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THE TICK-TOCK OF LANGUAGE: IS LANGUAGE PROCESSING SENSITIVE TO CIRCADIAN RHYTHMICITY AND ELEVATED SLEEP PRESSURE?

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The master circadian pacemaker emits signals that trigger organ-specific oscillators and, therefore, constitutes a basic biological process that enables organisms to anticipate daily environmental changes by adjusting behavior, physiology, and gene regulation. Although circadian rhythms are well characterized on a physiological level, little is known about circadian modulations of higher cognitive functions. Thus, we investigated circadian repercussions on language performance at the level of minimal syntactic processing by means of German noun phrases in ten young healthy men under the unmasking conditions of a 40 h constant-routine protocol. Language performance for both congruent and incongruent noun phrases displayed a clear diurnal rhythm with a peak performance decrement during the biological night. The nadirs, however, differed such that worst syntactic processing of incongruent noun phrases occurred 3 h earlier (07:00 h) than that of congruent noun phrases (10:00 h). Our results indicate that language performance displays an internally generated circadian rhythmicity with optimal time for parsing language between 3 to 6 h after the habitual wake time, which usually corresponds to 10:00–13:00 h. These results may have important ramifications for establishing optimal times for shift work changes or testing linguistically impaired people. (Author correspondence: christian.cajochen@upkbs.ch)

Keywords Syntactic processing, Constant routine, Language, Circadian rhythms, Gender-congruency effect

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INTRODUCTION

The suprachiasmatic nuclei (SCN), a population of some 20,000 neurons, beats time for every cell in the human organism and, hence, for all human activities in the course of the day. While both the molecular basis of the circadian oscillation and its repercussions on peripheral physiological functions have been investigated in much detail (Dardente & Cermakian, 2007; Foster & Kreitzmann, 2004; Hastings, 2003; Herzog & **Q1**, **Q2** Muglia, 2006; Hirayama et al., 2007), research on circadian regulation of central information processing is rare. On the other hand, there is mounting evidence that the circadian clock also controls diurnal variation in higher cognitive functions (for a review, see Schmidt et al., 2007).

Language processing requires a rather complex set of cognitive activation. Acknowledging the ubiquitous impact of the circadian system on cognitive functions, we assume that a circadian impact on the language system cannot be ruled out a priori. There are a small number of studies supporting the idea that an internal clock may mark time in language processing. For example, Reinberg et al. (1988) investigated circadian rhythmicity in prelexical access to syllables and sentence comprehension in linguistically impaired versus linguistically healthy school children's speech processing, and found that, at least for the healthy pupils, best performance for syllabic repetition was at 19:30 h, while sentence comprehension was best at 09:00 h. Oakhill and colleagues (Oakhill, 1986a, 1986b, 1988; Oakhill & Davies, 1991) conducted several experiments on text memory and integration at different times of day. They reported a shift from more superficial processing of a given text in the morning to a more meaning-based processing later in the day: the memory of participants for exact wording of the text was superior in the morning than evening, when they were attending to information central to understanding the text. Semantic processing has been reported to degrade in the early afternoon and improve in the morning (Folkard, 1975). In dementia research, some studies reported diurnal variation in word fluency measures, with performance peaks between 17:00 and 18:00 h (Yaretsky et al., 1995, 1996). Furthermore, Morton and Diubaldo (1993) tested diurnal variations in the processing of voicing. In a focused-attention paradigm for the processing of consonant-vowel combinations grouped according to the voiced and unvoiced stop consonants, a superior detection of voiced stimuli in the afternoon (13:30–16:00 h) than morning (08:30–11:30 h) group was reported. In a subsequent study, Morton and Diubaldo (1995) tested spelling proficiencies using a similar time-of-day design. The afternoon (13:30–15:00 h) group showed more phonetically inappropriate errors in comparison to the morning (09:30–11:00 h) group. The latter showed more phonetically appropriate errors. Dietrich (2006) observed circadian variation of syntactic processing in a chronometrical study, with subjects performing a syntactic comprehension task over 28 h of wakefulness. Performance was best in the late afternoon, around 19:00 h. In contrast to the studies mentioned above, which report time-of-day variations in language performance, Lingenhöhl (1980) found no time-of-day effect on the auditory perception of words.

A number of factors may have led to these contrasting results in the aforementioned studies. Obviously, these studies did not only differ in the domain of language (production vs. comprehension) and in the tasks used, but, moreover, they investigated different modules of language (spelling, text memory, word fluency, etc.). More importantly, time-of-day designs are unable to eliminate most masking effects on the diurnal variation. Any external factor, such as body posture, food, or light, and any internal factor, such as stress level or motivation, has the potential to mask the underlying circadian oscillation (Blatter & Cajochen, 2007; Herzog & Muglia, 2006; Hirayama et al., 2007). Therefore, the constant-routine protocol has been developed in which all known and relevant masking factors are held constant and reduced as much as possible (Czeisler et al., 1985; Mills et al., 1978). In addition, careful recruitment of participants helps reduce inter-individual differences, such as in chronotype, and in uncovering masking influences of the health and life status (e.g., drugs, shift work) on the inner biological clock (see Blatter & Cajochen, 2007). In the present study, a constant-routine design was chosen to test the hypothesis that the human brain follows a diurnal variation in language processing.

In recent years, many studies on word recognition in language comprehension have investigated the functional role of grammatical gender in natural language processing. In German, the grammatical gender of a noun determines which article has to precede it. In more detail, the definite article agrees in gender, case, and number with its corresponding noun. However, the system of German definite articles is not fully systematic and features a number of ambiguities. For our proposes, we only consider the nominative singular: $\text{der}_{\text{masculine}}$, $\text{die}_{\text{feminine}}$, and $\text{das}_{\text{neuter}}$. Grammatical gender plays an important role as a device to establish local and global coherence in sentences and discourse. Interestingly, gender plays a facilitating role in sentence processing because gender increases the cohesion of a sentence (Desrochers, 1986). In addition, gender cues may facilitate the recognition of words (Wicha et al., 2005), and gender can sometimes disambiguate homophones (Van Berkum, 1996). In languages that have gender agreement, incongruent gender marking usually slows the processing of the following noun relative to a congruent marking. This effect has been established as the Gender Congruency Effect (GCE; Friederici & Jacobsen, 1999; Schriefers, 1993). It is assumed the gender information given prior to a noun is relevant at a post-lexical stage of parsing a noun phrase (Seidenberg et al., 1984; West &

Stanovich, 1982, 1986; Wright & Garrett, 1984). Gender information provided by the context is active until it can be checked against the gender information provided by the noun. Thus, gender priming effects are described as a syntactic congruency check that takes less time for a gender-congruent element than for a gender-incongruent element. An alternative view assumes gender information is not checked postlexically but that there is a prelexical activation of the corresponding noun and, consequently, the search space in the mental lexicon is reduced (Wicha et al., 2005). However, the computational costs involved in preactivating all gender-matching nouns in a lexicon would be rather high, as the set of lexical items would be very large (O'Seaghdha, 1997; Tannenhaus et al., 1987).

We hypothesized that the human brain follows a daily pattern of sequential phases, varying from more to less capacity in language comprehension as assessed by minimal syntactic processing. Thus, we designed a syntactic decision task to investigate circadian modulation in minimal syntactic parsing. In the visual modality, masculine, feminine, and neuter nouns were presented, preceded either by a gender congruent (*die Biene*, "the bee") or an incongruent (*das Biene*) definite article. We expected to observe significantly higher reaction times for the incongruent than for the congruent condition (i.e., the gender congruency effect). By calculating the difference between the reaction times of the congruent and the incongruent conditions for each clock-time session, we were able to investigate circadian influences on the extra processing time for parsing an incongruent noun phrase.

MATERIAL AND METHODS

Participants

The recruitment of participants and the experimental protocol conformed to international ethical standards (Portaluppi et al., 2008). Participants were recruited by advertisement and then carefully screened for their actual health status and to minimize inter-individual differences. Ten young men (mean age 24.9; SD $\pm$ 2.96 yrs; range 21–29 yrs) were selected for study. By self-report, they were non-smokers and free from medical disorders, allergies, and alcohol or drug problems. Moreover, each individual's caffeine consumption was no more than four cups/day. All participants had no history of night or shift work or crossing more than two time zones for at least the three months prior to the study. One week before admission to the laboratory, the participants were examined by a medical doctor to verify their self-reported particulars.

None of the participants showed symptoms of a possible sleep disorder according to the Pittsburgh Sleep Quality Inventory (Buysse et al., 1989) or the Epworth Sleepiness Scale (Chervin, 2003), and none was in a depressed state according to the Beck Depression Inventory (Beck & Steer, 2006). All participants were right handed according to the Hand-Dominanz-Test (Steingrüber & Lienert, 1976) and native speakers of German. Furthermore, none suffered from dyslexia as assessed by dictations (Kersting & Althoff, 2004).

All participants were classified as intermediate chronotypes, based on the midpoint of sleep on free days adjusted for individual sleep deficit on work days as assessed by the Munich Chronotype Questionnaire (Roenneberg et al., 2007). The average midsleep time on free days, corrected for sleep deficit, was 04:38 h (SD $\pm$ 0.38 h; range 4.01–5.12 h). The average habitual bedtime was 22:51 h (SD $\pm$ 1.08 h; range 22:00–01:00 h), and the average wake time was 07:03 h (SD $\pm$ 1.17 h; range 05:00–08:30 h). Subjects were instructed to keep a regular sleep-wake schedule during the last week prior to admission to the study facility for assessment under constant routine conditions. Compliance was verified by sleep diaries and wrist actimetry ("Actiwatch"; Cambridge Neurotechnology Ltd, Cambridge, UK). The latter is a non-invasive method of monitoring human rest-activity cycles (Chevalier et al., 2003).

Procedure of the Constant Routine (CR)

The participants were studied during 40 h of constant wakeful bedrest (starting at 08:00 h) as part of a larger study on circadian rhythmicity in cognitive function. The evening before the CR start, participants attended a practice session. Practice sessions are important to become familiarized with the tasks and characteristics of the CR and are commonly conducted before commencement of the CR protocol (Blatter et al., 2005; Bratzke et al., 2007; Frey et al., 2004) Additionally, they spent a baseline night before as well as a recovery night after the CR sleeping in the laboratory. During the CR and practice session, subjects were kept under controlled conditions of dim light ($\sim$10 lux), temperature (20–23°C), and meals (i.e., small isocaloric snacks were eaten at hourly intervals with water throughout to provide a constant energy supply). Participants were under constant surveillance of the experimenter to assure they remained awake. To minimize the masking effects of motor activity, they lay in a semi-recumbent position ($\sim$45º). Participants were allowed to read when not being tested. No external time cues were given, and no social interaction with other study participants was possible.

Procedure of the Syntactic Decision Task

The syntactic decision task was carried out at 3 h intervals starting at 10:00 h. Participants remained in bed for 40 h in a semi-recumbent position (with the head tilted up by 45°) at a distance of 70 cm from the computer screen. Their task was to perform syntactic decisions. Each trial began with the presentation of a fixation cross centered on the screen for 700 ms. Afterward, the cross was replaced by a definite article, and 250 ms later a noun was added on the screen. The noun was placed to the right of the definite article, while the definite article did not change position on the screen. Participants had to determine whether the definite article and the nouns formed a syntactically correct German noun phrase of the nominative case by pressing one of two response keys (Yes or No) as fast and accurately as possible. The time interval between the appearance of the noun on the screen and the time of the participant's key press response was defined as the reaction time in units of milliseconds (ms). For example, the German definite article *das* ("the") was set on the screen, and the noun *Biene* ("bee") was added to the definite article after 250 ms. In this case, participants had to press the "No" key as the accurate response because *das Biene* is a syntactically incorrect German noun phrase. The inter-trial interval was set to 1000 ms.

Stimuli and Tasks

The material consisted of 240 items (see Appendix). Every item appeared in a congruent as well as incongruent condition. The distribution of definite articles resembled that found in German language usage, with 50% masculine, 30% feminine, and 20% neuter articles (Bauch, 1971; Hohlfeld, 2006). The nouns were controlled by Equiword software, a program for constructing word lists (Lahl & Pietrowsky, 2006). Importantly, to avoid confounding with the independent variable, psycholinguistic properties of word lists should match as closely as possible. For example, the noun "flower" is more frequently used than the noun "daffodil," which determines a special kind of flower. When both words are used in reaction time tasks, we would expect faster reaction times for the word "flower" than for "daffodil," because the first one is definitely more frequent. Therefore, it is important to control for such influences on the dependent variable when word lists are used (Lahl & Pietrowsky, 2006). Equiword computes several coefficients of distance for word pairs according to a range of attributes. The material was automated by selecting words with the lowest distant coefficients for the following attributes: imagery, meaningfulness, Osgood's scales of evaluation, potency and activity, word length, and frequency of use in accordance to the CELEX database (Baayen et al., 1995). In the experimental word list, no more than three items of the same condition (congruent or incongruent) followed immediately after each other. All stimuli were presented in a white 28-point Courier New type font on a black background to avoid possible masking effects of ambient light levels >10 lux. The algorithm ran on Asus Pentium PC portable computers, using the Experiment Builder software (SR Research, Canada).

Psychometric Status

Participants rated subjective sleepiness, mood, relaxation, hunger, and bodily comfort on a scale from 1 (no impact) to 10 (severe impact), at hourly intervals (Wewers & Lowe, 1990). Subjective sleepiness was rated on the Karolinska Sleepiness scale (KSS; Akerstedt & Gillberg, 1990). All scales were programmed in electronic diaries and implemented using Palmtops (Tungsten E; Pendragon Forms 4.0).

Circadian Phase Marker

Melatonin was assayed in saliva samples collected under dim light and controlled posture conditions. Approximately 1 ml of saliva was collected at hourly intervals. Meals were scheduled after saliva collection to eliminate the influence of food on the samples. After meals, subjects were allowed to brush their teeth using water only. The analysis of melatonin in the saliva samples was accomplished by direct double-antibody radioimmunoassay, which has been validated by gas-chromatography-mass spectroscopy. The minimum detectable concentration of melatonin (analytical sensitivity) is 0.2 pg/ml, whereas the functional least detectable concentration using the $<20\%$ coefficient of interassay variation criterion is <0.65 pg/ml (Weber et al., 1997). The entire 24 h melatonin rhythm and the calculated dim light melatonin onset (DLMO) are essential representative indices of internal timing (Seithikurippu et al., 2007). In adults, DLMO can be defined as the time when a salivary concentration of melatonin ≥ 3 pg/ml is reached (Seithikurippu et al., 2007). In the present study, every participant reached the threshold of 3 pg/ml; thus, no low secretors were present.

Data Analysis and Statistics

As practice and learning can exert masking effects on the underlying circadian oscillation, we excluded the very first session prior to the baseline night, which served as a training session. Accordingly, 13 sessions remained for analyses. Reaction times and the accuracy of response were assessed and analyses of variance were conducted on both measures. The Kolmogorov-Smirnoff test confirmed the reaction-time data of the congruent as well as incongruent condition were distributed normally (congruent: Kolmogorov-Smirnoff-Z $= .92, p = .37$; incongruent: Kolmogorov-Smirnoff-Z $= .58, p = .89$). Thus, reaction times were subjected to a two-way ANOVA for repeated measures with the repeated factors condition (congruent vs. incongruent) and time (13 sessions). Post-hoc tests of differences between the sessions were conducted as a follow-up on the ANOVA for the factor time.

The design of the study protocol enabled us to calculate difference values between the incongruent and congruent condition for each experimental session, i.e., $D_{RT} = RT(incongruent) - RT(congruent)$. The dependent variable D_{RT} was analyzed using a one-way ANOVA with time as the repeated measurement factor.

The individual DLMO represents the internal time determined by the circadian pacemaker, as melatonin secretion by the pineal gland is controlled by the suprachiasmatic nuculei. Therefore, to adjust the data according to internal time, the clock-time points of testing were adjusted to the individual DLMO before averaging across all subjects. Thus, the time point of the DLMO was set to zero for every subject and used as an individual offset for internal time. Accordingly, the individual time-of-day reaction times were then converted to a distance from this "zero" time and binned in 3 h intervals (-3, 3, -6, 6, -9, 9, etc.) and averaged afterward across subjects.

Erroneous responses were excluded from the reaction-time analyses, as were reaction times that were more than two standard deviations beyond the participant's mean (per experimental condition and session). The percentage of outliers was 4.77% of the correct responses (97.88%). In all analyses, p values were, whenever appropriate, adjusted for violations of the sphericity assumption by the Huynh-Feldt correction.

RESULTS

Reaction Times

Gender congruency showed a significant effect on reaction times, with faster mean response latencies for congruent (970 ms; SD $\pm$ 145 ms) than for incongruent noun phrases (1082 ms; SD $\pm$ 184 ms, factor condition: $F[1,9] = 32.3$, $p < .001$, $\eta^2 = .78$). Furthermore, the factor time ($F(12,108) = 4.2$, $p < .05$, $\eta^2 = .32$), interaction condition (i.e., congruent vs. incongruent phrases), and time yielded significance ($F[12,108] = 2.9$, $p < .05$, $\eta^2 = .24$).

Paired t-tests, corrected for multiple comparisons, showed that almost all sessions evidenced significant differences between the incongruent and congruent reaction times ($p < .05$; see Figure 1, panel A). The only exceptions were the first two sessions, at 10:00 and 13:00 h the first day, and the sessions at 04:00, 10:00, and 13:00 h the second day.

For items of the congruent condition, participants showed slowest reaction times at 10:00 h the second day (1307 ms; see Figure 1, panel A). This nadir in performing congruent items was significantly different from performing congruent items during the other sessions, except for the

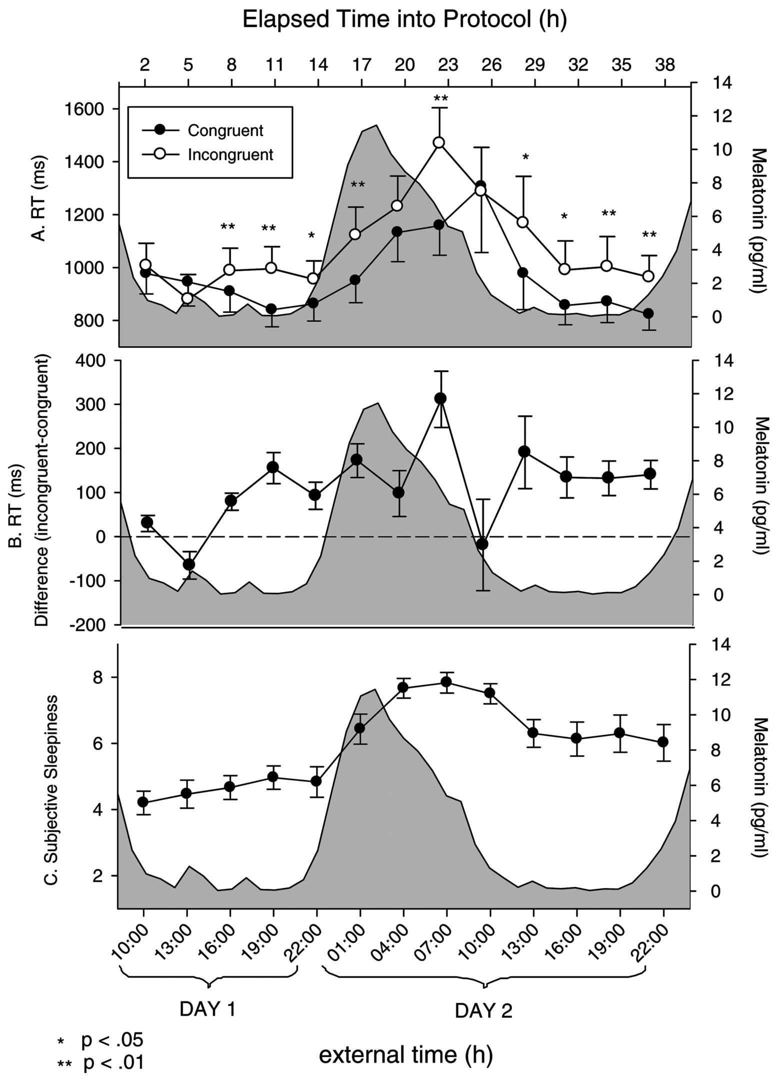

FIGURE 1 Time course of performance in a syntactic decision task and of subjective sleepiness assessed in 3 h intervals across 40 h of sustained wakefulness during constant routine conditions. Salivary melatonin (pg/ml) is represented in the background (grey). Presented are mean values and $\pm$ SEM (standard error of mean) for the participants (n=10). Data are plotted against average clock time and elapsed time into protocol. (a) Mean reaction times (RT, ms) in the congruent and the incongruent condition. Asterisks indicate significant differences between the RT of the incongruent and congruent condition, corrected for multiple comparisons. (b) Mean difference scores (incongruent minus congruent RTs). Asterisks mark significant differences from zero, corrected for multiple comparisons. Dashed line marks x-axis at 0. (c) Subjective sleepiness as assessed on the Karolinska Sleepiness Scale (KSS).

sessions at 04:00, 07:00, and 13:00 h the second day ($p < .05$). When parsing an incongruent noun phrase, participants took the most time at 07:00 h the second day (1453 ms; see Figure 1, panel A); thus, the peak time of the reaction times for incongruent noun phrase task occurred 3 h earlier than it did for the congruent reaction times. The findings of this 07:00 h session were significantly different from all other sessions during this CR, except the neighboring sessions at 04:00 and 10:00 h the second day ($p < .05$). The greatest difference in values of performing the congruent vs. incongruent tasks was found at the 07:00 h test time the second day (311 ms; see Figure 1, panel B), and the performance difference at this session was significantly different from that of all the other sessions ($p < .05$).

Internal Time

According to the individual DLMO of the subjects, gender congruency showed a significant effect on reaction times, with faster mean response latencies for congruent than for incongruent noun phrases ($F(1,7) = 22.34, p < .01, \eta^2 = .76$). Collapsing the reaction times for both congruent and incongruent items yielded a significant effect of the DLMO-adjusted time ($F(12,84) = 3.29,\ p < .05,\ \eta^2 = .32$). Two-way ANOVA with the repeated factor condition (i.e., congruent vs. incongruent) and DLMO-adjusted time revealed a significant interaction (condition × time: $F(12,84) = 2.3, p < .05, \eta^2 = .25$), which equaled the main effect of time on D_{RT}. To conclude, the results of the reaction time data, when analyzed according to the DLMO, yielded the same significant results as the aforementioned ones that were based directly on the mean reaction times of each session.

Error Percentages

Overall, the participants performed at ceiling (97.9% correct). There were significantly ($F[1,9] = 37.72, p < .001, \eta^2 = .81$) fewer errors in the congruent (0.3%) than incongruent condition (1.8%). On average, the highest percentage of correct answers was given at 22:00 h (98.5%) the first day and at 10:00 h (98.5%) the second day. Participants made the most errors at 04:00 h, on average 2.9% incorrect responses. However, the factor of time of day did not yield any significance for the error rates ($F[12,108] = 0.95, p = .48, \eta^2 = .096$).

Psychometric Status

Significant time-of-day effects ($F[38,266] = 8.26,\ p < .001,\ \eta^2 = .54$) were found for subjective sleepiness (KSS; see Figure 1, panel C) and subjective feeling of hunger, $F(38,266) = 3.9, p < .001, \eta^2 = .36$. There was a tendency of a time-of-day effect ($F(38,266) = 1.7,\ p = .06,\ \eta^2 = .2$) for subjective mood. There were no significant time-of-day effects for the subjective parameters of relaxation ($F[38,266] = 1.24,\ p = .27,\ \eta^2 = .15$)

and bodily comfort (F[38,266] = .59, $p = .373$, $\eta^2 = .08$). The highest subjective values for sleepiness occurred at 07:00 h the second day (7.9 on the KSS), for hunger at 13:00 h the first day (5.8), and for mood at 13:00 h the second day (6.7). Whereas the peak of subjective sleepiness coincided with the slowest reaction times of the incongruent condition, the feeling of hunger and mood did not coincide with the nadirs of reaction times.

Circadian Phase Marker

The mean DLMO of the participants occurred at 22:30 h (SD ± 96 mins, min=20:34 h and max=23.42 h). As expected, melatonin exhibited the well known circadian profile (F[38,266] = 7.15, $p < .001$, $\eta^2 = .7$) as shown in Figure 1, panels A–C.

DISCUSSION

Our results corroborate the Gender Congruency Effect (Friederici & Jacobsen, 1999; Schriefers, 1993), as congruent noun phrases were parsed faster than incongruent ones. However, the Gender Congruency Effect was not stable across the 40 h of imposed wakefulness, but exhibited significant time-of-day effects. Processing time for both the congruent and incongruent noun phrases were longer during the biological night, when endogenous melatonin levels were high, than during the subjective day, when endogenous melatonin levels were low. Although performance for both the congruent and incongruent items displayed a clear diurnal rhythm, with peak performance decrement during the biological night, the performance nadirs differed such that the worst syntactic processing of incongruent noun phrases occurred 3 h earlier (07:00 h) than that of congruent noun phrases (10:00 h). This was also reflected in a significant congruency type × time-of-day interaction. Thus, from a circadian perspective, it seems that performance of congruent phrases attains its maximal performance decrement 3 h later than the performance of incongruent phrases. This can be explained by the fact that congruent phrases are very easy to detect by native German speakers and thus can be performed at rather stable levels for a remarkable duration of sustained wakefulness. To our knowledge, this study is the first report showing a time-of-day dependency of the Gender Congruency Effect.

Overall reaction time performance after 38 h of scheduled wakefulness was not significantly impaired, despite the dramatic increase in subjective sleepiness in the course of the protocol (see Figure 1, panel A). Interestingly, analysis of the extra processing amount of an incongruent noun phrase revealed that the participants had no difficulties parsing an incongruent item as fast as a congruent noun phrase, even after 26 h of constant wakefulness (see Figure 1, panel B). However, reaction times were longer after 26 h of prior wakefulness at 10:00 h (day 2) than after only 2 h of prior wakefulness at 10:00 h (day 1), possibly reflecting a superimposed effect of elevated sleep pressure on the circadian profile of language processing. The number of unintentional sleep attacks resulting in performance lapses is highest after 24–26 h of prior wakefulness when it coincides with the circadian trough in the early morning (Cajochen et al., 1999; Graw et al., 2004), and this may explain the general increase in reaction time during the syntactic decision task at a time when the circadian pacemaker promotes sleep. It could also be that a practice effect on the syntactic decision task counteracted the effects of increasing sleep pressure across the 40 h protocol, thus leading to relatively stable performance at the end of the second day of sleep deprivation. Interestingly, there was no significant difference between parsing an incongruent or congruent item at 10:00 h the second day, but thereafter participants required significantly more time for incongruent noun phrases again, which cannot be explained by a learning effect on discriminating congruent from incongruent noun phrases faster.

Previous studies, which used tasks of mental arithmetic, logical reasoning, and tracking, found diurnal variation that showed a decrement during the night (Angus & Heslegrave, 1985; Dinges & Kribbs, 1991). As Monk **Q4**
and Carrier (1997) suggested, the increase in reaction times could be due to a change in mood or parameters of subjective comfort. Concerning the syntactic decision task, the nadir of the reaction times of the incongruent condition and the highest difference value at 07:00 h the second day coincided only with subjective sleepiness and not with other psychometric variables, thus supporting our earlier assumption that reaction times increased due to elevated sleep pressure. However, psychomotor slowing has been reported during the night as well (Monk & Carrier, 1997), which may have contributed substantially to the circadian rhythm that is being attributed to processing of the syntactic decision task.

Concerning the participant's accuracy, incongruent items were more error-prone than congruent items. Although the overall accuracy was high (97.88%), participants made the most errors at 04:00 h. Interestingly, the performance nadir in accuracy preceded the nadir in reaction times. Monk and Carrier (1997) pointed out that it is quite possible for people to approach a given task differently when sleep pressure increases. Thus, their strategy can change when there is need to fight off sleep (Williams & Lubin, 1967). Perhaps our participants realized their tendency to produce more errors and, consequently, in order to maintain accuracy, their performance resulted in slower response times. This phenomenon of slowing reaction time to increase accuracy has been referred to as the "speed-accuracy trade-off" (Angus & Heslegrave, 1985; Webb & Levy, 1982).

From a practical point of view, the present results have implications for shift work, dementia, and linguistically impaired people. For instance, the fact that shift workers' performance in communication is severely affected at non-optimal times results in reduced safety. Thus, finding optimal times for shift changes is crucial to increase safety in the shift work environment (for a review, see Åkerstedt et al., 2007; Driscoll **Q5** et al., 2007; Folkard, 2008; Petrilli et al., 2006; Signal et al., 2008). From a clinical perspective, our results may be of importance in assessing cognitive abilities of demented persons or linguistically impaired children. Based on the here-tested linguistic domain (i.e., minimal syntactic processing), our results indicate, from a circadian perspective, that the optimal time for parsing language is approximately 3 h after one's habitual wake time, which corresponds to around 10 a.m. in the majority of diurnally active persons.

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DECLARATION OF INTEREST

The authors report no conflicts of interest. The authors alone are responsible for the content and writing of the paper.

REFERENCES

Åkerstedt T, Ingre M, Kecklund G, Folkard S, Axelsson. (2008). Accounting for partial sleep deprivation and cumulative sleepiness in the three process model of alertness regulation. *Chronobiol. Int*. 25:309–319.

Angus RG, Heslegrave RJ. (1985). Effects of sleep loss on sustained cognitive performance during a command and control stimulation. *Behav. Res. Meth. Instr*. 17:55–67.

Baayen RH, Piepenbrock R, Gulikers L. (1995). *The Celex lexical database (CD-Rom)*. Philadelphia: University of Pennsylvania.

Bauch HJ. (1971). Zum Informationsgehalt der Kategorie Genus im Deutschen, Englischen und Polnischen. *Wissenschaftliche Zeitschrift Der Universität Rostock: Gesellschafts-und Sprachwissenschaftliche Reihe*, Heft 6.

Beck AT, Steer RA. (2006). *BDI-II Beck Depressions-Inventar*. Franfurt/M: Gregory, K. Brown Harcourt Test Services GMBH.

Blatter K, Cajochen C. (2007). Circadian rhythms in cognitive performance: Methodological constraints, protocols, theoretical underpinnings. *Physiol. Behav*. 90:196–208.

Blatter K, Opwis K, Munch M, Wirz-Justice A, Cajochen C. (2005). Sleep loss-related decrements in planning performance in healthy elderly depend on task difficulty. *J. Sleep Res*. 14:409–417.

Bratzke D, Rolf U, Rolke B, Peters M. (2007). Central slowing during the night. *Psych. Sci*. 18: 456–461.

Buysse DJ, Reynolds CF, Monk TH, Berman SR, Kupfer DJ. (1989). The Pittsburgh Sleep Quality Index: A new instrument for psychiatric practice and research. *J. Psychiat. Res*. 28:193–213.

Cajochen C, Khalsa SB, Wyatt JK, Czeisler CA, Dijk DJ. (1999). EEG and Ocular Correlates of Circadian Melatonin Phase and Human Performance Decrements during Sleep Loss. *Am. J. Physiol*. 277:640–649.

Chervin RD. (2003). Epworth Sleepiness Scale. *Sleep Med*. 4:175–176.

Chevalier V, Mormont MC, Curé H, Chollet P. (2003). Assessment of Circadian Rhythms by Actimetry in Healthy Subjects and Patients with Advanced Colorectal Cancer. *Oncol. Reports* 10:733–737.

Curran-Everett D. (2000). Multiple comparisons: Philosophies and illustrations. *Am. J. Physiol*. 279:R1–R8. **Q6**

Czeisler CA, Ronda JM, Kronauer RE. (1985). A clinical method to assess the endogenous circadian phase of the deep circadian oscillator in men. *Sleep* 14:295. **Q7**

Dardente H, Cermakian N. (2007). Molecular circadian rhythms in central and peripheral clocks in mammals. *Chronobiol. Int*. 24:195–213.

Desrochers A. (1986). Genre grammatical et classification nominale. *Can. J. Psych*. 40:224–250.

Dietrich R. (2006). Modularity and the tic-toc of language. In Fuss SG (ed.) *Form, structure and grammar: A Festschrift presented to Günther Grewendorf on the occasion of his 60th birthday*. Berlin: Akademie Verlag, pp. 299–311.

Driscoll TR, Grunstein RR, Rogers NL. (2007). A systematic review of the neurobehavioural and physiological effects of shiftwork systems. *Sleep Med. Rev*. 11:179–194.

Folkard S. (1975). Diurnal variation in logical reasoning. *Br. J. Psych*. 66:1–8.

Folkard S. (2008). Shift work, safety, and aging. *Chronobiol. Int*. 25:183–198.

Frey DJ, Badia P, Wright KP. (2004). Inter- and intra-individual variability in performance near the circadian nadir during sleep deprivation. *J. Sleep Res*. 13:305–315.

Friederici AD, Jacobsen T. (1999). Processing grammatical gender during language comprehension. *J. Psychol. Res*. 28:467–484.

Graw P, Kräuchi K, Knoblauch V, Renz C, Wirz-Justice A, Cajochen C. (2004). Circadian and wake-dependent modulation of fastest and slowest reaction times of the psychomotor vigilance task (PVT). *Physiol. Behav*. 80:695–701.

Herzog ED, Muglia LJ. (2006). You are when you eat. *Nat. Neurosci*. 9:300–302.

Hirayama J, Saurabh S, Grimaldi B, Tamaru T, Takamatsu K, Yasukaza N, Sassone-Corsi P. (2007). Clock-mediated acetylation of Bmal1 controls circadian function. *Nat*. 450:1086–1091.

Hohlfeld A. (2006). Accessing grammatical gender in German: The impact of gender-marking regularities. *App. Psychol*. 27:127–142.

Kersting M, Althoff K. (2004). *Rechtschreibungstest (Rt)*. Göttingen: Hogrefe.

Lahl O, Pietrowsky R. (2006). A software application for the automatic creation of truly equivalent word lists. *Behav. Res. Meth*. 38:146–152.

Lingenhöhl H. (1980). Einfluss von Tageszeit und Sedierung auf die Ergebnisse im Sprachaudiogramm, Doctoral Thesis. University of Tübingen. **Q8**

Mills JN, Minors DS, Waterhouse JM. (1978). Adaptation to abrupt time shifts of the oscillator(s) controlling human circadian rhythms. *J. Physiol*. 285:455–470.

Monk TH, Carrier J. (1997). Speed of mental processing in the middle of the night. *Sleep*. 20:399–401.

Morton LL, Diubaldo D. (1993). Circadian differences in the dichotic processing of voicing. *Int. J. Neurosci*. 68:43–52.

Morton LL, Diubaldo D. (1995). Circadian differences in hemisphere-linked spelling proficiencies. *Int. J. Neurosci*. 81:101–110.

Oakhill JV. (1986a). Effects of time of day and information importance on adults' memory for a short story. *Quart. J. Exp. Psych*. 38A:419–430.

Oakhill JV. (1986b). Effects of time of day on the integration of information in text. *Br. J. Psych*. 77:481–488.

Oakhill JV. (1988). Text memory and integration at different times of day. *App. Cog. Psych*. 2: 203–212.

Oakhill JV, Davies A. (1991). The effects of test expectancy on quality of note taking and recall of text at different times of day. *Br. J. Psych*. 82:179–189.

O'Seaghdha PG. (1997). Conjoint and dissociable effects of syntactic and semantic context. *J. Exp. Psychol*. 23:807–828.

Petrilli RM, Roach GD, Dawson D, Lamond N. (2006). The sleep, subjective fatigue, and sustained attention of commercial airline pilots during an international pattern. *Chronobiol. Int*. 23:1347–1362.

Portaluppi F, Touitou Y, Smolensky MH. (2008). Ethical and methodological standards for laboratory and medical biological rhythm research. *Chronobiol. Int*. 25:999–1016.

Reinberg AC, Ugolini Y, Motohashi C, Fravigny A, Bicakova-Rocher F. (1988). Diurnal rhythms in performance tests of school children with and without language disorders. *Chronobiol. Int*. 5:291–299.

Roenneberg T, Kuehnle T, Juda M, Kantermann T, Allebrandt K, Gordijn M, Merrow M. (2007). Epidemiology of the human circadian clock. *Sleep Med. Rev*. 11:429–438.

Schmidt C, Colette F, Cajochen C, Peigneux P. (2007). A time to think: Circadian rhythms in human cognition. *Cog. Neuropsych*. 24:755–789.

Schriefers H. (1993). Syntactic processes in the production of noun phrases. *J. Exp. Psych*. 19: 841–850.

Seidenberg MS, Waters GS, Sanders M, Langer P. (1984). Pre- and postlexical loci of contextual effects on word recognition. *Mem. Cog*. 12:315–328.

Seithikurippu RP, Smiths M, Spence W, Srinivasan V, Cardinali DP, Lowe AD, Kayumov L. (2007). Dim light melatonin onset (DLMO): A tool for the analysis of circadian phase in human sleep and chronobiological disorders. *Prog. Neuropsychopharmacol. Biol. Psychiat*. 32:1–11.

Signal TL, Ratieta D, Gander P. (2008). Flight crew fatigue management in a more felxible regulatory environment: An overview of the New Zealand Aviation Industry. *Chronobiol. Int*. 25:373–388.

Steingrüber HJ, Lienert GA. (1976). *Hand-dominanz-test (H-D-T)*. Göttingen, Toronto, Zürich: Verlag Für Psychologie, Dr.C.J. Hogrefe.

Tannenhaus MK, Dell GS, Carlson G (eds). (1987). *Context effects and lexical processing: A connectionist approach to modularity*. Cambridge, Mass: MIT Press, pp. 83–108.

Van Berkum JJA. (1996). *The psycholinguistics of grammatical gender*. Nijmegen University Press, Nijmegen.

Webb W, Levy C. (1982). Age, sleep deprivation and performance. *Psych. Physiol*. 19:272–276.

Weber JM, Schwander JC, Unger I, Meier D. (1997). A direct ultrasensitive RIA for the determination of melatonin in human saliva: Comparison with serum levels. *J. Sleep Res*. 26:757. **Q9**

West RF, Stanovich KE. (1982). Source of inhibition in experiments on the effect of sentence context on word recognition. *J. Exp. Psych*. 5:385–399.

West RF, Stanovich KE. (1986). Robust effects of syntactic structure on visual word processing. *Mem. Cog*. 14:104–112.

Wewers ME, Lowe NK. (1990). A critical review of visual analogue scales in the measurement of clinical phenomena. *Res. Nurs. Health* 13:227–236.

Wicha NY, Orozco-Figueroa A, Reyer I, Hernandez A, Barreto LG, Bates E. (2005). When zebras become painted monkeys: Grammatical gender and semantic priming interact during picture integration in a spoken spanish sentence. *Lang. Cog. Proc*. 20:553–587.

Williams HL, Lubin A. (1967). Speeded addition and sleep loss. *J. Exp. Psych*. 73:313–317.

Wright B, Garrett M. (1984). Lexical decision in sentences: Effects of syntactic structure. *Mem. Cog*. 12:25–64.

Yaretsky A, Arzi T, Ashkenazi IE. (1995). Diurnal variation in language tests and its relevance to early detection of dementia: Time dependence of language tests in healthy adults. *J. Am. Geriatr. Soc*. 43:199–200.

Yaretsky A, Arzi T, Ashkenazi I. (1996). Diurnal variation in language tests and relevance to early detection of dementia: Disruption of time dependency in dementing subjects. *J. Am. Geriatr. Soc*. 44:882–883.

APPENDIX: STIMULUS MATERIAL

German noun	English translation	German noun	English translation
Abend	Evening	Krise	crisis
Abfall	Rubbish	Kritik	criticism
Abgrund	Abyss	Kuchen	cake
Adler	Eagle	Künstler	artist
Ahnung	presentiment	Küste	coast
Akzent	Accent	Kugel	sphere
Alarm	Alarm	Kummer	sorrow
Allee	Avenue	Landschaft	landscape
Anfang	beginning	Laune	mood
Angriff	Attack	Leiche	corpse
Anteil	Part	Liebe	love
Antwort	Answer	Löffel	spoon
Anzug	Suit	Lösung	solution
Ärger	Trouble	Löwe	lion
Armut	Poverty	Lüge	lie
Atom	Atom	Magnet	magnet
Auftakt	Prelude	Makel	blemish
Auftrag	Order	Maler	painter
Auge	Eye	Mangel	lack
Balkon	Balcony	Meinung	opinion
Bankier	Banker	Meister	master
Basis	Basis	Merkmal	characteristics
Beginn	Start	Metall	metal
Begriff	Term	Monat	month
Beispiel	Example	Moral	moral
Beitrag	contribution	Motor	motor
Bereich	Section	Mutter	mother
Beruf	profession	Nachteil	disadvantage
Bescheid	Reply	Nagel	nail
Besitz	posession	Neffe	nephew
Betrag	Amount	Niveau	niveau
Beweis	evidence	Nonne	nun
Biene	Bee	Objekt	object
Blüte	Bloom	Palast	palace
Bündnis	alliance	Papier	paper
Butter	Butter	Partner	partner
Chaos	Chaos	Patent	patent
Detail	Detail	Person	person
Dichter	Poet	Pfeife	pipe
Diebstahl	Theft	Pflanze	plant
Diener	servant	Pirat	pirat
Doktor	Doctor	Plakat	placard
Dozent	lecturer	Poster	poster
Drama	Drama	Priester	priest
Effekt	Effect	Prinzip	principle
Ehe	marriage	Problem	problem
Eindruck	appearance	Profil	profile
Einfall	Idea	Prüfung	examination
Einfluß	influence	Quadrat	square

(*Continued*)

APPENDIX. Continued.

German noun	English translation	German noun	English translation
Einwand	objection	Räuber	robber
Elend	misery	Redner	speaker
Erde	ground	Regel	rule
Fabrik	factory	Rekord	record
Fahne	flag	Richter	judge
Fazit	result	Richtung	direction
Feier	celebration	Rolle	role
Figur	figure	Sache	thing
Fischer	fisherman	Sänger	singer
Flasche	bottle	Schädel	skull
Folge	succession	Schatten	shadow
Format	format	Schauspiel	play
Fortschritt	progress	Schicksal	destiny
Frage	question	Schlange	snake
Frieden	peace	Schleier	veil
Funktion	function	Schöpfer	creator
Gangster	gangster	Schüler	pupil
Garten	garden	Schwerpunkt	centre of gravity
Gebet	prayer	Seele	soul
Gedicht	poem	Segel	sail
Geduld	patience	Segen	blessing
Gehalt	salary	Sessel	armchair
Gemüt	nature	Siedlung	settlement
Geruch	smell	Sprache	language
Geschenk	gift	Standpunkt	point of view
Geschick	skill	Stempel	stamp
Gespenst	ghost	Stille	quitness
Getränk	drink	Stimmung	mood
Gleichnis	parable	Straße	street
Gnade	mercy	Struktur	structure
Grundsatz	principle	Substanz	substance
Gruppe	group	Symptom	symptom
Hafer	oats	System	system
Halle	hall	Tarif	rate
Härte	hardness	Täuschung	deception
Hektar	hectar	Teufel	devil
Herrscher	ruler	Thema	topic
Himmel	sky	Transport	transportation
Honig	honey	Umgang	contact
Hotel	hotel	Umstand	circumstance
Hügel	hill	Unglück	misfortune
Hürde	hurdle	Unsinn	nonsense
Hütte	hut	Ursprung	origin
Humor	humor	Vampir	vampire
Idee	idea	Verdacht	suspicion
Imbiss	snack	Verlauf	course
Inhalt	content	Verlust	loss
Irrtum	mistake	Verstand	intellect
Kabel	wire	Vertrag	contract
Kaffee	coffee	Vogel	bird
Kamel	camel	Vorfall	occurrence

(*Continued*)

APPENDIX. Continued.

German noun	English translation	German noun	English translation
Kanal	channel	Vortrag	talk
Käse	cheese	Wahrheit	truth
Kasten	box	Wechsel	change
Katze	cat	Werbung	advertising
Keller	cellar	Wiese	meadow
Kenntnis	knowledge	Winkel	angle
Kino	cinema	Winter	winter
Kirche	church	Wirkung	effect
Klavier	piano	Wohlstand	prosperity
Kleidung	clothes	Wohnung	flat
Klima	climate	Wolle	wool
Knochen	bone	Zeitung	newspaper
Komma	comma	Zimmer	room
König	king	Zitat	citation
Konzept	concept	Zucker	Sugar
Körper	body	Zufall	coincidence
Kosten	costs	Zukunft	future
Kragen	collar	Zustand	state
Krankheit	illness	Zuwachs	increase
Kreislauf	circulation	Zweifel	Doubt