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Predicting drowsiness accidents from personal attributes, eye blinks and ongoing driving behaviour

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Abstract

26 participants drove at night for 135 min on a simulated two lane rural road with light traffic and filled out a battery of questionnaires. Six drivers left the road entirely and ten others left the pavement with one or two wheels. Drivers scoring high on an ‘‘extraversion-boredom’’ personality cluster were more likely to depart from the road due to falling asleep. Drivers scoring high on a ‘‘disinhibition-honesty’’ cluster were more likely to cross solid lane markings but did not seem to fall asleep. The best predicting measures for poor driving were the frequency of eye-closures exceeding 1 s and the number of times that time-to-line crossings were below 0.5 s. The participants' own judgements on susceptibility to drowsiness was a poor predictor. Dissociation of physiological and subjective measures was observed and explained by a two level information processing model. © 1999 Elsevier Science Ltd. All rights reserved.

1. Introduction

People gradually perform more poorly on tasks performed for extended periods of time at night and following loss or disturbance of sleep. Depending on the assumed causes, several terms have been used to refer to the cause of this performance deterioration. Poor performance has been attributed to drowsiness, sleepiness, fatigue and inattentiveness. Some have argued

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that drowsiness is a consequence of fatigue. Others noted that monotony may also cause drowsiness. For pragmatic reasons, we will stick to the term drowsiness to refer to the psychological and physiological state that leads to a deterioration of performance when driving for a long time, at night, in a monotonous environment.

There is a broad consensus that the conditions associated with drowsiness accidents in car driving are the time and duration of a drive, especially when monotonous (e.g. Knipling & Wang, 1994; Summala & Mikkola, 1994). Estimates of drowsiness-related accidents vary between 1.2–3.2% (USA: Knipling & Wang, 1995; NHTSA, 1996), 2.5% (UK: Maycock, 1995) and 8.4% (in France: Thomas & Attard, 1994). Drivers are usually aware of their drowsiness state and many have experienced driving in that condition. In a recent telephone survey of 1000 drivers in New York state (McCartt, Ribner, Pack & Hammer, 1995), 55% of the drivers reported having driven in a drowsy state in the last year, 23% of the drivers reported to have fallen asleep at the wheel at some time and 4.7% reported having had a crash due to falling asleep or being drowsy. In a survey in the UK, 29% of the interviewees had at least one experience of a serious drowsiness episode during the last year (Maycock, 1995). All in all, these figures demonstrate that there is a need to develop countermeasures for the occurrence of drowsiness accidents in road traffic (Hancock & Verwey, 1997).

One countermeasure is suggested by a recent simulator study that was similar to the present one (Verwey & Zaidel, 1999). This study demonstrated that alertness in drivers can be maintained in drowsiness inducing conditions by playing a demanding game. Artificial secondary tasks did not always show this effect. So, we argued that alertness can only be properly maintained if such a game is challenging and can be used at will. Yet, care should be taken that alertness maintenance systems do not distract drivers in more demanding driving situations. Another countermeasure against drowsiness induced accidents, that has received considerable empirical attention in recent years, is a system warning drivers if their behaviour shows signs of drowsiness (e.g. Dingus, Hardee & Wierwille, 1987; Khardi & Vallet, 1994; Wierwille, Ellsworth, Wreggit, Fairbanks & Kirn, 1994; Shimotani et al., 1996). Most of these studies tested the predictive value of certain types of behaviours for severe drowsiness rather than for the occurrence of actual accidents, the assumption being that severe drowsiness is a direct precursor of an accident. Drowsiness is usually determined from electroencephalogram (EEG) records or by judgements based on drivers' facial expression, especially with respect to the eyes. Predictor variables usually included vehicle performance measures related to the control of speed, steering and lateral position but sometimes measures of eye-lid closures were taken into account as well.

In the present study we attempted to relate such measures directly to critical driving events (road and lane departure errors in the context of a simulated drive) using drowsiness indicators as another predictor rather than as a proxy for an accident. We treated driving errors as a hierarchy from very serious and rare, to simple and common ones. Specifically, the following errors were distinguished: (a) leaving the pavement with all four wheels (*road departure error)*, (b) leaving the pavement with one or two wheels (*moderate lane crossing error*), (c) crossing the solid lane markings with one or two wheels (*minor lane crossing error*) and (d) crossing the solid lane marking within 0.5 s if no action is taken (time-to-line crossing or TLC < 0.5 s; Godthelp, Milgram & Blaauw, 1984). We considered the less serious and more common errors as possible predictors for the more serious ones.

Anecdotal and empirical evidence clearly demonstrates that there are large individual differences in drivers' susceptibility to becoming drowsy. In all experimental studies of drowsiness and fatigue there were drivers whose performance was greatly affected by the conditions of the study and others who were relatively little affected. For example, in a particularly demanding study (Artaud et al., 1994), 50% of the test drivers had episodes of falling asleep, but 50% did not and 20% did not even display any physiological signs of drowsiness. Monitoring 80 truck drivers during a week of their regular long haul trips revealed that 14% of the drivers accounted for more than half of the drowsy periods whereas 36% of the drivers did not show a single drowsy period (Wylie, Shultz, Miller, Mitler & Mackie, 1996).

These apparently large individual differences raise the question of what differentiates these drivers. Surprisingly, there has been little direct research on this issue despite the obvious implications for selection, training and scheduling of professional drivers. Vigilance research in laboratory situations, watch-keeping in operational settings and adaptation to night shift work indicated that the personality dimension of *extraversion-introversion* is most likely related to vigilance performance (Eysenck, 1967; Davies, Shackleton & Parasuraman, 1983). However, a meta-analysis showed that the over-all effect size (i.e. the correlation) was only about 7% and only for a subset of two extreme participant groups in a particular type of task the effect size was 29% (Koelega, 1992). Other personality constructs that seem to be related to vigilance performance are *boredom susceptibility* (Thackray, Bailey & Touchstone, 1977; Sawin & Scerbo, 1995), *evening versus morning types* (Moog & Hildebrandt, 1985), *locus of control* (Rotter, 1966; Sanders, Halcomb, Fray & Owens, 1976) and *sensation seeking* (Zuckerman, Kolin, Price & Zoob, 1964; Zuckerman, 1971). Smith (1981) argued that, in the case of driving, it is better to have people indicate directly how susceptible they are to effects of boredom and drowsiness but others doubt this (Itoi et al., 1993). There is little clarity as to how these various personality constructs relate to each other. Perhaps a combination of the scales predicts performance decrement best.

Drowsiness has been measured by subjective estimates and by physiological indicators such as the 0.1 Hz frequency component of heart rate variability (Mulder & Mulder-Hajonides van der Meulen, 1973; Mulder, 1980). Even though it was initially believed that information processing demands or workload during vigilance tasks are minimal, vigilance tasks are now considered effort demanding (see Hancock & Warm, 1989 for a review). Indeed, this is what subjective workload ratings show. The problem is that physiological measures dissociate from subjective measures because physiological measures suggest that mental effort reduces over time (e.g. Riemersma et al., 1977; Thackray et al., 1977; Egelund, 1982; Mascord & Heath, 1992).

A potential solution to this dissociation of subjective and physiological drowsiness measures comes from the notion that information processing involves two hierarchically ordered levels (Broadbent, 1971; Norman & Shallice, 1985). The hierarchically lower level processes would function in a reflexive, open-loop fashion and would mainly involve automatic processing. Processing at this level appears susceptible to sleepiness and noise (e.g. Heuer et al., 1998). The upper level ('executive') processes would control the lower level and act more flexibly, in closed loop fashion and is associated with controlled processing. These upper level processes would be less efficient early in the morning, in more extraverted people and would be more efficient if people get knowledge of results or if incentives are provided (Eysenck, 1982; Matthews, 1989).

The upper level processes would be capable of compensating for sleepiness effects on the lower level processes by exerting effort (Mulder, 1986), that is, by trying harder.

Our hypothesis is that physiological measures index the state of processes at the lower, automatic level whereas subjective drowsiness and workload measures indicate effort investment by the higher level processes. This notion nicely fits results from a study that assessed the merits of various types of workload measures under situations of high workload (Verwey & Veltman, 1996). Even though the various measures showed the same general effects of imposed visual and mental workload, factor analysis revealed that subjective measures and performance of secondary tasks were statistically independent from physiological workload measures. So, different mechanisms seem to underlie both groups of workload measures. While in high workload situations these measures usually converge, the two level hypothesis predicts that physiological and subjective measures of effort will dissociate under drowsiness inducing conditions.

In short, the present study assessed the extent that road departure and lane crossing errors in monotonous, long, night driving can be predicted from minor driving errors, from eye-closures and from drivers' personality and self ratings of susceptibility to drowsiness. The study also examined the agreement between subjective and physiological indices of mental effort and how they relate to drivers' personality and their driving performance in the simulator.

2. Method

2.1. Participants

People from the TNO participant database were selected for interviewing if they drove regularly and were 22 to 55 years old. If, in the interview, participants indicated that they drive less than 5000 km a year, had their driving licence for less than five years, or worked regularly in night shifts, they were screened out. The remaining 112 potential participants were classified in a low and a high drowsiness group on the basis of 13 questions dealing with matters like long driving at night, liking that kind of activity and tendency to get drowsy, tired, or sleepy during monotonous activities. 66 interviewees were classified as less susceptible to drowsiness and 46 as highly susceptible.

Given their availability during the period of the study, 13 drivers were randomly selected from each group (age: 25 to 49 years, mean age: 38 years, in possession of driver licence for an average of 17 years). There were 12 female and 14 male drivers. None used medication that could affect driving performance. Participants in the first shift were paid Dfl. 100 (about 45 £) for participation, those in the second shift, Dfl. 125 and those in the third shift Dfl. 150. One participant who got motion sick during the experiment was replaced. Participants were promised a bonus for safe driving which, in practice, everybody received.

2.2. Questionnaires

Participants filled out four types of questionnaires: personal information (name, age, sex, use of medicines, driving experience), standard personality questionnaires, driving behaviour

Table 1
Overview of the published questionnaires used in the present study

Name, reference	Scales (high-end scores are described)	Remarks
Amsterdam Biographic Questionnaire (ABV); Wilde (1970)	*extraversion*: social extraversion *neuroticism*: unadapted behavioural patterns and lability manifested in psycho-neurotic complaints *neurotic lability*: unadapted behavioural patterns and lability manifested in physical complaints *test attitude*: tendency to perform poorly ('lie-scale')	Dutch, validated
Spanningsbehoeftelijst (SBL; sensation seeking; Feij & van Zuilen, 1984)	*boredom susceptibility*: dislike of repetition of experience, restlessness when things are monotonous *disinhibition*: the desire to find release through social disinhibition (e.g. going to wild uninhibited parties) *thrill and adventure seeking*: the desire to engage in activities involving speed and danger *experience seeking*: seeking of new experiences through an unconventional, nonconforming life style (total = sensation seeking)	Dutch, validated
Pavlov's Temperament Scale (PTS); van Heck, Raad and Vingerhoets (1993)	*excitation*: ability to respond adequately under intense or prolonged situations *inhibition*: ability to perform without feedback *mobility*: ability to respond flexibly to new situations	Dutch, validated, tests stress susceptibility

(continued on next page)

Table 1 (*continued*)

Name, reference	Scales (high-end scores are described)	Remarks
Locus of control; Andriessen (1972)	*locus of control*: tendency to perceive events as caused more by luck, fate, or chance (as opposed to by one's own behaviour)	translated into Dutch from Rotter (1966), validated
Morningness/eveningness; Horne and Östberg (1976)	*morningness*	own translation
Epworth Daytime Sleepiness; Johns (1992)	*daytime sleepiness*	own translation
Driver error; Parker et al. (1995)	*lapses*: absent mindedness *violations*: deliberate contraventions of safe driving practice *errors*: misjudgements and failures of observation	own translation
Driver unrealistic optimism; DeJoy (1989)	*driver optimism*	own translation
NASA-Task Load Index (NASA-TLX); Hart and Staveland (1988)	*mental demands*: how much mental and perceptual activity was required? *physical demands*: how much physical activity was required? *temporal demands*: how much time pressure did one feel? *own performance*: how successful with accomplishing one's goals? *effort*: how hard did the person work to accomplish the goals? *frustration*: how insecure, discouraged, irritated, stressed and annoyed was the person?	this study: post-drive responses for first and last half hour of drive

related questionnaires and questions dealing specifically with the experimental variables and their effects on the drivers (Table 1).

2.3. Apparatus

2.3.1. Driving simulator

The experiment took place in the fixed base driving simulator at the TNO Human Factors Research Institute. The simulator included a Volvo 240 mock up, with force feedback on the steering wheel and realistic sounds of engine noise, wind, tyres and other vehicles. The outside scene was made up of three 1024×1024 pixel projections in full colour, on a curved screen in front of the car. The three BARCOGRAPHICS 800 projectors used a refresh rate of 60 Hz. From the driver's point of view, the visual angle of the image amounted to 120° horizontally and 30° vertically. There was no rear view. The experimenter monitored the inside of the car, the traffic scene and driver's face via video and communicated with the driver via an intercom.

2.3.2. Scenario

The roadway scenario was designed to be monotonous yet realistic enough to maintain ecological validity. The road was a two lane, 7.2 m wide road which had 0.20 m white road markings and 0.40 m pavement strips on either side and a 0.15 m centreline. Participants were told that the legal speed limit on this type of road was 80 kph. The road curved gently through a flat rural landscape and sight-distance was 800 m. Scenery was similar throughout the drive and included lane markings, kilometre posts (without numbers), scattered trees and shrubs and some outline of topographical features. Light conditions simulated an early dawn. Other vehicles had their lights on.

The scenario embedded events which required more attention from the drivers: There were five sharp curves per ten km road with solid centre-lines (radius 200–700 m), 14–16 oncoming cars per 15 min, 1–2 parked cars per 15 min which in passing required shifting to the left and 1–2 leading vehicles per 15 min driving 60 kph and requiring overtaking.

2.3.3. Data registration

Drivers' face and eyes were video-recorded during the drive with a small infra-red camera on the dashboard. Heart rate was measured with a standard procedure using electrodes and registered by a portable data acquisition system (VitaPort). Vehicle performance data were registered at 30 Hz and stored at 5 Hz; the heart rate signal was processed by the VitaPort at 100 Hz and registered at 30 Hz. A response box with seven marked buttons, indicating a drowsiness scale, was placed on the dashboard, to the right of the driver and in easy view and reach. A small light emitting diode (LED) inside the instrument panel lit for 10 s every 25–35 min instructing drivers to give a drowsiness rating.

2.4. Experimental design and data analysis

The basic experimental design was a type of driver (2: low versus high drowsiness) × shift (3) × block (9 periods of 15 min each) design, with type and shift as between-participant factors. The difficulty of staying awake was determined by time of driving (shift 1, 23.00–01.15; shift 2, 01.30–03.45 a.m.; shift 3, 04.00–06.15 a.m.). Circadian effects can be expected to have an influence but these were assumed to be largely in step and similar to the lack of sleep effect. Dependent variables were driving performance measures, driver drowsiness measures, blinking, eye-closure and self-rating of sleepiness on a seven key scale every 25–35 min, and driver mental effort. Subjective mental workload was assessed with the NASA-TLX scale. A physiological measure of mental effort was the 0.1 Hz spectrum component of the heart rate variability (Mulder, 1980; Aasman, Mulder & Mulder, 1987).

In the event of a driving error, it counted for only one error category, the most serious one, so that double-counts did not occur. Individual data records (in-vehicle subjective ratings, vehicle performance, heart rate and eye-closures) were truncated when the first road departure error occurred. Visual inspection of the video records confirmed that in most cases, performance following a road departure error only got worse, indicating that that error was not a chance occurrence. Data with binomial distributions, such as frequency data, were transformed logarithmically before subjecting them to analyses expecting normal distributions (ANOVAs, Pearson correlations, multiple regressions; e.g. Winer, Brown & Michels, 1991). Due to the exploratory character of this study, a large number of statistical tests was used and a significance level of 0.01 was adopted.

For quantitative analysis of eye behaviour, closures were marked only as 'closure' when longer than 1 s. Shorter ones were considered blinks. Sample-wise analyses of a couple of participants' data at low video tape speed indicated that the average time of a blink amounted to about 200 ms. The video analyst was ignorant about membership of individual participants to shift and type of driver groups. Due to missing data, caused by technical failure or not filling out all questionnaires, some analyses were based on fewer than 26 drivers.

2.5. Procedure

Before participating, drivers had a normal day of activity without sleep. Coffee and alcohol were not allowed after 18.00. Participants in the first shift were brought by taxi to the institute at 22.00, those participating in later shifts arrived by taxi at midnight. Upon arrival, they filled out consent forms and questionnaires. They waited in a special area, provided with radio, television, videocassette recorder and video tapes, magazines and soft drinks. To prevent drowsiness due to low blood-glucose levels, light snacks were available as well. The experimenter frequently checked that waiting participants did not fall asleep. None did.

After being fitted with the physiological sensors, participants were instructed about the use of the simulator car, the location and use of the alertness/sleepiness rating box and the nature of the task. They were asked to drive safely, the way they would normally do. Participants then practised a couple of minutes in the simulator until they indicated that they were ready and felt comfortable driving the simulator. At the conclusion of the driving session, each participant filled out a post-drive questionnaire and was taken home by taxi.

3. Results

3.1. Effects on individual dependent variables

The pre-drive questionnaires showed that 46% (12) of the participants had experience with "almost falling asleep at the wheel" and 12% (3) indicated to have had an accident due to drowsiness.

Most measures of drowsiness were affected in the expected direction by shift, time on task and type of participant but this was not always statistically significant. Time on task had significant effects in the expected direction on all subjective ratings and physiological measures. The effects of shift and type of participant were also in the expected direction but the effect of shift was significant for only blink and eye-closure frequencies. Type of driver had a significant effect on eye-closure percentage only.

Table 2 presents the occurrence and timing of road departure errors, moderate and minor lane crossing errors and the numbers and proportions of drivers involved in these unsafe events. 42% of the drivers (11 out 26) succeeded in finishing the arduous task without any critical event. Almost all road departure and lane crossing errors occurred during the second half of the drive. Despite the fact that each participant encountered about 160 vehicles, there was not a single collision.

After the drive a total of 17 drivers reported to have experienced one or more instances of falling asleep. Of these, nine had a moderate lane crossing error and five a road departure error. Still, eight of these drivers did not even have moderate lane crossings and twelve did not have road departure errors. Of those who did not experience falling asleep at the wheel, none had road departure errors or lane crossing errors. Road departure errors occurred more often

Table 2
Overview of the occurrence of road departure errors and moderate and minor lane crossing errors

Measure	value
Number of drivers with a road departure error	6 (=23%)
Mean time to road departure error	87 (25)[a] min
Number of drivers with a moderate lane crossing error	10 (=38%)
Moderate lane crossing errors per driver in the group of drivers with such errors	4.6
Mean time to first moderate lane crossing error	83 (32) min
Number of drivers with minor lane crossing errors	11 (=42%)
Minor lane crossing errors per driver in the group of drivers with such errors	3.9
Mean time to first minor lane crossing	64 (36) min
Number of drivers with any event	15 (=58%)
Total number of events (road departure errors, moderate and minor lane crossing errors)	81
Mean number of events per driver	3.2[b]

[a] Bracketed numbers are standard deviations.
[b] Some values are based on 25 drivers.

in later shifts (0, 2 and 4, respectively) and with high drowsiness type drivers (2 versus 4) but these figures are too small for statistical evaluation. The log-linear test of lane crossings revealed a shift effect [4, 13 and 31, respectively, $\chi^2(2, N = 48) = 22.8$, $p < 0.001$].

To determine the sensitivity of the various individual dependent measures to drowsiness, group × period interactions were tested. Group differentiates between drivers with and without road departure or moderate lane crossing errors. Period distinguishes between dependent measures registered in an early period (9–15 min after start of the drive) and in a late period (for those without driving errors 83–89 min and for those with errors, the averages during the 6 min periods preceding those errors[2]). With a view for practical application and in line with Wierwille et al.'s (1994) choice we chose a 6 min period prior to road departure and moderate lane crossing errors as the interval to detect any deviation from safe driving. Very close to the event we might actually be dealing with the event's beginning; too long an interval before might not be relevant anymore to the specific event.

Significant group by period interactions were found for frequency of minor lane crossing errors [$\chi^2(1, N = 20) = 4.8$, $p < 0.05$], TLC < 0.05 s frequencies [$\chi^2(1, N = 91) = 4.1$, $p < 0.05$], the 0.1 Hz heart rate component [$F(1, 22) = 9.8$, $p < 0.01$], eye-closure frequency [$\chi^2(1, N = 41) = 18.1$, $p < 0.001$] and eye-closure percentage [$F(1,24) = 27.9$, $p < 0.001$]. All in all, these results suggest that there are enough individual differences and effects of the independent variables to investigate the extent that poor driving can be predicted from personality characteristics and subjective, physiological and performance variables.

3.2. Predicting driving behaviour from personality characteristics

For the categorical variable road departure error, the predictive value of the independent variables was determined by forward stepwise discriminant analysis. The predictive value of lane crossing errors and TLC < 0.5 s frequencies were assessed by forward stepwise multiple regression analyses. Table 3 presents the best three predictors for each of the main driving performance variables. For each predictor variable the weight in the regression function for the given dependent measure is shown.

On the basis of the discriminant function in Table 3, 85 % (20) of the 26 participants were classified correctly with respect to road departure errors predicting four out of the six road departure errors. The driver error (incl. the lapses of attention scale) and driver unrealistic optimism questionnaires are not true personality tests in that they are limited in scope to driving situations. Also, the Dutch versions have not been standardised. Their predictive value (especially of the driver error questionnaire) is perhaps so good in the present context because they specifically deal with driving and tap not only attitudes but also past experiences of driving which reflect, in part, the respondent's habitual behaviour.

How did our participants' pre-experimental estimates of their own susceptibility to drowsiness relate to their actual performance? Across all participants, correlations with road departure errors, lane crossing errors and TLC < 0.5 s frequencies amounted to 0.23, −0.10

[2] The 83–89 min period was used for drivers without errors because, with drivers having errors, the average driving error occurred after 89 min.

Table 3
Summary of discriminant and regression functions for predicting poor driving performance from personality variables

Predicted variable	Predictor 1	$\beta_1{}^{a}/\lambda_{\text{partial 1}}$	Predictor 2	$\beta_2/\lambda_{\text{partial 2}}$	Predictor 3	$\beta_3/\lambda_{\text{partial 3}}$	Model reliability
Occurrence of a road departure error	sensation seeking (SBL)	0.74	locus of control	0.85	lapses (driver error *Q*)	0.86	$\lambda_w = 0.66^{b}$, $p < 0.03$
Lane crossing error frequency	driver unrealistic optimism	0.53	lapses (driver error *Q*)	0.48	extraversion (ABV)	0.46	$R = 0.56$, $p < 0.06$
TLC < 0.5 s frequency	errors (driver error *Q*)	0.50	neuroticism (ABV)	0.25	boredom (SBL)	0.21	$R = 0.56$, $p < 0.05$

[a] Greater β (weight in multiple regression analyses) and smaller λ_{partial} (weight in discriminant analyses) indicate greater contributions of the predictors.
[b] λ_W (Wilks' lambda) is the ordinal equivalent of the multiple correlation coefficient *R*.

Table 4
Predicting road departure and lane crossing errors (minor and moderate) from behaviour in the six minutes before the event

Predicted variable	Predictor 1	$\beta_1/\lambda_{\text{partial 1}}$	Predictor 2	$\beta_2/\lambda_{\text{partial 2}}$	Predictor 3	$\beta_3/\lambda_{\text{partial 3}}$	Model reliability
Road departure error	eyes closed %	0.62	TLC < 0.5 s frequency	0.44	moderate lane crossing error frequency	0.40	$\lambda_w = 0.35$, $p < 0.001$
Lane crossing error frequency	TLC < 0.5 s frequency	0.66	eye-closure frequency	0.29	standard deviation of lane position	0.23	$R = 0.80$, $p < 0.001$
TLC < 0.5 s frequency	eyes closed %	0.36	lane position	0.28			$R = 0.54$, $p < 0.05$

Table 5
Predicting road departure and lane crossing errors (minor and moderate) from all available predictor variables

Predicted variable	Predictor 1	$\beta_1/\lambda_{\text{partial 1}}$	Predictor 2	$\beta_2/\lambda_{\text{partial 2}}$	Predictor 3	$\beta_3/\lambda_{\text{partial 3}}$	Model reliability
Road departure error	TLC < 0.5 s frequency	0.60	locus of control	0.87	eyes closed %	0.90	$\lambda_w = 0.46$, $p < 0.001$
Lane crossing error frequency	TLC < 0.5 s frequency	0.49	eye-closure freq.	0.38	sensation seeking	0.37	$R = 0.78$, $p < 0.001$
TLC < 0.5 s frequency	errors (driver error Q.)	0.52	lane position	0.45	eyes closed %	0.33	$R = 0.75$, $p < 0.01$

and 0.02 ($ps > 0.10$). Within individual shifts these correlations were not very different. Morningness did not show significant correlations with the above three performance measures either. In our sample, drivers' prior self ratings in terms of sleep and drowsiness characteristics do not appear to say too much about their actual performance.

Extraversion, the most promising personality characteristic, showed a modest correlation with performance; extraverted people had more road departure errors ($r = 0.28$, $p > 0.15$). This correlation matches the one reported by Koelega (1992) for a homogeneous subsample of studies ($r = 0.29$) which was higher than the overall correlation (0.07) he reported. After completion of the drive, extraverted participants stated to have fallen asleep more often ($r = 0.46$, $p < 0.05$) and stated to have crossed the edge-line more often ($r = 0.40$, $p < 0.05$) than introverted participants, but this was not reflected in their actual driving performance; correlations between extraversion and actual lane crossing errors and TLC < 0.5 s events were virtually negligible (rs < 0.20).

3.3. Predicting driving behaviour from earlier driver behaviour

Road departure errors were predicted best by eye-closure percentage, frequency of TLC < 0.5 s events and the number of earlier moderate lane crossing errors (Table 4). The best predictors of lane crossing errors were frequency of TLC < 0.5 s events, eye-closure frequency and the standard deviation of the lane position. Finally, TLC < 0.5 s events could be predicted from a limited number of variables only (i.e. lane position, S.D. of lane position, steering frequency and eye lid closure data). The multiple regression analysis showed that the set of best predictors consisted of only two variables: eye-closure percentage and average lane position. The positive sign of the lane position weight in the equation indicates that the car drove more to the right hand side of the road prior to a TLC < 0.5 s event. In general, Table 4 demonstrates that both actual behaviour of the vehicle and eye closing measures (but not blink rate) can be used as predictors for imminent moderate lane crossing errors and road departure errors.

3.4. Relative contributions of personal and behavioural variables to predictions

To assess the relative importance of the various personality and behavioural variables, all available predictor variables were included in a discriminant and a multiple regression analysis. The results are presented in Table 5 and show that performance variables, eye-closure measures and personality attributes all contribute significantly to prediction of poor driving, with TLC < 0.5 s frequency being the most important predictor for severe driving errors. The discriminant equation in Table 5 classified 88 % (22) of the 26 participants correctly with respect to whether or not they had a road departure error. It predicted four out of the six road departure errors.

We are aware that, given the limited number of participants and the great number of variables in this study, these results should be interpreted with caution and can be considered speculative only. The main value of these results lies in the demonstration that observable driving behaviour, eye-closures and personality attributes all contribute to the prediction of road departure and lane crossing errors.

3.5. Underlying personality components

The discriminant and multiple regression analyses on personality variables (Table 3) showed that different personality constructs predicted different types of driving errors. To explore this further a principal components analysis was performed on the questionnaire data, which was followed by a varimax rotation. The eigenvalues of the first six components in the principal component analysis amounted to 5.2, 3.7, 2.2, 1.9, 1.5 and 1.4, suggesting a levelling off after the third eigenvalue and, hence, that three components underlie the personality constructs in our questionnaires. These components are presented in the upper half of Table 6 and can be characterised as *disinhibition-honesty*, *extraversion-boredom* and *optimism-stability*.

Validity of these three dimensions is suggested by similar findings in the literature on much bigger participant samples. The extraversion-boredom and optimism-stability components are related to extraversion–introversion and neuroticism–stability described by Eysenck (1983). The finding of a component including sensation seeking and time of going to bed is in line with the observation that sensation seekers say they have less need for sleep (Feij et al., 1985). Together, the three components explained 46% of the variance in our questionnaire data.

Given these three underlying personality components, the lower half of Table 6 indicates that road departure errors, lane crossing errors and small TLCs load on different components. Drivers who scored high on the disinhibition-honesty component had somewhat more lane crossing errors in the experiment but they did not differ from others in road departure probability. They also had relatively few eye-closures which is in line with the finding that sensation seekers would need little sleep. This suggests that the lane crossing errors found with these people were not necessarily associated with drowsiness. They might reflect a tendency of disinhibited drivers to explore the limits of the driving simulation.

Drivers scoring high on extraversion-boredom were indeed those who were most likely to depart from the road in the experiment. They also showed an increase in the 0.1 Hz component suggesting that they were really becoming drowsy. Yet, this was not accompanied by more eye-closures.

Finally, drivers who scored high on the optimism-stability component stated they invested relatively little effort and did not feel very sleepy. They had few TLC < 0.5 s events but did not differ from others in the frequency of road departures or lane crossings. It seems that these people differed from the other drivers by their attitude towards the experiment or towards driving in general, rather than in actual drowsiness.

While cautioning again for the preliminary nature of a principal component analysis on such a small number of participants, these results seem to offer an important explanation for individual differences in vigilance performance in terms of three underlying personality characteristics. Disinhibited drivers had more moderate and minor lane crossing errors and, consequently, seem more likely to test the limits of their task. Extraverted-bored people were more likely to fall asleep and have road departure errors. Drivers who had a stable and optimistic attitude rated subjective effort and sleepiness low, but they were no different with respect to their driving errors. It should be remembered that, although these three components describe independent aspects of personality, in reality they exist, in different degrees, in each person simultaneously. Future studies on driver drowsiness might consider using participants scoring high on extraversion and low on social disinhibition.

Table 6
Principal components of the questionnaire results and the most important loadings of performance variables on these components

	Component 1: *disinhibition-honesty*	Component 2: *extraversion-boredom*	Component 3: *optimism-stability*
Explained variance (for questionnaire results)	19%	16%	11%
	violations (driver error questionnaire) 0.80	mobility (PTS) 0.77	driver optimism 0.73
	social disinhibition (SBL) 0.75	extraversion (ABV) 0.63	errors (driver error questionnaire) –0.69
	max. driving time at day 0.75	boredom (SBL) 0.63	lapses (driver error questionnaire) –0.65
	test attitude (ABV) –0.64	experience seeking (SBL) 0.60	inhibition (PTS) 0.52
	time to bed. 061	education 0.60	neuroticism (ABV) –0.51
	sensation seeking (SBL) 0.59	locus of control 0.56	
Measured behaviour			
Road departure error	0.10	0.40	0.05
Lane crossing error frequency	0.23	0.04	−0.06
TLC < 0.5 s frequency	0.08	0.07	−0.43
Eye-closure frequency	−0.29	−0.05	0.08
Eyes closed %	−0.30	0.00	−0.12
Sleepiness rating (4th)	−0.17	0.09	−0.45
Subjective effort (TLX)	−0.03	−0.08	−0.62
0.1 Hz component	0.22	0.26	0.03

Table 7
Independent components underlying physiological and subjective drowsiness measures (upper half of the table) and loadings of some personality and performance variables that are associated with these components (lower half of the table)

	Component 1 (indicating upper process)	Component 2 (indicating lower process)
Explained variance (basic model)	52%	30%
0.1 Hz component	−0.02	0.92
Subjective effort (TLX)	0.90	0.17
Subjective workload (TLX)	0.92	−0.02
Sleepiness (4th rating)	0.85	0.32
Eyes closed %	0.51	0.71
Eye-closure freq.	0.70	0.54
Loadings of other variables in basic model		
Extraversion	0.00	0.64
Age	−0.06	−0.77
Morningness	−0.03	0.73
Neurotic lability	0.10	−0.70
Lapses	0.47	0.11

3.6. Testing the two level processing model

In line with the two level processing model of information processing described in the introduction, the correlation coefficient between subjective and physiological effort indicators (i.e. 0.1 Hz and TLX-effort scale) across participants was essentially zero ($r = 0.07$). This suggests that these indicators changed in the same direction for some and in opposite directions for other participants. The two level processing model implies that physiological and subjective measures are associated with independent processing levels. This was confirmed by a principal component analysis on the physiological and subjective effort and drowsiness variables (see upper part of Table 7). Sleepiness estimates, subjective workload and subjective effort appear to be determined by one mechanism and the 0.1 Hz component and eye-closure percentage, by another one.

Subsequently, the locations of the personality and behavioural variables in the two dimensional component space were determined to find out which variables were related with each hypothesised mechanism. The lower part of Table 7 shows that the component that probably reflects the state of the lower mechanism, is associated with extraverted, young, morning types and with people with few neurotic-physical complaints. Lapses of attention seem more related to the upper, control process. Other variables, including our major performance measures and the participants' drowsiness susceptibility estimates, did not load specifically on one or the other component. They, probably, result from an interplay between processes associated with both components. This is not surprising for a task that can probably be controlled from both levels.

4. Discussion

Initial analyses indicated that the present study was suited for predicting poor driving as caused by drowsiness. Our participants had about as much experience with drowsiness in driving as reported in other studies and most dependent measures were affected in the expected directions. Finally, the number of road departure errors and critical driving errors seemed sufficient to assess the predictive value of various variables.

4.1. Predicting poor driving

When drivers are drowsy, a lane crossing event appears a strong indication that a road departure error is not far away. This finding agrees well with common experience. Another common experience supported by our findings, is that long eye-closure and inaccurate steering are good predictors of subsequent moderate and minor lane crossing errors. The frequency of TLC $<$ 0.5 s events, which is a higher order measure of swerving, appeared to capture the essence of degraded driving performance better than the more traditional measures of steering, speed, lane position and standard deviation of lane position.

As expected, people scoring high on extraversion had more road departure errors. The effect was limited ($r = 0.28$) but comparable to the one reported by Koelega (1992) for his best subset of vigilance studies. People scoring high on boredom and who had an external locus of control also had more road departure errors ($r = 0.32$ and 0.36, respectively), suggesting that these personality characteristics have predictive value for vigilance performance in the driving environment too.

Discriminant and multiple regression analyses showed that the occurrence of road departure and lane crossing errors is more likely for people with a certain personality, but different personality constructs were associated with the three types of driving errors. Initially, this finding disturbed us. However, a principal components analysis suggested a possible interpretation. It suggested that the various personality scales are representations of three underlying components: disinhibition-honesty, extraversion-boredom and optimism-stability, the validity of which is indicated by other reports (Smith, 1981; Eysenck, 1983; Feij et al., 1985; Sawin & Scerbo, 1995). This three component model suggests why different personality scales were associated with the three different driving errors (Table 6). Extraverted-bored people seem to be more likely to fall asleep, whereas disinhibited-honest people seem more likely to show erratic (‘risky’ is barely an appropriate term for a simulator) behaviour without being drowsy (in fact they had fewer eye-closures than others). They were probably more bored and did not feel inhibited to explore the possibilities of the driving simulator. To our knowledge, this is the first study indicating that poor performance in vigilance studies may also be due to people being bored, rather than being drowsy. Finally, some people showed a positive attitude towards driving but they did not differ in driving performance.

Important with respect to the prediction of poor driving in prolonged driving situations at night, is that the three types of dependent variables (performance, personality and eye-closures), appeared about equally important for predicting poor driving performance. In contrast, neither the drivers’ own pre-experimental estimation of their susceptibility to drowsiness while driving at night, nor the time of driving (i.e. shift) predicted poor performance well. These variables did not appear in any of the discriminant and multiple regression analyses and the correlations with actual driving performance were not significant. Three participants (12%) even claimed they could drive safely for 3 h or more, but in the experiment they ended up with a road departure error. Ratings of drowsiness during the drive may have indicated drivers' subjective feeling at the time, but these ratings, too, did not have much predictive value.

So, an in-vehicle driver impairment monitoring system should certainly have to monitor actual vehicle performance measures and drivers' eye-closure behaviour. It would also benefit from knowledge about the personality of the current driver. For introverted drivers the system should be less tolerant with respect to crossing solid lane markings whereas for socially disinhibited drivers, it should be less tolerant with respect to eye-closure percentage.

How knowledge about drivers' personality could be obtained, in practice, is not yet clear. A car key in the form of a smart-card might provide the system with such information once the driver has carried out personality tests. The present results could also be applied in the selection and scheduling of professional drivers. They suggest that professional drivers should preferably be introverted and not be bored easily, so that they will resist drowsiness better, and be socially inhibited and not seeking sensation, so that they will not demonstrate exploratory and, perhaps, risky behaviour in boring conditions.

4.2. Assessing mental effort in vigilance tasks

In line with earlier research, subjective indications of mental effort increased over time while the 0.1 Hz component suggested a gradual reduction in mental effort, especially just prior to moderate lane crossing errors. In line with the hypothesis that physiological and subjective measures are determined at different levels of information processing, our analyses showed that, across participants, the physiological and subjective 'effort' indicators were statistically independent ($r = 0.07$). A principal component analysis confirmed that subjective effort, drowsiness and workload estimates make up one component and that 0.1 Hz and eye-closure percentage make up another. This is an 'individual differences' confirmation of the two level processing model described in the introduction and confirms a similar independence as found by Verwey and Veltman (1996) in high workload situations.

So, in vigilance tasks, subjective estimates of effort, drowsiness and workload seem to be based on the state of the upper, executive processes. Absent mindedness, as measured by the traffic oriented "lapses of attention scale", probably is a property of this level. Lower level processes, which are responsible for the execution of more or less automatic behavioural patterns, seem to determine the physiological effort and drowsiness parameters (0.1 Hz and eye-closure percentage). Fitting personality measures into this model indicated that in prolonged task performance especially extraverted, young people who are morning types and have few neurotic-physical complaints are likely to fall prey to inefficiency of lower level processes in prolonged task performance. Yet, even these people seem to be capable of compensating for inefficient lower processes for short periods as none of the participants hit another car.

These results endorse behavioural and neuropsychological models that assume that familiar behavioural patterns are controlled by both conscious and attention demanding processes and unconscious, automatic processes (e.g. Rasmussen, 1983; Michon, 1985; Willingham, 1998). People seem to differ in the ability to perform over long periods of time in relatively simple, automated perceptual-motor tasks and in the control they exert over lower level processes. Moreover, personality might affect the amount of effort one uses for maintaining performance.

5. Conclusions

While cautioning the reader that this study is exploratory because of the large number of dependent variables and the limited number of participants, it does present a coherent picture of the relationships between several behavioural and personality variables and vigilant driving performance. The results confirm that prediction of road departure errors and moderate and minor lane crossing errors is possible and show that a driver monitoring system should integrate information about drivers' personality with on-line data about the drivers' eye-closures and vehicle control performance. Measurement of personality profiles is a cumbersome job but, once measured, usage of a smart card-based car key might solve the problem of data provision. Individual and societal acceptance of such a scheme is, of course, a different matter. From a methodological point of view, the present results hold a warning for those investigating vigilance performance in that participants scoring high on disinhibition and sensation seeking scales seem more likely to ignore their instructions without being sleepy.

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