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On the linearity of subjective sleepiness measures

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This study investigates the linearity of response measures used in research on mechanisms underlying sleepiness-alertness regulation. A major contribution to understanding these mechanisms was provided by Borbély (1982) with the two-process model of sleep regulation. Sleep propensity is influenced by a sleep-dependent factor (Process S or the homeostatic factor) and a sleep-independent factor (Process C or the circadian factor). Process S represents an alleged drive for sleep that increases exponentially during wakefulness and declines during sleep. Process C represents the variation of sleep propensity during approximately 24 hrs due to a biological circadian oscillator. Borbély's model is widely accepted in sleep research and was found to be useful in predicting cognitive performance and subjective alertness-sleepiness in field studies (Dijk, Duffy, & Czeisler, 1992; Åkerstedt & Folkard, 1994). However, some reservations were formulated concerning the basic assumptions of the model (Achermann, 2004). One of these assumptions is that its common constituent Processes S and C are independently related to one another. Recently, Jewett & Kronauer (1999) included a non-linear interaction term in a mathematical extension of Borbély's model. Their results showed that the amplitude of the circadian component was low upon awakening, increased gradually during approximately the first 15 hrs of wakefulness and then remained quite constant, suggesting an effect of prior sleep duration on the amplitude of the circadian phase. In a review of the literature on the subject, however, Achermann (2004) questions some of these results on the basis that the observed non-linear interactions may possibly be caused by the use of non-linear metrics.

The present study is an attempt to contribute to this debate by applying functional measurement (FM) methodology (Anderson, 1981, 1982,

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2001) using one specific kind of response measures. In two experiments we used the Karolinska Sleepiness Scale (KSS, Åkerstedt & Gillberg, 1990) and a Visual Analogue Scale (VAS) as response measures. The KSS is a nine-point rating scale with verbal labels from "*extremely alert*" to "*extremely sleepy, fighting sleep, an effort to stay wake*". The VAS enables participants to rate graphically their actual level of wakefulness by marking a horizontal line on a "*very alert*" to "*very sleepy*" continuum (Curcio, Casagrande, & Bertini, 2001). Both instruments are common in clinical and experimental sleep research.

In Borbély's theory (1982), Processes S and C are *strictly* additive. According to the FM paradigm, the data would show parallelism in a factorial plot, i.e., significant main effects of Processes S and C and a non-significant interaction. This particular finding would imply that (1) the perception of a certain level of sleepiness can be described by the addition of the magnitudes of the effects of Process S and Process C, (2) that Processes S and C do not interact in the psychological process of formulating a single response on a subjective sleepiness scale, and (3) that the response measure used to translate the subjective feeling of sleepiness yields linear data since otherwise an non-linear overt response would violate parallelism in the factorial plot, even if the additive integration model holds (Anderson, 1977). If Borbély's suggestion is valid, an additive integration rule would describe the integration of Processes S and C and any deviation from parallelism found in our experiments would then be solely attributable to the non-linearity of the response scale.

Experiment 1

Method

Participants. Thirteen healthy individuals, 6 males and 7 females, between 19 and 32 years old (mean age, 24) enrolled in a partial sleep deprivation study after being informed of the research protocol and giving their informed consent. All participants received a financial compensation of € 120 for their participation.

Stimuli and design. Stimuli were presented according to a 2 × 3 full-factorial design. The stimuli were the actual time of day: 9 AM, 11 AM, or 1 PM (Process C) after a night of 2.5 or 8.00 hrs time in bed (Process S).

Procedure. The present study was part of a larger study on the effects of cognitive arousal on sleep onset duration (De Valck, Mairesse, Quanten, Berckmans, & Cluydts, 2006). In the baseline condition, participants were allowed to spend 8 hrs in bed while in the deprivation condition they were only allowed 2.5 hrs of sleep. Participants were admitted at 10 PM to our sleep lab and were permitted to involve in calm, recreational activities until 11:30 PM in the baseline condition, and until 4:30 AM in the deprivation condition. Participants woke up at 7 AM. At 9 AM the participants completed the subjective sleepiness scales KSS and VAS and were subsequently administered the Multiple Sleep Latency Test (MSLT) and the Maintenance of Wakefulness Test (MWT) to determine sleep latency (for a detailed description of these tests we refer to Kryger, Roth, & Dement, 2005). The KSS and the VAS were administered between and after every counterbalanced MSLT/MWT session. The whole procedure took approximately 1 hr and was repeated at 11 AM and 1 PM. After the three consecutive MSLT/MWT sessions, participants performed a 40 min vigilance test until the end of the testing day, which was at 3 PM.

Results and discussion

Only the self-reported sleepiness measures prior to each MSLT/MWT session were included in the analysis. Figure 1 shows the results. Visual inspection of the factorial plots of VAS and KSS reveals parallelism. Additivity of Processes S and C and the linearity of the response function are both supported by non-significant interaction effects [$F(2, 24) = 0.23$ and $F(2, 24)= 0.21$, respectively]. These findings suggest that an additive model describes best the integration process of circadian and homeostatic factors in the evaluation of sleepiness and implies linearity of both KSS and VAS.

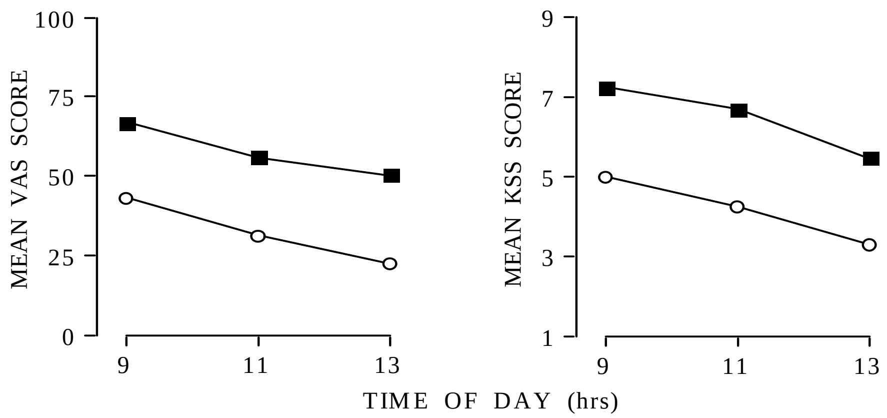

Figure 1. Mean VAS and KSS scores plotted against time of day: 9 AM, 11 AM, and 1 PM (Process C) for 2.5 (■) or 8 hrs (○) of prior time in bed (Process S).

The KSS and the VAS indeed yielded very similar results in Experiment 1. Even though KSS and VAS were presented in alternation according to a counterbalanced design, cross-contamination may still have occurred. That is, the VAS may have benefited from the quantity and the clarity of the labels of the KSS and on the other hand, the responses on the KSS could have been influenced positively by the linear morphology of the VAS. Also, we do not have any conclusive evidence that the nature of the relation between Processes S and C during the day is *strictly* additive as suggested by Dijk & Larkin (2004). The design of our first experiment did not enable us to check for a possible *averaging* integration rule due to the impossibility to present either Process S or Process C independently from one another. However, this has no implications for the linearity of the response measures and will therefore not be discussed thoroughly in this paper.

Experiment 2

Method

Participants. Forty-six individuals ranging from 17 to 29 years old (mean age, 19.5) enrolled in a FM experiment. Ten of them were males. All participants were undergraduate students from the Vrije Universiteit Brussel and were rewarded with course credits for their participation.

Stimuli and procedure. We used verbal descriptions of the experimental trials from our first study as stimuli for this second experiment. The descriptions were presented in random order according to a 3 × 3 full-factorial design with 3 replications. Stimuli were for instance: “Last night, you were allowed to spend 8 hrs in bed and it is now 11 AM” (Process S level 1 and Process C level 2) or “It is now 9 AM” (Process S level 0 or blank, and Process C level 1). Participants were then instructed to evaluate how sleepy they would feel in case of the described situation and given that they had to wake up at 7 AM that morning. Subjective sleepiness ratings were obtained by means of a 600 pixel wide slider presented in the middle of the screen with “very alert” and “very sleepy” as end anchors in the VAS condition. In the KSS condition, the KSS was transcribed from paper to screen and radio-buttons were used for the selection of scale categories. Participants were randomly assigned to one of both conditions. All participants were seated in separate PC-equipped sound proof rooms in front a 1024 × 768 pixel PC screen. In order to avoid non-compliance by clicking through the trials, a 2-seconds delay before the appearance of the next-button was built in. The whole experiment was designed using FM BUILDER, a JAVA-based software program developed to conduct full-factorial FM experiments using text and image stimuli (Mairesse & Theuns, in preparation).

Results and discussion

Figure 2 shows the results. Visual inspection of group data averaged over repetitions and participants reveals parallelism in either of both conditions.

No interaction was observed in the VAS condition [$F(4, 92) = 2.53$] or in the KSS condition [$F(4, 84) = 1.68$]. However, the effect of Process C (VAS) was not significant [$F(2, 46) = 0.15$]. Failure to detect a main effect of Process C is not due to a larger interindividual variability in this experiment in comparison to the first experiment [$F(1, 33) = 3.90$ for VAS and $F(1, 33) = 0.02$ for KSS]. Mean difference across levels of Process C were significantly smaller in the second experiment [$F(1, 34) = 15.08$, $p < 0.001$ for VAS, and $F(1, 33) = 10.52$, $p < 0.01$ for KSS]. Visual inspection of single-subject factorial plots showed indeed little variation in the ratings across the levels of Process C and in three participants there were indications that

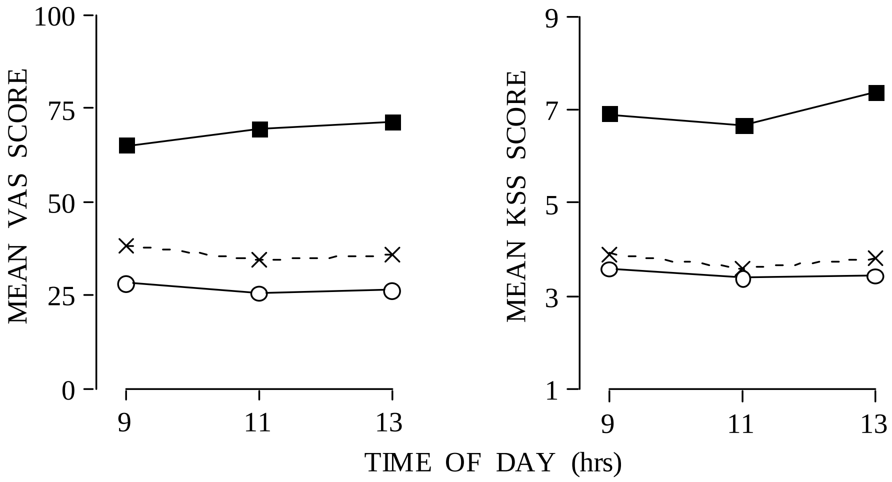

Figure 2. Mean VAS and KSS scores plotted against time of day: 9 AM, 11 AM, and 1 PM (Process C) for 2.5 (■) or 8 hrs (○) of prior time in bed (Process S). The dashed line shows the results for the uncombined Process C (×).

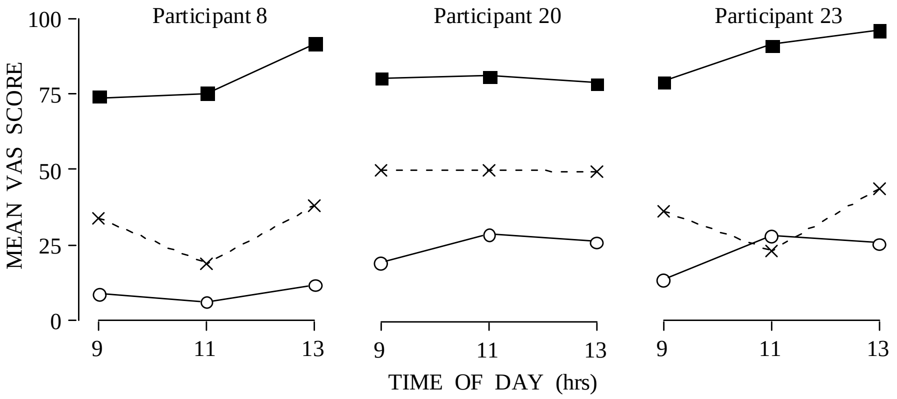

Figure 3. Results of Participants 8, 20, and 23 in the VAS condition. Mean VAS scores plotted against time of day: 9 AM, 11 AM, and 1 PM (Process C) for 2.5 (■) or 8 hrs (○) of prior time in bed (Process S). The dashed line shows the results for the uncombined Process C (×).

Process C played almost no role in the evaluation of imagined sleepiness. Three recurrent patterns were observed in the individual factorial plots of the participants in each condition. Figure 3 shows examples of these patterns in the VAS condition.

Parallelism was observed for 16 of the 24 participants in the VAS condition and for 17 of the 22 participants in the KSS condition. In the VAS condition an averaging integration pattern was observed in two participants and in the KSS condition this was the case for seven of them. Eight of the 16 participants in the VAS conditions exhibited V-like parallelism against six participants who exhibited Λ-like patterns. Similar results are observed in the KSS condition (8 V-like and 7 Λ-like patterns). The co-occurrence of V-like and Λ-like patterns in the data probably balanced out the group means of levels of Process C, causing the failure to detect a significant effect of Process C in the group analysis of variance.

General discussion

As expected and consistent with Borbély (1982) we found in Experiment 1 that Processes S and C are additive. Single-subject analyses of the data from our replication experiment using symbolic stimuli reveal a majority of participants integrating Processes S and C according to an additive rule. Within FM, the observed parallelism in the factorial plot and the analysis of variance results simultaneously support additivity of the integration rule and linearity of the response function. In other words, the VAS and the KSS yield data at the interval level of measurement. Between-subjects replication of the first experiment showed that KSS and VAS yield similar results. Using either one scale or the other is left to the preference of the researcher or the participants. In order to minimize memory-effects or improve response differentiation, one could prefer the VAS over the KSS. On the other hand, for purposes of label clarity or scoring facility one could opt for the KSS.

Evidence of KSS and VAS being linear response measures has implications for the discussion of the interaction of Processes S and C. According to the concept of generality (Anderson, 2001), if a response measure is found to be linear in a specific integration task, it is likely to be linear in other similar integration tasks. Interactions found in other studies may therefore be considered as genuine. Nevertheless, even with a linear response scale a statistical interaction could still be an artifact of the analysis of variance model (Anderson, 2001). Research by Dijk et al. (1992) seemingly supports the assumption of a linear interaction between Processes S and C using subjective sleepiness/alertness reports by means of VASs. In their study they report that prior wakefulness had an effect on alertness in all circadian phases and find relief for their statement in a statistical significant linear interaction for Processes S and C. However, the analysis of variance was based on 6142 observations. This large number yields such high statistical power that any minor departure from parallelism would be found to be statistically significant, but with little meaning in terms of true interaction.

Unfortunately, any strong statement about the independence of both processes cannot be drawn from the results of our studies, as our design yielded only three measurements over a period of only 4 hrs within a single circadian phase. The empirical studies of Dijk & Larkin (2004) suggest that additive models may be only effective to predict performance in sleep deprived subjects during the biological day, but be less effective in estimating performance deterioration during the biological night. Åkerstedt & Folkard (1994) report that performance data and subjective sleepiness measurements yield similar results in terms of circadian rhythmicity. It is therefore probable that sleepiness evaluations by means of VAS and KSS for levels of Process C, varying over 24 hrs in different circadian phases, could uncover true interactions between Processes S and C. Our choice not to include such widely extended levels of Process C in our second experiment resulted from a methodological concern. As FM has to our knowledge never been applied in sleep research, we wanted to secure the ecological validity of the technique. Therefore we opted for replicating the conditions of the actual sleep deprivation experiment as closely as possible using symbolic stimuli. Despite some limitations, it appears that the technique is applicable for research on perception of sleepiness. One of the major advantages of the technique in comparison with sleep deprivation studies is the considerable gain of time, labor, and money in conducting the experiment. A disadvantage of the method lies in the object of the task, which may seem to be artificial (rating “imagined” sleepiness). To observe clear patterns in the data, the effect of the different factors has to be distinctive and familiar enough for individuals to visualize themselves in the described situation. In all participants, picturing themselves restricted from sleep yielded strong effects in both experiments, but changes in sleepiness due to circadian phase were only observed clearly in the actual sleep deprivation experiment. In three participants in the second experiment, the effects of Process C were so subtle that there were no distinct indications of an integration of Processes S and C.

When the integration actually took place, it was best described by an additive rule in a majority of participants. However, an averaging integration rule was also observed in a total of nine participants. Averaging is definitely considerable within the framework of sleep-wake regulation. Achermann & Borbély (1994) found that during approximately two-thirds of a waking episode, Processes S and C compensate each other, which is what averaging theory predicts (Anderson, 2001). Nevertheless, in this case of integration of Processes S and C, including an uncombined factor C in the FM experiment is questionable. It remains yet unclear if participants are able to make a judgement of sleepiness for a certain time of day regardless of information on prior sleep. In further research it would be useful to collect collateral information on how participants make that judgement. Additionally, levels of Process S could be manipulated according to proportions of the participants’ reported habitual sleep time. Convergence of the cell means of the levels of the uncombined factor C and the participants’ habitual sleep time could imply that they use the latter as a reference to evaluate the uncombined levels of C, and thereby ruling out its applicability.

In summary, this study provides evidence for the linear relation between scores on the VAS and KSS and the underlying sleepiness-alertness continuum. Reanalysis of KSS and VAS data from forced desynchrony studies within the framework of Information Integration Theory may therefore add substantially to our knowledge about the true nature of the interaction of Processes S and C. Finally, cognitive algebra of sleepiness in dose-response sleep deprivation studies may improve our grasp on how extended wakefulness and time of day amplify the effect of sleepiness caused by restricted sleep duration in daily settings.

References

Achermann, P. (2004). The two-process model of sleep regulation revisited. *Aviation, Space, and Environmental Medicine*, *75*, A37-A43.
Achermann, P., & Borbély, A. A. (1994). Simulation of daytime vigilance by the additive interaction of a homeostatic and a circadian process. *Biological Cybernetics*, *71*, 115-121.
Åkerstedt, T., & Gillberg, M. (1990). Subjective and objective sleepiness in the active individual. *International Journal of Neuroscience*, *52*, 29-37.
Åkerstedt, T., & Folkard, S. (1994). Prediction of intentional and unintentional sleep onset. In R. Ogilvie & J. R. Harsch (Eds.), *Sleep onset: Normal and abnormal processes* (pp. 73-87). Washington DC: American Psychological Association.
Anderson, N. H. (1977). Note on functional measurement and data analysis. *Perception & Psychophysics*, *21*, 201-215.
Anderson, N. H. (1981). *Foundations of information integration theory*. New York: Academic Press.
Anderson, N. H. (1982). *Methods of information integration theory*. New York: Academic Press.
Anderson, N. H. (2001). *Empirical direction in design and analysis.* Mahwah, NJ: Erlbaum.
Borbély, A. A. (1982). A two-process model of sleep regulation. *Human Neurobiology*, *1*, 195-204.
Curcio, G., Casagrande, M., & Bertini, M. (2001). Sleepiness: Evaluating and quantifying methods. *International Journal of Psychophysiology*, *41*, 251-263.
Dijk, D. J., Duffy, J. F., & Czeisler, C. A. (1992). Circadian sleep/wake dependent aspects of subjective alertness and cognitive performance. *Journal of Sleep Research*, *1*, 112-117.
Dijk, D. J., & Larkin, W. (2004). Fatigue and performance models: General background and commentary on the circadian alertness simulator for fatigue risk assessment in transportation. *Aviation, Space, and Environmental Medicine, 75*, A119-A121.
De Valck, E., Mairesse, O., Quanten, S., Berckmans, D., & Cluydts, R. (2006). Acute stress effects on the MSLT versus the MWT. *Journal of Sleep Research, 15(Suppl. 1),* 132.
Jewett, M. E., & Kronauer, R. E. (1999). Interactive mathematical models of subjective alertness and cognitive throughput in humans. *Journal of Biological Rhythms*, *14*, 588-597.
Kryger, M. H., Roth, T., & Dement, W. C. (2005). *Principles and practice of sleep medicine*. Philadelphia: Saunders.
Mairesse, O., & Theuns, P. (in preparation). FM BUILDER, a JAVA-based software to conduct Functional Measurement experiments.

Abstract

The present study was conducted to investigate the linearity of subjective sleepiness scales and to contribute to the debate about the nature of the interaction between circadian (C) and homeostatic (S) processes in models of alertness-sleepiness regulation. In this study, a partial sleep deprivation experiment was conducted and replicated in an experiment using verbal descriptions of the manipulations in the actual sleep deprivation study. Our findings provide support for the linearity of subjective sleepiness scales. Consistent with the basic assumptions of Borbély's model, an additive integration of Processes S and C was noted in a majority of participants, which suggests the independence of these processes during the biological day. These results were observed for the actual sleep deprivation experiment as well as for the replication study, which provide additional support for the ecological validity of functional measurement experiments using symbolic stimuli.

Riassunto

Il presente studio è stato condotto per investigare la linearità delle scale soggettive di sonnolenza e per contribuire al dibattito circa la natura della interazione tra processi circadiani (C) e omeostatici (S) nei modelli della regolazione vigilanza-sonnolenza. In questo studio, è stato condotto un esperimento di deprivazione parziale del sonno che successivamente è stato ripetuto in un esperimento con sole descrizioni verbali delle manipolazioni relative allo studio sulla deprivazione del sonno. I nostri risultati forniscono prova della linearità delle scale soggettive di sonnolenza. In accordo con le assunzioni di base del modello di Borbély, nella maggioranza dei partecipanti è stata osservata una integrazione additiva dei Processi S e C, la quale suggerisce che questi processi sono indipendenti durante il giorno biologico. Questi risultati sono stati osservati sia nell'esperimento di deprivazione sensoriale vero e proprio che nella sua ripetizione, il che costituisce una prova aggiuntiva della validità ecologica degli esperimenti di misurazione funzionale con stimoli simbolici.

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