Time Estimation during Prolonged Sleep Deprivation and Its Relation to Activation Measures

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This is the first study to analyze variations in time estimation during 60 h of sleep deprivation and the relation between time estimation performance and the activation measures of skin resistance level, body temperature, and Stanford Sleepiness Scale (SSS) scores. Among 30 healthy participants 18 to 24 years of age, for a 10-s interval using the production method, we found a lengthening in time estimations that was modulated by circadian oscillations. No differences in gender were found in the time estimation task during sleep deprivation. The variations in time estimation correlated significantly with body temperature, skin resistance level, and SSS throughout the sleep deprivation period. When body temperature is elevated, indicating a high level of activation, the interval tends to be underestimated, and vice versa. When the skin resistance level or SSS is elevated (low activation), time estimation is lengthened, and vice versa. This lengthening is important because many everyday situations involve duration estimation under moderate to severe sleep loss. Actual or potential applications of this research include transportation systems, emergency response work, sporting activities, and industrial settings in which accuracy in anticipation or coincidence timing is important for safety or efficiency.

INTRODUCTION

Disturbances in the sleep-wake rhythm and sleep deprivation are frequent events. Many people – for instance, night-shift workers, truck drivers, airplane pilots, soldiers on military operations, and on-call doctors – can be chronically sleep deprived. Sleep deprivation has been shown to negatively affect a wide range of cognitive, behavioral, physiological, and emotional measures (Dinges, 1992; Mertens & Collins, 1986; Naitoh & Townsend, 1970; Pilcher & Huffcutt, 1996). Lapsus, slowing of reaction time, electroencephalographic (EEG) deactivation signs, and subjective reports of sleepiness are some of the most characteristic findings in sleep deprivation studies. Such deteriorations in vigilance and activation, which are frequently the cause of industrial or automobile accidents, are added to the list of so-called human errors (Fairclough & Graham, 1999; Kuhn, 2001).

The effects of sleep deprivation have been studied on practically every physiological or psychological variable, so it is surprising that time perception has been almost ignored. The perception and estimation of time are key control mechanisms for representing the immediate external environment and for modulating behavior. For example, driving or crossing a busy street requires the continual estimation of speed and duration.

The performance of time estimation has been explained by the assumption of a hypothetical internal clock (Treisman, 1984; Treisman, Cook, Naish, & MacCrone, 1994). The term *internal clock* is a convenient form to refer to a complex system formed by various components, among which are a pacemaker, a counter (or

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accumulator), and a comparator (Treisman et al., 1994). The pacemaker is the part of the system in charge of producing, at a given rate, the pulses that will serve as the origin of information about time. For example, the estimated duration of a temporal interval is related proportionately to the quantity of the stored pulses.

The speed of the pacemaker may be influenced by physiological processes such as metabolic rate and arousal (Treisman et al., 1994). It has been demonstrated that the artificial manipulation of body temperature produces modifications in time estimation. François (1927) was the first to modify the subjective experience in the calculation of an interval by elevating the temperature of his experimental participants. Wearden and Penton-Voak (1995), who revised the works published between 1927 and 1993 about the relation between temperature and time judgment, found that the rate of subjective time increased when body temperature increased above normal, and vice versa. Also, the administration of stimulant drugs such as marijuana and methamphetamine, which produce an increase in clock speed (Kraemer, Randall, Dose, & Brown, 1997; Maricq & Church, 1983), and exposure to stressful situations that increase activation (Watts & Sharrock, 1984) lead to faster time estimation (TE), or underestimation of an interval. Conversely, production responses were lengthened (overestimated) when the internal clock's pacemaker was slowed, as occurs, for example, in the case of alcohol consumption (Maricq & Church, 1983), the use of benzodiazepines (Fernández-Guardiola, Jurado, & Aguilar-Jimenéz, 1984), and the aging process (Craik & Hay, 1999; Espinosa-Fernández, 1996).

Sleep deprivation is another example of the type of condition that would slow the internal clock's pacemaker. However, to our knowledge only two studies have evaluated the performance of time estimation tasks during sleep deprivation (SD). Balkin, O'Donnell, Kamimori, Redmond, and Belenky (1989) analyzed, in a sample of 45 men (18–39 years old), the effects of triazolam on recovery sleep that followed 24 hr of SD. Immediately before recovery sleep, a drug or a placebo was administered, and afterward another 18 hr of SD was included. During the two periods of SD a battery of cognitive tests, including a time estimation task, took place every 2 hr. This task consisted of calculating when a dot of light falling from the top of a computer screen would reach a designated line at the bottom. Although the majority of the psychomotor tests were sensitive to sleep loss, the TE task was not, and it showed no change under any condition.

Bohnen and Gaillard (1994) analyzed the effects of 24 hr of sleep deprivation on a monotonous searching task and on time estimation in 16 young men. Both tasks simulated situations experienced by air traffic controllers, implying monotonous vigilance and the necessity to make periodic checks. For their TE task, the participants estimated 2- and 3-min intervals consecutively during a single session lasting 30 min. There were three experimental conditions: a passive condition (a clock on the monitor screen continually showed the time), an active condition (the participants could obtain time information by pressing a key), and a condition that designated status (by pressing a key, the participant could obtain information about whether or not the interval had finished). In spite of notable deterioration in vigilance, no similar deterioration was found in TE. During the session, participants accessed the time information with increasing frequency, which may indicate that SD leads to greater uncertainty, although the proportionate feedback seems to have reduced the sensitivity to this task (Bohnen & Gaillard, 1994).

The objective of the present study is to analyze the effect of 60 hr of sleep deprivation on the capacity to estimate time. The performance of time estimation will be related to well-established activation measures, such as body temperature, electrodermal resistance, and the level of subjective sleepiness. We will also explore the possible existence of gender differences.

METHOD

Participants

A total of 30 healthy volunteers (15 men and 15 women) ranging in age from 18 to 24 years (mean age = 20.06 ± 4.38 years) participated in this study. The final sample was selected by means of a questionnaire created for this purpose. The questionnaire explored topics such as physical and psychological health; consumption of tobacco, medication, alcohol, and other drugs; ingestion of coffee, tea, and other stimulants; menstrual cycle regularity in the case of women; regularity in sleep schedules; and the possible existence of sleep disorders. The Horne and Östberg Morningness-Eveningness Scale for determining each participant's circadian type was administered along with the selection questionnaire. Participants who obtained scores greater than 21 (*clearly morning-type*) or less than 8 (*clearly evening-type*) were not selected for study.

The Beck Depression Inventory (BDI), State-Trait Anxiety Inventory: Trait Scale (STAI), and Eysenck Personality Questionnaire (EPQ-A) were also administered. The basis for exclusion was a score greater than 9 on the BDI, a raw score on the STAI, or neuroticism and psychoticism dimensions on the EPQ-A greater than the 70th percentile. These last exclusions were established to ensure that the participants did not experience extreme variations in mood or have personality characteristics that could indicate the presence of behavior disturbances that produce an uncommon response to sleep deprivation.

All of the selected participants presented good health and did not consume any type of medication. Each had a regular sleep pattern of 7 to 9 hr, with a bedtime between 11:30 p.m. and 2:30 a.m. and a wake-up time between 7:30 a.m. and 10:30 a.m. Those participants who did not consume more than three cups of coffee per day were admitted. Participants who reported high tobacco consumption (>15 cigarettes/day) or low tobacco consumption (≤5 cigarettes/per day) were excluded in an attempt to even out the effects of nicotine by impeding an excessive nicotine habituation or shortage. The final sample included 10 smokers (5 women and 5 men). Finally, the women began their participation on a date between the last day of their menstruation and the following five days (preovulation phase).

Apparatus and Materials

A computer task was employed for measuring time estimation. We used the method of production, in which the participant is instructed to produce a time interval (10 s) that had previously been established by an experimenter. Specifically, the participant was instructed to press the Enter key when he or she felt that 10 s had elapsed after the presentation of a stimulus: a white letter *A* (4 mm in height) in the center of the screen (12 inches, or 30.5 cm) on a black background. This method requires translation from an objectively labeled duration to a subjectively experienced duration and therefore is adequate for investigating individual differences or effects of variables that may influence the rate of the internal processes (Zakay & Shub, 1998). Participants were instructed to mentally count at an estimated rate of 1/s in order to standardize the strategies used in each case.

The stimulus was presented 30 times in each recording session, with an intertrial interval that ranged randomly from 0.5 to 3.0 s. A filter was incorporated into the software program to detect and eliminate any anticipatory responses (those responses produced before the stimulus is presented or up to 2 s after its presentation), in which case the trial was considered void and the presentation of that stimulus was repeated. The entire TE task lasted about 5 min. No concurrent task was undertaken throughout the duration of the estimation (empty interval), nor did the participants receive any feedback about their performance.

A Biocyber (Barcelona, Spain) model Dermback CY-15 polygraph module for electrodermal activity provided the measurement for skin resistance level (SRL). This device reads 4 data/s and averages a total of 60 s (240 SRL values per minute), providing this information in a digitalized display (which the participant was prevented from viewing) or in a computerized recording by means of a Windows 95 software program. San-ei sodic chloride conductive gel (NaCl, 0.29 g/100mL) facilitated contact with electrodes (silver coated in silver chloride, 1 cm^2) fixed to the participants with Velcro. A Keito (Tokyo, Japan) model KT-70 digital thermometer recorded the axillary body temperature.

The Stanford Sleepiness Scale (SSS; Hoddes, Zarcone, Smythe, Phillips, & Dement, 1973) evaluates the activation-sleepiness state with seven items referring to different subjective somnolence descriptions. The participant must mark the statement that best describes his or her activation state at that moment. The scores range from 0 (indicating the lowest somnolence) to 7 (indicating the highest sleepiness level).

Procedure

All participants received precise instructions that they should sleep according to their normal schedules the week prior to the investigation. The day before the experiment, participants were familiarized with the experimental task. On the first day of the study the participants (always a mixed-gender group of 5 to 7) arrived at the laboratory at 8:30 a.m., were reminded of the participation rules of the experiment, and signed a written consent binding them to such norms. They were free to withdraw from the study at any time. They were not allowed to consume coffee, tea, cola, alcohol, or medication. They could not shower (they could freshen up and change clothing) or do any physical exercise that could facilitate activation. Smoking was allowed only immediately after finishing each data recording (every 2 hr) in order to prevent a withdrawal effect that could influence the task.

The investigation began at 9:00 a.m. on Tuesday morning and continued until 9:00 p.m. Thursday evening. Throughout 60 hr of sleep deprivation the participants remained in a large room (equipped with a bathroom) that could be left only to go to an adjacent laboratory, where the TE task and the psychophysiological recordings were performed every 2 hr. A total of 30 recordings were completed, always at the same times of day: 9:00 a.m., 11:00 a.m., 1:00 p.m., and so forth. Sleepiness was evaluated every hour (at 9:00 a.m., 10:00 a.m., etc), resulting in a total of 60 measures. The room temperature in both areas was maintained at a thermoneutral level (22°–25° C) by means of an air conditioner with thermostat. The lighting was constant, and there was isolation from any noise.

Each recording session in the laboratory consisted of a TE task in which SRL (the average value of the second minute) and body temperature were recorded in order to standardize the recording context. The electrodes for the SRL recording were placed on the middle phalanges of the index and middle fingers of the left hand, previously washed with soap, and the thermistor was placed in the left axilla after the area was cleaned with alcohol (all participants were right handed).

When Participant 1 completed a data recording session in the laboratory and returned to the room, Participant 2 arrived, and this process was repeated with all participants until the entire group had completed the recording session. Participants could use the remaining free time between data recordings to read, listen to music, watch television, and so forth. They were under the constant supervision of two experimenters to prevent them from sleeping. Breakfast was provided at 8:30 a.m. and the main meal at 2:30 p.m., with the same menu for all participants. Dinner was provided at 8:30 p.m., and a snack was available at 2:30 a.m.

Data Analysis

A two-way analysis of variance (ANOVA) for repeated measures was performed in order to verify whether TE was significantly modified as a function of SD time. The ANOVA was performed with one factor (gender) manipulated by between-group selection, and another factor (SD time) was manipulated within subjects with a total of 30 levels (60 for SSS), with significance levels corrected for sphericity by Greenhouse-Geisser epsilon.

The data collected during SD imply the interaction of rhythmic circadian fluctuations and effects related to sleep deprivation per se. It has been established that a lineal or monotonic function would be related to the accumulated effect of sleep loss, whereas circadian and/or ultradian rhythmicity would be specified in other types of functions (Babkoff, Caspy, Mikulincer, & Sing, 1991). If the ANOVA for TE was significant, we determined by means of planned complex comparisons whether or not the effects attributable to SD occurred across the diurnal periods and across the nocturnal periods.

Complex comparisons were done for the following periods: Day 1 (9:00 a.m.–7:00 p.m.), Night 1 (9:00 p.m.–7:00 a.m.), Day 2 (9:00 a.m.–7:00 p.m.), Night 2 (9:00 p.m.–7:00 a.m.), and Day 3 (9:00 a.m.–7:00 p.m.). The TE scores were averaged for each period. Our hypothesis was that the intense deactivation that accompanies SD would generate slower production of the established time interval (overestimation). The effects would be greater on Day 2 than on Day 1, on Day 3 than on Day 2, and on Day 3 than on Day 1. However, the alteration would be more pronounced on Night 2 than on Night 1, and the greatest level of deactivation was expected on Night 2. The values of Night 1 versus Day 2 and Night 2 versus Day 3 would be compared in order to verify to what extent maintenance of the circadian rhythm can produce a recovery of scores in the diurnal versus the nocturnal periods.

Trend analyses were applied to the 30 levels of the variable to determine the relation between SD and TE. In addition, the percentage of data variance accounted for by each significant trend was estimated. An ascendant or descendant lineal trend would mainly be related to the SD effect (Babkoff et al., 1991). We limited the maximum order for the trend components to 9 after applying an analysis with components up to the 29th order and verifying that the significant trends were the same in both cases.

Finally, the relation between TE and the remaining variables (SRL, SSS, and temperature) during SD was revealed in a partial intercorrelation matrix between such measures. Each Pearson's correlation coefficient was based on 30 pairs of scores for each of the 30 participants during the days of sleep deprivation. The correlations were performed within each participant separately, then we assessed the average correlation for each pair of variables to determine the 95% confidence limits around the *r*.

RESULTS

Time Estimation

A significant main effect of the SD factor was found in the ANOVA for repeated measures $F(29, 812) = 4.16$, $p < .001$. There was no significant main effect for the gender factor or for the interaction between gender and SD. Table 1 summarizes the results for the planned complex comparisons effected between the TE values in the different SD periods.

TABLE 1: Planned Complex Comparisons for Time Estimation

	Mean TE (s)
Day 1–Day 2	8.69–9.43**
Day 2–Day 3	9.43–9.90**
Day 1–Day 3	8.69–9.90***
Night 1–Night 2	9.50–9.93*
Night 1–Day 2	9.50–9.43
Night 2–Day 3	9.93–9.90

* $p < .05$; ** $p < .01$; *** $p < .001$.

The comparisons between Day 1 and Day 2, $F(1, 28) = 10.73$, $p < .01$; Day 2 and Day 3, $F(1, 28) = 6.20$, $p < .01$; Day 1 and Day 3, $F(1, 28) = 15.00$, $p < .001$; and Night 1 and Night 2, $F(1, 28) = 5.02$, $p < .05$, are significant. TE values increased throughout the 60 hr of SD, accompanied by slight circadian fluctuations (see Figure 1). Mean TE scores during SD progressively increased across the diurnal periods, from Day 1 (8.69 ± 1.85 s) to Day 2 (9.43 ± 1.97 s) and from Day 2 (9.43 ± 1.97 s) to Day 3 (9.90 ± 1.95 s), as well as across the nocturnal periods, from Night 1 (9.50 ± 2.00 s) to Night 2 (9.93 ± 2.16 s), in which the maximum TE values were reached during the early morning (5:00–9:00 a.m.).

Finally, there appears to be no evidence of a significant recovery (decrease) of a circadian nature from Night 1 (9.50 ± 2.00 s) to Day 2 (9.43 ± 1.97 s) or from Night 2 (9.93 ± 2.16 s) to Day 3 (9.90 ± 1.95 s), although the scores indicate a very slight trend toward such recovery.

The trend analysis of the TE scores in relation to SD period is shown in Table 2. The trends found to be significant are the lineal, $F(1, 28) = 14.37$, $p < .001$; quadratic, $F(1, 28) = 5.13$, $p < .05$; quintic, $F(1, 28) = 4.83$, $p < .05$; and sextic $F(1, 28) = 7.27$, $p < .01$. The significant trend that explains a greater percentage of variability (77.34%) in TE during the SD period is an ascending or positive lineal function supposedly related to the sleep loss effect (see Figure 1).

Other variability percentages accounted for by greater-order trends mainly associated with rhythmic aspects can be observed in Table 2. For example, the quadratic function (which explains 7.28% of the variability in TE) seems to be attributable to the notable increase in TE scores on Night 2, for which we found values that were higher than those in any other period.

Relations between Variables

Table 3 presents the partial correlations between TE and the other variables analyzed. All these variables showed significant modifications

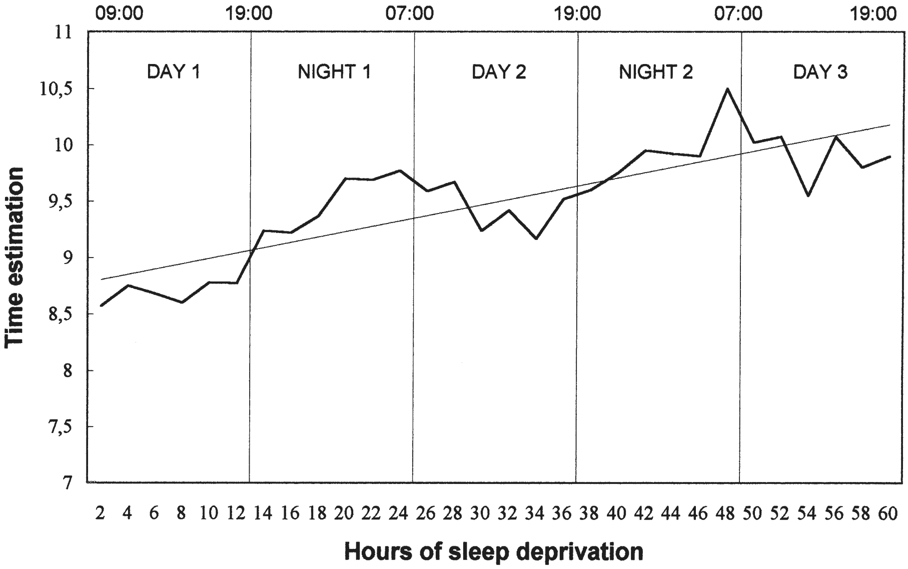

Figure 1. Mean TEs during SD for the total sample (dark line) and lineal adjustment trend for TE (light line).

during the SD period. A detailed description of the significant changes in SRL, body temperature, and self-perceived sleepiness (SSS) during SD is given in Miró, Cano, and Buela-Casal (2002). Here our focus is solely on the relations between all these variables and TE. The changes in time estimation throughout sleep deprivation significantly correlate with the variations in body temperature ($p < .025$), SRL ($p < .025$), and SSS ($p < .025$). There are no significant changes as a function of gender in any of the correlations performed. When the TE values are high, the body temperature values tend to be low, and vice versa (see Figure 2). In addition, when the TE values are high, the SRL values (electrodermal resistance) and SSS scores also tend to be high (see Figures 3 and 4).

DISCUSSION

In this study, 60 hr of sleep deprivation lengthened participants' time estimations of 10 s. These changes in TE were adjusted to an ascendant lineal function, related to the accumulated effect of SD, which explains 77.34% of variability in TE as well as diverse polynomial trends of a major order mainly associated with rhythmic aspects. TE changed on average from 8.69 s on Day 1 to 9.90 s on Day 3 and reached its higher values on Night 2 (e.g., 10.50 s at 7:00 a.m.). Also, standard deviations for each participant tended to increase across sessions, paralleling the modifications in mean TE during SD.

All participants showed the same general pattern, with small and stable standard deviations between them. The changes in TE were observable from the first 24 hr of SD. The only two investigations about SD that have analyzed the performance of TE tasks did not observe many changes in TE (Balkin et al., 1989; Bohnen & Gaillard, 1994). However, in the Bohnen and Gaillard work, for example, TE was evaluated on only one occasion, and the participants received feedback about their performance, which could have weakened the sensitivity of this measurement to SD.

TABLE 2: Trend Analysis for Time Estimation

	R^2
Lineal***	77.34%
Quadratic*	7.28%
Quintic*	3.86%
Sextic**	8.45%

Note: The determination coefficients (R^2) of polynomial regression express the variability accounted for by each of the significant trends.
* $p < .05$; ** $p < .01$; *** $p < .001$.

TABLE 3: Mean Correlations between the Different Analyzed Variables and 95% Confidence Boundaries around Each Condition

	Temperature	SRL	SSS
TE	*r* = –0.375	*r* = 0.278	*r* = 0.245
95% confidence limits	(–0.491, –0.259)*	(0.18, 0.376)*	(0.174, 0.316)*

* $p < .025$.

The presence of underestimation throughout the main part of the period analyzed seems to agree with the findings that both prospective and retrospective duration judgments tend to be underestimates (Block & Zakay, 1997). Underestimation of time intervals is characteristic in children and young people, whereas overestimation predominates in the elderly (Carrasco, Bernal, & Redolat, 2001; Espinosa-Fernández, 1996). The intersubject variability we found was small, which coincides with reports that participants estimate durations relatively well within a short range (e.g., between 1 and 40 s; Predebon, 1995), especially if a counting strategy is allowed, as in our study (Guay & Salmoni, 1988; Marmaras, Vassilakis, & Dounias, 1995). A longer interval or the prohibition of counting would have increased the size and variability of the error.

No differences in gender were found in the TE task throughout SD. The two studies on SD that explored TE used only male participants (Balkin et al., 1989; Bohnen & Gaillard, 1994), thus preventing any comparison with our results. In the general field of TE, some authors have found more precision and less variability in estimations made by male than by female participants (Eisler & Eisler, 1992; Rammsayer & Lustnauer, 1988). However, other, similar studies show no such difference between men and women (Marmaras et al., 1995; Rammsayer & Rammstedt, 2000).

There seem to be circadian rhythmic fluctuations in the TE values throughout the period analyzed. The night periods generated the greatest slowing in the production of TEs, especially around 7:00 a.m. The day periods showed a certain leveling out, or lack of continuation, in the

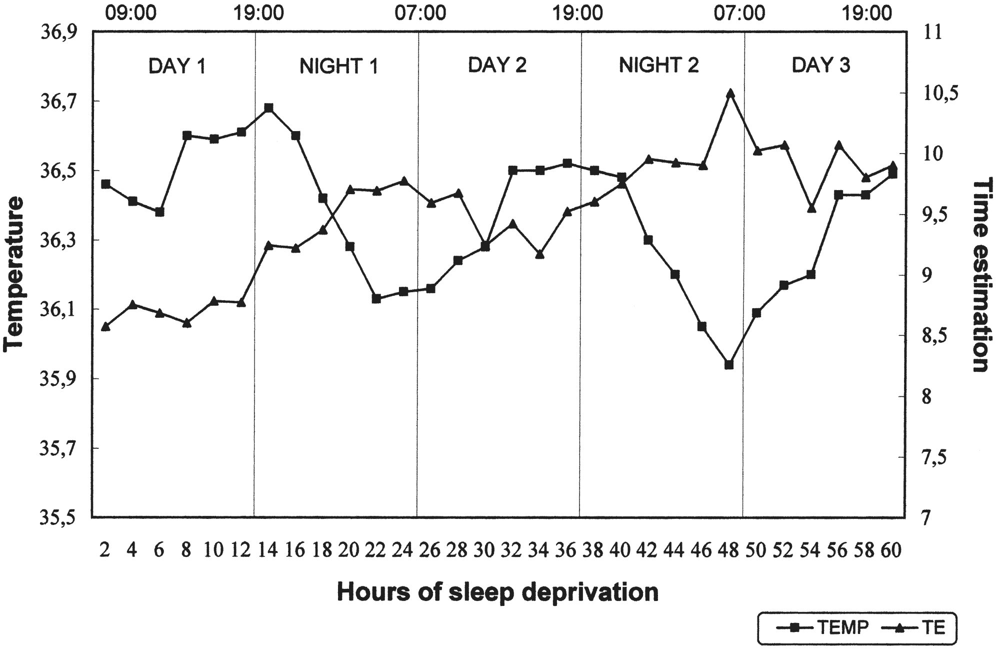

Figure 2. Relation between TEs and body temperature (TEMP, °C) for the total sample.

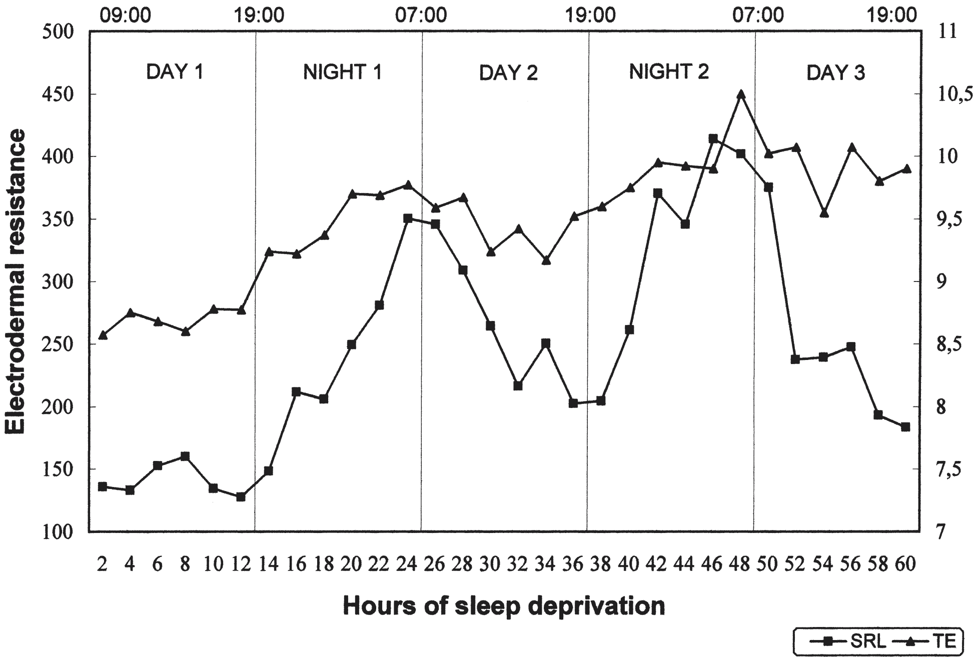

Figure 3. Relation between TE and SRL (electrodermal resistance) for the total sample.

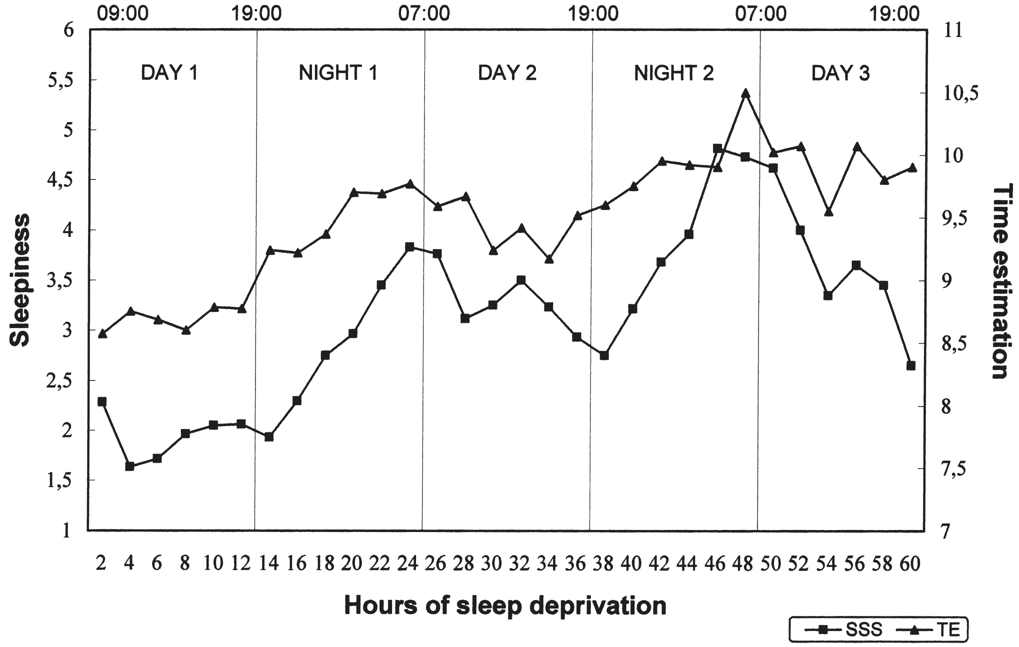

Figure 4. Relation between TEs and SSS (self-perceived sleepiness on the Stanford Sleepiness Scale) for the total sample.

trend associated with SD. Some authors have raised doubts about the existence of a circadian rhythm in time estimation (Campbell, 1990), although the present results coincide with the majority of studies, which have documented a circadian rhythm in TE (Hancock, Vercruyssen, & Rodenburg, 1992; Pati & Gupta, 1994).

Interestingly, variations in TE correlated significantly with body temperature changes, SRL, and SSS throughout SD (see Table 3). As we reported in a previous work, body temperature decreased during the 60 hr of SD, accompanied by strong circadian oscillations, whereas SRL and sleepiness increased notably throughout SD and were also modulated by circadian fluctuations (Miró et al., 2002). When temperature values were elevated, indicating a high level of activation, the participants tended to underestimate the time interval, and vice versa. Conversely, when the SRL or SSS was elevated (low activation), the participants' TEs were lengthened, and vice versa.

These results coincide with other reports of significant correlations between TE performance and diverse indices of activation, such as the presence of sleepiness as detected electroencephalographically or by deterioration in a reaction time task (Jurado, Luna-Villegas, & Buela-Casal, 1989; Raevskaya & Dzhebrailova, 1987). Among shiftworkers, Pati and Gupta (1994) found that more accurate TE coincided with peak body temperature. Aschoff (1998) found that in participants who had no access to time information, the production of TEs of 5 and 10 s were negatively correlated with rectal temperature (mean $r = 0.367$). The several studies that attempted to change the rate of the hypothesized internal clock by manipulating body temperature are also in agreement with our results (Wearden & Penton-Voak, 1995). However, we have to take into account that none of the cited studies examined SD, which may limit the comparisons that can be established.

One common factor that could explain the relationships is the participant's activation level. This view concurs with formulations of the biological clock (Treisman et al., 1994). The intense deactivation produced by SD decelerates the hypothetical internal clock, leading to slower TEs (overestimations), whereas underestimation, which was most pronounced at the beginning of the study, is related to a greater level of activation. The neurobiology of this internal clock is still not sufficiently well understood. Pharmacologic, lesion, and brain imagery studies have focused mainly on the cerebellum, frontal lobes, and basal ganglia (Casini & Macar, 1999; Gibbon, Malapani, Dale, & Gallistel, 1997; Mimura, Kinsbourne, & O'Connor, 2000). EEG studies have found that prefrontal and parietal brain areas are activated during the estimation of intervals lasting for several seconds (for a review, see Gibbon et al., 1997). It is important to note that some authors have proposed that SD generates reversible deficits in neuropsychological tests of the prefrontal cortex (Horne, 1992; Harrison & Horne, 1998). In fact, the most significant decreases in glucose uptake during SD are observed in the bilateral prefrontal cortex (Thomas, Sing, & Belenky, 1993).

We have highlighted the relevance of the physiological model of TE, but well-established cognitive factors are also important. For example, retrospective judgments use the information present in the environment to construct elapsed time, so that in this case we can talk about remembered duration (Block & Zakay, 1997). However, a period of prospective time is an experienced duration (as in the present study), and under these conditions we can also highlight the importance of an attentional model (Brown, 1997; Hicks, Miller, & Kinsbourne, 1976; Zakay & Shub, 1998). This model assumes that attentional resources are shared among all the tasks that an organism can perform. A cognitive clock or "timer" produces and codes temporal information. As more attentional resources are allocated to the temporal task, more pulses or units are accumulated by the timer. Given that from this point of view the increase in attention to time leads to longer TEs, we have to conclude that our participants paid more attention to time as the experiment advanced. This is not easy to assimilate if we take into account that SD itself induces considerable attentional deterioration. One possible interpretation is that boredom, or the distaste generated by the task itself, made the participants more attentive to the task during counting.

Other authors have stressed a major role for working memory in prospective TE (Fortin, 1999; Shinohara, 1999; Venneri, Pestell, Gray, Della Sala, & Nichelli, 1998). For example, in Fortin's study (1999), TEs were lengthened by increasing the amount of short-term memory processing performed in a concurrent search task. In our study there are no concurrent nontemporal tasks, but perhaps the known deterioration in working memory that accompanies SD (Horne, 1992) interferes with performance of the TE task, leading to longer TE production.

In conclusion, these TE results seem to concur with theories that put forward the idea that people calculate time on the basis of an internal clock. However, one cannot discard the implication for the existence of another series of cognitive factors that are fundamentally attentional and that pertain to working memory. In the near future studies of experienced duration will have to clarify the contribution of each of these mechanisms.

PRACTICAL IMPLICATIONS

The finding that time estimations for a 10-s interval were lengthened during sleep deprivation is important because many everyday situations involve TE. The findings of the present study have implications in situations in which accuracy in anticipation or coincidence timing is important for safety or when performance is affected by the discrepancy between endogenous and exogenous time. The perception of time available to complete a task has a significant impact on efficiency. For example, firefighters, soldiers, paramedics, and other emergency response personnel are required to respond quickly and accurately to cognitive task demands while experiencing moderate to severe sleep debt. An intrinsic part of many cognitive tasks is the necessity to accurately experience the passage of time. In industrial settings another relevant aspect is scheduling work in terms of intervals during which the human operator has to perform predetermined actions. Whenever there is a risk of a worker performing under conditions of sleep loss (e.g., shiftworkers), we recommend alarm-initiated activities.

TE is also an important specific factor in sporting activities. In competitive sports it can be witnessed that success is heavily dependent on the athlete's ability to accurately experience time (e.g., a long-distance runner must be able to pace different events). Similarly, in musical performance a perfect perception of time is needed to produce each note for its precise time value, adjusting it to the exact rhythm required. In addition, accurate TE is important for ensuring that activities such as conversations, meetings, solitary work, and so forth do not interfere with events that follow.

An especially relevant application of our findings concerns the traffic-transportation system. In virtually every aspect of the driving task, the operator must use prospective timing skills in order to engage in appropriate actions at the correct time (Buela-Casal, Montoro, & Miró, 1995; Sidaway, Fairweather, Sekiya, & McNitt-Gray, 1996). The present work highlights that sleep-deprived drivers will perceive that they have more time to respond or to perform a maneuver (e.g., overtaking, steering, or braking) than they actually do, which might significantly increase the risk of having a traffic accident – especially at night or in the early morning (e.g., 7:00 a.m.), when overestimation reaches its peak. Moreover, it is known that SD produces a reduction in reaction time (Dinges, 1992); this, along with the aforementioned perception that one has more time to perform a maneuver than one actually has, leads drivers to decide to commence an action later than they usually would and, when they do start the action, perform it more slowly. This change between the driver's new capacity and base capacity may be sufficiently significant to reduce safety in driving.

Sleep deprivation is a persistent occupational hazard for professional drivers, such as bus and truck drivers (Hancock & Verwey, 1997; Lee, Stevenson, Wang, & Yau, 2002). Many automobile fatalities involve a driver who is sleepy (e.g., 35%–42%; Arnedt, Wilde, Munt, & MacLean, 2001; Leger, 1994). In some of these cases an error of time calculation may be a relevant factor.

Although the deleterious effects of alcohol on performance are reasonably well quantified, and many countries have established a legal limit for alcohol consumption in relation to driving, no similar standards exist for sleepiness. An effort should be made to develop practical countermeasures via engineering, education, or enforcement. At the moment, however, there is no single indicator that can be used to determine driver sleepiness. Several of the more reliable indexes are physiological; subjective sleepiness, however, cannot be reliable beyond a certain point, which has adverse implications for any plan based solely on drivers self-monitoring their status (Hancock & Verwey, 1997).

Time estimation is an objective, sensitive, noninvasive measure and is well related to other activation parameters, all of which makes TE a potentially useful tool for ergonomists (e.g., in current efforts to develop dynamic adaptation systems in cars). However, the relevance of our findings depends on the consequences of TE errors in real-world settings. A note of caution must be made regarding the laboratory conditions used in the present experiment. Similarly, it must be noted that the careful selection of the sample employed (see Method section) may restrict the practical applicability of our results – for instance, none of our participants had high consumption of coffee or tobacco, experienced extreme variations in mood or personality, or were clearly morning types or evening types. Studies that include a wide range of individual differences and field testing conditions should be performed.

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