The influences of time-of-day and sleep deprivation on postural control
Your article is protected by copyright and all rights are held exclusively by Springer-Verlag. This e-offprint is for personal use only and shall not be self-archived in electronic repositories. If you wish to self-archive your work, please use the accepted author’s version for posting to your own website or your institution’s repository. You may further deposit the accepted author’s version on a funder’s repository at a funder’s request, provided it is not made publicly available until 12 months after publication.
The influences of time-of-day and sleep deprivation on postural control

Clement Bougard · Marie-Charlotte Lepelley · Damien Davenne

Abstract The aim of this study was to check the combined and/or dissociated influences of time-of-day and sleep deprivation on postural control. Twenty subjects participated in test sessions which took place at 6:00 am, 10:00 am, 2:00 pm and 6:00 pm either after a normal night’s sleep or after a night of total sleep deprivation. Postural control was evaluated by COP surface area, LFS ratio and Romberg’s index. The results showed that postural control fluctuates diurnally according to three different periods, pronounced by sleep deprivation: (1) at 6:00 am, there was no modification by sleep deprivation; (2) at 10:00 am and 2:00 pm, an interaction effect was observed for COP surface area and LFS ratio after sleep deprivation. Values of COP surface area were significantly higher (\(P<0.01\)) following the night of sleep deprivation than after the normal night’s sleep (139.36 ± 63.82 mm\(^2\) vs. 221.72 ± 137.13 mm\(^2\) and 143.78 ± 75.31 mm\(^2\) vs. 228.65 ± 125.09 mm\(^2\), respectively); (3) at 6:00 pm, the LFS ratio was higher than during the two other periods (\(P<0.001\)) whereas COP surface area decreased to the level observed at 6:00 am. At this time-of-day, only the LFS ratio was significantly increased (\(P<0.05\)) by the night of sleep deprivation (0.89 ± 0.14 vs. 1.03 ± 0.30).

This temporal evolution in postural control does not seem to be related to any deterioration in visual input as Romberg’s index (150.09 ± 97.91) was not modified, regardless of the test session.

Keywords Postural control · Sleep deprivation · Time-of-day

Introduction

Maintaining balance requires the continuous integration of visual, vestibular and proprioceptive inputs (Teasdale and Simoneau 2001) by the central nervous system (CNS) (cerebellum, thalamus, prefrontal cortex) (Ouchi et al. 1999). This allows determining of the position of the various body segments compared with the others as well as the body position in space. This sensory integration, making it possible to contract muscles adequately in order to maintain balance, requires a high level of vigilance, particularly when one of the sensory inputs is no longer effective (Redfern et al. 2001). As vigilance is mainly determined either by circadian rhythmicity or by sleep deprivation, postural control may also be influenced by these two factors. Interactions between these two processes have been illustrated in a model proposed by Borbely (for review, Borbely 2009). This model clearly shows that the two processes, i.e. circadian rhythmicity and sleep deprivation, cannot be studied separately.

Although several studies have reported that postural control is influenced by the time-of-day, only a few were conducted across an entire nychthemeron. Postural control is low between 5:00 and 8:00 am (Avni et al. 2006; Morad et al. 2007) and around 1:00 pm (Forsman et al. 2007). These time periods correspond to the bathyphase of the
body temperature rhythm (Reilly 1990) and to the post-lunch dip observed in the vigilance level (Clodore et al. 1986). Apart from these two periods of lower efficiency, postural control improves during the morning and in the afternoon to reach a maximal level around 10:00 pm (Avni et al. 2006; Gribble et al. 2007; Nakano et al. 2001). Consequently, the rhythm of postural control might be influenced by either vigilance and/or body temperature (Avni et al. 2006; Forsman et al. 2007). When the different sensory inputs are manipulated, the diurnal fluctuations in postural control seem to be mainly related to the vestibular system (Kohen-Raz et al. 1996).

Other studies focused on the efficiency of postural control during sustained waking for up to 36 h. It has been suggested that sleep deprivation could be a risk factor for postural control (Gomez et al. 2008). Most of the studies indicate that postural sway is affected during the night, between 0:00 and 6:00 am if the day is prolonged without sleep (Fabbri et al. 2006; Liu et al. 2001). However, when recorded in the morning (between 8:00 and 9:00 am) after a night without sleep, the results are controversial. Some authors highlighted a deleterious effect of sleep deprivation on postural control (Avni et al. 2006; Nakano et al. 2001; Patel et al. 2008), whereas others found no effect (Uimonen et al. 1994) or observed a decrease in postural efficiency only under particularly demanding conditions. The latter were either (1) disturbances of visual and proprioceptive inputs (Gomez et al. 2008; Seliga et al. 1991) or (2) a dual-task paradigm (multiple choice reaction times) on an unstable support (Schlesinger et al. 1998). When measurements were carried out after 9:00 am during a day following a night of sleep deprivation, the standing balance system was altered but seemed to continue to fluctuate according to the circadian rhythm (Forsman et al. 2008). Performances after 36 h of being awake (at the end of the afternoon) were thus less affected than those in the morning (Gribble and Hertel 2004; Patel et al. 2008) in comparison with a baseline level obtained around 12:00 am. Various assumptions have been made to explain sleep deprivation effects on postural control. According to Patel et al. (2008), it seems that following sleep deprivation, visual information is poorer or at least its integration, which requires a high level of vigilance, becomes defective or slower. As a consequence, following a night of sleep deprivation, postural sway is more pronounced with the eyes closed (EC) than with the eyes opened (EO) (Fabbri et al. 2006; Liu et al. 2001). Other authors indicated, on the basis of analysis by frequency bands, that the band designed as low (0.1–1.0 Hz), which is sensitive to vestibular stress and disturbances (de Wit 1972), is affected by a lack of sleep (Avni et al. 2006; Liu et al. 2001).

The majority of the studies described previously particularly focused on analysing the effects of circadian rhythmicity or sleep deprivation on postural control. However, in these studies, a distinction cannot be made between the two processes because none of these studies compared the results obtained at the same time-of-day after a sleep deprivation with the ones obtained after a normal night of sleep. Moreover, a lot of differences in the experimental protocols used were observed (age and chronotype of the subjects, evaluation criteria and frequency bands chosen for analysis, and acquisition duration), which explains the differences in the results.

The aim of this study was to observe the combined effects of the time-of-day and sleep deprivation on postural control using a methodology adapted for observing these fluctuations. The criteria used for evaluating postural control were kept simple and commonplace to allow a comparison between studies.

Methods and materials

Subjects

Twenty male subjects (age: 24.6 ± 4.6 years; height: 178.4 ± 8.9 cm; weight: 75.7 ± 18.1 kg) voluntarily took part in the experiment and signed an informed consent form before being included in this study. The study was granted ethical approval by the local ethics committee, the CHU Côte de Nacre, Caen, France, and was therefore performed in accordance with the ethical standards laid down in the 1964 Declaration of Helsinki.

In order to guarantee sample homogeneity, the subjects were selected according to their chronotype and their answers to the Horne and Ostberg (1976) questionnaire. All of the subjects were "no type". The recruitment of subjects presenting extreme chronotypes (definitively evening and definitively morning types) could have masked the possible effects of the factors tested because of the advance/delay phase which characterises the circadian rhythmicity of these subjects compared with intermediate ones (Kerkhof and van Dongen 1996).

Procedure

Each subject was evaluated during four test sessions which took place at 6:00 am, 10:00 am, 2:00 pm and 6:00 pm, following a night with or without sleep, in a counterbalanced order (Fig. 1). It seems that a minimum of 5 h is required to observe any evolution between the results obtained at different times of the day (Forsman et al. 2007; Høggström et al. 2006). Moreover, as postural control may develop concomitantly with body temperature and/or vigilance rhythm, it seemed necessary to carry out recordings at the bathyphase and acrophase of these rhythms.
Consequently, two test sessions had to be set up at 6:00 am and 6:00 pm at least, thus separated by 12 h. In order to accurately determine circadian fluctuations, it is better to set up numerous test sessions at equal intervals from these time periods (Gauthier et al. 1997). However, it is necessary to find a compromise between test session repetitions, which can result in a fatigue phenomenon and fine circadian process descriptions. As a consequence, the two other time points were set up with 4-h intervals.

In this study, the control of a number of factors recommended for diurnal fluctuation studies was taken into account (large sample of subjects, chronotype). Masking effects such as the consumption of stimulant drinks (coffee, tea), meals or even physical activity (Reilly and Bambaeichi 2003) were also controlled as suggested by Forsman et al. (2007). All of the subjects came to the laboratory (21.6 ± 0.8°C) at 7:00 pm, the day before the tests. A standardised meal was then offered. When the subjects were evaluated following a normal night’s sleep, they were asked to go to sleep at 10:30 pm in order to guarantee a minimum of 6 h in bed. The subjects were then awoken by an experimenter at 5:00 am. For the night of sleep deprivation, the subjects were in the presence of an experimenter and were not allowed to lie down. The subjects were only able to take part in activities that did not involve any physical load or excitement (reading, looking at a film, playing cards, for example), and energy-giving and stimulating drinks (coffee, tea, for example) were not allowed. The 2 days of tests were separated by a period of 1 week to let the participants recover from the night of sleep deprivation.

A standardised breakfast was offered at 8:30 am after the experimental session at 6:00 am (Baxter and Reilly 1983) in order to limit interindividual variability of the results (Bougard et al. 2009). A standardised meal was also offered at 12:00 am. An apple was offered at 4:30 pm.

Posturographic assessments

Postural control was evaluated by measurements carried out on a force platform (PostureWin®, Techno Concept®, Cereste, France; 40 Hz frequency, 12-bits A/D conversion), which records the displacements of the centre of foot pressure (COP) with three strain gauges. The subjects were placed according to precise markers. Their legs were extended and their feet formed a 30° angle relative to each other (inter-malleolar distance of 5 cm). The subjects were first requested to maintain balance with the eyes opened (EO) and then with the eyes closed (EC). In the EO condition, the subjects looked at a fixed level target at a distance of 90 cm. In the EC condition, they were asked to keep their gaze straight ahead. The test lasted 51.2 s.

The COP surface area (90% confidence ellipse) evaluated the subject’s postural performance: the smaller the area, the better the performance (Caron et al. 2000). The LFS ratio corresponding to the length of the COP displacement as a function of the surface (index of energy expenditure (Gagey and Weber 1999)) and Romberg’s index (RI) [(surface EC/surface EO) × 100] evaluating the contribution of vision to maintaining posture (Njioikitjien and van Parys 1976) were also measured. Although there is no consensus on which criterion is the most sensitive to chronobiological influences (Forsman et al. 2007; Liu et al. 2001), the three evaluation criteria (COP surface area, LFS ratio, RI) for evaluating postural control fluctuations were chosen according to their previous use in either (1) biological rhythm (Nakano et al. 2001) and/or (2) sleep deprivation studies (Fabbri et al. 2006; Liu et al. 2001).

Statistical analysis

The data recorded during the eight test sessions were analysed by a 2 (sleep conditions: normal night; sleep deprivation) × 4 time-of-day (6:00 am; 10:00 am; 2:00 pm and 6:00 pm) repeated-measure analysis of variance (ANOVA). In addition, for all the collected data, the condition of sphericity was also tested (Mauchly’s test). The $P$-value levels were corrected for possible deviations from sphericity by means of the Huynh–Feldt epsilon ($\varepsilon$). We report the uncorrected degrees of freedom, the $\varepsilon$ value and the $P$-value according to the corrected degrees of freedom. When significant differences were observed ($P < 0.05$), a post hoc analysis was then performed with a Fischer–Snedecor least significant difference (LSD) test.

In addition, in order to test our a priori hypothesis which postulates that diurnal fluctuations, i.e. the difference between the minimal and maximal values recorded for each variable (in this case, between the values recorded at 6:00
am and 6:00 pm), are determined by the previous sleep condition (normal or sleep deprivation), planned comparisons were applied. Similarly, in order to check the a priori hypothesis, according to which the temporal evolution of the variable studied across the day was modified by the lack of sleep, planned comparisons were applied to the values obtained at each test session organised at the same time-of-day, according to the previous sleep condition. For each significant effect, we estimated the size effect using the partial eta squared (partial $\eta^2$).

**Results**

COP surface area

The ANOVA indicated a significant effect of time-of-day on the COP surface area ($F_{(3,57)} = 5.13; \varepsilon = 0.99; P < 0.01$; partial $\eta^2 = 0.20$). The COP surface area was more important at 10:00 am (180.54 ± 113.51 mm²) and at 2:00 pm (186.22 ± 110.61 mm²) than at 6:00 am (141.87 ± 69.23 mm²) or at 6:00 pm (140.23 ± 63.91 mm²) (Fig. 2). Moreover, the COP surface area was smaller following the normal night’s sleep (137.93 ± 66.31 mm²) than after the night of sleep deprivation (186.50 ± 110.03 mm²) ($F_{(1,19)} = 19.67; \varepsilon = 1.00; P < 0.001$; partial $\eta^2 = 0.49$).

More importantly, an interaction effect of ‘time-of-day’ × ‘sleep condition’ was also highlighted ($F_{(3,57)} = 3.80; \varepsilon = 0.94; P < 0.05$; partial $\eta^2 = 0.16$). The analysis of the planned comparisons did not indicate any effect of the sleep condition on the COP surface area diurnal fluctuation (6:00 am vs. 6:00 pm) ($F_{(1,19)} = 1.74; P = 0.20$). On the other hand, the planned comparisons did highlight the fact that measurements of the COP surface area recorded at 10:00 am ($F_{(1,19)} = 8.89; P < 0.01$) and at 2:00 pm ($F_{(1,19)} = 12.07; P < 0.01$) were significantly higher following the night of sleep deprivation than after the normal night (139.36 ± 63.82 mm² vs. 221.72 ± 137.13 mm² and 143.78 ± 75.31 mm² vs. 228.65 ± 125.09 mm², respectively). Moreover, measurements of the COP surface area at 6:00 am ($F_{(1,19)} = 0.00; P = 0.99$) and at 6:00 pm ($F_{(1,19)} = 3.63; P = 0.07$) did not depend on the previous sleep condition (141.95 ± 77.58 mm² vs. 141.78 ± 61.79 mm² and 126.61 ± 48.25 mm² vs. 153.84 ± 75.28 mm², respectively).

**LFS ratio**

The statistical analysis indicated that the LFS ratio was affected by ‘time-of-day’ ($F_{(3,57)} = 8.80; \varepsilon = 0.99; P < 0.001$). The subjects spent less energy in order to maintain their balance at 6:00 am (0.9 ± 0.11) than at 10:00 am (0.88 ± 0.19), 2:00 pm (0.93 ± 0.21) or 6:00 pm (0.96 ± 0.24). The subjects also spent less energy on remaining steady at 10:00 am than at 6:00 pm. In contrast, the LFS ratio was not affected by the previous sleep condition ($F_{(1,19)} = 3.84; \varepsilon = 1.00; P = 0.06$). The subjects spent as much energy maintaining their balance following a normal night (0.86 ± 0.17) as after a night of sleep deprivation (0.92 ± 0.23).

No interaction effect of ‘time-of-day’ × ‘sleep condition’ ($F_{(3,57)} = 1.64; \varepsilon = 0.94; P = 0.19$) was observed on the LFS ratio. The analysis of the planned comparisons confirmed that the amplitude of the diurnal fluctuation (6:00 am vs. 6:00 pm) was not determined by the previous sleep condition ($F_{(1,19)} = 1.35; P = 0.26$) (Fig. 3). Measurements of the LFS ratio carried out at 6:00 am ($F_{(1,19)} = 2.43; P = 0.13$), 10:00 am ($F_{(1,19)} = 0.68; P = 0.42$) and 2:00 pm ($F_{(1,19)} = 0.03; P = 0.85$) did not depend on the previous sleep condition (0.77 ± 0.11 vs. 0.82 ± 0.11 and 0.86 ± 0.19 vs. 0.89 ± 0.19 and 0.93 ± 0.19 vs. 0.92 ± 0.24, respectively). On the other hand, measurements of the LFS ratio carried out at 6:00 pm ($F_{(1,19)} = 4.60; P < 0.05$) were significantly higher following the night of sleep deprivation (0.99 ± 0.17; partial $\eta^2 = 0.20$).

---

**Fig. 2** COP surface area recorded at 6:00 am, 10:00 am, 2:00 pm and 6:00 pm following a normal night and a night of sleep deprivation (average ± SD; $N = 20$) (*significant difference according to the sleep condition for the same time-of-day)

**Fig. 3** LFS ratio at 6:00 am, 10:00 am, 2:00 pm and 6:00 pm following a normal night and a night of sleep deprivation (average ± SD; $N = 20$) (*significant difference according to the sleep condition for the same time-of-day)
deprivation than after the normal night (0.89 ± 0.14 vs. 1.03 ± 0.30).

Romberg’s index

The RI measurement was not influenced by the time-of-day ($F_{(3,57)} = 0.80; \varepsilon = 0.99; \ P = 0.49$) or by the previous sleep condition ($F_{(1,19)} = 0.38; \varepsilon = 1.00; \ P = 0.54$). The use of visual inputs by the subjects was the same regardless of the experimental session considered (150.09 ± 97.91).

No interaction effect of ‘time-of-day’ × ‘sleep condition’ ($F_{(3,57)} = 2.41; \varepsilon = 0.97; \ P = 0.10$) was observed on the RI values. The analysis of the planned comparisons indicated that the amplitude of the fluctuation between the sessions at 6:00 am and 6:00 pm did not depend on the previous sleep condition ($F_{(1,19)} = 0.12; \ P = 0.73$). The RI measurements indicated that the subjects used the same amount of visual information at 6:00 am ($F_{(1,19)} = 2.79; \ P = 0.11$), 10:00 am ($F_{(1,19)} = 0.34; \ P = 0.57$), 2:00 pm ($F_{(1,19)} = 0.22; \ P = 0.64$) and 6:00 pm ($F_{(1,19)} = 0.88; \ P = 0.36$) regardless of the previous sleep condition.

Discussion

Our study aimed to evaluate the influences of time-of-day and sleep deprivation on postural control using simple and commonly used evaluation criteria. The results show (1) diurnal fluctuations of the COP surface area and the LFS ratio but none for RI and (2) a deleterious effect of sleep deprivation. Setting up test sessions during the day after a normal night’s sleep and after a night of sleep deprivation made it possible to check for the influence of sleep deprivation on the temporal evolution of postural control.

At 6:00 am, the results did not differ between the two sleep conditions. After the normal night’s sleep, our results confirmed that the COP surface area is high in the early morning (Liu et al. 2001; Nakano et al. 2001). They also confirmed the finding that sleep deprivation has no effect on postural control at that time-of-day, i.e. after 24 h without sleep (Schlesinger et al. 1998; Uimonen et al. 1994). At this time-of-day, the level of vigilance is low and the difference between a normal day and a day following a total sleep deprivation is not significant (Casagrande et al. 1997). This could also explain the lack of differences found in postural sway.

Between 10:00 am and 2:00 pm, the COP surface area and LFS ratio were higher. This confirms that postural control is low around midday (Forsman et al. 2007). Despite increased energy expenditure (Gagey and Weber 1999), subjects were unable to improve their stability. The increase observed for the two criteria after a normal night’s sleep was more pronounced following the night of sleep deprivation. The values of the LFS ratio indicated a comparable investment between the two sleep conditions, but the subjects were unable to maintain their balance efficiently (COP surface area was higher after sleep deprivation than after the normal night’s sleep). These results confirm a noxious effect of sleep deprivation on postural control after 30 h of wakefulness, i.e. from 10:00 am (Morad et al. 2007; Patel et al. 2008).

At 6:00 pm, the COP surface area was lower than at 2:00 pm and the same as the ones obtained at 6:00 am. In contrast, the LFS ratio was high at this time-of-day. As a consequence, the statokinesigram length was high at 6:00 pm regardless of the previous sleep condition (Gagey and Weber 1999). These results are similar to those obtained by Gribble and Hertel (2004) and Gribble et al. (2007), who observed lower COP velocities in the morning than in the evening after a normal night’s sleep. For Gagey and Weber (1999), an increase in the LFS ratio was interpreted as an increase in energy expenditure. As for physical performance, the availability of energy resources, provided by food intake, partly determines the expenditure the organism is ready to provide in order to perform the same task at different times-of-day (Reilly et al. 1984; Reilly and Brooks 1990). This aspect can be related to the increase in the concentration of carbohydrates at the hepatic level during the day (Ciok and Dolna 2006; Nabb and Benton 2006). Following the night of sleep deprivation, the COP surface area decreased to levels obtained at 6:00 am. This observation confirmed that balance abilities could improve throughout the day, even following total sleep deprivation of up to 36 h (Forsman et al. 2007; Gribble and Hertel 2004; Patel et al. 2008). Nevertheless, as Patel et al. (2008) emphasised, even if postural sways are comparable after 36 h of continuous wakefulness, various signs indicate that postural control is affected by the lack of sleep. For example, in our study, the LFS ratio increased to a higher level than after the normal night’s sleep, which indicated (1) increased energy expenditure (Gribble and Hertel 2004) and (2) that compensatory mechanisms may take place between the various cerebral resources. For example, at this time-of-day, there is an increased level of vigilance (Lavie 1985), which was even observed after a night of sleep deprivation (Lorenzo et al. 1995). This increase in vigilance should allow a compensatory recruitment of cerebral areas (Drummond and Brown 2001; Lorenzo et al. 1995). Another possible compensatory mechanism may be associated with the COP surface area limitation at this time-of-day. This induces less important but more frequent muscular contractions of postural muscles of the legs in order to reduce the muscular fatigue observed with an increase in time awake (Guette et al. 2005, 2006).

Our results did not show any modification of the contribution of visual information to postural control. As the
values of the RI indicated, postural sway became increasingly more pronounced in the EC condition. Contrary to Fabbri et al. (2006), however, there was no amplification of the effects of time-of-day or lack of sleep. Therefore, our results echo those obtained in various other studies suggesting that the increase in postural sway with sleep deprivation is due to a decrease in vestibular system efficiency (Avni et al. 2006; Kohen-Raz et al. 1996; Morad et al. 2007) and/or to the integration of the various sensory inputs (Teasdale and Simonneau 2001).

In conclusion, our results indicate an improvement of postural control according to time-of-day after a normal night’s sleep. When the subjects were sleep deprived, postural control was affected, particularly in the middle of the day (10:00 am and 2:00 pm). To the best of our knowledge, the LFS ratio has not been recorded during the day in previous studies. Interestingly, however, the combination of the results obtained for COP surface area and LFS ratio in our study indicates that postural control fluctuates according to a rhythm which is close to that of body temperature and/or vigilance. Further research is needed to clarify the origins of these fluctuations.

Acknowledgments This work was supported in part by a PREDIT-GO4 contract. Clément Bougard was awarded a grant for his PhD thesis by the Conseil Régional de Basse-Normandie (Regional council of Lower Normandy) and the Institut National de Recherche sur les Transports et leur Sécurité (The French National Institute for Transport and Safety Research).

References


