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Circadian rhythmicity of cognitive performance

Evaluated during a 50-hour ultrashort sleep-wake schedule

Abstract: It was investigated whether cognitive performance shows a circadian rhythm during a 50 h-long forced desynchrony sleep-wake-schedule. We asked whether it would be possible to estimate the circadian period of cognitive performance under such circumstances and how strong it correlates to subjective sleepiness rating as well as body temperature.

Cognitive performance was evaluated using the Bowles-Langley test (BLT), which estimates cognitive performance by capturing reaction time and counting errors in a 2-choice visual search task.

Power spectral densities (PSD) were estimated by the Lomb-Scargle periodogram [1]. The circadian period τ_c was estimated from peak PSD. PSD of BLT scores showed lowest, yet distinct, circadian amplitude.

In addition to the circadian period estimation we analyzed the correlation of the acquired variables against each other. Pearson's correlation coefficients were significant but varied strongly at a commonly low level.

Despite the obstacle of a plethora of influencing factors [2] BLT scores are sensitive to the circadian rhythm and provide correct estimates of τ_c compared to rectal body temperature (RBT) as reference. Subjective measures failed estimating τ_c.

Keywords: circadian rhythmicity, cognitive performance, sleepiness, spectral density estimation, Lomb-Scargle periodogram, periodogram

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1 Introduction

In our laboratory we investigated different approaches for predicting fitness for duty. Among them well known tests, like the psychomotor vigilance task [3] and the pupillographic sleepiness test [4] as well as alternative approaches, like predicting fitness for duty by assessing postural stability [5]. It has been shown, that the before mentioned tests are to some extend sensitive to the general degradation of human performance caused by prolonged wakefulness, sleep deprivation, low sleep quality and comparable factors.

The question arises, whether or not these general approaches are appropriate to predict the individual workplace performance particularly for cognitive demanding tasks. For completion, tests that focus on cognitive functions have been proposed.

In this contribution we focus on one of the latter: the Bowles-Langley test (BLT). As a first approach it is evaluated whether or not the test scores follow a circadian rhythmicity and whether or not the outcomes correlate to other variables modulated by the human circadian rhythm.

2 Material and methods

2.1 Experiments

Eight young volunteers (4 male, 4 female, age: $23 \pm 4.7\,\text{yrs}$) completed a forced desynchrony sleep-wake protocol with 100 cycles of 20 minutes of wakefulness and 10 minutes of attempted sleep. This schedule was inspired by the experiments of Lavie, yielding, for example, the forbidden zones of sleep [6]. This slightly more than two days lasting schedule is the least extent to assess the circadian rhythmicity of cognitive performance under controlled circumstances.
During the phase of attempted sleep subjects lay down and are allowed to sleep. During the phase of wakefulness a constant set of tasks were demanded, including BLT, subjective self-rating of sleepiness on the Karolinska

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sleepiness scale (KSS) and on a visual analogue scale (VAS). Three further tasks are still under analysis and therefore not reported. Rectal body temperature (RBT) was recorded continuously as an objective measure of the circadian rhythm.

The protocol was strictly adhered to. If any disturbance occurred during wakefulness, the laboratory staff was instructed to skip tests. The 20 minutes were not used up completely by the tests, leaving room for the subject to drink and eat within balanced constraints.

Prior to the experiments subjects were asked to keep sleep diaries over at least 10 days using a provided mobile device. Additionally body movement was recorded using a wrist-actometry device. Starting three days before and lasting until the evening of the experiments in-ear body temperature sensors were applied. The data acquired by these means was used to identify the individual circadian phase and to align the data of all subjects with respect to that phase.

2.2 Bowles-Langley test

The Bowles-Langley test (BLT) evaluates cognitive performance by capturing reaction time and counting errors in a 2-choice task. The frame set consists of a 4 x 5 checker board matrix with line patterns drawn on the white squares. A single pattern within that set of 10 can have a slight irregularity that has to be detected (Figure 1). The subject receives immediate feedback after each response.

Each subject was required to perform training sessions in order to a) minimize training effects during experiments and b) obtain an individual baseline (Figure 2). Therefore these training sessions were conducted at a time of day where the subject was alert.

The library of frame sets offers patterns of varying difficulty. According to the individual baseline performance of a subject the sets presented during experiments are randomly chosen with respect to the baseline performance, presenting a comparable workload with being neither too easy nor too difficult to solve.

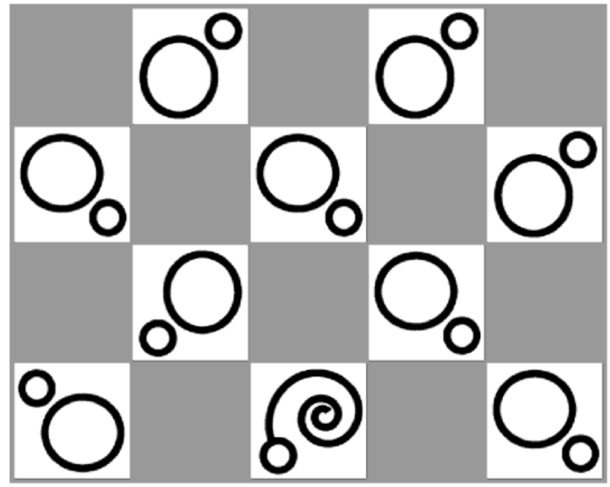

Figure 1: The BLT presents the user a series of 10 high contrast shapes. In this example, the subject is required to detect the deviating pattern in the middle of the lowest row and react accordingly within a limited period of time.

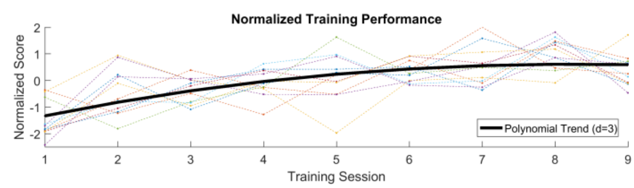

Figure 2: The average scores achieved during training sessions show that the achieved performance stagnates after approximately 7-8 training sessions.

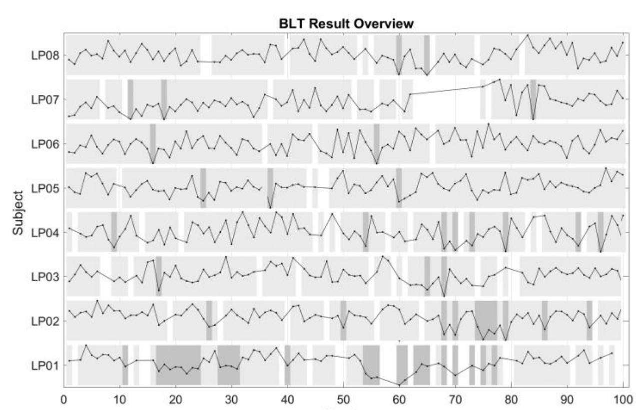

Figure 3: The normalized individual BLT scores of all subjects show highly dynamic behaviour without observable circadian rhythmicity. Dark gray backgrounds indicated failed tests, light gray backgrounds indicate passed tests, white backgrounds indicate skipped test sessions

2.3 Circadian period estimation

As described in section 2.1 the laboratory staff was required to skip tests if any disturbance would break the 10-20 sleep-wake pattern. The individual data of a subject therefore will have missing values. In contrast to, e.g. the modified periodogram, the Lomb-Scargle periodogram does not require an equidistant sampling of the data to be analyzed. Therefore methods of handling missing data and re-aligning deviating sampling times are not required. In order to estimate the beneficial effect of that aspect, we compared the outcome of the Lomb-Scargle method to applying the modified periodogram to resampled time series. The circadian period τ_c was estimated from peak PSD.

2.4 Correlation analysis

Correlation analysis was performed on an individual as well as a group averaged level. In the latter case data was z-scaled and aligned by the individual circadian nadir prior to calculating the mean over all subjects. After averaging no missing values remained, since there were at least 4 samples for each bin.

3 Results

PSD of BLT scores showed lowest, yet distinct, circadian amplitude culminating at $\tau_C = 24.0$ h. RBT, KSS, and VAS culminated at $\tau_C = 24.0$ h, $\tau_C = 21.3$ h, $\tau_C = 21.3$ h, respectively. There were only minor differences between the outcome of the modified periodogram and the Lomb-Scargle periodogram, peak PSD was not affected. Subjective measures failed estimating τ_c. Pearson's correlation coefficients differed vastly among the subjects, trends could not be identified.

Pearson's correlation coefficients for the averaged data between BLT and RBT, KSS, VAS were $r = 0.29$, $r = -0.12$, and $r = 0.09$, respectively. In contrast, correlations between RBT and KSS, VAS were $r = 0.47$ and $r = 0.49$, respectively. Each correlation was significant ($\alpha = 0.01$).

4 Discussion

Among the z-scored variables, RBT yielded the highest PSD peak, followed by both subjective self ratings of sleepiness (KSS, VAS). Results could only be obtained from mean estimates; individual values of the variables had too small amplitude-to-noise ratios to estimate τ_c robustly.

The BLT data shows minor sampling jitter and since only group averaged data without missing values yielded any circadian period the modified periodogram performed as well as the Lomb-Scargle periodogram.

The chosen number of 9 training sessions seems to be sufficient for the initial rating of the subject.

5 Conclusion

Despite the obstacle of a plethora of influencing factors [2] BLT scores are sensitive to the circadian rhythm and provide correct estimates of τ_c compared to RBT as reference. Since individual BLT scores did not yield a reliable estimation of τ_c the test setup should be revised in order to eliminate additional factors as far as possible, e.g. the effects of the immediate feedback after each response need to examined.

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