Relationship Between Alertness, Performance and Body Temperature in Humans

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Running Title: Human Performance and Body Temperature
Abstract

Body temperature has been reported to influence human performance. Performance is reported to be better when body temperature is high/near its circadian peak and worse when body temperature is low/near its circadian minimum. We assessed whether this relationship between performance and body temperature reflects the regulation of both the internal biological timekeeping system and/or the influence of body temperature on performance independent of circadian phase. Fourteen subjects participated in a forced desynchrony protocol allowing assessment of the relationship between body temperature and performance while controlling for circadian phase and hours awake. Most neurobehavioral measures varied as a function of internal biological time and duration of wakefulness. A number of performance measures were better when body temperature was elevated, including working memory, subjective alertness, visual attention, and the slowest 10% of reaction times. These findings demonstrate that an increased body temperature, associated with and independent of internal biological time, is correlated with improved performance and alertness. These results support the hypothesis that body temperature modulates neurobehavioral function in humans.

Key words: Sleep Homeostasis, Circadian Phase, Neurobehavioral Performance, Forced Desynchrony, Core Body Temperature.
Introduction

Considerable effort has been devoted to understanding the relationship between body temperature and human performance (2;4;12;24;34;48). Kleitman (32-34) originally proposed that body temperature was an underlying mechanism regulating performance. “Assuming that the effect of temperature indicates that we are dealing with a chemical phenomenon, there are two interpretations of the relationship between temperature and reaction time possible: either a, mental processes represent chemical reactions in themselves, or b, the speed of thinking depends upon the level of metabolic activity of the cells of the cerebral cortex, and by the raising of the latter through an increase in body temperature we indirectly speed up the thought process.” pp. 501 (34). Kleitman’s hypothesis is supported by results from studies using in vitro and in vivo preparations in which it was reported that synaptic function is altered by supraphysiological changes in brain temperature (40),(39;47) such that higher brain temperatures resulted in faster transmission, whereas lower brain temperature resulted in slower transmission.

Brain mechanisms involved in the regulation of body temperature include the pre–optic area and the suprachiasmatic nuclei, both of which are located in the hypothalamus. The pre–optic area regulates homeostatic mechanisms to maintain body and brain temperature in mammals within a limited range in response to physiological and environmental conditions and the suprachiasmatic nuclei regulates the circadian or near-24-hour rhythm of temperature (28;43;44). Homeostatic and circadian mechanisms influence cutaneous vasodilatation, peripheral vasoconstriction and basal metabolism, all which change the rate at which body heat is lost and gained (36). The circadian peak to
trough range of body temperature, when examined under controlled environmental conditions (e.g., constant ambient temperature, constant dim light, supine posture, restricted activity and periodic nutrition intake), is ~ 1 °C. The daily pattern of brain temperature is reported to vary with the circadian rhythm of body temperature, although the rhythm in brain temperature was not tested in constant conditions that controlled for changes in wakefulness-sleep state (37). Yet, even under controlled conditions, the amplitude of the body temperature rhythm is reported to be influenced by other factors such as age (8;11;16;21) and menstrual cycle phase (6;49).

It has long been recognized that there exists a positive relationship between daily rhythms of body temperature and neurobehavioral performance and alertness in humans (4;32-34;38). During total sleep deprivation, increased homeostatic sleep drive results in impaired performance, but when examined under constant conditions, body temperature and neurobehavioral performance levels still exhibit a circadian pattern with higher levels during the habitual waking day and lower levels during habitual sleep time at night (5). The positive relationship between rhythms in performance and body temperature has been verified by studies that have controlled for factors that can influence body temperature and performance; such as light exposure, activity, posture, nutrition and drug intake (i.e., constant routine) (5;31;42;49-52). In studies that have manipulated body temperature via external means (e.g., altering ambient temperature, cold water immersion) it has generally been reported that cognitive function is improved by increasing body temperature slightly above the normal temperature of ~37°C and that cognitive function is reduced by decreasing body temperature below normal (3;23-26;46;48).
Low performance associated with low body temperature has also been reported in studies of shift work and continuous night operations (10;13;17;33). In forced desynchrony studies, which experimentally separate circadian and sleep-wake homeostatic influences on neurobehavioral function, it has also been reported that performance tends to be lowest during the biological night near to the minimum of the body temperature rhythm regardless of the duration of prior wakefulness (14;18;30;54). Yet, it has been unclear from prior studies whether performance is directly affected by body temperature or whether both body temperature and performance simply covary with circadian phase. To address the latter, we used a 28-hr forced desynchrony protocol to investigate whether higher body temperature levels were associated with higher neurobehavioral performance levels while controlling for both circadian phase and hours awake.

**Methods**

**Subjects**

Fourteen healthy adults, 3 females and 11 males (mean ± SD age 31.6 ± 6.4; range 20-41) participated. Participants each gave informed consent in writing. The Brigham and Women’s Hospital/Partners Health Care System Human Research Committee approved the procedures for the protocol. The investigation was conducted according to the principles expressed in the Declaration of Helsinki. Participants were healthy based upon medical history, physical and psychological exams, blood and urine chemistries and electrocardiogram. Toxicology screens for drug use verified that participants were drug free near the beginning of the screening process and upon admission to the laboratory.
Experimental Procedures

Participants maintained consistent sleep-wake schedules with approximately 8 hr of sleep for three weeks prior to admission, verified by call-in times to a time stamped voice recorder, sleep logs and for at least one week by wrist actigraphy (Minimitter, Sun River, OR). On days 35 to 49 of a 55-day inpatient protocol (53) participants were scheduled to a forced desynchrony protocol (Fig. 1) for 12 consecutive 28-hr days (18.66 hr of scheduled wakefulness and 9.33 hr of scheduled sleep). Subjects were scheduled to sleep in darkness and during scheduled wakefulness they were exposed to very dim room light. The first subject tested was exposed to ~3 lux in the angle of gaze (< 5 lux ambient at ~76 cm and < 15 lux maximum at ~183 cm in the direction of the ceiling fixtures) during the forced desynchrony. The remaining 13 subjects were exposed to ~ 1.5 lux in the angle of gaze (< 3 lux ambient and < 8 lux maximum). The 28-hr day length is known to be outside the range of entrainment of the human circadian clock under these dim light conditions, i.e., the circadian clock can not adapt to the 28-hr day length and instead it continues to oscillate at its near-24-hour intrinsic period (15;53).

Body temperature was measured every minute by means of a rectal thermistor (Yellow Springs Instrument Incorporated, Yellow Springs, OH), except during showers and bowel movements, and room temperature was maintained at ~24.5 °C as measured with an air thermistor.

Performance Tests

Participants performed a ~30 minute battery of neurobehavioral function tests every 2 hours beginning 2 hr after scheduled wake time. Working memory and cognitive throughput was measured with the Digit Symbol Substitution Test (DSST) and a
mathematical addition test (ADD). Recall memory was measured with the Probed Recall Memory (PRM) task and subjective alertness was measured with a visual analog scale (VAS). Visual vigilance/attention was measured with the Psychomotor Vigilance Task (PVT), for which we assessed the number of lapses, median reaction time, and the fastest and slowest 10% reaction time (19). These tests were selected because they are known to vary with the circadian rhythm of body temperature and to be sensitive to sleep loss (9;18;19;54).

Data Analysis

The intrinsic circadian period of the body temperature rhythm was estimated using a non-orthogonal spectral analysis technique. That is, temperature data were fitted with periodic components corresponding to both the forced period of the imposed sleep-wake cycle and the sought-for period of the endogenous circadian rhythm, together with their harmonics, using an exact maximum likelihood fitting procedure (7). This technique is described in detail in (41). Neurobehavioral performance and alertness data were then averaged into 60-degree (4-hr) bins with the phase of the body temperature minimum (Tmin) assigned to 0° and into 2-hr bins, from hours 2 through 16 of scheduled wakefulness. Body temperature data were averaged into 1-hr bins during scheduled wakefulness and averaged into 15-degree (1-hr) bins for the circadian component. Body temperature data are plotted for the hour during which the performance battery occurred. Performance data were transformed into deviation from the forced desynchrony mean in order to control for individual differences in performance capability. Performance scores were then categorized as being associated with the highest or lowest body temperature value for each separate circadian phase/hours awake bin for each individual. If more than
two performance tests and body temperature values occurred at the same bin, only the
scores associated with the highest and lowest body temperature level were used in the
ANOVA analyses. For example, if three performance batteries, with associated hourly
body temperature values of 36.8, 37.5, 37.8 °C, occurred at the 0° Circadian Phase/2 hr
Hours Awake bin, then the performance battery associated with the 37.8 °C body
temperature level was categorized as the “HIGHEST body temperature performance” and
the performance battery associated with the 36.8 °C temperature level was categorized as
the “LOWEST body temperature performance” for that bin. However, there were often
only two data points within each individual circadian/time awake bin. This is the reason
we selected a high versus low and not a high-medium-low analysis structure.

High-low body temperature test categorizations were distributed evenly across the
forced desynchrony protocol. Repeated measures ANOVA with factors HIGHEST VERSUS
LOWEST body temperature and TIME [circadian phase (degrees 0, 60, 120, 180, 240, 300)
or hours awake (hours 2, 4, 6, 8, 10, 12, 14, 16)] were analyzed. Modified Bonferonni
Correction Factors were used for determining significance of comparisons when there
was a significant interaction effect. Partial correlation techniques were used to examine
the relationship between body temperature level and raw performance scores for each
individual subject using all the tests performed by that subject, while controlling for both
circadian phase and hours awake.

Results

Results for most neurobehavioral performance measures and for body temperature
level showed significant main effects of factor TIME (Table 1). Performance levels were
lowest near the body temperature minimum and decreased across scheduled wakefulness
Furthermore, participants performed better when body temperature levels were highest at the same circadian and hours awake bin for cognitive throughput on the DSST (Fig. 3A), as evidenced by a significant main effect for the factor HIGHEST VERSUS LOWEST body temperature (Table 1). Addition performance tended to be better when body temperature was highest within a given circadian and hours awake bin (Table 1, Fig. 3B). Recall memory on the PRM task was better when body temperature was highest for the circadian component (Table 1). In addition, an interaction between factors HIGHEST VERSUS LOWEST body temperature and TIME revealed better recall memory within a bin near the middle of scheduled wakefulness when body temperature was lowest (Hour Awake 10; P = 0.0234), and at the end of scheduled wakefulness (Hour Awake 16; P = 0.0212) when body temperature was highest (Fig. 3C right panel). Across hours awake, alertness was rated higher when body temperature was high whereas a significant interaction between HIGHEST VERSUS LOWEST body temperature and TIME showed alertness to be higher at the phase of the body temperature minimum (Circadian Phase=0°, P= 0.00002; Fig. 3D). The number of lapses in attention on the PVT was fewer when body temperature was highest within a given bin, but only during the biological night (Circadian Phase=300° and 0°, P=0.0279 and P=0.0026 respectively; Fig. 4A left panel) as demonstrated by a significant interaction between factors HIGHEST VERSUS LOWEST body temperature and TIME (Table 1). Median reaction time and fastest 10% reaction time performance on the PVT did not significantly differ based upon HIGHEST VERSUS LOWEST temperature. The large variability in performance for median reaction times during the circadian bin 60 degrees was due to poor performance in one individual at that time. However, an analysis of the slowest 10% reaction time showed a
significant difference for HIGHEST VERSUS LOWEST body temperature for circadian phase and hours awake (Table 1; Fig. 4D).

Significant main effects for high-low temperature performance (Table 2) revealed that regardless of time awake or circadian phase, an increase in core body temperature of ~0.17 °C was associated with an improvement in performance for working memory and cognitive throughput on the DSST of approximately 2 correct answers and on the ADD of approximately 1 correct answer; an improvement of recall memory performance of only 0.12 words recalled; an improvement in subjective alertness of approximately 3 points; and a speeding of the 10% slowest reaction time by approximately 150 msec.

We next calculated individual subject partial correlations between body temperature level and neurobehavioral function level using all available tests conducted during the forced desynchrony protocol [90.93 ± 4.45 (mean ± SD), range 80 to 94 tests per subject], while controlling for the factors circadian phase and hours awake. We recognize that circadian phase is a circular variable, and therefore we computed the partial correlations assigning circadian phase both negative and positive (negative 180 to positive 180 degrees) and only positive (0-360 degrees) phase assignments. We observed a negligible difference between the two analyses (mean correlation difference of 0.003 ± 0.026 and the number of significant individual subject partial correlations were very similar). Most participants showed significant relationships between body temperature level and neurobehavioral function level while partialling out the influence of circadian phase and hours awake (Table 2). With the exception of recall memory (PRM), higher body temperature was significantly associated with better performance and alertness. As body temperature increased, working memory improved (DSST, ADD), subjective
alertness increased (VAS Alertness), visual attention lapses decreased (PVT number of lapses) and reaction time quickened (PVT Median reaction time, PVT Fastest l0% reaction time, PVT Slowest l0% reaction time).

**Discussion**

Overall, the current results demonstrate that changes in body temperature are associated with changes in human performance even after controlling for the effects of circadian phase and hours awake. Cognitive performance on the Digit Symbol Substitution Test, a measure of working memory requiring matching symbols and numbers, was better when body temperature was higher at the same circadian phase and hours awake. Cognitive performance on a two-digit mathematical addition test, as well as the slowest 10% reaction time performance on a 10-minute version of the Psychomotor Vigilance Task, tended to be better when body temperature was higher at the same circadian phase and hours awake. Although we observed a main effect for highest versus lowest body temperature performance and no interaction with time, it appears that the slowest 10% reaction time performance is best only during the biological night. The number of lapses in attention was fewer when body temperature was higher, but only during the biological night. Recall memory on a 6-word pair version of the Probed Recall Memory task was better when body temperature was higher at the same circadian phase, but results for hours awake were mixed. The reason for the mixed results for the Probed Recall Memory task for the high-low temperature performance analysis is unclear, but the task may not be sensitive to differences in body temperature since this was the only performance task that was not better when temperature was higher as assessed with the partial correlation analysis. Subjective alertness on the visual analog
scale was higher when body temperature was higher across hours awake and during the biological night at the phase of the body temperature minimum. Median reaction time and the fastest 10% reaction time performance on the Psychomotor Vigilance Task was however not significantly different between high and low body temperature at any circadian phase or hours awake bin. In general, these results indicate that a higher body temperature within the normal circadian range is associated with better performance regardless of circadian phase or hours awake. However, with respect to HIGHEST VERSUS LOWEST body temperature performance across circadian phase for subjective alertness and lapses in attention, neurobehavioral function was better when body temperature was higher during the biological night but not the biological day.

In the current study, individual subject correlations between neurobehavioral performance and body temperature, while partialling out the influence of circadian phase and hours awake, also showed that most neurobehavioral functions were better when body temperature was high than when it was low. This result in individual subjects is consistent with previous work that did not control for circadian phase and hours awake (23;24) and is also consistent with the HIGHEST VERSUS LOWEST group analysis of the current study.

The current result showing that body temperature was low during the biological night, increased near habitual wake time and was high during the biological day is consistent with previous work showing that body temperature is strongly influenced by internal biological time (6;14;49). The hours awake component showed body temperature to be low near scheduled wake time with an evoked increase in body temperature likely due to the shower and a decrease in body temperature thereafter. As
noted in the introduction, the results from previous forced desynchrony studies indicated that neurobehavioral function decreased across the day as a function of hours awake, and was worst during the biological night near the minimum of the body temperature rhythm (14;18;30;54). The present results are consistent with these past findings. However, in these aforementioned studies and in our study, performance was not evaluated immediately upon awakening from sleep; therefore, the reported pattern of decreased performance across the day does not include the influence of sleep inertia (impaired performance upon awakening from sleep). Additional research is necessary to examine the influence of circadian phase and sleep inertia on human performance.

The current results for the highest versus lowest body temperature performance are also consistent with results from studies in which performance was examined during and following extreme body cooling and heating (3;23-26;46;48). For example, Giesbrecht and colleagues (26) immersed participants in cold water that was 8°C for 55-80 minutes until participants body temperature was reduced from ~37.0 to 33.0-34.8°C, as measured in the esophagus at heart level. Compared to their performance prior to and immediately upon immersion when body temperature was near normal, participants performed significantly worse on cognitive tasks such as backward digit span and the Stroop interference test. Little effect of the reduced body temperature was observed for auditory attention or visual recognition. In general, results from others studies using similar methodologies support the finding that tasks with a high cognitive load are most affected by extreme changes in body temperature (12;48). The current study also found no effect of high versus low body temperature on median reaction time and the fastest 10% reaction time performance. However, when the slowest 10% reaction times were
analyzed, significant effects of high versus low body temperature were observed. These vigilance/attention results suggest that even tasks with a small cognitive load are also sensitive to changes in body temperature when examined in greater detail, specifically when the slowest reaction times are examined.

In other related studies, body temperature was raised and changes in performance reported (1;2;24;29;48). Wilkinson and colleagues raised subjects’ body temperature from the normal temperature of ~37.0°C, up to 37.3-38.5°C, by exposing subjects to a hot 43°C humid climate (48). Auditory vigilance performance improved as body temperature rose, whereas, addition performance improved when body temperature was increased to 37.3°C but worsened when body temperature was increased to 38.5°C. These results suggest that different types of brain function may have different zones of thermal sensitivity with respect to performance. In the current analysis of high-low body temperature performance, we found that a higher average body temperature of only ~0.15°C was associated with higher performance, suggesting that small changes in body temperature can influence human performance.

Reports from other areas of research provide evidence that altering body temperature level through pharmacological agents (melatonin, caffeine, modafinil) and bright light exposure also influenced neurobehavioral performance. For example, melatonin administration during the biological day decreased body temperature and reduced performance and alertness (20;27;35;45). Exposure to bright light and/or the ingestion of caffeine increased nocturnal body temperature level and improved performance when examined under controlled constant routine conditions (5;22;50;51). While these pharmacological, physiological and environmental stimuli are likely to affect
performance via mechanisms other than body temperature (e.g., blocking of adenosine receptors by caffeine), the findings from the current study suggest that the change in body temperature that was associated with these stimuli may have contributed to the change in performance that was observed.

While there are many factors that can influence body temperature, the mechanism underlying the variation in high versus low body temperature at the same circadian phase/hours wake bin is unknown and requires further study. However, it is evident that the spontaneous high versus low variations in body temperature at the same circadian phase and hours awake were not due to a) ambient temperature, since subjects were maintained in a comfortable constant temperature environment; b) ambient light exposure, since subjects were maintained in very dim light during scheduled wakefulness; c) changes in sleep-wakefulness state (28), since napping was proscribed and since performance and body temperature were assessed during wakefulness beginning 2 hr after scheduled wake time; d) nutrition intake, since the timing of meals were regularly scheduled; and e) drug intake or exercise, since they were both proscribed.

Overall, our present findings demonstrate the relationship between body temperature and performance while controlling for circadian phase and hours awake, they indicate that within the normal circadian range of body temperature a higher body temperature represents physiological arousal that enhances human performance, and they provide strong support for Kleitman’s hypothesis (32-34) that body temperature is an underlying mechanism modulating neurobehavioral performance. In other studies it has been reported that extreme body temperature heating or cooling resulted in impaired human performance. Whether body temperature and arousal influence performance
independent of each other is unclear from the present data and requires further study. However, taken together, these results are consistent with an arousal hypothesis asserting that within an optimal thermal zone a higher body temperature will be associated with a higher performance in humans.

Reference List


temperature and melatonin rhythms, sleep, and neurobehavioral function in humans
Figure Legends

Fig 1. Raster plot of 28-hr forced desynchrony protocol. Data are double plotted such that subsequent days are next to and beneath the other. Black bars represent scheduled sleep episodes. In this forced desynchrony protocol sleep and wakefulness are scheduled to occur 4 hr later each day.

Fig 2. Average high and low body temperature of 14 subjects across circadian phase (left panel – data double plotted) and hours awake (right panel). Error bars represent ±SEM.

Fig 3. Circadian phase (left panel – data double plotted) and hours awake (right panel) dependant variation of cognitive throughput/working memory [Digit Symbol Substitution Test (3-A), Addition Performance (3-B)], recall memory [Probed Recall Memory (3-C)] and subjective alertness (3-D) associated with high versus low body temperature. Neurobehavioral data are expressed in deviation from individual subject’s mean. Scores in the upward direction represent better performance. The group mean (N=14) is added to the high-low deviation scores to indicate the amount of change in performance. Error bars represent ±SEM. Dotted line represents the group mean.

Fig 4. Circadian phase (left panel – data double plotted) and hours awake (right panel) dependant variation of Psychomotor Vigilance Task (PVT) performance associated with high verses low body temperature [Number of lapses (4-A), Median reaction time (4-B), Fastest 10% reaction time (4-C) and Slowest 10% reaction time (4-D)]. Neurobehavioral data are expressed in deviation from individual subject’s mean. Scores in the upward direction represent better performance. The group mean (N=14) is added to the high-low deviation scores to indicate the amount of change in performance. Error bars represent ±SEM. Dotted line represents the group mean.
Fig 1.
Fig 2.

**Body Temperature**

- High Temperature
- Low Temperature

CIRCADIAN

HOURS AWAKE

![Graph showing body temperature and circadian phase against relative clock hour and hours awake.](image-url)
Fig 3.

Cognitive Performance

- High Temperature Performance
- Low Temperature Performance

3-A
Digit Symbol Substitution Test
Deviation From Mean Cognitive Throughput
3-B
Addition Performance
Deviation From Mean Cognitive Throughput
3-C
Probed Recall Memory
Deviation From Mean Number Recalled
3-D
Alertness
Deviation From Mean VAS (mm)

T_{min}=0^\circ
Circadian Phase

Hours Awake
Fig 4.

**Psychomotor Vigilance Task**

- High Temperature Performance
- Low Temperature Performance

**4-A**
Number of Lapses

**4-B**
Median Reaction Time

**4-C**
Fastest 10% Reaction Time

**4-D**
Slowest 10% Reaction Time

Deviation From Mean

Hours Awake

Circadian Phase

T_{min}=0^\circ

Fastest 10%

Slowest 10%

Worse

Better

4-C

4-B

4-A
Table 1. Summary of results of repeated measure ANOVA with factors HIGHEST VERSUS LOWEST body temperature performance and TIME (Circadian Phase degrees 0, 60, 120, 180, 240, 300 or Hours Awake 2, 4, 6, 8, 10, 12, 14, 16).

<table>
<thead>
<tr>
<th>Neurobehavioral Measure</th>
<th>HIGHEST VERSUS LOWEST Temperature Performance</th>
<th>TIME</th>
<th>HIGHEST VERSUS LOWEST Temperature Performance x TIME</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td><strong>F</strong></td>
<td><strong>F</strong></td>
<td><strong>F</strong></td>
</tr>
<tr>
<td><strong>Body Temperature – °C</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CIRCADIAN PHASE</td>
<td>99.81****</td>
<td>126.27****</td>
<td>1.48 (ns)</td>
</tr>
<tr>
<td>HOURS AWAKE</td>
<td>284.53****</td>
<td>16.65****</td>
<td>1.82 (0.094)</td>
</tr>
<tr>
<td><strong>DSST – Cognitive Throughput</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CIRCADIAN PHASE</td>
<td>23.18****</td>
<td>20.51****</td>
<td>0.40 (ns)</td>
</tr>
<tr>
<td>HOURS AWAKE</td>
<td>21.49****</td>
<td>6.53 ****</td>
<td>0.58 (ns)</td>
</tr>
<tr>
<td><strong>ADD – Cognitive Throughput</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CIRCADIAN PHASE</td>
<td>3.78 (0.074)</td>
<td>10.56****</td>
<td>0.65 (ns)</td>
</tr>
<tr>
<td>HOURS AWAKE</td>
<td>3.93 (0.069)</td>
<td>3.81 ***</td>
<td>0.97 (ns)</td>
</tr>
<tr>
<td><strong>PRM – Number Recalled</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CIRCADIAN PHASE</td>
<td>5.40*</td>
<td>1.83 (ns)</td>
<td>1.09 (ns)</td>
</tr>
<tr>
<td>HOURS AWAKE</td>
<td>5.51*</td>
<td>7.97****</td>
<td>2.47*</td>
</tr>
<tr>
<td><strong>VAS – Alertness</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CIRCADIAN PHASE</td>
<td>12.09**</td>
<td>11.40****</td>
<td>2.84*</td>
</tr>
<tr>
<td>HOURS AWAKE</td>
<td>9.29**</td>
<td>16.58****</td>
<td>0.91 (ns)</td>
</tr>
<tr>
<td><strong>PVT–Number of Lapses</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CIRCADIAN PHASE</td>
<td>2.36 (ns)</td>
<td>14.02****</td>
<td>2.71*</td>
</tr>
<tr>
<td>HOURS AWAKE</td>
<td>2.09 (ns)</td>
<td>8.25****</td>
<td>0.55 (ns)</td>
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<tr>
<td><strong>PVT–Median Reaction Time</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CIRCADIAN PHASE</td>
<td>1.32 (ns)</td>
<td>1.82 (ns)</td>
<td>0.96 (ns)</td>
</tr>
<tr>
<td>HOURS AWAKE</td>
<td>1.27 (ns)</td>
<td>1.42 (ns)</td>
<td>1.03 (ns)</td>
</tr>
<tr>
<td></td>
<td>Circadian Phase</td>
<td>Hours Awake</td>
<td></td>
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<td>------------------</td>
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</tr>
<tr>
<td><strong>PVT–Fastest 10% Reaction Time</strong></td>
<td>0.05 (ns)</td>
<td>16.21****</td>
<td>1.09 (ns)</td>
</tr>
<tr>
<td></td>
<td>0.00 (ns)</td>
<td>3.26 **</td>
<td>0.79 (ns)</td>
</tr>
<tr>
<td><strong>PVT–Slowest 10% Reaction Time</strong></td>
<td>4.45 (0.055)</td>
<td>6.11****</td>
<td>1.42 (ns)</td>
</tr>
<tr>
<td></td>
<td>4.80*</td>
<td>3.96***</td>
<td>1.19 (ns)</td>
</tr>
</tbody>
</table>

* P <0.05; ** P < 0.01; *** P < 0.001; **** P < 0.0001 ns, not significant; number in parentheses represent trends (P < 0.10); df HIGHEST VERSUS LOWEST temperature performance 1,13; df TIME and df HIGHEST VERSUS LOWEST temperature performance X TIME: Hours Awake 7,91; Circadian Phase 5,65.
Table 2. Summary of Results for individual subject partial correlation analysis (N=14) between body temperature and neurobehavioral function while controlling for circadian phase and hours awake.

<table>
<thead>
<tr>
<th>Neurobehavioral Measure</th>
<th>Number of Subjects With Significant Partial Correlations</th>
<th>Average±SD Individual Subject Correlation</th>
</tr>
</thead>
<tbody>
<tr>
<td>DSST – Cognitive Throughput</td>
<td>10</td>
<td>0.27±0.09</td>
</tr>
<tr>
<td>ADD – Cognitive Throughput</td>
<td>10</td>
<td>0.21±0.14</td>
</tr>
<tr>
<td>PRM – Number Recalled</td>
<td>1</td>
<td>0.07±0.11</td>
</tr>
<tr>
<td>VAS – Alertness</td>
<td>9</td>
<td>0.29±0.15</td>
</tr>
<tr>
<td>PVT–Number of Lapses</td>
<td>9</td>
<td>-0.25±0.16</td>
</tr>
<tr>
<td>PVT–Median Reaction Time</td>
<td>10</td>
<td>-0.31±0.20</td>
</tr>
<tr>
<td>PVT–Fastest 10% Reaction Time</td>
<td>10</td>
<td>-0.25±0.18</td>
</tr>
<tr>
<td>PVT–Slowest 10% Reaction Time</td>
<td>9</td>
<td>-0.24±0.13</td>
</tr>
</tbody>
</table>