<table>
<thead>
<tr>
<th>Variable</th>
<th>ANOVA</th>
<th>Linearity</th>
<th>Cosinor raw&lt;sup&gt;c&lt;/sup&gt;</th>
<th>Cosinor detrended&lt;sup&gt;c&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Greenhouse-Geisser epsilon</td>
<td>p</td>
<td>F&lt;sup&gt;a&lt;/sup&gt;</td>
<td>p</td>
</tr>
<tr>
<td>Energy</td>
<td>17.34</td>
<td>0.668</td>
<td>&lt;0.001</td>
<td>25.95</td>
</tr>
<tr>
<td>Tension</td>
<td>6.44</td>
<td>0.539</td>
<td>0.001</td>
<td>16.02</td>
</tr>
<tr>
<td>Temperature</td>
<td>32.51</td>
<td>0.565</td>
<td>&lt;0.001</td>
<td>1.50</td>
</tr>
<tr>
<td>NS.EDR freq</td>
<td>1.34</td>
<td>0.667</td>
<td>n.s.</td>
<td>0.09</td>
</tr>
<tr>
<td>Signal reaction time</td>
<td>5.46</td>
<td>0.710</td>
<td>0.001</td>
<td>14.32</td>
</tr>
<tr>
<td>Number of errors</td>
<td>20.20</td>
<td>0.650</td>
<td>&lt;0.001</td>
<td>38.31</td>
</tr>
</tbody>
</table>

<sup>a</sup>df = 5/135.
<sup>b</sup>df = 1/27.
<sup>c</sup>df = 2/84.
<sup>d</sup>Time of worst performance.
<sup>c</sup>M = mesor; 24 time series mean; A = amplitude (one peak-to-trough variation during 24 h), and Φ = acrophase (peak time referenced to local midnight)—all determined by cosine approximation of time series data by the method of least squares by a 24 h cosine curve (see text for further details).
Two sets of correlation analyses were performed to explore 24 h covariation of the different indices of activation and performance. First, the correlations on the intraindividual level were calculated. The observed results of each participant per variable were standardized over the six measurement timepoints, with the mean 24 h change of each participant set to zero (S.D. = 1). In this way the interindividual variability was removed from the data. After standardization, Pearson $r$ correlation coefficients were calculated for the sample of $N=168$ (28 participants $\times$ 6 measurements). The correlations are presented in Table 2.

A second set of correlation analyses was performed between the parameters of the estimated circadian rhythms in order to explore covariation at the interindividual level. The individual rhythm parameters of energy, tension, temperature, and number of errors on the vigilance task were correlated. These results indicate that knowing one rhythm’s parameter does not allow prediction of another rhythm’s parameter. The only exception was a moderate positive correlation of 0.52 ($p < 0.05$) between the acrophases of temperature and number of performance errors. The participants whose temperature rhythm peaked at earlier time also made the most mistakes at earlier hours.

**DISCUSSION**

In this study significant 24 h changes in both energy and tension were found, and cosinor analyses confirmed these changes to be rhythmic. However, a significant linear trend was also observed in both dimensions of subjective activation. A general fall in energy and a progressive rise in tension may have been the result of participants’ perception of the laboratory conditions, which included restriction of physical activity, constant light, deprivation of stimulants like nicotine and caffeine, and a generally calm and destimulating environment. In addition, fragmentation and reduction of sleep could have further decreased energy and increased tension during the night. After removing the linear trend, energy still exhibited rhythmic changes, while tension did not. This finding suggested strong endogenous circadian control of...
energy, and strong nonrhythmic determination of 24 h changes in tension. If there were an endogenous circadian rhythm of tension, it would have been detected, as in the case of energy. Laboratory conditions might have changed the characteristics of the variations, e.g., altering the amplitude or changing the mean level, but not eliminating the rhythm.

Other studies found that mood factors named tension and negative affect are situationally specific, and do not exhibit time-of-day variation in a healthy population, as reviewed by Monk (1994). For example, the laboratory studies of Monk et al. (1985) and Owens et al. (2000) failed to find time-of-day changes in tension and calmness (components of tension), while changes in sleepiness, wakefulness, and fatigue (components of energy) showed expected time-of-day variations. Monk (1994) also reported that time-of-day changes in negative affect are detectable in circadian rhythm disorders such as sleep deprivation, rhythm desynchronization due to shift work or jet lag, and in pathological states such as depression. Thus, for example, Prizmić et al. (1995) found significant time-of-day changes of negative affect in shiftworkers, but such variations have not been detected in day workers.

The well-documented 24 h rhythm of temperature was confirmed in our study. However, no systematic time-of-day change in another measure of physiological activation, frequency of nonspecific electrodermal responses, was found. The negative finding concerning 24 h variation in the frequency of nonspecific electrodermal responses was somewhat surprising. Bohlin and Kjellberg (1973) found that variations in the frequency of nonspecific electrodermal responses during the night were significantly correlated with variations in subjective activation (energy). Radošević-Vidaček (1966) found a significant circadian rhythm in the frequency of specific electrodermal responses to 72 signal stimuli presented during a visual vigilance task. The rhythm’s mesor was estimated to be 29.98 responses, amplitude 9.12 responses, and acrophase at 14:04 h. The frequency of specific and nonspecific electrodermal responses has been shown to correlate highly positively, and the same regulatory mechanisms were hypothesized (Crider, 1992). It was also found that the frequency of electrodermal responses changed linearly with change in activation level (Boucsein, 1992).

Negative findings concerning 24 h variation in the frequency of nonspecific electrodermal responses might be ascribed to factors that could elicit electrodermal responses in a state of a relaxed sitting lasting for a certain period of time. Thus, episodes of micro sleeps followed by sudden awakenings were observed in some participants during the nighttime. It is known that these conditions provoke electrodermal responses; therefore, individual differences in the level of sleepiness could have increased the variability of the results. Another factor that could have influenced the frequency of electrodermal responses may have been the occurrence of spontaneous cognitive processes that could not be controlled for. In the study of Radošević-Vidaček (1996), control of cognitive processes was obtained by the exposure of all participants to the same set of the vigilance task stimuli. The authors think the differences in the time-of-day variation of the different indices of electrodermal activity require further study.

Efficiency on most of the performance tasks is affected by repeated measurements, which can mask circadian influences on performance efficiency.
A way to deal with this unwanted influence is to practice the participants in a particular task. With the long and monotonous vigilance task, the practice sessions could negatively influence the participant’s motivation for performance, and therefore the results could reflect the willingness, rather than ability, to perform at a particular time of day (Colquhoun, 1981). In this study, the prolonged practice of the vigilance task could also alter the subjective activation on the day of study (e.g., enhance tension). Another way of dealing with the practice effect is to introduce participants to the experiment at different times of the day. However, that would not have allowed us to have control over the factors such as daily stressors, nutrition, intake of stimulative beverages, and daily activities before coming to the laboratory. The third approach could have been the use of an easier and shorter vigilance task (e.g., the 10 min PVT) that would allow for practicing the participants. Since we wanted to analyze both quantitative and qualitative aspects of 24 h variation in performance (Adan, 1993), we decided to use the longer and more difficult task and to deal with the practice effect by removing the linear trend from the data, if found.

Performance of the visual vigilance task in this study systematically varied over the 24 h. Inspection of the observed results indicated progressive shortening of the response latencies as well as reduction in the number of errors, which pointed to a practice effect. The results of the group cosinor analyses, conducted prior to removing the linear trend, documented a significant circadian rhythm in the number of errors indicating possible combined exogenous and endogenous influences on the 24 h variation in this performance measure. The peak and trough of this rhythm represented the inversion of the typical peak and trough in a number of vigilance detections obtained in other studies (e.g., Colquhoun et al., 1968). However, group cosinor analysis conducted after the removal of the linear trend indicated stronger exogenous determination of the 24 h change in the number of errors on this particular task. The other measure of performance efficiency, signal reaction time, did not show a significant rhythmic pattern, which means that its 24 h variation could exclusively be ascribed to the exogenous factor of practice. Vidaček et al. (1988) found significant 24 h change in signal reaction time and detections on the vigilance task, but the range of the change was small. Summarizing the results of a series of experiments, Colquhoun (1971) stated that the circadian change in reaction time on the vigilance task is highly dependent on experimental conditions.

In order to examine Thayer’s model of relationships between subjective activation, physiological activation, and performance, 24 h covariations of energy, tension, temperature, and performance efficiency in the vigilance task were analyzed. The level of activation was manipulated by measurements taken at different times of day that were expected to elicit different activation. It was hypothesized that the pattern of 24 h change in energy and tension should correspond to change in physiological parameters, if there was a firm connection between them as Thayer assumed. Correlation analyses were conducted in such a way to provide the answer about the relationship between current subjective and physiological activation states on the intraindividual level. Our results indicated similarity in the form of the 24 h variation of energy and oral temperature. Moderate positive correlation of 0.45 indicated a possibility of predicting the 24 h variation in one variable on the basis of the 24 h variation in the other. However, the results of the correlation analyses on the interindividual level did not support the assumption of stable individual differences.
in characteristics of the circadian rhythms of energy and temperature. These findings are consistent with those of other studies that explored 24 h covariations of body temperature with either energy or self-ratings of alertness (e.g., Åkerstedt and Fröberg, 1976; Bohlin and Kjellberg, 1973; Fröberg, 1977; Monk et al., 1985, Owens et al., 2000).

The 24 h variation of tension was not related to the 24 h variation in temperature, but contrary to expectations, it was correlated with variation in performance. The weak negative correlations indicated that performance was better (shorter reaction time, less errors) at the times when tension was higher. This finding could best be explained by the linear trends that dominated the 24 h variation in all three variables. Tension continuously rose throughout the experiment, while the number of errors and response latencies fell continuously. The mechanisms underlying such changes were different. The changes in the indices of performance were dominantly determined by practice effect, while the linear rise of tension was most probably the result of the perception of the experimental conditions, in addition to sleep fragmentation and reduction (e.g., Pilcher and Huffcutt, 1996).

In this study body temperature and performance efficiency did not covary over the 24 h period. On one hand, the covariation of temperature and performance over the 24 h was expected considering the nature of the task used. Performance on the tasks with low memory load that require continuous attention has been shown to covary with time-of-day change in body temperature (Colquhoun, 1971; Folkard and Monk (1985)). On the other hand, results of recent studies conducted with a constant routine protocol, indicate parallelism between the 24 h variation of body temperature and performance, regardless of the type of task used (e.g., Dijk et al., 1992). Current models argue that time-of-day variation in cognitive and psychomotor performance is determined both by the interaction of homeostatic process (time since awake) and the circadian rhythmic process, and that intertask differences in the 24 h variation in performance are the result of inadequate experimental control rather than different oscillatory control (Van Dongen and Dinges, 2000).

However, factors such as motivation of the subject, perception of the task, distraction by nontask events, and practice effect influence performance efficiency as well (Monk, 1994). The continuous improvement in performance speed and accuracy observed in this study indicates the practice effect overpowered both the detrimental influence of naturally occurring accumulation of sleep pressure as well as the circadian timing system influences. Since the practice effect obviously explains the majority of variance in the time-of-day change in performance efficiency, the covariation with endogenous sinusoidal variations in temperature could not have been found.

According to Thayer’s model at low to moderate levels of energy expenditure energy and tension are positively correlated, while at high levels of energy expenditure they are supposed to correlate negatively. This means that moderate energy can be experienced at the same time as moderate tension, while high energy and high tension cannot be experienced simultaneously. In this study the highest mean values observed at a particular time of day were 2.51 for energy and 1.91 for tension, while the theoretical values for both dimensions ranged from 1 to 4. Subjective activation was not expected to reach extremely high values, since the laboratory conditions were constant and understimulating. Under such conditions of
low to moderate activation the 24 h variation of energy and tension was significantly negatively correlated. Although the correlation was low, it meant that when energy was higher tension was lower, and vice versa.

In conclusion, our study shows the 24 h variation of energy has a strong circadian component and is related to the 24 h variation of body temperature. On the other hand, a circadian component in the 24 h variation of tension is nonexistent after mathematical removal of linear trend in the data. Furthermore, the present findings indicate that within the normal circadian range of energy and tension, higher energy is associated with lower tension. These findings do not provide support for Thayer's hypothesis of positive relationship between energy and tension at low and intermediate levels of activation.

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