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The effects of sleep deprivation and incentives on human performance

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Summary. This study explores whether KR (knowledge of results) and reward compensate for the negative joint effects of sleep deprivation and signal degradation in a choice-reaction task. The negative effect of signal degradation on performance was aggravated by sleep loss and time-on-task, whereas KR improved performance, especially when signals were degraded. Reward changed the effects of time-on-task owing to lack of sleep. Performance was also improved by a brief task interruption after 30 minutes' work, with 5 more minutes to go. These results can be interpreted in terms of the performance model of Sanders (1983), which links energetic mechanisms to stages of information processing. A lack of energetic supply from the arousal mechanism to perceptual processing, induced by signal degradation, sleep deprivation, and time-on-task, was effectively counteracted by KR: KR enables the mobilization of effort to compensate for this lack of arousal. The relation between reward and KR is not yet clear. The interruption effect suggests that the influence of time-on-task is not due to loss of arousal, but causes a reallocation of resources by effort.

Introduction

Sanders (1983) has proposed a model in which the flow of information is described in terms of linear processing stages (Donders, 1869/1969; Sanders, 1980; Sternberg, 1969) receiving energetic supply or resources from separate and independent energetic mechanisms (Gopher & Sanders, 1984; Pribram & McGuinness, 1975). Stages of perceptual encoding and motor adjustment are supposed to be provided with resources from an arousal and an activation mechanism respectively. A third mechanism, effort, is thought to provide resources to the central response-choice stage. Furthermore, it is proposed that the effort mechanism coordinates the operation of arousal and activation to maintain an optimum state. The load on the various stages depends on aspects of the task executed. Earlier research suggests that signal degradation, S-R compatibility, and time uncertainty are variables that affect the load on the stages of perceptual encoding, response choice, and motor adjustment respectively (Frowein & Sanders, 1978; Sanders, 1977, 1980, 1983).

Normally, arousal and activation are capable of serving the stages adequately. But under suboptimal circumstances the energetic mechanisms become inadequate, so that performance will decline. It is known that arousal (Sanders, Wijnen, & van Arkel, 1982; Steyvers, 1987) as well as activation (Frowein, 1981) are sensitive to lack of sleep. Yet these negative effects may be counteracted by effort, provided that information about the quality of performance is available, and that there is the willingness to invest effort. One way to do this is by presenting knowledge of results (KR) of the performance. Wilkinson (1961) found that performance does not decline with lack of sleep when KR is provided. Whether this effect is due to increased arousal, or activation, or both, cannot be concluded from his study. In order to identify the locus-of-effect of KR, it is necessary to combine sleep deprivation and KR with task variables that are known to influence a specific processing stage. To identify the locus-of-effect of KR on information-processing stages is the first aim of the present study.

A second question concerns the aspect of KR that causes the performance improvement. The following possibilities may exist: (1) a general enhancement of motivation, (2) the fact that an extra stimulus is presented, and (3) the knowledge of performance presented to the subject. The second aim of this study is to distinguish between these possibilities. In the no-KR condition a signal will be given that is similar to the KR signal, but noncontingent with performance. In previous studies (see Steyvers, 1991), a neutral constant signal was presented in the no-KR condition. In these studies there was a marked performance improvement in the KR condition, as compared to the no-KR condition, especially with sleep loss. If KR in these

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cases worked because it is an extra stimulus – varying and somehow "interesting" – then no difference should be found between the KR and the no-KR condition in the present study. If the informational content of the KR signal invokes the performance improvement, then this improvement should be found again compared to the fake-KR. In addition, in the present study a financial reward will be introduced, contingent upon performance, in both the KR and the no-KR conditions. If KR has some kind of general motivating property, then effects of KR should somehow be influenced by the reward condition. Hence, in this case an interaction between the effects of KR and reward is expected. On the one hand it is possible that KR lacks effect in addition to reward, because subjects already do their utmost: a ceiling effect. On the other hand it is possible that the effect of KR is enhanced by reward. For the second possibility some evidence is given by Locke (1968; also Locke, Shaw, Saari, & Latham, 1981), who suggest that the goal-setting properties of monetary reward are even necessary to invoke a performance improvement with KR.

The third aim of this study is to explore the nature of the interaction between sleep deprivation and time-on-task. In general, the effect of sleep deprivation gradually increases during a longer working period (Sanders et al., 1982; Steyvers, 1987; Wilkinson, 1961). The question is whether the gradual buildup of the sleep-deprivation effect is caused by a growing loss of resources (from arousal or activation), or by an increasing ineffectiveness of the control over resource provision (by effort). Put in other words: are resources becoming scarce with increasing time-on-task, or does the effectiveness of distribution diminish? To answer this question the task is interrupted after 30 minutes of continuous work, and subjects are told that only 5 more minutes are due. If resources are really depleted, such incitement will hardly cause an improvement of performance. However, if subjects have lost control over resource allocation, it should be possible to regain control, and improve performance to a normal level, or at least to the level of the first 5 minutes of the task execution.

Method

Subjects. Sixteen healthy male persons served as subjects. They were between 21 and 34 years of age and had no prior experience with the task. They received Dfl. 225 for participation and, in addition, a performance-related reward.

Apparatus. The experiment was controlled by a micro-PDP 11/73, connected to an LSI 11/23. The signals were generated by a graphic controller and presented on a TV monitor. RT was externally measured with an accuracy of 1 ms. More technical details are reported elsewhere (Steyvers, 1988). The subject was seated in an armchair in a sound-attenuating – ambient noise level 30 dB(A) – dimly illuminated cubicle. The monitor for signal presentation was visible through a window in the cubicle. Two response buttons were mounted on both armrests of the subject's chair. The hands of a subject were positioned on the armrests so that the index and middle fingers of each hand rested on the response buttons without pushing them down.

Stimuli and responses. The trial started with a warning signal (WS, 400-ms duration), followed 1 s after onset by an action signal (AS, 400-ms duration). Subjects were given time to respond within 2,000 ms after AS onset. KR was presented within 100 ms after the response and lasted 400 ms. If RT lasted longer than 1,600 ms, the duration of KR presentation was reduced to the time left until the next WS. When no response was recorded within 2,000 ms after AS onset, this was registered as an omission. The WS of the next trial was presented 2 s after AS onset, and so on for 30 minutes.

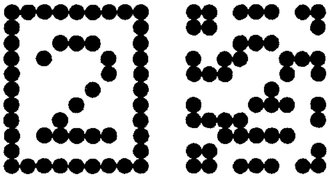

Fig. 1. Example of the stimuli. Left: intact, right: degraded

The WS consisted of an X-shaped dot pattern, in a rectangular dotted frame, placed centrally on the screen. The AS was one of the digits 2–5. The digits were composed of a dot pattern in a rectangular dotted frame (Frowein, Gaillard, & Varey, 1981). Stimuli covered an area of 9 × 11 cm, which corresponded to a visual angle of 4.2° for the viewing distance of the subjects. The spatial range of possible stimulus locations on the screen was within 8° of visual angle. The luminance of the stimulus dots was 5.95 cd/m^2, whereas the screen luminance was 0.57 cd/m^2. In one condition the AS was degraded by dots from the surrounding frame of the intact stimuli being placed in random positions within the frame on places not occupied by dots of the digits. An example is shown in Figure 1.

AS was presented either to the left or to the right of the center of the screen, indicating which hand should be used in the response. The mapping between the digit value and the buttons was irrespective of the hand to be used; the digits 2 and 3 corresponded to the left button, and the digits 4 and 5 to the right button. This mapping was valid for the sets of buttons in both armrests. Thus the digit 2 or 3 presented at the left side of the screen should lead to a response with the left button of the left armrest, that is, the middle finger of the left hand. The digit 4 or 5 at the left side of the screen should be followed by a response with the right button of the left armrest, the button under index finger of the left hand. Alternatively, the digit 2 or 3 presented at the right side of the screen should lead to a response with the left button of the right armrest, that is, the index finger of the right hand. Again, the digit 4 or 5 at the right side of the screen should be responded to with the right button of the right armrest, the button under the middle finger of the right hand. This arrangement of stimuli and responses was identical with one used in a performance-task battery (Taskomat: Boer, Gaillard, & Jorna, 1987). There is a dual-stimulus aspect to it, which may influence responding, but only in case of independent manipulation of the response of the fingers and hands. This is not so in this study. Hence no particular effects are expected other than effects from the signal-quality manipulation. See also Steyvers (1991) for a thorough discussion.

KR and reward. In the KR condition a signal was presented after the response, informing the subject about latency and accuracy. The KR signal consisted of a dot, which was presented above or below a horizontal line. The vertical placement of the dot was determined by the latency of the response; the shorter the RT, the higher the dot was placed on the screen. The horizontal line was always in the middle of the screen. It represented an individually determined RT criterion, which is the mean RT plus twice the SD of the last block of training trials of that particular condition. An RT below this criterion would lead to a dot in the upper half of the screen, whereas an RT above the criterion would result in a dot on the lower half of the screen. In this way, the latency of the response in relation to the subject's criterion was signalled. The color of the line and of dot was either green, in case of a correct response, or red, in case of an error. In the no-KR condition a signal was presented that was identical with the KR signal, but noncontingent to the response. In this case the color of the signal and the place of the dot were determined with a random number algorithm in the computer.

In half of the sessions subjects were able to earn a financial reward. The reward was calculated in bonus points earned during task execution. On each trial, a maximum of 4 bonus points was earned when the response was correct and when RT was less than 300 ms. For responses between 300 ms and the KR criterion the number of bonus points varied from 4 to 0 points. RTs longer than the KR criterion were "punished" with negative points, varying from 0 to –4 points for RTs ranging from KR criterion to 2,000 ms. When the response was incorrect, the outcome was reduced with 4 points, thus from 0 to –8 points. The total number of points earned in all sessions was transformed into a financial reward so that the worst performing subject would earn Dfl 25. The subject was informed about his reward score after completion of a block of trials.

Task interruption. After 30 minutes the door of the cubicle was opened and the subject was informed that half an hour was completed, and that one more block of 5 minutes was required. The task was resumed immediately after this interruption, lasting at most 1 minute, during which the subject remained seated. It was decided not to let only half of the subjects have the interruption and the other half not, to act as a control, since the already large and complicated design would then have an extra (between-subject) variable, thus unduly weakening the statistical power. Furthermore it is expected that the effect of time-on-task will be a more or less linear increment in RT, and therefore an effect of the interruption can be assessed by comparison of the post-interruption period with the period immediately before the interruption.

Design. Sleep deprivation, KR, signal quality, and reward were all manipulated within subjects. The order of sleep state was balanced between subjects: one half of the subjects had normal sleep before the first test day and were sleep deprived before the second test day. For the other half of the subjects this order was reversed. For each level of sleep state subjects received four experimental sessions. Manipulation of KR and reward was between these sessions. Reward was confined to the last two sessions to prevent subjects losing motivation for task execution when the first sessions would be with reward and the last without. The order of KR levels for each reward level was alternated between subjects. Signal quality was randomly varied from trial to trial. The total duration of one entire session was about 30 minutes. Time-on-task was studied by analysis of each session in six separate periods of 5 minutes. In this way a (2×2×2×2×6) factorial design was made with sleep deprivation, signal quality, KR, reward, and time-on-task.

Procedure. Two subjects at a time participated on one day in each of three weeks in the experiment. The first day was used for instruction and presentation of eight 10-minute periods of practice trials. Subjects were instructed to respond as fast as possible, but to try to make correct responses. They should try to keep the dot above the reference line, which indicated the RT criterion they should be able to manage. The exact nature of the criterion was not explained to them, but the negative consequences in failing to reach it for the reward calculation were explained. They were told that after 2 s of no response the task would continue with the next trial, and an omission would be recorded. The results of the last four periods were used to determine the KR-criterion values. The actual experiment was run on the second and third days. In the normal-sleep condition, subjects reported at the lab at 9 o'clock a. m. In the sleep-deprivation condition, subjects reported at the lab at 9 o'clock p. m. on the evening before the test day. During the night and the following test day the subjects were supervised by an assistant to prevent them from sleeping. They watched non-exciting videotapes, played computer and board games, read books, studied, whatever they liked. Light food, soft drinks, and decaffeinated coffee were available. Measurements started at noon and lasted until 5.30 p. m. The subjects participated in the sessions alternately; their watches were removed before they entered the cubicle to make sure that no information about time-on-task was available.

Results

Data analysis

Data analysis was carried out with the BMDP and the SPSS statistical packages. Performance was assessed by measurement of mean RT, proportion of errors, and proportion of omissions. Because the RT may have been artificially influenced by the latency limit of 2,000 ms, the median RT was also calculated for each period of 5 minutes. Separate ANOVAs were carried out for individual mean and median RTs, arcsin-transformed proportion of errors and omissions (see Winer, 1971, p. 400, who recommends this transformation in case of proportion data). To assess the effect of task interruption, ANOVAs for the dependent variables were done with the factor period, that had two levels: the last 5-minute period of the 30-minute session, and the 5-minute post-interruption period. To explore whether the post-interruption performance recovered to the level of initial performance of the half-hour period, four ANOVAs were carried out with the factor period consisting of the first 5-minute period of the 30-minute session, and the 5-minute post-interruption period.

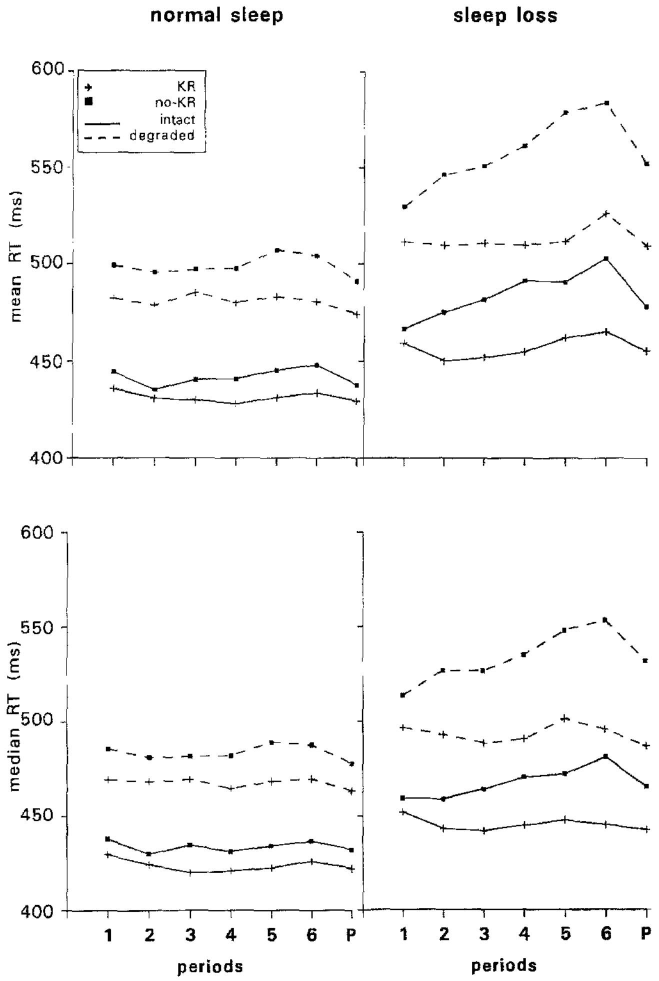

Fig. 2. Mean and median RTs separately for sleep-deprivation conditions, time-on-task, KR, and signal quality, averaged across reward and subjects, as function of 5-min periods (1–6), and post-interruption period (P)

The 30-minute period

Figure 2 shows mean and median RT as a function of 5-minute periods, and the post-interruption period. Figure 3 presents the results for errors and omissions.

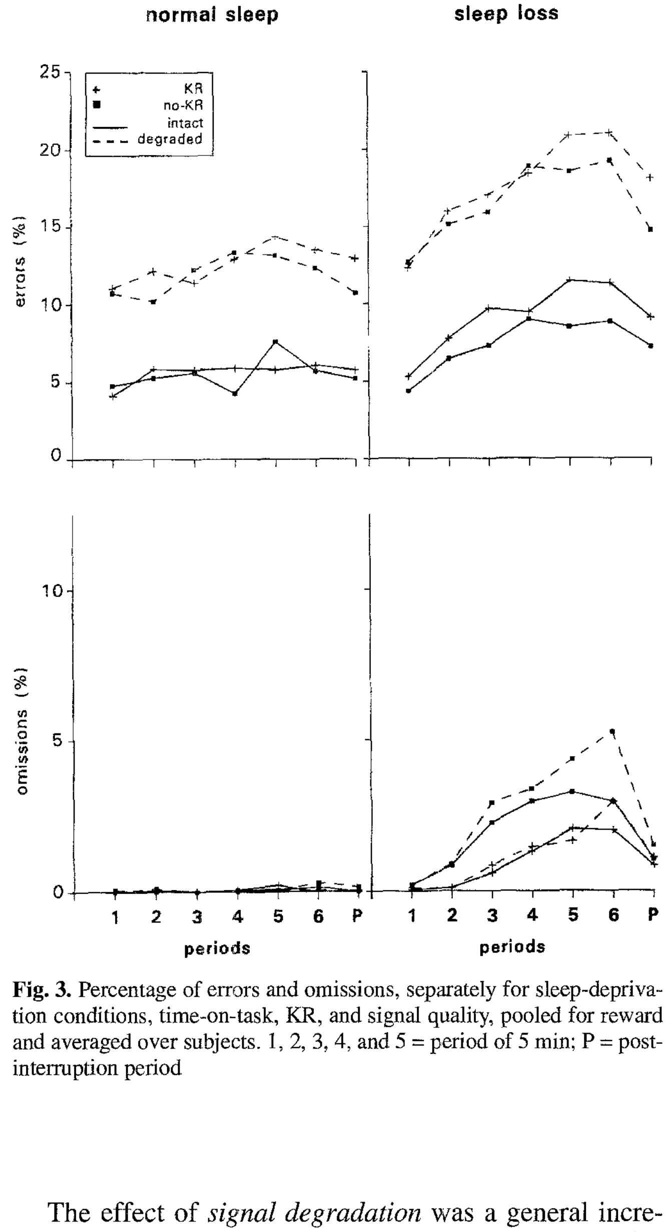

Fig. 3. Percentage of errors and omissions, separately for sleep-deprivation conditions, time-on-task, KR, and signal quality, pooled for reward and averaged over subjects. 1, 2, 3, 4, and 5 = period of 5 min; P = post-interruption period

The effect of *signal degradation* was a general increment of both mean and median RT, $F(1,15) = 166.99$, $p < .001$, for mean RT, and $F(1,15) = 140.30$, $p < .001$ for median RT respectively. The proportion of errors also increased, $F(1,15) = 305.28$, $p < .001$. This general effect of the manipulation of signal quality was enhanced after sleep deprivation, $F(1,15) = 15.84$, $p < .001$, for mean RT, and $F(1,15) = 11.64$, $p < .01$ for the median. *Sleep deprivation* itself increased the mean values of all four dependent variables; F-values for mean RT, median RT, errors and omissions are respectively $F(1,15) = 24.81$, $F(1,15) = 21.38$, $F(1,15) = 23.00$, $p < .001$; and $F(1,15) = 9.17$, $p < .01$. *Time-on-task* also increased the mean values of the four dependent variables $F(5,75) = 5.08$, $p < .001$, $F(5,75) = 2.90$, $p < .05$, $F(5,75) = 15.67$, and $F(5,75) = 8.81$, $p < .001$, respectively. The effect of time-on-task was enhanced by sleep loss, $F(5,75) = 4.61$, $p < .001$; $F(5,75) = 3.17$, $p < .05$; $F(5,75) = 8.10$, and $F(5,75) = 6.90$, $p < .001$, for mean and median RT, errors, and omissions respectively. The effect of signal quality was enhanced by time-on-task for the median RT and the proportion of omissions, $F(5,75) = 2.56$ and 2.72, $p < .05$, in each case respectively.

The effect of the nonindependent sequence of time-on-task levels was assessed by taking them as a polynominal contrast in an SPSS-MANOVA analysis, which equals a trend analysis. Only the linear trend was found to be significant for the main effect of time-on-task and various combinations of time-on-task with other variables. Hence, the increment in RT (and the proportion of errors and omissions) by time-on-task is more or less a straight line, at least within the period of 30 minutes for which the sessions of this experiment lasted.

The availability of KR caused a decrement of the mean and median RTs, $F(1,15) = 16.90$ and 17.30 respectively, $p < .001$, and also a decrement in the proportion of omissions, $F(1,15) = 8.19$, $p < .05$. The similarity in the direction of the effects of KR on the RT data and on the errors and omissions supports the assumption that KR did not cause a change in speed-accuracy trade-off. The effect of KR was most prominent with sleep loss, $F(1,15) = 9.02$, 6.42, and 7.05, for mean and median RTs, and proportion of omissions, $p < .05$, or after some time-on-task, $F(5,75) = 5.99$ and 4.41, for mean and median RTs, $p < .001$. The negative effect of signal degradation on RT was diminished when KR was provided, $F(1,15) = 9.47$ and 6.80, for mean and median RTs, $p < .01$ and $p < .05$ respectively. Although the interaction effect between signal quality, KR, and sleep deprivation on mean and median RTs and the proportion of errors failed to reach significance level, $p < .08$, the trend of the interaction was in the predicted, i. e., the over-additive, direction.

The effect of *reward* was not the expected improvement of performance. As may be seen in Figure 4, the mean and median RTs did not change, but the proportion of errors was higher with than without reward, $F(1,15) = 6.56$, $p < .05$. In combination with other variables (sleep loss, signal degradation), it appeared that reward seemed to impair performance. The effect of signal degradation was enhanced by reward on RT measures, $F(1,15) = 17.96$ and 12.77, for mean and median RTs respectively, $p < .001$ and $p < .01$; for proportion of errors, reward seemed to diminish the beneficial effect of KR, $F(1,15) = 6.09$, $p < .05$. Reward seemed to enhance the effect of signal degradation and KR, $F(1,15) = 19.6$ and 6.61, $p < .001$ and $p < .05$, respectively, for mean and median RTs. These effects may be explained by the fact that reward was always given in the second half of the afternoon; hence, it was confounded with an increment of sleep loss.

Only the influence of reward on mean RT as a function of time-on-task appeared different, especially with sleep loss, for the mean RT. With reward, the time-on-task effect was reduced, $F(5,75) = 4.48$, $p < .001$, and this effect was enlarged during sleep loss, $F(5,75) = 2.93$, $p < .05$. It appeared that with reward the intercept of the RT curve as a function of time-on-task was higher, and the slope was less steep than without reward.

In order to assess the nature of the changes that come about when incorrect responses were emitted, an additional analysis of the incorrect trials was executed by calculation of the mean RT of these trials. To obtain sufficient data, the trials of the whole 30-minute session were taken, with time-on-task discarded. The difference was calculated between the mean RTs of correct and incorrect trials: on these

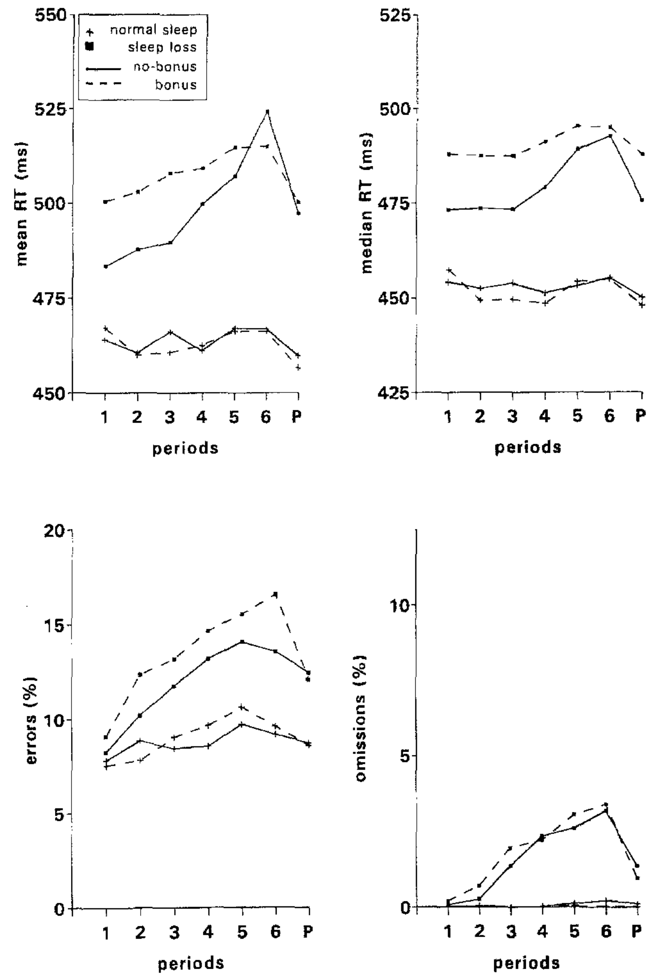

Fig. 4. Mean and median RTs, percentage of errors, and omissions separately for sleep-deprivation conditions, time-on-task and reward, pooled for KR and signal quality and averaged across subjects, as a function of 5-min periods (1–6) and post-interruption period (P)

difference scores an ANOVA was executed. The mean difference between correct and incorrect RTs was 2 ms, so at least overall, incorrect responses had about the same speed as correct responses. However, it was found that there was a main effect of sleep deprivation, $F(1,15) = 6.58$, $p < .05$; of KR, $F(1,15) = 7.12$, $p < .05$; and of signal quality, $F(1,15) = 15.35$, $p < .005$. With normal sleep, incorrect responses were 12 ms faster than correct responses, whereas with sleep deprivation, they were 16 ms slower. With KR, errors were 6 ms faster, and with no KR they were 10 ms slower. Intact signals gave 9-ms slower errors, whereas with degraded signals the errors were 4 ms faster. None of the other main effects or any of the interactions was significant.

Interruption effects

Significant effects of interruption were found, when the performance of the post-interruption period was related to the pre-interruption period (period 6 in the Figures). The main effect of period and interactions between the effect of period and other independent variables (with two levels: the pre- and the post-interruption period) reveals possible selective effects of the interruption. The interruption reduced the level of all four dependent variables, $F(1,15) = 11.41, 8.84, 11.48$, and 7.54, $p < .01$, $< .01$, $< .01$, and $< .05$, for mean and median RTs, errors, and omissions respectively. This effect tended to be larger with sleep deprivation than with normal sleep for the mean RT, $F(1,15) = 4.28$, $p < .056$, and for the errors and omissions, $F(1, 15) = 9.10$ and 5.89, $p < .01$ and $.05$ respectively. The reduction was smaller with than without KR, $F(1,15) = 5.95$ and 6.16, $p < .05$: 20 ms and 10 ms respectively for mean RT. For the errors the difference between the two periods was larger with than without bonus, $F(1,15) = 9.69$, $p < .05$. There was also an interaction between the effects of period, sleep loss, and reward on the mean RT, $F(1,15) = 5.32$, $p < .05$. With normal sleep the post-interruption improvement in error rate was larger with bonus than without: the level of errors was about the same in the pre-interruption period for both bonus conditions. In the post-interruption period it was smaller in the bonus condition than in the no-bonus condition. With sleep loss, however, the level of errors for the pre-interruption period was smaller with than without bonus. In the post-interruption period error rate became a little larger for bonus than for no bonus.

This analysis was also done for the comparison between the post-interruption period and the first 5-minute period (period 1 in the Figures). The main effect of period appeared to be significant only for errors and omissions. This means that the reduction in error and omission rates did not reach the level of the first 5-minute period, $F(1,15) = 15.79$ and 6.81, $p < .01$ and $.05$ respectively, for errors and omissions. All four dependent variables showed an interaction between period and sleep loss, $F(1,15) = 5.77, 5.42, 6.13$, and 5.06 respectively for mean and median RT, errors and omissions, $p < .05$: whereas after interruption performance with normal sleep approached, or even improved beyond, the inital performance level, with sleep loss this extent of improvement could not be reached. On mean RT, $F(1,15) = 6.43$, $p < .05$, and omissions, $F(1,15) = 5.22$, $p < .05$, reward and period showed an interaction of effects. For mean RT the difference between bonus and no bonus existed for the first period, but not for the post-interruption period. The difference in the first period came about by a larger RT in the bonus than in the no-bonus condition. For omissions, there was a difference between bonus and no bonus for the post-interruption period, but not for the first period. The difference in the post-interruption period existed because of more omissions in the no-bonus than in the bonus condition. For sleep deprivation, signal quality, and period, both mean and median RTs showed an interaction of effects, $F(1,15) = 5.61$ and 13.16, $p < .05$ and $.01$ respectively. With normal sleep the RT difference between the first and the post-interruption period was about the same for intact and degraded signals, and the RT was lower for the post-interruption than for the first period. With sleep loss, however, the RTs of the first period were lower than those of the post-interruption period. The difference between both periods was also larger for degraded than for intact signals. KR appeared to mediate the effect of sleep loss and period only for mean RT, $F(1,15) = 5.02$, $p < .05$: with normal sleep the mean RT for the post-interruption period was about 6 ms lower than for the first period, both for KR and no-KR conditions. With sleep loss, however, the mean RT for the post-interruption period was 4 ms lower than for the first period in the KR condition, whereas in the no-KR condition it was 14 ms higher in the post-interruption period. A third-order interaction (sleep deprivation, KR, reward, and period, $F(1,15) = 5.54$, $p < .05$), on errors, and a fourth-order interaction (all independent variables, $F(1,15) = 5.01$, $p < .05$) on omissions have to be reported. The interpretation of these effects is not clear.

Discussion

Sleep deprivation enhanced the effects of signal quality and of time-on-task. This replicates the results of previous studies (Sanders, Wijnen, & van Arkel, 1982; Steyvers, 1987), and is consistent with Sander's (1983) model, that lack of sleep decreases arousal – a selective impairment of the energetical supply to the perceptual-encoding stage.

KR improved performance, particularly after sleep loss. In terms of the Sanders model, KR incites effort to compensate for loss of energetic supply due to lack of sleep. The effect of KR did not result in a shift in speed-accuracy trade-off; this was a replication of an earlier experiment (Steyvers, 1987). The interaction between the effects of KR and signal quality suggests that KR compensates for loss of arousal, which is in contrast with the earlier experiment. The superior performance in the KR condition, as compared to the fake-KR condition, implies that response-contingent information in KR is essential. Since the same results were found in a previous experiment, the assumption (Sanders, 1983) is strengthened, that the effect of KR is based on the cognitive evaluation of performance, and that fake KR does not stimulate the subjects to invest effort.

Reward reduced the negative effect of time-on-task, especially with lack of sleep. The effect is, however, of a peculiar nature, and is displayed in Figure 4. Instead of levelling off the rise of RT as a function of time-on-task, the time-on-task effect was reduced by a larger offset at the start. This may have been caused by the confounding of reward and sleep loss, because the reward conditions were confined to the second half of the afternoon. However, in that case the normal gradual increase in RT during the 30-minute session would have been expected (e.g., Frowein et al., 1981; Sanders, 1980). Alternatively, it may be possible that the reward effect was caused by a change in strategy. Without reward subjects seem to start the task doing their utmost, and thus spend resources early in the working period. With reward, they appear to distribute their efforts more equally over the working period, resulting in a higher level at the start and reducing impairment over the working period.

The absence of any interaction between KR and reward, as well as the absence of a second-order interaction between KR, reward, and sleep state, suggests that reward and KR affect different energetic mechanisms. Since KR appears to influence arousal, the locus-of-effect of reward may be activation or effort: the energetical mechanisms for motor processing and central processing respectively, in the Sanders model. The signal-quality effect was larger with reward than without it. This, in fact, may reflect the well-known overadditive interaction between signal quality and the extent of sleep loss because of the confounding of reward with sleep loss. The finding that KR reduced the effect of signal quality more with a reward than without a reward may also be explained this way: KR might reduce the effect of signal quality more with greater lack of sleep. However, it cannot be excluded that the effects of reward and signal quality do have a genuine interaction, modulated by KR. This could be studied in an experiment that avoids confounding reward and sleep loss – and thus risking subjects who have the no-reward condition after the reward condition losing motivation and no longer trying hard.

The influence of reward and KR can also be explained in terms of a model of Locke (1968, Locke et al., 1981). In his review of the effects of motivational influences on task performance, Locke suggests that KR only works when task goals are set, and that the effect of KR is better with harder goals. Reward may be seen as a way to set task goals implicitly. This would suggest that with reward and KR, performance should be at its best. Signal quality may induce an extra aspect of difficulty, and therefore the effect of KR with reward is greater in the degraded than in the intact condition. There still remains the possibility of floor effects: with intact signals and KR, performance cannot improve too much, whereas with degraded signals the room for improvement is greater. Another question is the influence of the form of KR used. In the present study the reference mark on the display showed a subject-dependent RT criterion that subjects had to try to reach, or even pass. It was only in the reward condition that the failure to reach the criterion had any effect. Hence in this condition the KR display explicitly demonstrated the goal and the actual performance in relation to this goal. According to Locke's goal-setting model, this should mean that in the no-reward condition KR should have no effect, since there was no consequence from failing to reach the RT criterion. However, in both reward and no-reward conditions, KR had an effect. So the real effect of reward in relation to KR remains unclear.

The interruption of the task after the 30-minute session resulted in a performance improvement, particularly with lack of sleep. The negative effects of time-on-task vanished almost completely, especially in the KR condition: it appears that the decrement of effort, due to time-on-task in spite of KR, is restored by the interruption. In the fake-KR condition the absolute improvement was greatest. This discrepancy is probably a floor effect: with KR subjects already do their best, so there is no space left for improvement. In the fake-KR condition the restored effort has room for greater improvement. It is unlikely that the performance decrement of time-on-task is caused by the loss of resources, because in that case a brief interruption should not have caused such marked improvement. Since the effect of interruption does not interact with signal quality, it may be deduced, by the logic of the additive-factors method, that it does not work via the arousal mechanism. It seems that in spite of lack of sleep, energetic resources can be mobilized very fast, in order to compensate for a decrement.

The decision not to have a no-treatment control group in this study appears to be justifiable by the significant linear (and only linear) trend that was found for the RT (and for the errors and omissions) as a function of time-on-task. Hence, the expectation of performance without interruption is at least that of the preceding 5-minute period. So an analysis that uses this preceding period as a reference will reveal any improvement.

Is the performance decrement after sleep loss during the task due to an inability to maintain an optimal strategy for allocating resources over a longer period? In this case, the effect of time-on-task should disappear if subjects are aware of the elapsed time and of the time span ahead. However, in several studies on vigilance, in which subject had permanent knowledge of the time-on-task, it was found that performance decreased during the task (see, e.g., Mackie, 1977). But an alternative interpretation may be that the interruption caused supplementary stimulation. If only a shift in resource allocation is crucial for the improvement of performance after interruption, one would expect that knowledge about the start of the last 5 minutes would also elicit the improvement. No extra physical energy would be necessary. These ideas were tested in two experiments in which the time-on-task indication was presented without intrusion of the cubicle or any other disturbance of the working environment (Steyvers, 1991, pp. 162–165). It was found that a sole pause, a nonintrusive information procedure, or a noisy buzzer with time-on-task information did not contribute to the post-interruption improvement found in the present study. All effects were worn out within a few trials. Hence, it is likely that in the performance of monotonic and nonintellectual tasks under suboptimal conditions, a task interruption can only cause improvements when social interaction and environmental changes are possible. This finding may have consequences for the design and adjustment of tasks in applied settings.

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