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The algebra of sleepiness: investigating the interaction of homeostatic (S) and circadian (C) processes in sleepiness using linear metrics”

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The present studies were conducted to contribute to the debate on the interaction between circadian (C) and homeostatic (S) processes in models of sleep regulation. The Two-Process Model of Sleep Regulation assumes a linear relationship between processes S and C. However, recent elaborations of the model, based on data from forced desynchrony studies, suggest a nonlinear interaction between both processes. Whether this interaction is due to an interaction at substantial level or an artifact from the use of nonlinear metrics remain largely unknown, partly because usual experimental procedures in sleep research do not provide the necessary means to make this distinction. In this study we apply Functional Measurement methodology to demonstrate the linearity of two subjective sleepiness scales (Karolinska Sleepiness Scale and Visual Analogue Scale for sleepiness/alertness) and subsequently use these instruments in a judgment task based on information on prior sleep and time of day. Our results show that, when using linear metrics, processes S and C are integrated according to a differential weighting averaging rule, which consequently implies that both processes are psychologically related in a nonlinear way when sleepiness judgments are performed.

The notion of a combined action of circadian and homeostatic processes in sleep related regulatory mechanisms has been widely accepted

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since the introduction of Borbély's Two-Process Model of Sleep-Wake Regulation (Borbély, 1982). Sleep and wake are defined by the joint operation of process S, an exponentially increasing homeostatic sleep drive, and process C, a sinusoidal component of sleep propensity controlled by a ± 24 hour biological oscillator (Borbély and Achermann, 1999, 2000). A fundamental assumption in the Two-Process Model is that processes S and C can be manipulated independently from each other. This premise is supported by various animal studies where circadian rhythmicity has been undone by lesioning the suprachiasmatic nuclei (site of the circadian pacemaker) while EEG slow-wave activity remained unaffected (e.g. Edgar, Dement & Fuller, 1993; Trachsel, Edgar, Seidel, Heller & Dement, 1992) and in human studies where slow-wave activity seemed unaffected by the manipulation of circadian phase using bright light (Dijk, Beersma, Daan & Lewy, 1989). More recently however, Jewett and Kronauer (1999) proposed an elaboration of the Two-Process Model based on data from 28 hr forced desynchrony studies, refined with data from nearly two-hundred 30 to 50 hrs sleep deprivation studies. Including a nonlinear interaction term into the otherwise linear equation improved their simulations significantly, thereby rejecting the independence assumption from Borbély's seminal model. Other studies using cognitive performance data and ratings of subjective sleepiness in constant routine and forced desynchrony protocols reported similar results before (e.g. Dijk, Duffy & Czeisler, 1992). Despite these findings, Achermann (1999) raised the issue that nonlinear interactions between processes S and C may simply result from using nonlinear metrics. Ceiling effects of the tests used to assess alertness and cognitive throughput, rather than the underlying mechanism, may have caused the pattern of slow decay of subjective alertness during wake time.

The present study aims to tackle the problem of response linearity in mathematical models of sleepiness by applying Functional Measurement methodology (Anderson, 1981, 1982). Functional Measurement allows for the algebraic description of the cognitive integration processes when information is processed subjectively. Put differently, the method permits the study of the Psychological Law governing information integration. At the same time, linearity of the response scale can be tested using specific experimental constraints (Rundall and Weiss, 1994). Recently, Mairesse, Hofmans, De Valck, Cluydts and Theuns (2007) used Functional Measurement methodology in a partial sleep deprivation study to establish linearity of the Karolinska Sleepiness Scale (KSS: Åkerstedt and Gillberg, 1990) and the Visual Analogue Scale for sleepiness/alertness (VAS: Monk, 1987). Participants reported their subjective sleepiness after 8 hrs and 2.5 hrs time in bed (TIB) at different moments during the day (0900 hrs, 1100 hrs and 1300 hrs) according to a 2 × 3 full-factorial design. Their results showed parallelism in the data, suggesting the linearity of both response measures (Anderson, 1981). Based on this design, an FM experiment was set up, requiring participants presented with textual information on TIB and the moment of the day, to convey sleepiness judgments by means of the KSS (condition 1) or the VAS (condition 2). The results showed a similar pattern of parallelism as observed in the partial deprivation study in both conditions, providing additional support for the linearity of both response scales.

Even though the results are in favor of (1) an additive integration of processes S and C and (2) linearity of the KSS and the VAS, some remaining issues have to be addressed. First, the factorial design included only measurements across the subjective day. Dijk and Larkin (2004) pointed out that additive (linear) models may be suitable to describe sleepiness related performance during daytime, but may be less effective than nonlinear models in describing performance decrements during the night. Therefore, the additive integration model may fail when including nocturnal levels of process C. Secondly, the rationale followed by the authors may seem circular as they trade the implicitly assumed linearity of the response scale (Dijk, Duffy and Czeisler, 1999) for the assumption that processes S and C relate in a strict additive way. Because both the integration and the response function are validated simultaneously, testing the linearity of the response implies making assumptions about the integration function and vice versa. Because of this, a small probability exists that both the integration rule and the response functions are nonlinear, but that they compensate for each other yielding parallelism ("the problem of evidence", Anderson, 1986; Hofmans, Mairesse & Theuns, 2007). However, in establishing the linearity of the response in the context of other integration tasks, the probability of a problem of evidence to occur can be minimized (the "generality" principle, Anderson, 1981; see also the body of work of Hofmans, Theuns and Mairesse, 2007; Hofmans and Theuns, 2008 and Hofmans and Theuns, in press). It is also important to emphasize that in the context of Functional Measurement linearity is not solely considered as an attribute of the response measure itself, but explicitely refers to the relationship between the response scale and the underlying construct. This approach thus allows to add meaningfulness to the data and to go beyond *utilitarian* measurement into *functional* measurement.

In summary, the main objectives of the present study are to:

(1) further establish the linearity of subjective sleepiness response measures,

(2) control for floor and ceiling effects in the response measure and the design,

(3) test the additivity of processes S and C in subjective sleepiness judgments.

EXPERIMENT 1

METHOD

Participants. Thirty-two undergraduates from the Vrije Universiteit Brussel participated in an experiment on the impact of hypothetical sleep deprivation in daily life situations. Participants were randomly assigned to two test conditions; 5 males and 11 females (M_{age}= 21.25, *SD*= 3.28 yrs) were assigned to the KSS condition; 4 males and 12 females (M_{age}= 20.36, *SD*= 1.20 yrs) were assigned to the VAS condition. All subjects participated in partial fulfillment of a methods course at the Vrije Universiteit Brussel.

Stimuli and design. The stimuli were descriptions of eight daily life situations issued from the Epworth Sleepiness Scale (ESS: Johns, 1991) combined with information about prior sleep (S). Levels of S were presented both isolated and combined with ESS situations as a qualitative test for averaging integration. Absence of sleep (S= 0 hrs) was not included in the analysis, as this level only served to prevent ceiling effects (Muñoz Sartre, Mullet and Sorum, 1999). An overview of the stimuli used in the experiment is shown in Table 1.

Procedure. Participants were seated in cubicles equipped with PCs with 1024 × 768 pixel monitors. In order to control for floor and ceiling effects, all participants went through an anchoring procedure for the response instrument in question. The procedure consisted of choosing a combination of both factors that would correspond to maximal sleepiness and another such combination for maximal alertness. For the actual experiment, participants in the KSS condition were instructed to indicate which category of the KSS described best their level of sleepiness in the given combination of prior sleep and time of day. Responses were made by selecting the radio button next to the relevant KSS-category. Sleepiness judgments in the VAS condition were made by means of a 600 pixel wide slider in the middle of the screen with "very alert" and "very sleepy" as end labels. In order to avoid continuous clicking through the experimental trials, a 1-second delay before the appearance of the next-button was included. All experiments were designed using FM BUILDER, a JAVA-based software program developed to conduct FM experiments using textual and figural stimuli (Mairesse, Hofmans and Theuns, 2008). At the end of the experiment, all participants completed an exit questionnaire about task difficulty and their response strategy during the experiment.

Table 1. Overview of the descriptions used in Experiment 1. Actual stimuli were combinations of levels of process S and ESS situation. To test for averaging integration, levels of process S were presented uncombined (i.e. no stimulus information for the ESS factor).

Factor	Level	Stimulus
Process S	0 hrs	“You did not sleep”
	2 hrs	“You slept 2 hours”
	4 hrs	“You slept 4 hours”
	8 hrs	“You slept 8 hours”
ESS	Reading	“You are reading while seated”
	TV	“You are watching TV”
	Public place	“You are sitting inactive in a public place (e.g. a theater or a meeting)”
	Passenger	“You are a passenger in a car driving for an hour without a break”
	Lie-down	“You are lying down to rest in the afternoon”
	Talking	“You are talking to someone while seated”
	Post lunch	“You are sitting quietly after a lunch without having consumed alcohol”
	Traffic jam	“You are in a car, while stopped for a few minutes in traffic”
	uncombined	-

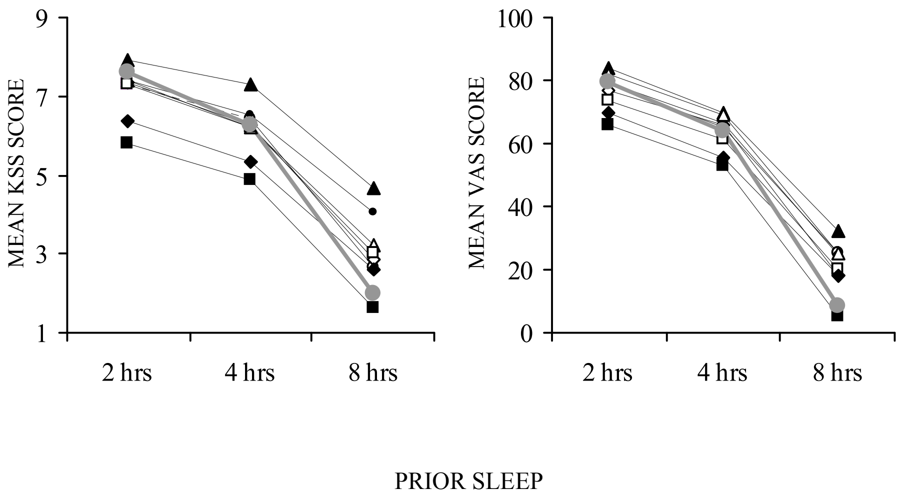

Figure 1. Mean KSS and VAS scores for ESS-levels plotted against prior sleep: 2 hrs, 4 hrs and 8 hrs (Process S). The black lines represent levels of the ESS factor [lie-down (▲), post-lunch (•), reading (◇), passenger (△), public place (□), TV (○), traffic jam (◆) and talking (■)]. The grey line shows the crossover pattern for the uncombined levels of process S (●).

RESULTS

Figure 1 shows the results: the left panel displays the results for the KSS group; the right panel displays the scores for the VAS group. Visual inspection of group data averaged over participants and repetitions reveals near-parallelism for the levels of the ESS and a crossover pattern for the uncombined levels of process S, as predicted by the equal weights averaging model. Significant main effects of prior sleep are observed in the KSS condition ($F[2,30] = 171.16$, $p < .001$, $\eta^2_p = .92$) and in the VAS condition ($F[2,30] = 244.11$, $p < .001$, $\eta^2_p = .94$). Also, the effect of ESS situation is significant in both the KSS condition ($F[7,105] = 14.86$, $p < .001$, $\eta^2_p = .50$) as in the VAS condition ($F[7,105] = 11.52$, $p < .001$, $\eta^2_p = .43$). In the VAS condition, the equal weights averaging pattern is supported statistically by a nonsignificant interaction ($F[7,105] = .99$, $p = .536$, $\eta^2_p = .06$), whereas in the KSS the interaction effect is small but significant ($F[7,105] = 2.34$, $p < .005$, $\eta^2_p = .13$).

When an equal weights averaging model is found, linearity of the response scale can be inferred according to parallelism theorem (Anderson, 1981). In the VAS condition, the visual and statistical tests suffice to accept the model and thus to infer response linearity (see Figure 2). In the KSS condition, however, the observed significant interaction effect may indicate nonlinearity in the response scale. This possibility is rejected as single-subject analyses support equal weights averaging in both the KSS and the VAS condition for the majority of the respondents. Nine participants in the KSS condition followed an equal weights averaging rule and 3 participants an additive integration rule. Three patterns were consistent with averaging with differential weights and 1 participant showed a "prior sleep only" rule (no effect of ESS situation). In the VAS condition, 8 participants showed integration patterns consistent with an averaging rule with equal weighting and 3 with unequal weighting. The remaining 5 participants used an additive integration rule.

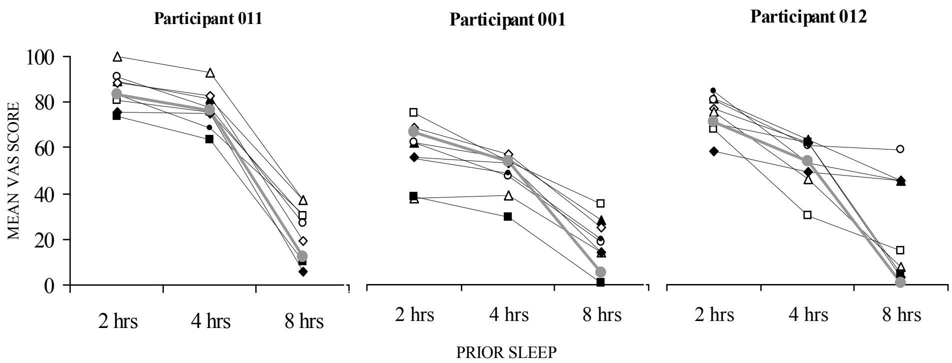

Figure 2. Examples of individual factorial graphs of participants in the VAS-condition. The graphs represent VAS scores per participant (averaged over 2 replications) for the ESS factor, plotted against prior sleep. The left panel shows an additive model: the factorial graph displays a set of parallel lines, including the curve representing the uncombined levels of process S (●). This pattern is supported by a small, non significant interaction effect (*F*[2,53] = .82, *p*= .651). The middle panel represents an equal weights averaging model: parallelism is fairly respected by the levels of the ESS factor, but is violated by the curve representing uncombined levels of process S, yielding a clear crossover pattern. The right panel represents a differential weighting averaging model: parallelism is severely violated by the levels of the ESS factor and by uncombined levels of process S. This pattern is also supported by a significant interaction effect (*F*[2,53]= 5,57, *p*< .001).

In summary, the visual and statistical examination support linearity of the VAS at the group level and at the individual level. As for the KSS, the statistical test fails at group level, despite observed near-parallelism in the factorial graph. However, a statistically significant interaction, even one with little substantive value, may be expected due to the large power of the design[1]. This interpretation is all the more legitimate as response linearity is supported at the level of the individual.

EXPERIMENT 2

In this series of experiments the first one (Experiment 2a) consists of judging sleepiness when presenting information on prior sleep and the moment of the day in a hypothetical sleep deprivation setting under entrained conditions. In order to approximate hypothetical free-running conditions (i.e. sleep and wake occurring at all circadian phases), the second experiment (Experiment 2b) uses the same procedure as Experiment 1, but controls for time after awakening.

METHOD

Participants. Eighty-seven participants were randomly assigned to one of 4 conditions. Five males and 16 females (M_{age}= 19.95, *SD*= 1.32 yrs) completed an experiment on hypothetical sleep deprivation using the KSS as response instrument. Two males and 19 females (M_{age}= 20.19, *SD*= 1.29 yrs) completed the same experiment using VASs. The remaining participants enrolled in an experiment on hypothetical sleep displacement. Five males and 19 females (M_{age}= 21.38, *SD*= 5.03 yrs) were assigned to the KSS condition; 4 males and 17 females (M_{age}= 20.24, *SD*= 1.04) to the VAS condition. All participants obeyed to the inclusion criteria as described in the Method section of Experiment 1.

Stimuli and design. Participants were presented with time lines (see Figure 3) according to a 3 × 7 full-factorial design with two replications

[1] Here, power is referred to as the likelihood of finding statistically significant results given a specified significance criterion (α= .05), sample size and population effect size (O'Keefe, 2007). In a factorial design and keeping everything else equal, the larger the design, the larger the power to detect statistically significant results. The "observed" power of the design in question (2*4*8) reached 1.00, which implies that given these specifications, small deviations of parallelism will result in a statistically significant interaction.

(prior sleep [S] : 2 hrs, 4 hrs and 8 hrs; time of day [C]: 0900, 1200, 1700, 2200, 0000, 0400 and 0700 hrs). Time of day stimuli were chosen based on Åkerstedt and Folkard's (1995) alertness nomogram in order to represent levels of high, reduced and critical alertness and to induce sufficient variability in process C. To rule out additivity, levels of S were presented without indications of time of day. As well as in Experiment 1, the lowest level of S (0 hrs slept) was excluded from the analysis because of their sole purpose to engender extreme ratings.

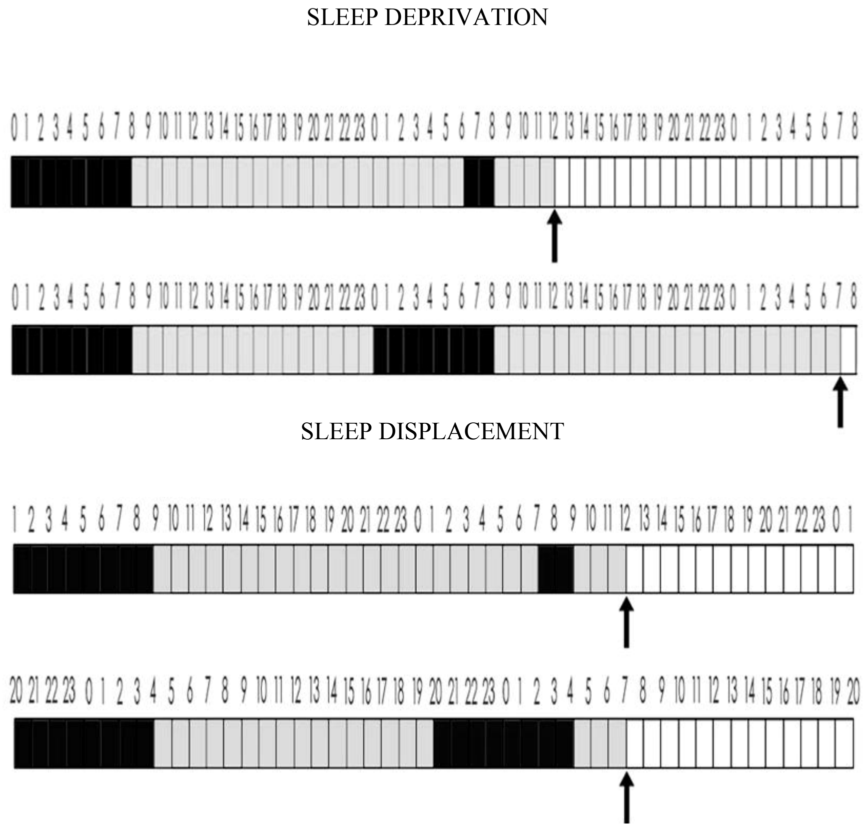

Figure 3. Examples of stimuli used in the sleep deprivation and sleep displacement conditions. Black blocks represent the prior sleep periods (S), grey blocks represent wake time and the black arrows indicate the time of day (C). Time lines were paired with verbal descriptions of prior sleep and time of day. In our example the upper time tables both conditions were paired with "It is now 1200 hrs and you slept 2 hrs." and the lower time tables with "It is now 0700 hrs and you slept 8 hrs".

Procedure. The experimental procedure is similar to Experiment 1. Here, anchoring the VAS and KSS consisted of choosing which time lines matched maximal sleepiness and maximal alertness from a list of all stimuli used in the experiment (including the no sleep-level of factor S).

RESULTS

Jewett and Kronauer (1999) further elaborated the Borbély's Two-Process Model (1982) by including a nonlinear interaction term. As this considerably improved their empirically-based model simulations, the strict additivity presumed in Borbély's seminal model was rejected in favor of a nonlinear expression of the model. In both expressions, linearity of the response measure is implicitely assumed. With respect to Information Integration Theory (Anderson, 1981) and to the results regarding response linearity previously observed in Mairesse et al. (2007) and now confirmed in Experiment 1, we expect that when sleepiness judgments are conveyed, homeostatic and circadian components integrate according to an averaging rule with differential weights.

Experiment 2a: Sleep deprivation. Inspection of the left panel group factorial plots (see Figure 4) reveals nonparallelism in both the KSS and the VAS condition. Statistically, this nonparallelism was supported for both the VAS and the KSS. Main effects are significant for process S (VAS: $F[2,40]= 233.22$, $p< .001$, $\eta^2_p= .99$; KSS: $F[2,40]= 147.77$, $p< .001$, $\eta^2_p= .88$) and for process C (VAS: $F[6,120]= 81.81$, $p< .001$, $\eta^2_p= .99$; KSS: $F[6,120]= 52.85$, $p< .001$, $\eta^2_p= .72$). More importantly, for both the VAS and the KSS a significant interaction effect is observed (VAS: $F[12,240]= 7.84$, $p< .001$, $\eta^2_p= .88$; KSS: $F[12,240]= 10.99$, $p< .001$, $\eta^2_p= .35$). A dividing operation seems to occur as the curves representing levels of Process C display a fan-like pattern when plotted against the marginal means of Process S. Theoretically, though, for a dividing model to be true the curves should intersect at a common point (Anderson, 1981, 1982). Inspection of the right panels of Figure 4 reveals that for the nighttime levels of Process C (0000 hrs, 0400 hrs and 0700 hrs) extrapolated trend lines cross at a common point, but for the daytime levels this is not the case. Moreover, in the left panel factorial graphs, a crossover pattern is observed for the uncombined levels of C, which supports differential weighting averaging.

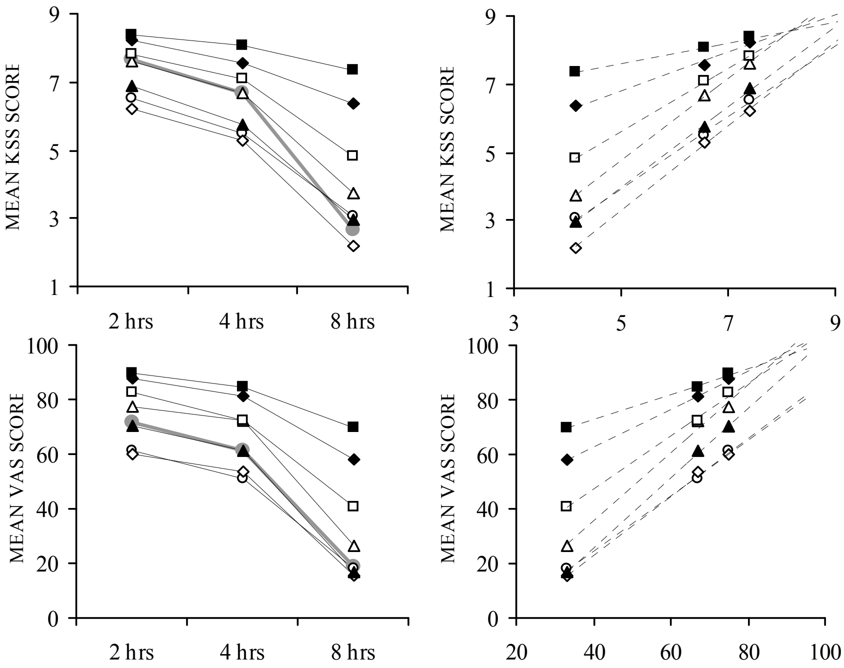

Figure 4. Plots of mean scores for KSS (top panels) and VAS (bottom panels) in the sleep deprivation condition. The left panels show mean scores plotted against prior sleep: 2 hrs, 4 hrs and 8 hrs (Process S). Black lines represent different moments during the day (Process C): 0700 hrs (■), 0400 hrs (◆), 0000 hrs (□), 2200 hrs (△), 0900 hrs (○), 1700 hrs (▲), 1200 hrs (◇). The grey line shows the results for the uncombined levels of Process S (●). The right panels show mean scores plotted on a functional scale (marginal means of S) for linear fan analysis. The dashed lines represent trend lines forecasts to uncover zero-crossings and rule out multiplicity.

At individual level, differential weighting is observed in the majority of the participants in both the KSS and the VAS condition (15 in the KSS condition and 12 in the VAS condition). In both conditions, 6 participants use a dividing integration rule. Finally, an additive integration rule was observed in 3 participants in the VAS condition. The single-subject analyses confirm the general differential weighting averaging model.

Experiment 2a: Sleep displacement. Consistent with the sleep deprivation condition, inspection of the factorial graphs for the group data (Figure 5) reveals nonparallelism in both KSS and VAS conditions. Although still present in the results of the ANOVA, the apparent dividing operation observed in the sleep deprivation condition (Experiment 2a) dissipates when keeping time after awaking constant. Similar to the sleep deprivation condition, main effects for process S are significant (VAS: $F[2,40]= 100.76$, $p< .001$, $\eta^2_p= .83$; KSS: $F[2,46]= 172.54$, $p< .001$, $\eta^2_p= .99$). Although smaller, main effects for process C too are statistically significant in both conditions (VAS: $F[6,120]= 2.79$, $p< .05$, $\eta^2_p= .12$; KSS: $F[6,138]= 10.28$, $p< .001$, $\eta^2_p= .91$). A significant interaction effect is observed in both the VAS and the KSS (VAS: $F[12,240]= 3.07$, $p< .001$, $\eta^2_p= .13$; KSS: $F[12,276]= 6.53$, $p< .001$, $\eta^2_p= .87$). Visual analysis of the factorial graphs shows a crossover pattern from the uncombined levels of S. Additionally, extrapolated trend lines in the right panels of Figure 5 clearly rule out convergence into a common cross-point, which supports a differential weighting averaging model.

The prominent model found at the individual level supports our group findings. In the KSS condition a vast majority of 18 participants follows a differential weighting averaging model, 3 of them an additive model, 2 a multiplicative model and 1 participant used a “prior sleep only” integration rule. A similar dominance of differential weighting averaging models is found in the VAS condition as well (14 participants). Two participants followed an equal weights averaging model, another 2 and additive model, whereas varying levels of process C did not influence the sleepiness judgments of 1 participant. Single-subject analyses strongly confirm the observed averaging with differential weighting integration rule detected at group level.

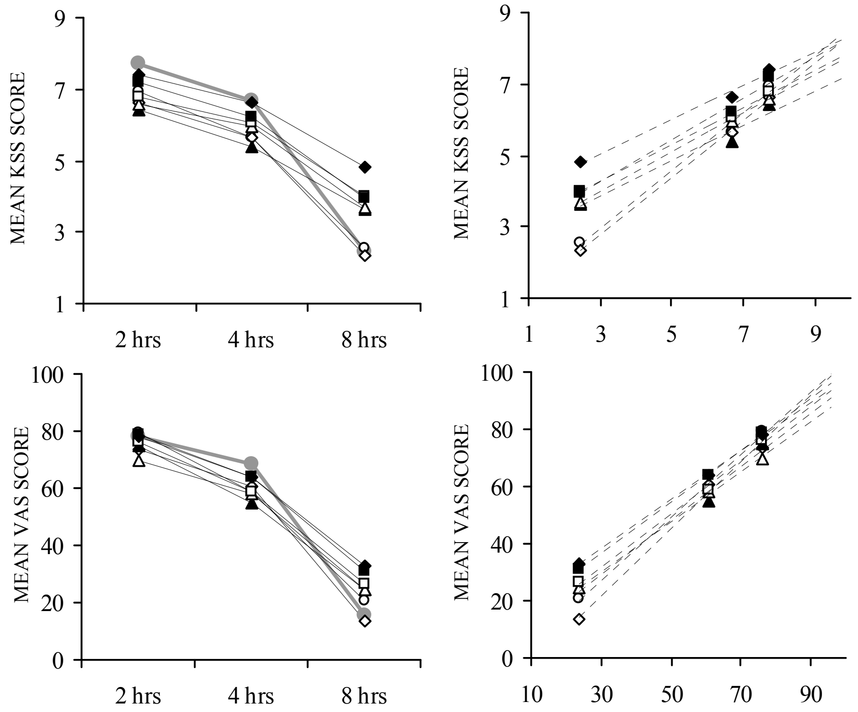

Figure 5. Plots of mean scores for KSS (top panels) and VAS (bottom panels) in the sleep displacement condition.

GENERAL DISCUSSION

The results of our first experiment confirm linearity of the KSS and the VAS. Using these instruments, we found that the integration of homeostatic and circadian processes in sleepiness judgments obeys an averaging rule with differential weighting. Our findings suggest that, for judged sleepiness, the assumption of strict additivity of process S and C, as initially suggested by Borbély (1982), should be reformulated in favor of a nonlinear relationship between both processes.

Previous research already suggested the presence of nonadditive interactions between processes S and C (Boivin et al, 1997; Dijk et al., 1992; Dijk & Czeisler, 1995; Jewett & Kronauer, 1999; Wyatt, Ritz-De Cecco, Czeisler & Dijk, 1999). However, as Achermann (1999, 2004) argued pertinently, these interactions could merely be an artifact of nonlinear metrics. In a previous study, Mairesse et al. (2007) established response linearity of the KSS and the VAS in the context of the Two-

Process Model. Here, we managed to demonstrate response linearity in a slightly different context. The finding that the overt response *R* is a linear function of the implicit response *r* has important implications on the results of the second experiment: any nonlinearity found in the second experiment may be considered as a genuine relation between process S and C. At the time Achermann raised the issue of nonlinearity, the discussion revolved mainly around possible ceiling and floor effects in the response measures. Therefore, we decided to take account of this in the present study by (1) deliberately omitting extreme levels of process S from the analysis, and (2) including an anchoring procedure preceding the experiment. When controlling for floor and ceiling effects in the response measure, the results still imply a nonlinear relation between homeostatic and circadian processes. In this context, it is important to note that in FM, linearity refers to the relationship between response scale and the underlying construct. As the KSS and the VAS seem to be linear response scales, it is conceivable that the reduced amplitude of the circadian component in subjective sleepiness (see a.o. Jewett and Kronauer, 1999; Van Dongen, 2004) can be explained by a ceiling effect of the *psychological* scale. It seems conceivable, indeed, that the hypothetical construct “subjective sleepiness” has a natural endpoint, a maximum that, when exceeded, results in the inevitable onset of sleep. This assumption reunites both the views from Achermann (1999) and Dijk and colleagues (Dijk et al., 1999): the observed nonlinear relation between S and C is genuine, but possibly due to ceiling/floor effects in the psychological scale.

Apart from the linearity of the response scales, the results of our second experiment support an averaging model with differential weighting in both the hypothetical sleep deprivation and the hypothetical sleep displacement condition. Differential weighting implies configurality together with adding-type information (Schlottmann and Anderson, 1993). Configurality itself implies that different stimulus levels may have different weights. In practice, this means that a particular time of day, say 1100 hrs, may differ in psychological value in comparison to another moment later that day, say 1400 hrs, but also in salience when combined with different amounts of prior sleep. When participants benefit a full night’s sleep, perceived sleepiness at 1100 hrs or at 1400 hrs may be virtually equal. However, after being deprived from sleep, sleepiness levels may be much higher around 1400 hrs than at 1100 hrs due to a greater importance of the circadian component. This illustration for varying weights has been observed empirically by Monk, Buysse, Reynolds III & Kupfer (1996) and is referred to as the appearance of a more salient “post lunch dip” after total sleep deprivation. The idea of an affected amplitude of the circadian component in subjective sleepiness ratings after extended wakefulness has already been described manifold (Babkoff, Mikulincer, Caspy, Kampinsky & Singh, 1988; Mikulincer, Babkoff & Caspy, 1989; Czeisler, Dijk & Duffy, 1994; Jewett & Kronauer, 1999; Wyatt et al., 1999). Compared to adding-type or multiplying models, differential weighting averaging can also account for the compensatory effects of the circadian component during periods of extreme prolongation of wakefulness. In a 72 hr sleep deprivation experiment subjective sleepiness ratings showed an increase in amplitude during the first 24 hrs, but the amplitude of the circadian remained stable during the second and the third day of sleep deprivation instead of increasing further (Mikulincer et al., 1989). In terms of differential weighting averaging this phenomenon could be translated as a relative stabilization of the weights after 24 hrs of sleep deprivation.

Obviously, the present study comes with some limitations. First, one must keep in mind that the nonparallelism observed in differential weighting averaging solely accounts for interactions at the level of psychological integration. Averaging does not allow assessing interactions at the physical level (valuation) of the stimuli (Schlottmann and Anderson, 1993). In the study of sleep and wake regulation however, the physical interaction of processes S and C is supported by the fact that neither of both processes can be present without the other. This has some limitations on the assessment of averaging models in actual sleep deprivation or forced desynchrony settings. In order to test for averaging integration the method of subdesigns is required, where at least one of the factors has to be presented without being paired to the other. In situations where the effect of one factor level depends on the effect of some level of another factor, the use of subdesigns may be problematic (Norman, 1976). Using strictly uncombined levels in real-life sleep deprivation or forced desynchrony settings is not possible. Sleepiness at a particular moment of the day always dependents on prior sleep, just as sleepiness after a certain amount of sleep always depends on the moment of assessment. Using sleepiness judgements on the other hand allows for the separation of both processes. Collateral information collected from the participants in our second experiment indicated that when asked to rate functional sleepiness after a certain amount of prior sleep (uncombined levels of process S), the majority of participants filled in missing information about the time of day by taking their average sleepiness over the whole day. This procedure suffices to rule out additivity of processes S and C, which was our main objective. Still, using hypothetical situations may be seen as a limitation in our experiments as it may not fully reflect how individuals perceive sleepiness in actual sleep deprivation or forced desynchrony settings. While this is a legitimate concern regarding the magnitude of the sleepiness levels, the probability of fundamentally different mechanisms at the integration level seems less probable. Previous studies have shown that at the level of the integration, data from the actual sleep deprivation experiments and the data from the judgment task exhibited more or less different values but a similar algebraic relation between S and C (Mairesse et al., 2007). Finally, it should be noted that the present study limits itself only to the investigation of the psychological law governing the integrative mechanisms of processes S and C. On the other hand, Borbély's seminal model was designed to describe the course of action of processes governed by what, when relating it to the context of IIT, could be described as a physiological law. Subsequent derivations of their model however, assumed that the same interactions also occur subjectively (e.g. Jewett and Kronauer, 1999). Based on the combined results of previous studies (Mairesse et al., 2007) and the current investigation we can only infer on the psychological integration of processes S and C, which implies that Borbély's original assumption of independence of processes S and C may still hold at the physiological level.

Summarizing, the present study used Functional Measurement as a technique imbedded in Information Integration Theory to assess the linearity of subjective measures of sleepiness (Experiment 1). Subsequently, we ruled out the strict additivity of processes S and C by uncovering a differential weighting averaging integration rule in both hypothetical sleep deprivation and sleep displacement contexts, after controlling for floor and ceiling effects in the response instruments (Experiment 2). In general, our results at group level were confirmed at the level of the individual in both the KSS and the VAS conditions and provide sufficient indications of the psychological interdependence of processes S and C.

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