

# The effect of 40 h constant wakefulness on task-switching efficiency

DANIEL BRATZKE, BETTINA ROLKE, MICHAEL B. STEINBORN and ROLF ULRICH

Cognitive and Biological Psychology, University of Tübingen, Tübingen, Germany

Accepted in revised form 13 November 2008; received 15 July 2008

**SUMMARY** This study investigated efficiency of switching between different tasks in 12 male participants (19–30 years) during 40 h of constant wakefulness. As index of task-switching efficiency, switch costs in reaction time were assessed every 3 h under controlled behavioural and environmental conditions. Overall reaction times and switch costs showed a temporal pattern consistent with the assumption of a combined influence of a sleep homeostatic and a circadian process. An additional analysis indicated that the variation in switch costs could not be attributed to interference of the current task with persisting activation from preceding tasks. We therefore conclude that sleep loss and the circadian system affect the ability to prepare the current task rather than automatic processing of irrelevant stimulus information.

**KEYWORDS** circadian rhythm, constant routine, executive function, sleep deprivation, task switching

## INTRODUCTION

Human cognitive functioning is clearly influenced by fluctuations in individual's alertness or sleepiness. Usually, two interlinked processes are assumed to contribute to these fluctuations in order to regulate the 24-h sleep-wake cycle: a homeostatic sleep process and a circadian process (Daan *et al.*, 1984; Dijk and Czeisler, 1995). Consistent with this assumption, performance decrements after sleep loss and time-of-day modulations have been found in a wide range of cognitive tasks (for reviews see Rogers *et al.*, 2003; Schmidt *et al.*, 2007). Furthermore, some studies have provided direct chronometric evidence for a circadian variation in the speed of mental processing with a slowing during the night (Bratzke *et al.*, 2007; Monk and Carrier, 1997).

The present study aimed to investigate the influence of the circadian system and sleep loss on task-switching efficiency. Many situations of everyday life as well as many workplaces require frequent switches between different tasks. Whenever such a switch occurs, an appropriate reconfiguration of mental

resources for the next task is required (e.g. Monsell, 2003). The ability to switch between tasks is regarded a fundamental executive function (e.g. Miyake *et al.*, 2000; Monsell, 2003) and has been shown to be associated with the prefrontal cortex in brain imaging studies (e.g. Dove *et al.*, 2000; Swainson *et al.*, 2003) as well as in neuropsychological studies (e.g. Aron *et al.*, 2004).

Extensive research has shown that task switching often cannot be achieved without costs. In classical task-switching paradigms, participants perform two tasks in an either random or predictable sequence. Longer reaction times and higher error rates are typically observed after a task-switch compared with the situation when the task repeats (e.g. Allport *et al.*, 1994; Jersild, 1927; Rogers and Monsell, 1995; Spector and Biedermann, 1976). It is widely accepted that a substantial part of these switch costs originates from a time-consuming control process of 'task-set reconfiguration' (e.g. Monsell, 2003; Rogers and Monsell, 1995). Others, however, have emphasized the role of involuntary processes for task switching suggesting that switch costs may also result from persisting task-set activation from trial to trial, a process referred to as 'task-set inertia' (Allport *et al.*, 1994) or 'proactive interference' (Goschke, 2000). Most of the current accounts of task switching assume that both active processes of task-set

*Correspondence:* Daniel Bratzke, Psychologisches Institut, Universität Tübingen, Friedrichstrasse 21, 72072 Tübingen, Germany. Tel.: +49 7071 29 74512; fax: +49 7071 29 2410; e-mail: daniel.bratzke@uni-tuebingen.de

reconfiguration and involuntary processes of proactive interference can contribute to switch costs (Goschke, 2000; Meiran *et al.*, 2000; Ruthruff *et al.*, 2001).

Previous studies have demonstrated that switch costs are modulated by temporal fluctuations in the neurophysiological state, for example because of sleep loss (Heuer *et al.*, 2004; Jennings *et al.*, 2003) or stress (Steinhauser *et al.*, 2007). As both the sleep homeostatic process and the circadian process affect individual's alertness, one may presume that performance indices sensitive to sleep loss might also show a circadian time-of-day variation. There is some evidence, however, that this is not necessarily the case. For instance, Harrison *et al.* (2007) revealed that performance in a frontal lobe task was affected by wake duration but not by circadian variation. Additionally, other executive functions, for example the inhibition of prepotent responses in the Stroop task, have been shown to be insensitive to sleep loss and time-of-day effects (Sagaspe *et al.*, 2006). In another study, Blatter *et al.* (2005) investigated the effect of sleep loss on planning performance and found performance to be affected only in a more complex version of the task. They suggested that the sensitivity of cognitive tasks to sleep loss and circadian variation may depend on task complexity with higher sensitivity for more complex tasks. Given these heterogeneous results, we aimed to provide further empirical evidence regarding the sensitivity of task-switching efficiency to sleep loss and, in addition, especially regarding its sensitivity to the circadian system. In the present study, we therefore assessed switch costs in a protocol that included 40 h of constant wakefulness and controlled behavioural and environmental conditions.

## METHODS

### Task-switching paradigm

The stimuli and tasks were similar to those used in the study by Heuer *et al.* (2004). In each trial, a pair of digits was presented on a computer screen above or below a central fixation cross, which was present during the whole trial. One of the two digits appeared directly above or below the fixation cross (i.e. the central position). The peripheral digit appeared either to the left or to the right of the central digit. The vertical localization of the digits indicated which one of two tasks had to be performed. When the digits appeared above the fixation cross, the participant's task was to press the left key if the centrally positioned digit was from the set '1 2 3 4' and to press the right key if it was from the set '6 7 8 9' (numerical judgement). When the two digits appeared below the fixation cross, the participant had to respond corresponding to the horizontal position of the peripheral digit (spatial judgement).

Each trial started 1200 ms after the preceding response. According to the alternating-runs procedure (Rogers and Monsell, 1995), the tasks were presented in a predictable sequence (AABBAA...), and the vertical position of the digits changed every second trial. Irrespective of the actual task, the

digits and the position of the lateral digit were chosen randomly. In each 10-min session, participants performed 144 experimental trials divided into six blocks of 24 trials.

Switch costs were calculated by subtracting reaction times in repetition trials from reaction times in switch trials. We also calculated incongruity costs to assess the influence of proactive interference from task-set activation on these switch costs (see Heuer *et al.*, 2004). Such incongruity costs emerge when the task-irrelevant stimulus feature automatically activates a response opposite to the correct response evoked by the task-relevant stimulus feature. These incongruity costs are usually stronger in switch than in repetition trials and therefore can substantially contribute to switch costs (e.g. Goschke, 2000). For the present paradigm, congruency was determined between the response side associated with the numerical value of the central digit (i.e. the relevant feature in the numerical task and the irrelevant feature in the spatial task) and the position of the peripheral digit (i.e. the relevant feature in the spatial task and the irrelevant feature in the numerical task). For example, when the numerical value of the central digit was below five and the peripheral digit appeared on the left (right) of the central digit, the trial was scored as congruent (incongruent). Analogous to the switch costs, incongruity costs were calculated by subtracting reaction times in congruent trials from those in incongruent trials.

### Participants

Twelve healthy young males (19–30 years, mean = 23.2) participated in the study. Only male subjects were included, so as to avoid masking effects because of the female menstrual cycle. All participants gave written informed consent and obtained 200 Euro for their participation. Participants were selected according to the following exclusion criteria: no shift-work in the last 3 months, no travel across more than two time-zones in the previous month, no smoking, no alcohol or drug abuse, no regular medication, no sleep disorders or any other serious somatic or mental disorders as assessed by a general health questionnaire and the Pittsburgh Sleep Quality Inventory (Buysse *et al.*, 1989). Participants were asked to maintain a regular sleep-wake schedule during the week prior to their admission to the laboratory. This was verified by wrist actigraphy (Daqtometer by Daqtix GbR, Oetzen, Germany) and sleep diaries (mean bedtime: 23:33 hours, SD = 01:02 hours; mean waketime: 07:06 hours, SD = 00:42 hours).<sup>1</sup> All participants had intermediate chronotypes (mid-sleep on free days corrected for sleep deficit, mean = 4.4, SD = 0.5) according to the Munich Chronotype Questionnaire (Roenneberg *et al.*, 2003).

<sup>1</sup>The bedtimes and waketimes of one participant were missing. Additionally, two of the 12 participants were recruited shortly before the study but affirmed that they had a regular sleep-wake schedule during the week prior to study begin.

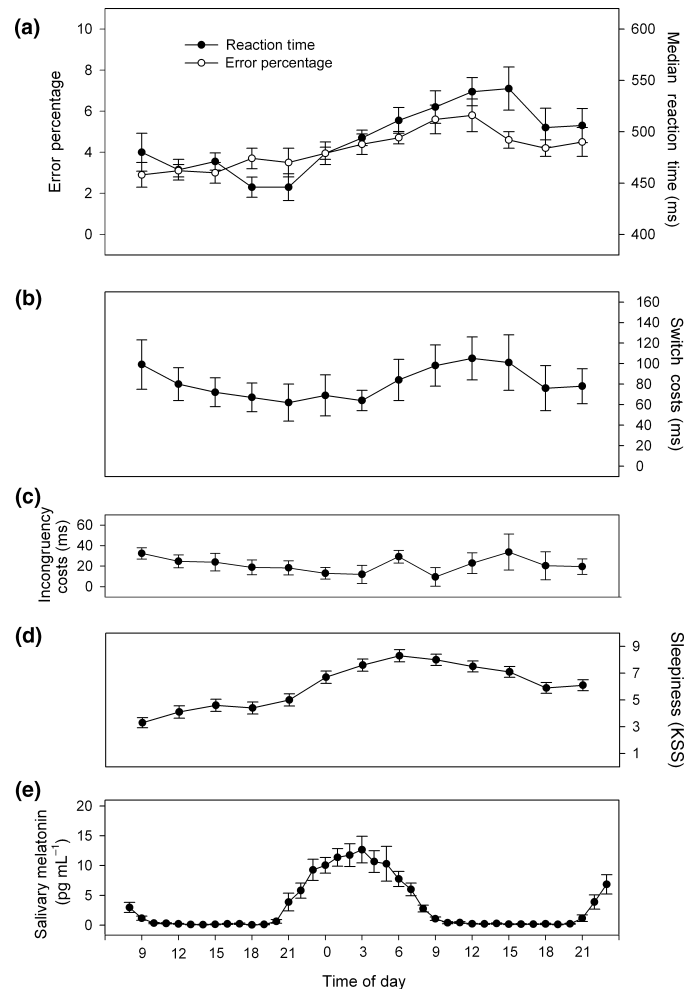
## Protocol

The experiment took place in an isolation facility at the department of Biology of the University of Groningen. Two groups of six participants each were tested on two separate weekends. Participants entered the isolation facility on late Friday afternoon. Beginning at 19:00 hours the participants attended a practice session. Then the participants slept in the isolation facility from 23:30 until 07:30 hours on Saturday morning. The experimental protocol started at 08:00 hours on Saturday and lasted for 40 h until 23:00 hours the next day. After a recovery night the participants left the laboratory on Monday morning.

As part of a larger study (including several other cognitive and sensorimotor tasks), each participant performed the task-switching paradigm at 3-hourly intervals (a total of 13 sessions; groups of two participants each started at 08:00, 09:00 and 10:00 hours). Subjective sleepiness was assessed via

the Karolinska Sleepiness Scale (KSS, Åkerstedt and Gillberg, 1990) at hourly intervals (amounting to a total of 40 sessions) at the same time as saliva collection for melatonin assay. Short breaks of about 10 min were provided between subsequent tasks. During the breaks, the participants were allowed to read magazines, to listen to music or to converse with the experimenters.

In order to minimize potential masking effects of environmental and behavioural changes on performance, the experiment was held under constant conditions. Light levels were maintained at about 10 lux and participants were closed off from external time cues. Physical activity was restricted to regular room changes (at hourly intervals) and toilet requirements. During the tasks the participants sat in an upright position. To minimize the influence of irregular food intake, isocaloric meals (*c.* 100 kcal) were provided hourly. Participants had free access to water, but they were not allowed to consume caffeinated or sugary drinks.



**Figure 1.** Performance measures, subjective sleepiness and melatonin secretion as a function of time-of-day. (a) Median reaction time and error percentage, (b) switch costs, (c) incongruency costs, (d) subjective sleepiness (KSS), (e) salivary melatonin. Error bars represent  $\pm 1$  SE. For reaction times, error rates, switch costs and incongruency costs, standard errors for within-subject designs were calculated according to Cousineau (2007). KSS, Karolinska Sleepiness Scale.

### Data analysis

For the task-switching data, the first trial of each block, error trials as well as trials which followed error trials were discarded from reaction time analyses. In order to minimize the influence of lapses and microsleeps, we analysed median reaction times rather than means (see Horowitz *et al.*, 2003). ANOVA for repeated measures (ANOVA) with the factors session (1–13), task sequence (switch versus repetition) and congruency (congruent versus incongruent) were conducted on median reaction time and error percentage. A separate ANOVA with the factor session was conducted on sleepiness ratings (binned into 3-hourly intervals). ANOVAs included Helmert contrasts to evaluate whether switch costs and sleepiness diminished in the subsequent sessions after their maxima. *P*-values were whenever appropriate adjusted by the Huyn-Feldt correction.

Saliva samples were assayed for melatonin by radio-immunoassay with an analytical least-detectable dose of 0.15 pg mL<sup>-1</sup> and a functional least-detectable dose of 0.65 pg mL<sup>-1</sup> (Weber *et al.*, 1997). The time of dim light melatonin onset as circadian phase marker was defined by crossing the threshold of 3 pg mL<sup>-1</sup>. In order to evaluate the phase relationship of melatonin secretion, subjective sleepiness and switch costs, we calculated cross-correlations between these variables. For this analysis, melatonin data were also binned into 3-hourly intervals.

### RESULTS

Fig. 1 depicts median reaction times and error percentages (Panel a), switch costs (Panel b), incongruency costs (Panel c), subjective sleepiness (Panel d) and salivary melatonin (Panel e) as a function of session. Time-of-day represents the average time-of-day of corresponding sessions. As is usually observed, session strongly affected overall reaction time performance,  $F(12, 132) = 4.7, P < 0.01$ . Initially, reaction times decreased until session 5 (21:00 hours) and then showed a continuous increase until session 11 (15:00 hours, day 2), but afterwards decreased again. More important, the ANOVA revealed the commonly observed switch costs (81 ms) and these switch costs were affected by session,  $F(12, 132) = 2.5, P < 0.05$ . Switch costs decreased from the first experimental session (09:00 hours) reaching lowest switch costs from session 5 (21:00 hours) to session 7 (03:00 hours). Then, switch costs increased continuously until its maximum around session 10 (12:00 hours, day 2). Importantly, switch costs decreased again during the last sessions as validated by the Helmert contrast between session 10 and the mean of subsequent sessions (11–13),  $F(1, 11) = 4.7, P = 0.05$ .

As can be seen in Fig. 1 (Panel c), reaction times showed the typical incongruency costs (23 ms),  $F(1, 11) = 10.4, P < 0.01$ . These incongruency costs were larger in switch (33 ms) than in repetition trials (13 ms),  $F(1, 11) = 6.1, P < 0.05$ . Crucially and in clear contrast to the switch costs, neither the incongruency costs nor the interaction of congru-

ency and task sequence were influenced by the factor session, both  $F < 1$ .

Participants made relatively few errors (4.1%). Overall, the pattern of errors closely resembled the pattern of reaction times. Error percentage increased until session 11 (12:00 hours, 2nd day) but then recovered in the subsequent sessions,  $F(12, 132) = 2.8, P < 0.05$ . The ANOVA also revealed a tendency towards more errors in switch trials (4.6%) than in repetition trials (3.7%),  $F(1, 11) = 4.5, P = 0.06$ , a finding that mirrors switch costs in reaction times. The incongruency costs in reaction times were also found in error percentages. Participants made more errors in incongruent trials (6.0%) than in congruent trials (2.3%),  $F(1, 11) = 18.1, P < 0.01$ . None of the two-way and three-way interactions except the task sequence  $\times$  congruency interaction,  $F(1, 11) = 6.7, P < 0.05$ , reached significance.

Session also strongly affected sleepiness (KSS),  $F(12, 132) = 29.6, P < 0.01$ . Sleepiness increased during the night from session 5 in the late evening (21:00 hours) until to a maximum in the morning of the 2nd day around session 8 (06:00 hours). After this maximum, sleepiness decreased to a moderate level (Helmert contrast between session 8 and subsequent sessions,  $F(1, 11) = 24.7, P < 0.01$ ). Salivary melatonin concentration showed the typical circadian pattern with a mean dim light melatonin onset in the late evening (mean = 21:45 hours; SD = 01:09 hours) and suppression of melatonin secretion during the biological day.

Cross-correlations revealed the highest correlation between melatonin and sleepiness at a lag of one session ( $r = 0.64$ ), between melatonin and switch costs at a lag of three sessions ( $r = 0.82$ ), and between sleepiness and switch costs at a lag of two sessions ( $r = 0.76$ ).

### DISCUSSION

The present results demonstrate that task-switching efficiency is affected by 40 h of constant wakefulness. The temporal pattern of switch costs suggests the influence of several factors on task-switching efficiency. First, the continuous decrease of switch costs during the 1st day can be attributed to two processes. On one hand, it may reflect an initial adaptation or practice effect due to repeated testing. Complex cognitive tasks such as task switching are particularly susceptible to such practice effects due to repeated testing (see Schmidt *et al.*, 2007). On the other hand, it may reflect the influence of the circadian process on performance which has been shown to parallel the rhythm of the core body temperature with better performance in the evening than in the morning of the waking day (e.g. Monk *et al.*, 1997). Secondly, the continuous increase in switch costs during the second half of the night that cumulated in the poorest task-switching performance in the forenoon of the 2nd day most probably reflects the combined influence of the sleep homeostatic process because of extended wakefulness and the circadian system that promotes sleep at that circadian phase. Finally, the finding that switch costs reduced again during the 2nd day indicates the opponent

influence of the circadian process that counteracts the increasing sleep pressure because of the sleep homeostat. Thus, the present results are consistent with the assumption that task switching efficiency is affected by the sleep homeostat and the circadian process.

Previous studies have often reported a close correspondence between cognitive performance and melatonin secretion (e.g. Bratzke *et al.*, 2007; Cajochen *et al.*, 2004; Horowitz *et al.*, 2003). In the present study, however, switch costs compared with melatonin secretion showed a phase delay of three sessions. As can be seen in Fig. 1, switch costs were relatively low during the night and did not increase until melatonin concentration reached its maximum. There are at least two possible explanations for this phase delay of switch costs. First, it may be the result of extended practice beyond the time of melatonin onset. In our view, this explanation appears somewhat unlikely as the decrease in switch costs during the last three sessions (i.e. a time interval of 9 h) prior to melatonin onset was relatively small and rather constant across these sessions (see Fig. 1). This seems to suggest that practice effects had already reached asymptote level at that point in time. Secondly, it is possible that participants were initially able to compensate for an anticipated performance loss because of increased sleepiness which followed melatonin secretion at a lag of one session. This suggestion is in line with the notion that subjects initially compensate for a perceived impairment of their psychophysiological state by reactive effort reinforcement (Düker, 1963; Freeman, 1932; Wilkinson, 1962). It is also in accord with previous findings that difficult tasks under sleep deprivation can elicit a compensatory brain response without impairment of overt performance (Drummond *et al.*, 2004). Therefore, we suggest that the phase delay of switch costs compared to melatonin onset and overall reaction time performance probably reflects an initial compensation of anticipated decrements in task switching performance.

The present evidence of a circadian rhythm in task switching efficiency is in line with previous results by Heuer *et al.* (2004). Although these authors mainly focused on the effects of sleep loss on task switching, they reported lower switch costs in the morning than in the afternoon across two subsequent days, a finding that is consistent with the assumption of a circadian variation in task-switching efficiency. The present results also mesh nicely with the recent finding of Bratzke *et al.* (2007) that dual-task performance is subject to a circadian variation as it has been suggested that task-switching and dual-task performance rely on similar cognitive processes and therefore are subject to the same cognitive limitations (Pashler, 2000).

Another important finding of the present study is that session did not or only little affect incongruency costs, which provides some insights in the underlying mechanism of switch costs variations. As noted before, incongruency costs can be attributed to preceding task-set activation that interferes with current task performance and contributes to switch costs (Goschke, 2000). As for the switch costs, we cannot rule out that practice effects may have influenced the pattern of

incongruency costs across sessions thereby masking the impact of circadian and sleep loss effects on this variable. Additionally, it is possible that the absence of a session variation in incongruency costs reflects insufficient statistical power to detect a possible effect. Nevertheless, incongruency costs did not show a regular variation similar to switch costs. Therefore, it seems rather unlikely that incongruency costs have contributed substantially to the variations in switch costs.

Heuer *et al.* (2004) reported a similar dissociation of these two indices of task-switching efficiency when subjects were sleep deprived for one night. Thus, there is converging evidence that proactive interference is probably not the crucial mechanism that underlies variations in task-switching efficiency due to extended wakefulness and the circadian system. We therefore suggest that the variations in switch costs reflect the participants' ability of task-set reconfiguration. After sufficient sleep loss and/or at circadian troughs, participants are probably no longer able to adequately reconfigure task-sets during the preparatory interval and, consequently, some part of this process must be completed after stimulus presentation (see Heuer *et al.*, 2004).

The present results indicate that executive functions can be modulated by the circadian system. Some studies, however, have failed to find such a modulation for other executive tasks. For example in a study of Sagaspe *et al.* (2006), Stroop interference did not show any fluctuation throughout 36 h of constant wakefulness. In another recent study, Harrison *et al.* (2007) found that response inhibition was affected by time awake but not by circadian phase. There are several possible explanations for these diverging findings, including differences in task duration, task difficulty or in the study design (see Blatter and Cajochen, 2007). Another yet plausible explanation is that executive functions differ in their sensitivity to sleep-related and circadian processes (see Jennings *et al.*, 2003; Sagaspe *et al.*, 2006), a suggestion that is consistent with the notion of diversity in executive functions (e.g. Miyake *et al.*, 2000).

The ability to deal with complex multi-task situations is clearly important to effectiveness in everyday life and work. Previous research has shown that multitasking often entails costs in terms of slower performance and higher error rates (e.g. Pashler, 2000). The results of the present study provide further evidence that the costs of multitasking can increase after sleep loss or at circadian troughs (see also Bratzke *et al.*, 2007). Understanding this interaction of sleep loss, endogenous biological rhythms, and the cognitive limitations of multitasking is an important prerequisite for the design of shift-work schedules to minimize the occurrence of errors and accidents.

In conclusion, the present results show that task-switching efficiency is affected by 40 h of constant wakefulness. The temporal pattern of switch costs across the 40 h indicates the combined influence of a sleep homeostatic process and the circadian system. Additionally, variations in switch costs in the present study most probably reflect fluctuations in participants' ability to prepare the current task rather than response

interference associated with automatic processing of irrelevant stimulus information.

## ACKNOWLEDGEMENTS

We thank Marijke Gordijn and Domien Beersma for providing the isolation facility at the Chronobiological Centre in Groningen, Marijke Gordijn and Isabelle Jasper for their assistance in planning and organizing this study, Claudia Renz for analysing the melatonin data, Andreas Häussler, Isabelle Jasper, Myriam Juda, Ildiko Meny, Sarah Postler, Kathrin Pusch, Claudia Renz, Jessica Rosenberg and Jakob Späti for their assistance in conducting the study, and the subjects for participating. This research was part of the project 'ClockWork' funded by the Gottlieb Daimler- and Karl Benz-Foundation.

## REFERENCES

- Åkerstedt, T. and Gillberg, M. Subjective and objective sleepiness in the active individual. *Int. J. Neurosci.*, 1990, 52: 29–37.
- Allport, D. A., Styles, E. A. and Hsieh, S. Shifting intentional set: exploring the dynamic control of tasks. In: C. Umiltà and M. Moscovitch (Eds) *Attention and Performance XV*. MIT Press, Cambridge, MA, 1994: 421–452.
- Aron, A. R., Monsell, S., Sahakian, B. J. and Robbins, T. W. A componential analysis of task-switching deficits associated with lesions of left and right frontal cortex. *Brain*, 2004, 127: 1561–1573.
- Blatter, K. and Cajochen, C. Circadian rhythms in cognitive performance: methodological constraints, protocols, theoretical underpinnings. *Physiol. Behav.*, 2007, 90: 196–208.
- Blatter, K., Opwis, K., Münch, M., Wirz-Justice, A. and Cajochen, C. Sleep loss-related decrements in planning performance in healthy elderly depend on task difficulty. *J. Sleep Res.*, 2005, 14: 409–417.
- Bratzke, D., Rolke, B., Ulrich, R. and Peters, M. Central slowing during the night. *Psychol. Sci.*, 2007, 18: 456–461.
- Buysse, D. J., Reynolds, C. F., Monk, T. H., Berman, S. R. and Kupfer, D. J. The Pittsburgh Sleep Quality Index (PSQI): a new instrument for psychiatric practice and research. *Psychiatry Res.*, 1989, 28: 193–213.
- Cajochen, C., Knoblauch, V., Wirz-Justice, A., Kräuchi, K., Graw, P. and Wallach, D. Circadian modulation of sequence learning under high and low sleep pressure conditions. *Behav. Brain Res.*, 2004, 15: 167–176.
- Cousineau, D. Confidence intervals in within-subjects designs: a simpler solution to Loftus and Masson's method. *Tutorials Quant. Methods Psychol.*, 2007, 1: 42–45.
- Daan, S., Beersma, D. G. M. and Borbély, A. A. Timing of human sleep: recovery process gated by a circadian pacemaker. *Am. J. Physiol.*, 1984, 246: 161–178.
- Dijk, D. J. and Czeisler, C. A. Contribution of the circadian pacemaker and the sleep homeostat to sleep propensity, sleep structure, electroencephalographic slow waves, and sleep spindle activity in humans. *J. Neurosci.*, 1995, 15: 3526–3538.
- Dove, A., Pollmann, S., Schubert, T., Wiggins, C. J. and von Cramon, D. Y. Prefrontal cortex activation in task switching: an event-related fMRI study. *Cogn. Brain Res.*, 2000, 9: 103–109.
- Drummond, S. P. A., Brown, G. G., Salamat, J. S. and Gillin, J. C. Increasing task difficulty facilitates the cerebral compensatory response to total sleep deprivation. *Sleep*, 2004, 27: 445–451.
- Düker, H. Über reaktive Anspannungssteigerung. *Z. Exp. Angew. Psychol.*, 1963, 10: 46–72.
- Freeman, G. L. Compensatory reinforcements of muscular tension subsequent to sleep loss. *J. Exp. Psychol.*, 1932, 15: 267–283.
- Goschke, T. Intentional reconfiguration and involuntary persistence in task set switching. In: S. Monsell and J. Driver (Eds) *Attention and Performance XVIII: Control of Cognitive Processes*. MIT Press, Cambridge, MA, 2000: 331–355.
- Harrison, Y., Jones, K. and Waterhouse, J. The influence of time awake and circadian rhythm upon performance on a frontal lobe task. *Neuropsychologia*, 2007, 45: 1966–1972.
- Heuer, H., Kleinsorge, T., Klein, W. and Kohlisch, O. Total sleep deprivation increases the costs of shifting between simple cognitive tasks. *Acta Psychol.*, 2004, 117: 29–64.
- Horowitz, T. S., Cade, B. E., Wolfe, J. M. and Czeisler, C. A. Searching night and day: a dissociation of effects of circadian phase and time awake on visual selective attention and vigilance. *Psychol. Sci.*, 2003, 14: 549–557.
- Jennings, J. R., Monk, T. H. and van der Molen, M. W. Sleep deprivation influences some but not all processes of supervisory attention. *Psychol. Sci.*, 2003, 5: 473–479.
- Jersild, A. T. Mental set and shift. *Arch. Psychol.*, 1927, 89: 5–82.
- Meiran, N., Chorev, Z. and Sapir, A. Component processes in task switching. *Cogn. Psychol.*, 2000, 41: 211–253.
- Miyake, A., Friedman, N. P., Emerson, M. J., Witzki, A. H., Howerter, A. and Wager, T. D. The unity and diversity of executive functions and their contributions to complex "frontal lobe" tasks: a latent variable analysis. *Cognitive Psychol.*, 2000, 41: 49–100.
- Monk, T. H. and Carrier, J. Speed of mental processing in the middle of the night. *Sleep*, 1997, 20: 399–401.
- Monk, T. H., Buysse, D. J., Reynolds, C. F., Berga, S. L., Jarrett, D. B., Begley, A. E. and Kupfer, D. J. Circadian rhythms in human performance and mood under constant conditions. *J. Sleep Res.*, 1997, 6: 9–18.
- Monsell, S. Task switching. *Trends Cogn. Sci.*, 2003, 7: 134–140.
- Pashler, H. Task switching and multitask performance. In: S. Monsell and J. Driver (Eds) *Attention and Performance XVIII: Control of Cognitive Processes*. MIT Press, Cambridge, MA, 2000: 277–307.
- Roenneberg, T., Wirz-Justice, A. and Mellow, M. Life between clocks: daily temporal patterns of human chronotypes. *J. Biol. Rhythm.*, 2003, 18: 80–90.
- Rogers, R. D. and Monsell, S. Costs of a predictable switch between simple cognitive tasks. *J. Exp. Psychol. Hum. Percept. Perform.*, 1995, 124: 207–231.
- Rogers, N., Dorrian, J. and Dinges, D. F. Sleep, waking and neurobehavioral performance. *Front. Biosci.*, 2003, 8: s1056–s1067.
- Ruthruff, E., Remington, R. W. and Johnston, J. C. Switching between simple cognitive tasks: the interaction between top-down and bottom-up factors. *J. Exp. Psychol. Hum. Percept. Perform.*, 2001, 27: 1404–1419.
- Sagaspe, P., Sanchez-Ortuno, M., Charles, A., Taillard, J., Valtat, C., Bioulac, B. and Phillip, P. Effects of sleep deprivation on color-word, emotional, and specific Stroop interference and on self-reported anxiety. *Brain Cogn.*, 2006, 60: 76–87.
- Schmidt, C., Colette, F., Cajochen, C. and Peigneux, P. A time to think: circadian rhythms in human cognition. *Cognit. Neuropsychiatry*, 2007, 24: 755–789.
- Spector, A. and Biedermann, I. Mental set and mental shift revisited. *Am. J. Psychol.*, 1976, 89: 669–679.
- Steinhauser, M., Maier, M. and Hübner, R. Cognitive control under stress: how stress affects strategies of task-set reconfiguration. *Psychol. Sci.*, 2007, 18: 540–545.
- Swanson, R., Cunnington, R., Jackson, G. M., Rorden, C., Peters, A. M., Morris, P. G. and Jackson, S. R. Cognitive control mechanisms revealed by ERP and fMRI: evidence from repeated task-switching. *J. Cognit. Neurosci.*, 2003, 15: 785–799.
- Weber, J. M., Schwander, J. C., Unger, I. and Meier, D. A direct ultrasensitive RIA for the determination of melatonin in human saliva: comparison with serum levels. *J. Sleep Res.*, 1997, 26: 757.
- Wilkinson, R. T. Muscle tension during mental work under sleep deprivation. *J. Exp. Psychol.*, 1962, 64: 565–571.