Neuroscience Research 63 (2009) 115–121

Contents lists available at ScienceDirect

Neuroscience Research

journal homepage: www.elsevier.com/locate/neures

Time estimation during sleep relates to the amount of slow wave sleep in humans

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ARTICLE INFO

Article history:
Received 14 July 2008
Received in revised form 14 October 2008
Accepted 6 November 2008
Available online 14 November 2008

Keywords:
Time estimation
Interval timing clock
Cognitive science
Sleep
Circadian phase
Insomnia

ABSTRACT

Humans have the ability to estimate the amount of time that has elapsed during sleep (time estimation ability; TEA) that enables a subset of individuals to wake up at a predetermined time without referring to a watch or alarm clock. Although previous studies have indicated sleep structure as a key factor that might influence TEA during sleep, which sleep parameters could affect the TEA has not been clarified. We carried out an experimental study in which 20 healthy volunteers participated in six time estimation trials during the 9-h nighttime sleep (NS) experiment or daytime sleep (DS) experiment. The time estimation ratio (TER, ratio of the subjective estimated time interval to actual time interval) decreased significantly from the first to the sixth trial in both the NS and DS experiments. TER correlated positively with slow wave sleep (SWS) in both experiments, suggesting that SWS was a determining factor in accurate time estimation, irrespective of circadian phase they slept. No other sleep parameters showed steady influence on TEA. The present findings demonstrate that longer period of SWS is associated with the longer sleep time they subjectively experienced during sleep.

1. Introduction

Growing evidence suggests that humans have the ability to estimate the amount of time that has elapsed on the order of milliseconds to several hours (time estimation ability, TEA) even under circumstances in which external time information is not available (Morell, 1996; Harrington et al., 1998; Lalonde and Hannequin, 1999; Rao et al., 2001; Ivry and Spencer, 2004). A series of studies has supported the notion that the TEA pervades sleep period; humans perceive the amount of time that has passed during sleep (Lewis, 1969; Tart, 1970; Zung and Wilson, 1971; Bell, 1972; Moiseeva, 1975; Lavie et al., 1979; Hartocollis, 1980; Campbell, 1986; Zepelin, 1986; Hawkins, 1989; Moorcroft et al., 1997; Born et al., 1999; Kaida et al., 2003; Aritake et al., 2004; Fichten et al., 2005). This ability enables a subset of individuals to wake up at a predetermined time without referring to a watch or alarm clock. Moorcroft et al. (1997) referred to this phenomenon as "self-awakening", and Born et al. (1999) referred to it as "anticipated sleep termination". Actually, several studies have reported that more than half of individuals surveyed were able to achieve "self-awakening" with a margin of error of plus or minus 10-odd min (Lavie et al., 1979; Moorcroft et al., 1997).

A large part of the physiological mechanism of TEA remains unclear, but previous studies have shown that several physiological and psychological factors influence TEA during sleep. These include psychological status prior to bedtime (Hawkins, 1989) altered neuroendocrine tonus (Born et al., 1999), and sleep structure (Kleitman, 1963; Tart, 1970; Zung and Wilson, 1971; Lavie et al., 1979; Zepelin, 1986; Aritake et al., 2004) preceding the predetermined wake time. For instance, strong motivation and the confidence that are will wake up at the predetermined time are associated with successful self-awakening (Hawkins, 1989; Moorcroft et al., 1997). Born et al. (1999) showed clearly that anticipated awakening at a predetermined time was preceded by an elevation in ACTH secretion (a particularly early, morning ACTH surge), a phenomenon that did not occur in relation to an unexpected ("surprise") awakening at the same clock time.

Several studies have focused on sleep structure as a key factor that might influence TEA during sleep; however, it remains controversial whether the preceding sleep stage or partial

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doi:10.1016/j.neures.2008.11.001

awakening prior to the predetermined wake time modifies TEA in humans (Kleitman, 1963; Zung and Wilson, 1971; Lavie et al., 1979; Zepelin, 1986; Aritake et al., 2004). We previously conducted a study to test whether the preceding sleep structure influenced the estimated passage of time during nighttime sleep which was divided into six time periods (90 min each) in healthy young subjects (Aritake et al., 2004). We found that, as sleep progressed, the subjects underestimated the amount of time that had passed in each time period. The estimated elapsed time correlated positively with the amount of slow wave sleep (SWS) and negatively with the amount of REM sleep. These findings support the notion that TEA pervades sleep and that it is affected by the preceding sleep status.

The aim of the present study was to clarify which sleep parameters could essentially influence on TEA by comparing the properties of estimated time interval during the usual nighttime sleep (NS) period with those during an arbitrary daytime sleep (DS) period in circadian antiphase. We expected REM sleep and SWS to show different time distributions between the two experimental conditions, and that this would enable us to more precisely detect functional interaction between the sleep structure and TEA during the sleep period.

2. Materials and methods

2.1. Participants

Twenty healthy men aged 18–23 years (mean, 21.1 ± 1.7 years), who had regular sleep habits, participated in the study. They were randomly allocated to on NS experiment or DS experiment. Three participants allocated to the DS experiment withdrew from the study (one due to infection during the pre-study period, one for an undisclosed reason, and one due to discomfort during the acute shift schedule). Thus, 10 participants completed the NS experiment (mean age, 20.2 ± 1.6 years) and 7 completed the DS experiment (mean age, 22.4 ± 0.7 years). They provided written informed consent after the possible risks and details of the study were explained to them. A physician and a psychiatrist examined all participants and found that none suffered from a neurological or psychiatric disorder, and none had a history of psychoactive drug use. Participants were instructed to keep to a regular sleep–wake schedule; record their sleep patterns in a sleep log; and abstain from caffeine, nicotine, and alcohol for 1 week prior to the experiment. All participants wore a wrist activity recorder (Actiwatch-L, Mini-Mitter Co., Inc., Bend, OR, USA) for 1 week prior to the experiment. Sleep onset and offset times were determined with Actiware Sleep software (V3.2 Mini-Mitter Co., Inc.). The details recorded in participants' sleep logs, together with their sleep onset and offset times, were used to confirm that they had regular sleep–-wake schedules. Because participants' attention to time could potentially affect the experimental results, we told them that the aim of the study was to investigate correlation between sleep parameters and subjective feeling; we did not disclose the study objectives until the end of the study. We confirmed that none of the participants had sensed the real purpose of the investigation until the end of this study. The study protocol was approved by the Institutional Review Board of the National Center of Neurology and Psychiatry.

2.2. Experimental procedures

Time estimation protocol is illustrated in Fig. 1.

2.2.1. NS experiment

The NS experiment was begun as follows: on day 1, the participant arrived at the laboratory at 19:00 h and slept in the laboratory bedroom from 0:00 h to 08:00 h for adaptation. After being woken at 08:00 h on day 2, the participant was kept awake until 00:00 h on day 3 under dim light conditions (150 lx). During waking hours, the participant was kept from knowing the clock time until the beginning of the time estimation protocol (TEP). His only awareness of the time of day would have been by the scheduled provision of an isocaloric meal (450 kcal) and mineral water every 4 h. At 00:00 h on day 3, the participant was instructed to go to bed and that the TEP would begin.

2.2.2. DS experiment

The DS experiment was begun as follows: on day 1, the participant arrived at the laboratory at 19:00 h and slept in the laboratory bedroom from 0:00 h to 08:00 h for adaptation. After being woken at 08:00 h on day 2, the participant was kept awake for 28 h until 12:00 h on day 3 under the same isolated condition as in the NS experiment. An isocaloric meal (450 kcal) and mineral water were provided every 4 h. After 28 h of enforced wakefulness,

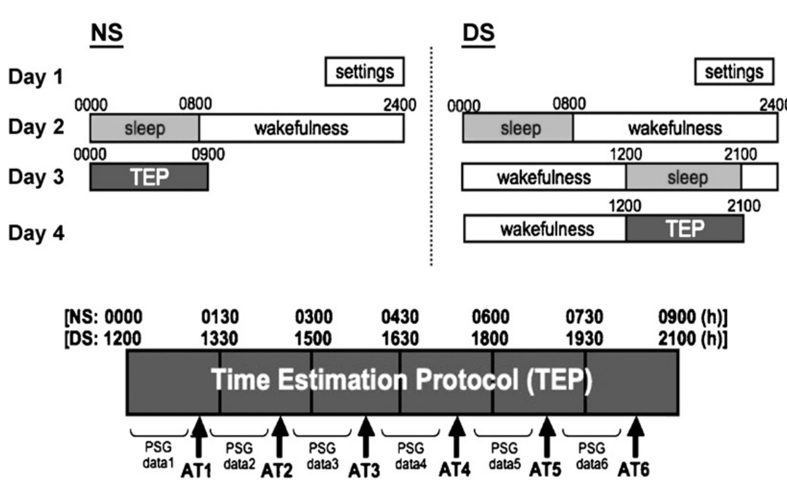

Fig. 1. Time estimation protocol (TEP). TEP was conducted between 00:00 h and 09:00 h (nighttime sleep: NS) or 12:00 h and 21:00 h (daytime sleep: DS). The 9-h polysomnography (PSG) recording periods were divided into six 90-min periods. We woke the participants and conducted a structured interview once during each 90-min period (awakening trial: AT). Participants were awakened for an AT when (1) they had slept for longer than 45 min after lights out or since the end of the prior AT; and (2) stage 2 sleep had continued for more than 3 min. PSG data between successive ATs were obtained. If these criteria were not satisfied until 75 min after the beginning of 90-min period, the participants were awakened at the end of each 90-min period. In the structured interview, we asked the several questions including, "What time do you think it is now? (subjective time of day)" to determine participants' spontaneous estimation of time, without encouraging them to focus their attention on time.