Quantifying the Performance Impairment associated with Sustained Wakefulness

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Sustained Wakefulness and Performance

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SUMMARY

The present study systematically compared the effects of sustained wakefulness and alcohol intoxication on a range of neurobehavioural tasks. By doing so, it was possible to quantify the performance impairment associated with sustained wakefulness and express it as a blood alcohol impairment equivalent. Twenty-two healthy subjects, aged 19 to 26 years, participated in three counterbalanced conditions. In the sustained wakefulness condition, subjects were kept awake for twenty-eight hours. In the alcohol and placebo conditions, subjects consumed either an alcoholic or non-alcoholic beverage at 30 minute intervals, until their blood alcohol concentration reached 0.10%. In each session, performance was measured at hourly intervals using four tasks from a standardised computer-based test battery. Analysis indicated that the placebo beverage did not significantly effect mean relative performance. In contrast, as blood alcohol concentration increased performance on all the tasks, except for one, significantly decreased. Similarly, as hours of wakefulness increased performance levels for four of the six parameters significantly decreased. More importantly, equating the performance impairment in the two conditions indicated that, depending on the task measured, approximately 20 to 25 hours of wakefulness produced performance decrements equivalent to those observed at a BAC of 0.10%. Overall, these results suggest that moderate levels of sustained wakefulness produce performance equivalent to or greater than those observed at levels of alcohol intoxication deemed unacceptable when driving, working and/or operating dangerous equipment.

KEY WORDS sustained wakefulness, alcohol intoxication, performance impairment

INTRODUCTION

The negative impact of sleep loss and fatigue on neurobehavioural performance is well documented (Gillberg *et al.*, 1994; Mullaney *et al.*, 1983; Tilley and Wilkinson, 1984). Studies have clearly shown that sustained wakefulness significantly impairs several components of performance, including response latency and variability, speed and accuracy, hand-eye coordination, decision-making and memory (Babkoff *et al.*, 1988; Linde and Bergstrom, 1992; Fiorica *et al.*, 1968). Nevertheless, understanding of the relative performance decrements produced by sleep loss and fatigue among policy-makers, and within the community, is poor.

By contrast, the impairing effects of alcohol intoxication are generally well accepted by the community and policy makers, resulting in strong enforcement of laws mandating that individuals whose blood alcohol concentration exceeds a certain level be restricted from driving, working and/or operating dangerous equipment. Consequently, several studies have used alcohol as a standard by which to compare impairment in psychomotor performance caused by other substances (Heishman *et al.*, 1989; Dick *et al.* 1984; Thapar *et al.*, 1995). By using alcohol as a reference point, such studies have provided more easily grasped results regarding the performance impairment associated with such substances.

In an attempt to provide policy makers and the community with an easily understood index of the relative risks associated with sleep loss and fatigue, Dawson and Reid (1997) equated the performance impairment of fatigue and alcohol intoxication using a computer-based unpredictable tracking task. By doing so, the authors demonstrated that one night of sleep deprivation produces performance impairment greater than is currently acceptable for alcohol intoxication.

While this initial study clearly established that fatigue and alcohol intoxication has quantitatively similar effects, it should be noted that performance on only one task was investigated. Thus, it is unclear at present whether these results are restricted to hand-eye coordination, or characteristic of the general cognitive effects of fatigue. While it is generally accepted that sleep loss and fatigue are associated with impaired neurobehavioural performance, recent research suggests that tasks may differ substantially in their sensitivity to sleep loss. Studies addressing this issue have suggested that tasks which are complex, high in workload, relatively monotonous and which require continuous attention are most vulnerable to sleep deprivation (Johnson, 1982; Wilkinson, 1964).

As conditions that cause deterioration in one particular function of performance may leave others unaffected, it is unreasonable to assume that one could predict all the effects of sleep loss from a single performance test. Thus, the current study sought to replicate and extend the initial findings of Dawson and Reid (1997) by systematically comparing the effects of sleep deprivation and alcohol intoxication on a range of performance tasks.

METHOD

Subjects

Twenty-two participants, aged 19 to 26 years, were recruited for the study using advertisements placed around local universities. Volunteers were required to complete a general health questionnaire and sleep/wake diary prior to the study. Subjects who had a current health problem, and/or a history of psychiatric or sleep disorders were excluded. Subjects who smoked cigarettes or who were taking medication known to interact with alcohol were also excluded. Participants were social drinkers who did not regularly consume more than six standard drinks per week.

Performance Battery

Neurobehavioural performance was measured using a standardised computer based test battery. The apparatus for the battery consists of an IBM compatible computer, microprocessor unit, response boxes and computer monitor. Based on a standard information processing model (Wickens, 1984), the battery sought to provide a broad sampling of various components of neurobehavioural performance. Four of twelve possible performance tests were used, such that the level of cognitive complexity ranged from simple to more complex (as listed below). Since speed and accuracy scores can be effected differently by sleep deprivation (Angus and Heslegrave, 1985; Webb and Levy, 1982), tasks that assessed both were investigated.

The simple sensory comparison task required participants to focus on an attention fixing spot displayed on the monitor for 750ms. Following this, a line of stimulus characters, divided into three blocks of either numbers, letters or a mixture was displayed. Participants were then required to respond to a visual cue, which appeared in the position of one of the stimulus blocks, by naming the block, which had been there. Verbal responses were scored as correct, partially correct or incorrect.

The unpredictable tracking task (three-minute trials) was performed using a joystick to control the position of a tracking cursor by centering it on a constantly moving target. Percentage of time on target was the performance measure.

The vigilance task (three and a half minute trials) required subjects to press one of six black buttons or a single red button, depending on which light was illuminated. If a single light was illuminated, subjects were required to press the corresponding black button underneath it. If however, two lights were illuminated simultaneously, subjects were required to press the red button. For this report, two vigilance measures were evaluated: 1) the number of correct responses (accuracy), and 2) increases in the duration of responses (response latency).

The grammatical reasoning task required subjects to indicate whether a logical statement, displayed on the monitor, was true or false. Subjects were presented with 32 statements per trial, and instructed to concentrate on accuracy, rather than speed. Both accuracy (percentage of correct responses) and response latency were evaluated in this report.

During test sessions, subjects were seated in front of the workstation in an isolated room, free of distraction, and were instructed to complete each task once (tasks were presented in a random order to prevent order effects). Each test session lasted approximately 15 minutes. Subjects received no feedback during the study, in order to avoid knowledge of results affecting performance levels.

Procedure

Subjects participated in a randomised cross-over design involving three experimental conditions: 1) an alcohol intoxication condition, 2) a placebo condition, and 3) a sustained wakefulness condition. During the week prior to commencement of the experimental conditions, all participants were individually trained on the performance battery, to familiarise themselves with the tasks and to minimise improvements in performance resulting from learning. Subjects were required to repeat each test until their performance reached a plateau.

The subjects reported to the laboratory at 8:00pm on the night prior to each condition. Prior to retiring at 11:00pm, subjects were required to complete additional practice trials on each tasks. Subjects were woken at 7:00am, following a night of sleep, and allowed to breakfast and shower prior to a baseline testing session, which started at 8:00am.

Alcohol Intoxication Condition

Subjects completed a performance testing session hourly. Following the 9:00am testing session, each subject was required to consume an alcoholic beverage, consisting of 40 percent vodka and a non-caffeinated softdrink mixer, at half hourly intervals. Twenty minutes after the consumption of each drink, blood alcohol concentrations (BAC) were estimated using a standard calibrated breathalyser (Lion Alcolmeter S-D2, Wales), accurate to 0.005% BAC. When a BAC of 0.10% was reached no further alcohol was given. Subjects were not informed of their BAC at anytime during the experimental period.

Placebo Condition

The procedure for the placebo condition was essentially identical to the alcohol condition. Subjects in the placebo condition had the rim of their glass dipped in ethanol to give the impression that it contained alcohol. To ensure that subjects remained blind to the treatment condition to which they had been allocated, approximately equal numbers of subjects received alcohol or placebo in any given laboratory session.

Sustained Wakefulness Condition

Subjects were deprived of sleep for one night. During this time, they completed a performance testing session every hour. In between their testing sessions, subjects could read, write, watch television or converse with other subjects, but were not allowed to exercise, shower or bath. Food and drinks containing caffeine were prohibited the night before and during the experimental conditions.

Statistical Analysis

To control for inter-individual variability on neurobehavioural performance, test scores for each subject were expressed relative to the average test scores they obtained during the baseline (8:00am) testing session of each condition. Relative scores within each interval (hour of wakefulness or 0.01% BAC intervals) were then averaged to obtain the mean relative performance across subjects. Neurobehavioural performance data in the sustained wakefulness and alcohol intoxication conditions were then collapsed into two-hour bins and 0.02% BAC intervals, respectively.

Evaluation of systematic changes in each performance parameter across time (hours of wakefulness) or blood alcohol concentration were assessed separately by repeated-measures analysis of variance (ANOVA), with significance levels corrected for sphericity by Greenhouse-Geisser epsilon.

Linear regression analysis was used to determine the relationship between test performance, hours of wakefulness and alcohol intoxication. The relationship between neurobehavioural performance and both hours of wakefulness and BAC are expressed as a percentage drop in performance for each hour of wakefulness or each percentage increase in BAC, respectively. For each performance parameter, the percentage drop in test performance in each of the two conditions was also equated, and the effects of sustained wakefulness on performance expressed as a BAC equivalent.

RESULTS

Alcohol Intoxication Condition

Table 1 displays the results of the ANOVAs run on each performance variable as a function of BAC. Five of the six performance parameters significantly ($p = 0.0008-0.0001$) decreased as BAC increased, with poorest performance resulting at a BAC of 0.10 or greater.

The linear relationship between increasing BAC and performance impairment was analysed by regressing mean relative performance against BAC for each 0.02% interval. As is evident in Table 2, there was a significant ($p = 0.0132-0.0002$) linear correlation between BAC and mean relative performance for all of the variables except one. It was found that for each 0.01% increase in BAC, the decrease in performance relative to baseline ranged from 0.29 to 2.68%.

Placebo Condition

To ensure that differences in performance reflected only the effects of actual alcohol intoxication a placebo condition was incorporated into the study. As indicated in Table 1, mean relative performance in the placebo condition did not significantly vary.

Sustained Wakefulness Condition

Table 1 displays the results of the ANOVAs for each performance variable as a function of hours of wakefulness. Four of the six performance parameters showed statistically significant ($p = 0.0001$) variation by hours of wakefulness. In general, the hours-of-wakefulness effect on each performance parameter was associated with poorest performance resulting after 25 to 27 hours of wakefulness.

Since there is a strong non-linear component to the performance data. which remained at a fairly stable level throughout the period which coincides with their normal waking day, the performance decrement per hour of wakefulness. was calculated using a linear regression between the seventeenth (equivalent to 11:00pm) and twenty-seventh hour of wakefulness.

As indicated in Table 2, regression analyses revealed a significant linear correlation ($p = 0.0011$-0.0001) between mean relative performance and hours of wakefulness for four of the six performance variables. Between the seventeenth and twenty-seventh hours of wakefulness, the decrease in performance relative to baseline ranged from 0.61 to 3.35% per hour (Table 2).

Sustained Wakefulness and Alcohol Intoxication

The primary aim of the present study was to express the effects of SW on a range of neurobehavioural performance tasks as a blood alcohol equivalent. Figures 1-6 illustrate the comparative effects of alcohol intoxication and sustained wakefulness on the six performance parameters. When compared to the impairment of performance caused by alcohol at a BAC of 0.10%. the same degree of impairment was produced after 20.3 (grammatical reasoning response latency). 22.3 (vigilance accuracy). 24.9 (vigilance response latency) or 25.1 (tracking accuracy) hours. Even after 28 hours of sustained wakefulness. neither of the remaining two performance variables (grammatical reasoning accuracy and simple sensory comparison) decreased to a level equivalent to the impairment observed at a BAC of 0.10%.

DISCUSSION

In the present study moderate levels of alcohol intoxication had a clearly measurable effect on neurobehavioural performance. We observed that as blood alcohol concentration increased performance on all the tasks, except for one, significantly decreased. A similar effect was observed in the sustained wakefulness condition. As hours of wakefulness increased performance levels for four of the six parameters significantly decreased. Comparison of the two effects indicated that moderate levels of sustained wakefulness produce performance decrements comparable to those observed at moderate levels of alcohol intoxication in social drinkers.

As previous research has found that some individuals tend to perform in a manner that is consistent with the expectation that they are intoxicated due to alcohol consumption (Brechenridge and Dodd, 1991), a placebo condition was included in this study. We found that the placebo beverage did not significantly effect mean relative performance. Thus, it was assumed that performance decrements observed during the alcohol condition were caused solely by increasing blood alcohol concentration. Moreover, it is worth noting that the placebo condition in this study generally did not create the perception of alcohol consumption. Furthermore, when participants had already experienced the alcohol condition, and thus the effects of alcohol on their subsequent behaviour and performance, placebo beverages were even less convincing, suggesting that inclusion of a placebo condition is not necessary in future studies of a similar nature.

In general, increasing blood alcohol concentrations were associated with a significant linear decrease in neurobehavioural performance. At a BAC of 0.10% mean relative performance was impaired by approximately 6.8% and 14.2% (grammatical reasoning accuracy and response latency, respectively), 2.3% and 20.5% (vigilance accuracy and response latency, respectively) or 21.4% (tracking). Overall, the decline in mean relative performance ranged from approximately 0.29% to 2.68% per 0.01% BAC. These results are consistent with previous findings that suggest that alcohol produces a dose-dependent decrease in neurobehavioural performance (Billings *et al.*, 1991).

In contrast, mean relative performance in the sustained wakefulness condition showed three distinct phases. Neurobehavioural performance remained at a relatively stable level during the period which coincided with the normal waking day (0 to 17 hours). In the second phase, performance decreased linearly, with poorest performance generally occurring after 25 to 27 hours of wakefulness. It was observed that mean relative performance increased again after 26 to 28 hours of wakefulness presumably reflecting either the well reported circadian variation in neurobehavioural performance (Folkard and Tottersdell, 1993) or an end of testing session effect.

The linear decrease in performance observed for four of the measures in this study is consistent with previous studies documenting neurobehavioural performance decreases for periods of sustained wakefulness between 12 and 86 hours (Linde *et al.* 1992; Storer *et al.* 1989; Fiorica *et al.* 1968). Between the seventeenth and twenty-seventh hours of wakefulness, mean relative performance significantly decreased at a rate of approximately 2.61% (grammatical reasoning response latency), 0.61 and 1.98% (vigilance accuracy and response latency, respectively) or 3.36% (tracking) per hour.

While the results in each of the experimental conditions are interesting in themselves, and have been previously established, the primary aim of the present study was to compare the effects of alcohol intoxication and sustained wakefulness. Equating the effects of the two conditions indicated that 17 to 27 hours of sustained wakefulness (from 12:00am to 10:00am) and moderate alcohol consumption have quantitatively similar effects on neurobehavioural performance. Indeed, the findings of this study suggest that after only 20 hours of sustained wakefulness performance impairment may be equivalent to that observed at a BAC of 0.10%.

This study has confirmed the suggestion made by Dawson and Reid (1997) that moderate levels of sustained wakefulness produce performance decrements equivalent to or greater than those observed at levels of alcohol intoxication deemed unacceptable when driving, working and/or operating dangerous equipment. More importantly, however, this study was designed to determine whether the results of Dawson and Reid (1997) were an isolated finding, or characteristic of the general cognitive effects of sleep deprivation. Using the degree of impairment caused by alcohol that produced a BAC of 0.10% as a standard, this study systematically compared the effects of sustained wakefulness on a range of neurobehavioural tasks. Results indicate that while, in general, sustained wakefulness had a detrimental effect on psychomotor performance, the specific components of performance differed in their degree of sensitivity to sleep deprivation.

The observed differences between the performance tasks with respect to the vulnerability to sleep deprivation can be explained by their relative degrees of complexity. That is to say, the more complex neurobehavioural parameters measured in the present study were more sensitive to sleep deprivation than were the simpler performance parameters. While only 20.3 hours of sustained wakefulness was necessary to produce a performance decrement on the most complex task (grammatical reasoning) equivalent to the impairment observed at a BAC of 0.10%, it was after

22.3 and 24.9 hours of sustained wakefulness that a similar result was seen in a less complex task (vigilance accuracy and response latency, respectively). Furthermore, on the unpredictable tracking task, a slightly less complex task than vigilance, a decrement in performance equivalent to that observed at a BAC of 0.10% was produced after 25.1 hours of wakefulness.

It was observed that, despite a slight downward trend, performance on the simplest of the four tasks did not significantly decrease, even following twenty-eight hours of sustained wakefulness. In contrast, performance on this task was significantly impaired after a dose of alcohol that produced a BAC of 0.10% (or greater). These results are in line with the suggestion that simple tasks are less sensitive to sleep deprivation (Johnson, 1982). Indeed, we believe it likely that impairment of performance on this task may have occurred if we had extended the period of sustained wakefulness. It is interesting to note that several studies (e.g. Dinges *et al.*, 1988) have reported that tasks similarly lacking in complexity, such as simple reaction time tasks, are affected early and profoundly by sleep loss, thus strongly suggesting that monotony may increase sensitivity to sustained wakefulness. Indeed, the fact that this task was not vulnerable to sustained wakefulness may possibly be explained by the interesting and challenging properties of the task.

It is also noteworthy that, while we observed a decrease in accuracy on the grammatical reasoning task, impairment of this performance parameter was not comparable to that produced by a BAC of 0.10%. While this may at first contradict the suggestion that in this study vulnerability to sustained wakefulness was, to a large degree, determined by task complexity, it should be noted that participants were instructed to concentrate on accuracy rather than speed when completing the grammatical reasoning task. Thus, our particular instructions to participants may explain, at least in part, this irregularity. Alternatively, this finding is in line with the suggestion of a natural 'speed-accuracy trade-off'. Similar results have been observed in several studies, which report a decline in speed of performance, but not accuracy, when sleep-deprived subjects are required to perform a logical-reasoning task (Angus and Heslegrave, 1985; Webb and Levy, 1982).

Interestingly, this was not the case with the vigilance task. In this instance, despite instruction to concentrate primarily on accuracy, this component was slightly more vulnerable to sleep deprivation than was response latency. The absence of a trade-off on this task may be explained by the different properties of the vigilance and grammatical reasoning tasks. In accordance with the distinction raised by Broadbent (1953), the latter of these tasks can be defined as an unpaced task, in which the subject determines the rate of stimuli presentation. In contrast, the vigilance task can be defined as a paced task, in which stimuli are presented at a speed controlled by the experimenter. In line with this distinction, our findings are consistent with those of Broadbent (1953) who observed that while a paced task rapidly deteriorated during the experimental period, in terms of speed, an unpaced version of the same task did not.

A further explanation for the differences observed between these two tasks, may relate to the extremely monotonous nature of the vigilance task. Indeed, we believe it likely that subjects were more motivated to perform well on the grammatical reasoning task, which was generally considered more interesting and challenging. Hence degree of motivation may explain why measures of both speed and accuracy decreased on the vigilance task, while on the former task, accuracy remained relatively stable. This suggestion is in line with previous studies that have found that motivation can, to a degree, counteract the effects of sleep loss (Horne and Pettitt, 1985).

Taken together, the results from this study support the suggestion that even moderate levels of sustained wakefulness produce performance decrements greater than is currently acceptable for alcohol intoxication. Furthermore, our findings suggest that while sleep deprivation has a generally detrimental effect on neurobehavioural performance, specific components of performance differ in their sensitivity to sustained wakefulness.

Since approximately 50 percent of shiftworkers typically spend at least twenty-four hours awake on the first night shift in a roster (Tepas *et al.*, 1981), these findings have important implications within the shiftwork industry. Indeed, the results of this study, if generalized to an applied setting, suggest that on the first night shift, on a number of tasks, a shiftworker would show a neurobehavioural performance decrement similar to or greater than is acceptable for alcohol intoxication.

While the current study supports the idea that sustained wakefulness may carry a risk comparable with moderate alcohol intoxication, it is difficult to know to what degree these results can be generalized to "real-life" settings. Indeed, laboratory measures and environments usually bear little resemblance to actual tasks and settings. Furthermore, while our study used a battery of tests to evaluate the effects of sustained wakefulness on performance, their is no guarantee that all the functions involved in "real-life tasks", such as driving, were utilized and assessed. An alternative approach would be to simulate the actual task, as accurately as possible. Given that, for practical and ethical reasons, it is difficult to experimentally study the relationship between sustained wakefulness and actual driving, simulators of varying realism have been used. Thus, protocols using simulators could be used to model "real-life" settings and establish a more accurate estimate of the BAC equivalence for the performance decrement associated with sleep loss and fatigue.

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TABLE 1. Summary of ANOVA results for neurobehavioural performance variables

	Placebo		Alcohol Intoxication		Sustained Wakefulness	
Performance Variable	$F_{7,147}$	P[a]	$F_{5,105}$	P[a]	$F_{13,273}$	P[a]
GRG Response Latency	0.82	NS	4.96	0.0021	13.77	0.0001
GRG Accuracy	0.63	NS	6.88	0.0001	2.20	NS
VIG Response Latency	2.19	NS	43.09	0.0001	33.74	0.0001
VIG Accuracy	2.02	NS	7.99	0.0008	11.04	0.0001
Unpredictable Tracking	2.63[b]	NS	5.32	0.0008	10.09	0.0001
Simple Sensory Comparison	0.78	NS	1.88	NS	1.47	NS

GRG, grammatical reasoning; VIG, vigilance

[a] corrected by Greenhouse-Geisser epsilon; [b] based on data from twenty subjects.

TABLE 1. Summary of linear regression analysis of neurobehavioural performance variables

Performance Parameter	DF	F	P	R2	%Decrease
SW Condition					(per hour)
GRG Response Latency	1,4	70.61	0.0011	0.95	2.69
GRG Accuracy	1,4	3.64	NS	--	--
VIG Response Latency	1,4	98.54	0.0006	0.96	1.98
VIG Accuracy	1,4	81.79	0.0008	0.95	0.61
Unpredictable Tracking	1,4	70.93	0.011	0.95	3.36
Simple Sensory	1,4	4.71	NS	--	--
Alcohol Condition					(per0.01% BAC)
GRG Response Latency[b]	1,2	74.30	0.0132	0.97	2.37
GRG Accuracy	1,4	31.07	0.0051	0.89	0.68
VIG Response Latency	1,4	12.65	0.0002	0.98	2.05
VIG Accuracy[a]	1,3	212.37	0.0007	0.99	0.29
Unpredictable Tracking[a]	1,3	238.52	0.0006	0.99	2.68
Simple Sensory	1,4	5.37	NS	--	--

[a] Based on data from 0.02%-0.10% BAC; [b] Based on data from 0.04% -0.10% BAC

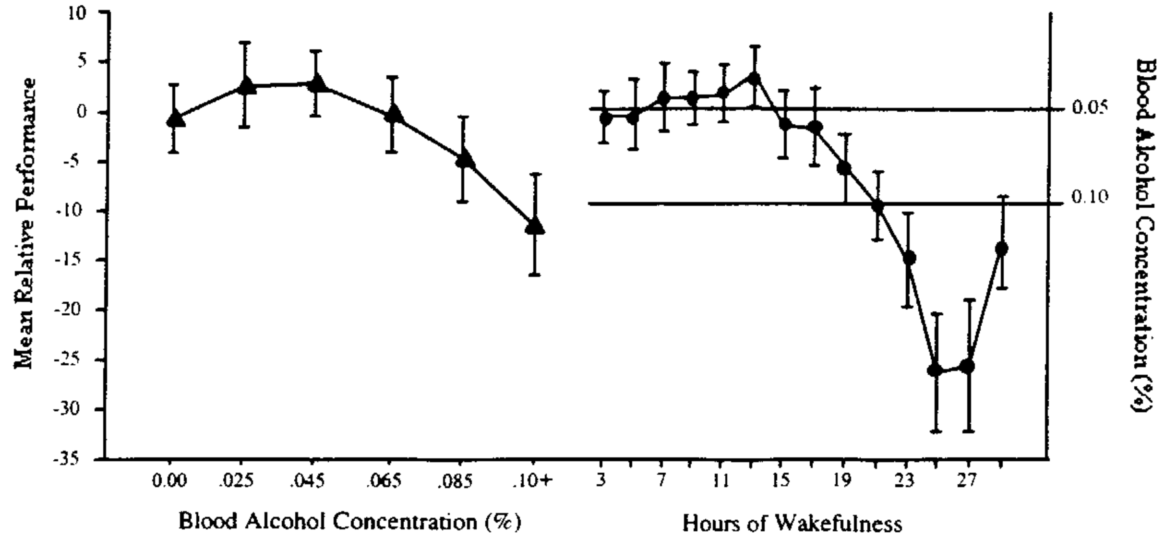

FIG. 1. Mean relative performance levels for the response latency component of the grammatical reasoning task in the alcohol intoxication (left) and sustained wakefulness condition. The equivalent performance decrement at a BAC of 0.05% and 0.10% are indicated on the right hand axis. Error bars indicate ± one s.e.m.

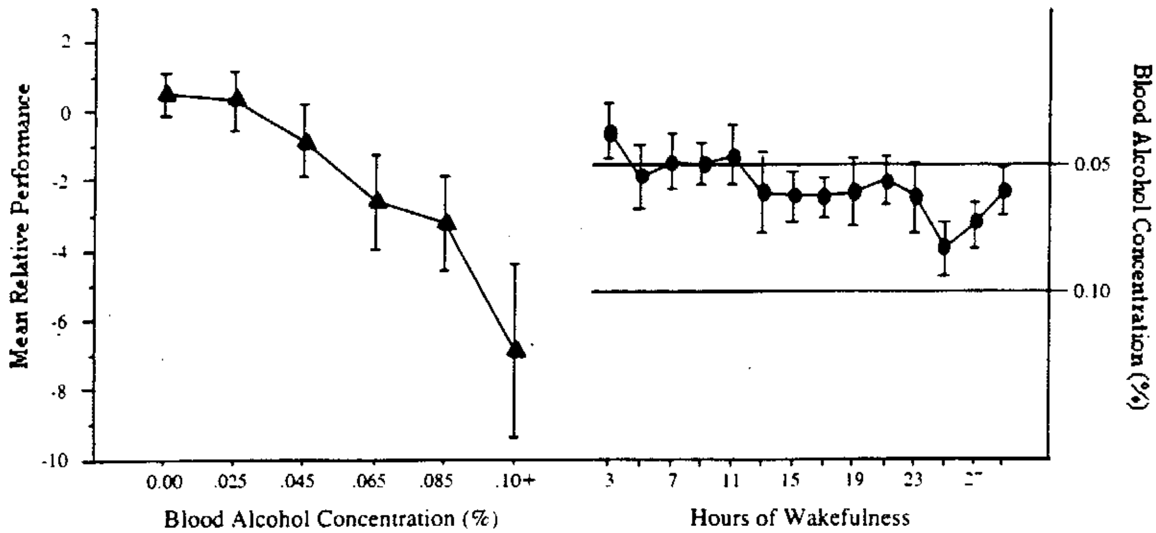

FIG. 2. Mean relative performance levels for the accuracy component of the grammatical reasoning task in the alcohol intoxication (left) and sustained wakefulness condition. The equivalent performance decrement at a BAC of 0.05% and 0.10% are indicated on the right hand axis. Error bars indicate ± one s.e.m.

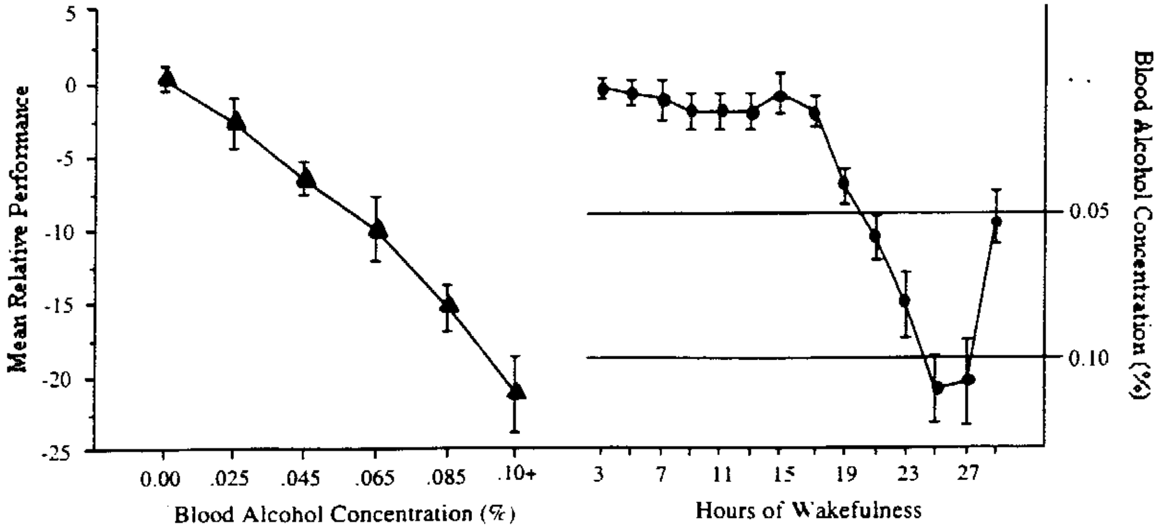

FIG. 3. Mean relative performance levels for the response latency component of the vigilance task in the alcohol intoxication (left) and sustained wakefulness condition. The equivalent performance decrement at a BAC of 0.05% and 0.10% are indicated on the right hand axis. Error bars indicate ± one s.e.m.

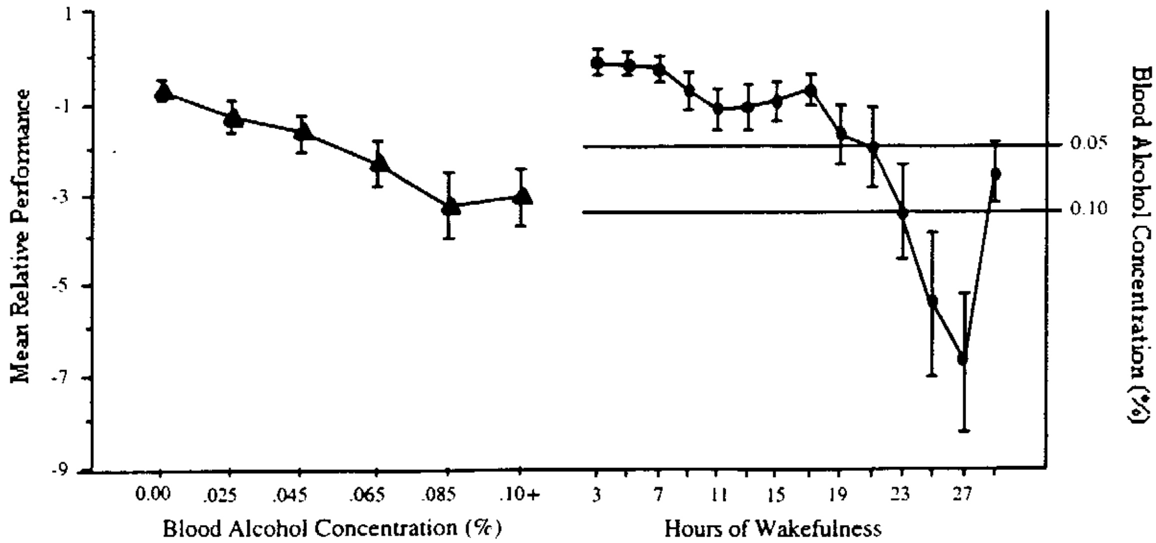

FIG. 4. Mean relative performance levels for the accuracy component of the vigilance task in the alcohol intoxication (left) and sustained wakefulness condition. The equivalent performance decrement at a BAC of 0.05% and 0.10% are indicated on the right hand axis. Error bars indicate ± one s.e.m.

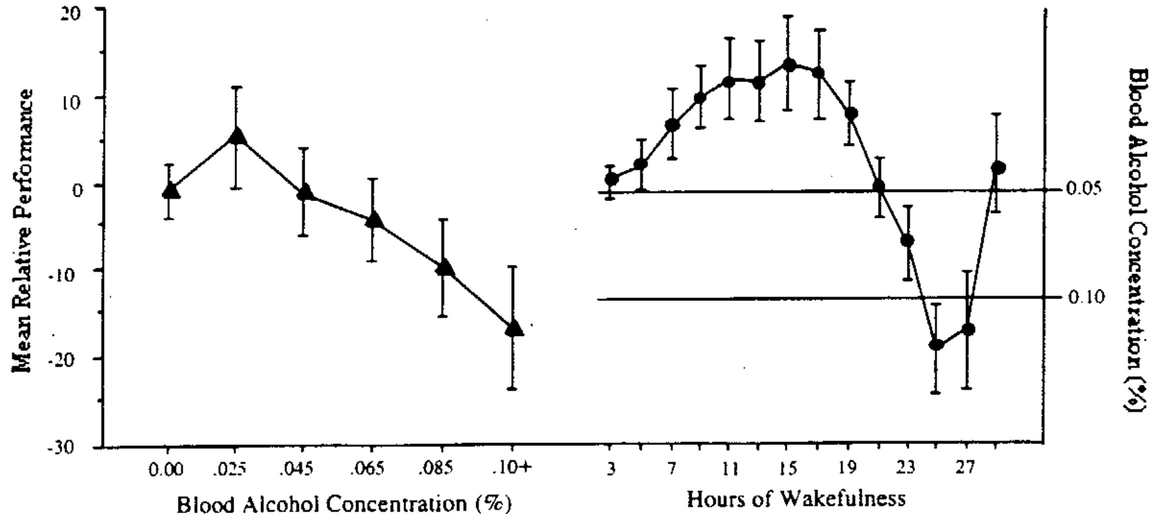

FIG. 5. Mean relative performance levels for the unpredictable tracking task in the alcohol intoxication (left) and sustained wakefulness condition. The equivalent performance decrement at a BAC of 0.05% and 0.10% are indicated on the right hand axis. Error bars indicate ± one s.e.m.

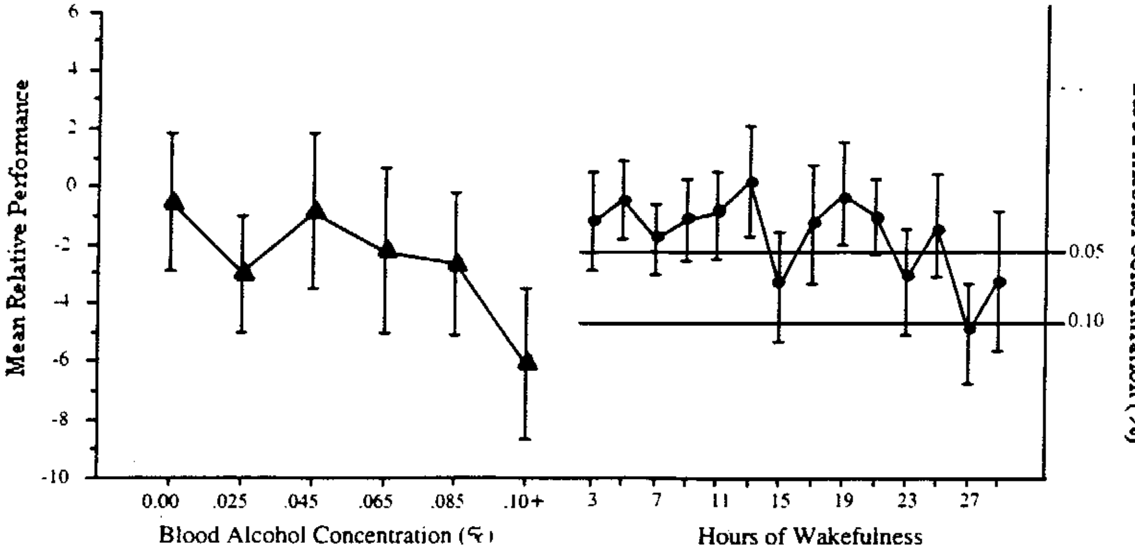

FIG. 6. Mean relative performance levels for the simple sensory comparison task in the alcohol intoxication (left) and sustained wakefulness condition. The equivalent performance decrement at a BAC of 0.05% and 0.10% are indicated on the right hand axis. Error bars indicate ± one s.e.m.