J. Sleep Res. (2006) **15**, 47–53

Subjective sleepiness, simulated driving performance and blink duration: examining individual differences

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Accepted in revised form 21 November 2005; received 15 March 2005

SUMMARY The present study aimed to provide subject-specific estimates of the relation between subjective sleepiness measured with the Karolinska Sleepiness Scale (KSS) and blink duration (BLINKD) and lane drifting calculated as the standard deviation of the lateral position (SDLAT) in a high-fidelity moving base driving simulator. Five male and five female shift workers were recruited to participate in a 2-h drive (08:00–10:00 hours) after a normal night sleep and after working a night shift. Subjective sleepiness was rated on the KSS in 5-min intervals during the drive, electro-occulogram (EOG) was measured continuously to calculate BLINKD, and SDLAT was collected from the simulator. A mixed model ANOVA showed a significant ($P < 0.001$) effect of the KSS for both dependent variables. A test for a quadratic trend suggests a curvilinear effect with a steeper increase at high KSS levels for both SDLAT ($P < 0.001$) and BLINKD ($P = 0.003$). Large individual differences were observed for the intercept ($P < 0.001$), suggesting that subjects differed in their overall driving performance and blink duration independent of sleepiness levels. The results have implications for any application that needs prediction at the subject level (e.g. driver fatigue warning systems) as well as for research design and the interpretation of group average data.

KEYWORDS lane drifting, mixed models, standard deviation of lateral position

INTRODUCTION

It is well known that prolonged wakefulness, partial sleep deprivation and high sleepiness levels have negative effects on many performance measures (Rogers *et al.*, 2003). Sleepiness has also been identified as a major risk factor for road accidents (Dinges, 1995). Even though subjective sleepiness has shown high intra-individual correlations with electroencephalogram indicators of sleep (Åkerstedt and Gillberg, 1990; Cajochen *et al.*, 1999; Horne and Baulk, 2004; Torsvall and Åkerstedt, 1987) and subjective sleepiness has been found to predict performance (Dorrian *et al.*, 2000; Gillberg *et al.*, 1994), it has been pointed out that subjective sleepiness is far from perfect in predicting performance (Rogers and Dinges, 2003).

Contextual factors might explain why subjective sleepiness sometimes shows a weak association with performance. Yang *et al.* (2004) found that an instruction to calm down with eyes closed for 1 min substantially increased the correlations between subjective sleepiness and performance. Another cause of weak associations could be individual differences that complicate the relation between sleepiness and performance. Recent studies have reported large individual differences on both 'objective' performance measures and subjective sleepiness ratings during sleep loss (Van Dongen *et al.*, 2003, 2004). Thus, there is a need for further studies of subjective sleepiness in relation to performance and physiology under well-controlled conditions with individual differences accounted for. This paper presents such a study focused on two variables with well-established sensitivity to sleepiness.

One of these variables is eye blink duration (Stern *et al.*, 1984). Increased subjective sleepiness on the Karolinska Sleepiness Scale (KSS) has been related to increased amounts of slow eye movements (Åkerstedt and Gillberg, 1990) and higher

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levels of sleepiness on a visual analogue scale has been related to longer eye blink durations (Caffier *et al*., 2003). None of these studies provided any direct estimates of individual differences.

Lane drifting while driving a vehicle is an established indicator of sleepiness related performance (O'Hanlon and Kelly, 1974). It can be calculated as the standard deviation (SD) of the lateral position of the vehicle, which has been shown to be a very sensitive measure of performance decrements after treatment with hypnotics and anti-depressant drugs (O'Hanlon, 1984). The SD of the lateral position has also been used to assess decrements in driving performance after prolonged wakefulness and alcohol intake in a driving simulator (Arnedt *et al*., 2000, 2001). None of these studies provided any information about individual differences; however, O'Hanlon and Kelley (1977, p. 88) reported large individual differences in an early study on lane drifting and sleepiness: 'However, we were impressed at the time by the wide range of individual differences with respect to changes in both performance and physiology as a function of time on the road: Some drivers never appeared to tire, whereas others behaved in a progressively more erratic manner, and a few lost control within a relatively short time span…'.

Other researchers have also recognized the presence of individual differences. For example, Hanowski *et al.* (2003) reported that 5% of the subjects accounted for 26% of the incidents in a study of truck drivers. Similarly, Mitler *et al.* (1997) reported that 10% of the drivers accounted for 54% of the video-recorded segments of drowsiness. Moreover, M. Ingre *et al.* (unpublished data) found large individual differences in accident propensity, independent of sleepiness levels, by applying a Generalized Linear Mixed Model approach on accident data recorded in the present study.

In the presence of individual differences, group average estimates, which dominate the literature, may lead to inaccurate conclusions if they are used to infer effects in individual subjects (i.e. the 'ecological fallacy'). When large individual differences are expected, researchers have to be very careful when interpreting group average data, or apply statistical methods that explicitly estimate the effects at the subject level so that individual differences may be evaluated and described. The present study takes the latter approach.

In a recent paper from the same study, Åkerstedt *et al.* (2005) reported increased subjective sleepiness levels, longer blink durations and increased lane drifting with increased driving time and after working a night shift. The main objective of the present study was to estimate the direct association between subjective sleepiness measured with the KSS on the one hand and blink duration and lane drifting on the other with special focus on individual differences. A linear mixed model approach was used to provide subject-specific estimates to evaluate individual differences.

METHOD

The overall design of the study was a within-subject experimental design with two conditions: a 'Night sleep' condition when subjects had a normal night sleep and a 'Night work' condition when the subjects had stayed up all night working. In both conditions, subjects drove in a high-fidelity (HI-FI) car simulator between 08:00 and 10:00 hours. The subjects participated in the two conditions in a counter-balanced order with at least 3 days between conditions.

Five male and five female shift workers were recruited through advertisements in local companies with night work. Most came from hospitals, newspapers and an energy plant. They had a mean age of 37 years (SD = 12), drove annually an average of 9500 km (SD = 6800) and had 5–9 years of experience as shift workers. Three participants worked only at night while the rest alternated between night and day work. They received a monetary compensation of approximately €110. The study was carried out by the Swedish National Road and Transport Research Institute, under their study guidelines, including the Declaration of Helsinki.

The subjects were instructed to maintain their normal/work sleep pattern and behaviour in connection with night and day work during experiment. Before the study proper, the subjects had a practice drive in the simulator for 20 min and practice at using the rating scale (described below), which had been sent out beforehand. They arrived at approximately 07:00–07:30 hours, directly after night work or rising respectively. After the drive the subjects were debriefed and sent home. In the Night work condition the drivers were brought to and from the test centre by a taxi.

A dynamic, HI-FI, moving base driving simulator was used. The car cab was a Volvo 850 (Volvo AB, Gothenburg, Sweden) and the system simulated acceleration in three dimensions through roll, pitch and linear lateral motion. The visual system presented the scenario on a 120° wide screen 2.5 m in front of the driver. The sound system generated noise and infrasound that resembles the internal environment in a modern passenger car. The vibration system simulated the sensations the driver experiences from the contact between the road surface and the vehicle. The driving scenario was a rural two-lane road with lanes 3.6 m wide with a 0.5 m hard shoulder. The conditions were 'summer' with a slightly hazy sky. The signed speed limit was 90 km h^{-1} and there was sparse oncoming traffic or cars to follow or pass.

The measures obtained from the system included speed (mean + variability), lateral position (mean + variability), time to Line Crossing, steering wheel angle (mean + variability). Driving behaviour was recorded at a frequency of 12.5 Hz. In the present study, the standard deviation of the lateral position (SDLAT) was selected as previous studies suggested that this may be the most sleepiness sensitive continuous performance measure (O'Hanlon and Kelly, 1974; Arnedt *et al*., 2000).

To calculate blink durations (BLINKD), the EOG was also recorded by means of a Vitaport recorder (TEMEC Instruments, B.V., Kerkrade, The Netherlands) using horizontal and vertical derivations above and below the right eye. Data were collected with a sampling rate of 128 Hz and a band pass filter set at 0.3–25 Hz. Raw data were analysed with a modified

MATLAB program developed by the Centre for Applied and Environmental Physiology (Dr A Muzet, CEPA, Strassbourg, France). It essentially involves using a low-pass filter to establish a stable baseline for the signal, finding a threshold that has to be exceeded to define a blink (done visually). The definition of the start/end of the blink is based on slope and the measurement of blink duration is carried out at mid-slope. To reduce problems with concurrence of eye movements and eye blinks, blink durations were calculated by finding the half amplitude of the upswing and downswing of each blink and computing the time elapsed between the two.

Sleepiness was rated every 5 min prompted by an instruction displayed on the windshield, with the response given orally, using the scale pasted to the steering wheel. This yielded a total of 48 measures for an individual for the two conditions. The scale used was the KSS ranging 1–9 where 1 = very alert, 3 = alert, 5 = neither sleepy nor alert, 7 = sleepy but no effort to remain awake, and 9 = very sleepy, fighting sleep, difficulty staying awake (Åkerstedt and Gillberg, 1990). The scale was modified to have labels on all nine steps (Reyner and Horne, 1998) and subjects were also allowed to rate intermediate steps with half points yielding a highest possible rating of 9.5; however, only the integer part was used in the analyses. The modifications of the scale were motivated by a high-rating frequency in a highly controlled environment where the subjects had continuous access to the scale at the steering wheel.

Data were analysed with mixed effects regression analysis by means of restricted maximum likelihood estimation using the Stata procedure xtmixed (StataCorp, 2003). The fixed effect estimates were modelled as an ANOVA structure with a nine-level factor variable for the KSS (1–9). The KSS was used to predict the mean level of the dependent variable in the subsequent 5-min segment. A random intercept was included in the model to account for individual differences in the overall level of the dependent variable. A second random effect was modelled for the factor of the KSS with a single variance component and zero covariance between levels, to account for level-specific individual differences. The significance of the fixed effect estimates was tested by means of a Wald test and the significance of the random effects was tested by means of a likelihood ratio test.

RESULT

In the Night sleep condition the subjects rose at 06:51 hours ± 13 min (mean ± SEM) and slept for 7.6 ± 0.32 h. In the Night shift condition the subjects finished work around 07:25 hours ± 17 min in the morning and obtained 2.2 ± 0.8 h of sleep, mainly during the prior morning or afternoon.

From descriptive data presented in Fig. 1 it is evident that all subjects reached high levels of sleepiness as indicated by the KSS. The figure also shows large individual differences in all three variables measured in the present study.

The results from the estimated model with SDLAT as the dependent variable are presented in Table 1 and show that

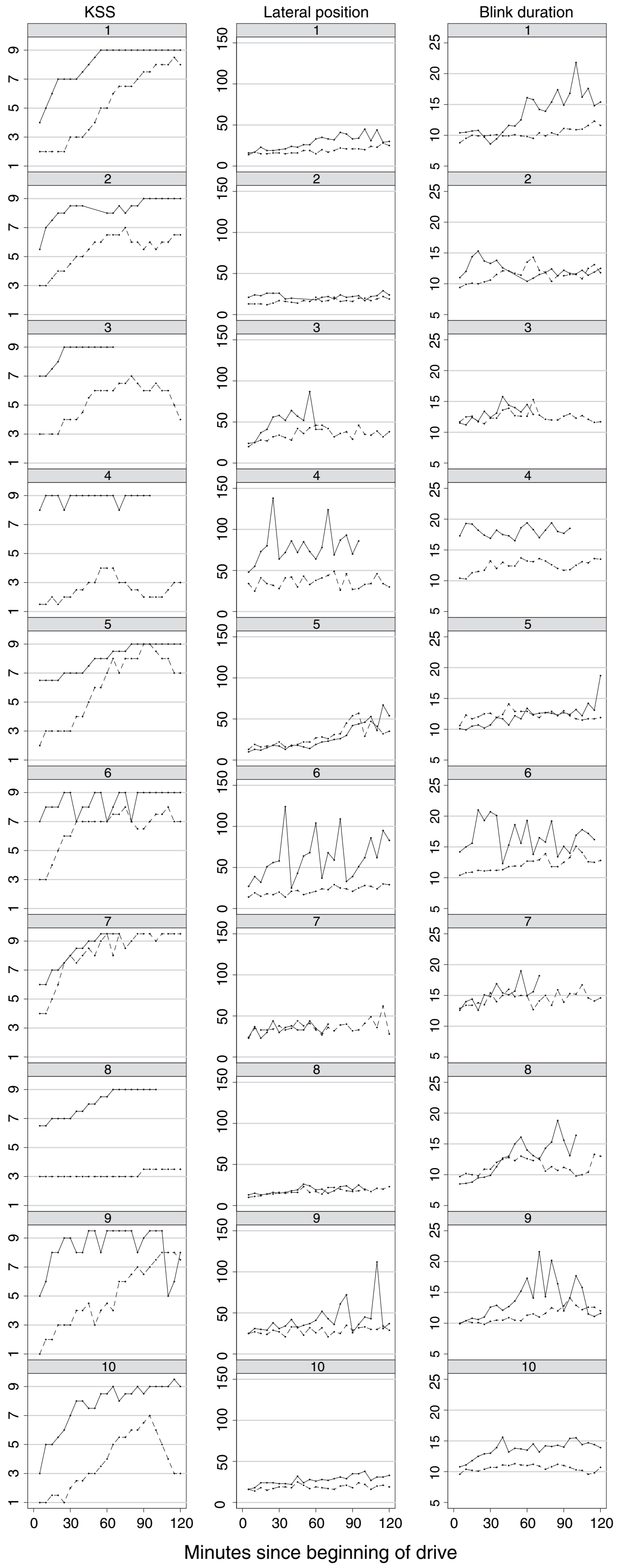

Figure 1. Observed data for the Karolinska Sleepiness Scale (left) standard deviation of lateral position in centimetres (middle) and blink duration in 1/100-s (right) during the Night work (solid line) and Night sleep (dashed line) conditions for all subjects (1–10).

Table 1 Summary of estimated models

Parameters	*SD of the lateral position (m)*		*Eye blink duration (s)*	
KSS levels	*mean*	*SEM*	*mean*	*SEM*
1	0.1911	0.0632	0.1023	0.0084
2	0.2123	0.0513	0.1109	0.0066
3	0.2211	0.0421	0.1137	0.0050
4	0.2421	0.0441	0.1184	0.0053
5	0.2615	0.0463	0.1183	0.0057
6	0.2573	0.0416	0.1190	0.0049
7	0.2774	0.0415	0.1250	0.0049
8	0.3576	0.0405	0.1402	0.0047
9	0.4654	0.0395	0.1512	0.0046
Wald test of factor	df	χ^2 (*P*-value)	df	χ^2 (*P*-value)
KSS	8	80.54 (0.000)	8	104 (0.000)
Random effects	SD	SE (*P*-value)	SD	SE (*P*-value)
Intercept	0.1008	0.0264 (0.000)	0.0096	0.0028 (0.000)
KSS	0.0669	0.0084 (0.000)	0.0098	0.0013 (0.000)
Error	0.0952	0.0035	0.0134	0.0005
Log-likelihood		323		1136

The table shows estimated means (mean), standard error of the mean (SEM) and the standard deviation (SD) with standard error (SE) of the random effects. A Wald test was used to test for significance of the KSS and a one-degree-of-freedom likelihood ratio test was used to test for significance of the random effects. The models included 10 subjects and a total of 424 observations.

SDLAT was significantly related to the KSS. Moreover, the significant random effect SD of the intercept shows that subjects differed in the overall level of SDLAT independent of the KSS levels. The significant random effect of the factor variable KSS shows that subjects also differed with respect to specific levels of the KSS. The fixed (group mean) effect is illustrated in Fig. 2 which shows an increasing SDLAT with increased sleepiness. The figure also describes large individual differences, for example, when comparing 4 and 6 with 2 and 8. The former show a much higher SDLAT at all sleepiness levels when compared with the latter and also a stronger increase at the highest levels.

The plots in Fig. 1 suggest that there might be a curvilinear relation between the KSS and SDLAT, with a stronger increase in SDLAT at high KSS levels when compared with low KSS levels. To test this assumption, three models were estimated with the method of maximum likelihood so that a likelihood ratio test could be used to assess the increase in model fit. The random effects were identical to the model presented in Table 1 but the fixed effect in the first model was only a constant. In the second model, a linear trend of the KSS was added and in the third model, a squared component of the KSS was also added. The result suggests that there was a linear trend of the KSS ($\chi^2 = 38$, df $= 1$, $P < 0.001$) with an average increase of 0.032 m (SE = 0.004) for each level of the KSS. Adding a squared component further increased model fit ($\chi^2 = 11$, df $= 1$, $P < 0.001$) suggesting a curvilinear relation between the KSS and SDLAT.

The intra-class correlation coefficient (ICC) was calculated to be 0.49 using estimates from a final model similar to the one presented in Table 1 but with only one random effect (the intercept).

The estimates for BLINKD showed a similar pattern as for SDLAT but with a larger heterogeneity in the subject-specific estimates between different levels of the KSS (Table 1, Fig. 1). Using the procedure described above revealed a significant linear trend ($\chi^2 = 49$, df $= 1$, $P < 0.001$) with an average increase of 0.0056 s (SE = 0.0006) with each level of the KSS but also a squared component ($\chi^2 = 8.78$, df $= 1$, $P = 0.003$) and ICC = 0.30.

DISCUSSION

In an earlier paper (Åkerstedt *et al.*, 2005), the effects of time and condition on the KSS, blink duration (BLINKD) and standard deviation of lateral position (SDLAT) has been reported. The present study extends the knowledge with estimates of the direct association between the KSS and SDLAT/BLINKD and information about individual differences. The results have shown that there is a relation between the KSS and 'objective' measures of driving performance (SD of the lateral position) and sleepiness (blink duration). However, large individual differences were observed, which suggests a complicated relation where the absolute level, as well as the relative effect, has to be adjusted between individuals. The effect seems to be curvilinear with a steeper rise at high KSS levels especially for the SD of the lateral position. This conclusion agrees well with previous research on subjective and objective sleepiness (Åkerstedt and Gillberg, 1990) and suggests that serious behavioural and physiological changes do not occur until relatively high levels of sleepiness (KSS ≥ 7) are reached.

During the experiment the subjects were alone in a HI-FI car simulator cab in a static environment. All subjects had

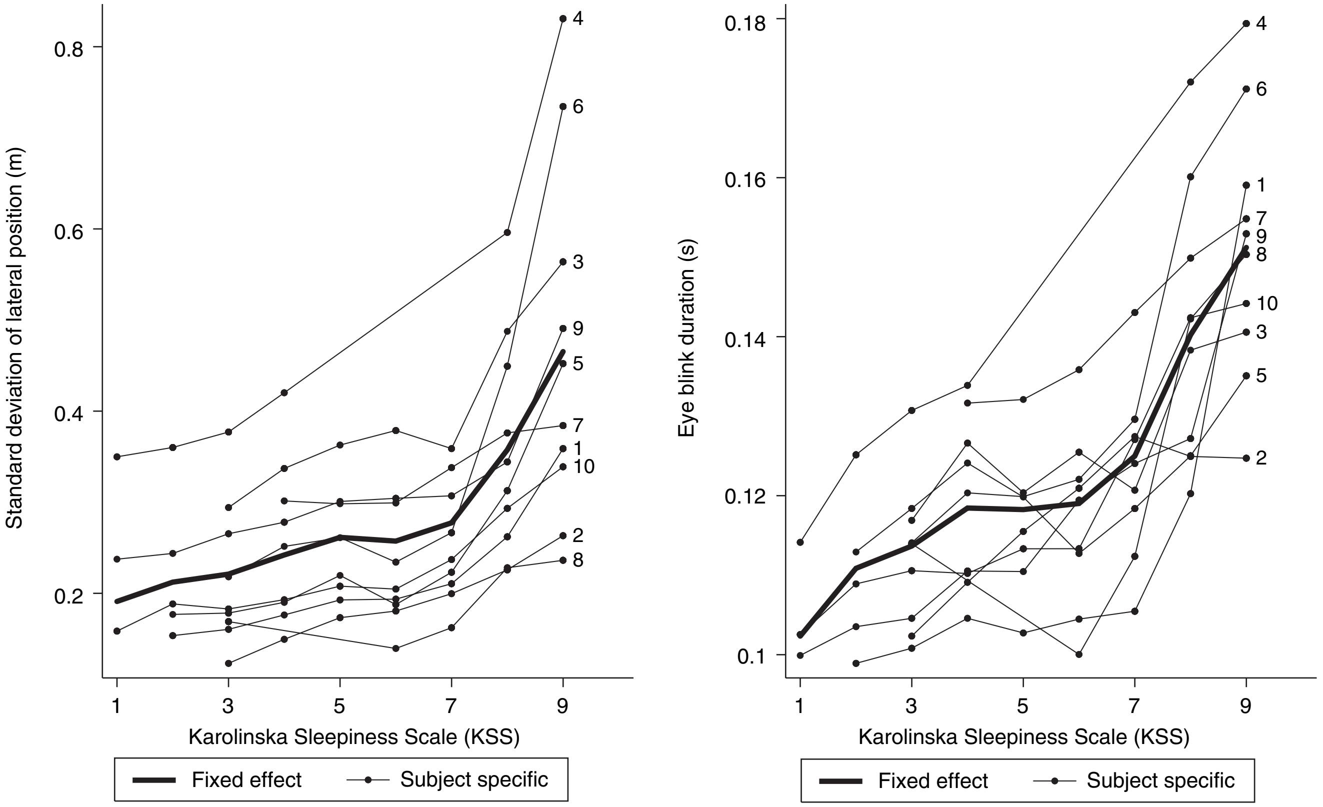

Figure 2. Prediction of the standard deviation of lateral position (left) and eye blink durations (right) for KSS levels 1–9. The figure shows the estimated fixed effect (thick lines) and best linear unbiased predictions for individual subjects (thin lines). Numbers to the right identify individual subjects. Subject-specific lines indicate the range of the observed KSS and dots indicate actual observations.

identical conditions and they were not engaged in any other activity than driving the car and giving oral ratings of sleepiness at 5-min intervals. This was an ideal situation for obtaining subjective ratings (and objective measures) uncontaminated by other activities or other distracting situational factors. Thus, reliable estimates of the association between the KSS and SDLAT/BLINKD could be obtained somewhat similar to what Yang *et al.* (2004) found, even though subjects had their eyes closed in that study.

Similar to the findings of O'Hanlon and Kelley (1977), one of the most striking effects observed in the present study was the individual differences. Such differences have been found in many areas, recently reviewed by Van Dongen *et al.* (2005), and they offer some challenges. Thus, they need to be accounted for by the statistical model and they need to be taken into account when interpreting and generalizing from the results. In the present study, the statistical model included random effects to account for individual differences.

The SD of the random intercept for SDLAT was estimated at 0.10 m, which is approximately the same as the average increase between 8 and 9 on the KSS or three times the average increase between any two levels. This finding indicates substantial heterogeneity between subjects in overall driving performance independent of sleepiness. The results were similar for BLINKD but with a SD of 1.7 times the average increase between two levels of the KSS. Individual differences in performance have previously been observed during sleep deprivation (Van Dongen *et al.*, 2004) and were expected. The present study adds to these findings that individual differences were to a large extent independent of subjective sleepiness. All subjects showed impaired performance at high sleepiness levels but their baseline levels were different which seem to reflect individual differences in overall driving skill or driving accuracy. Interestingly, similar differences were also observed for blink duration, suggesting individual differences also in basic physiological eye-blink processes.

There were also significant random effect SDs of the factor variable (KSS) for both dependent variables. The results suggest that subjects also differed from the fixed effect estimates with respect to specific levels of the KSS, indicating individual differences also in the shape of the function.

Very little is known about the mechanisms behind the observed individual differences and these issues have only recently been addressed in research with statistical methods capable of modelling effects at the individual subject level (Van Dongen *et al.*, 2004). As of today, one might only speculate on their underlying mechanism and origin. Further research is needed that explicitly addresses these issues.

An important question is whether the reported individual differences should be considered a stable trait (Van Dongen *et al.*, 2004). However, this cannot be determined in the present study because it would require replicating the experimental conditions several times during a longer time period. The present study can only address the issue of stability/reliability during the two 'snap-shots' in time that the study captured. Moreover, the KSS is a measure with error (like most measures) and that will add to the error variance when reliability estimates of the dependent variables are calculated. The reported reliability estimates, calculated as the ICC, suggests that 49% of the total error variance in SDLAT and 30% of the error variance in BLINKD was explained by stable individual differences in the intercept after removing the fixed effect of the KSS.

One possible problem with the interpretation of the random effects in the present study is the relative lack of control over the experimental manipulation. Subjects were allowed a normal sleep at home before one condition and were working the night shift before the other condition. While this approach has several advantages in terms of external validity (it reflects real-life conditions) it could have made subjects behave differently so that part of the differences between subjects in the overall level of the studied variables may be due to differences in work content and behaviour (e.g. napping and coffee consumption) before the driving sessions. However, the main objective of the present study was to study the association between sleepiness and the outcome variables (SDLAT/BLINKD) and while a possible lack of experimental control might have had an effect on both KSS and the outcomes, the association between the KSS and the outcomes is less likely to be confounded by differences in behaviour and work content before the drive although it cannot be completely ruled out.

One possible confounder with respect to the association could be caffeine intake. The effect of caffeine and/or hypnotics on the association between subjective sleepiness and performance was studied by Johnson *et al.* (1990) in four groups given hypnotics or placebo the night before and placebo or caffeine in the morning. The correlations were negative in all groups and weaker in the caffeine conditions but none was significant. The results suggest that neither caffeine nor hypnotics at bedtime had a significant effect on the association between subjective sleepiness and performance. However, statistical power was rather low because of the small group sizes ($n = 10$–40). Moreover, the results from the present study indicate that the between-subjects design may be problematic. The large random variance observed in the intercept for driving performance (SDLAT) will affect the between-subjects association. Small groups may show very different between-subjects correlations even before treatment, just by chance. A within-subject design that explicitly models subject-specific effects is needed to adequately address this issue.

One major implication of individual differences like those reported in the present study, is that they will make predictions at the subject level suffer from systematic error if they are made from the same parameters for all subjects. This is an important issue in any application that needs precision at the subject level, for example, driver fatigue warning systems. If only the group (fixed effect) estimates were used in such a system, driving performance (SDLAT) would be approximately predicted from the KSS for subjects that behave like subject #9 but systematically underestimated for #4 and with frequent false alarms for #8. Predictions for #6 should probably have a steeper rise at high sleepiness levels than predictions for #8. To achieve predictions at the subject level, random effects have to be added to the fixed effects model, i.e. a mixed effects model. This issue has also been discussed in relation to predictions from bio-mathematical models of fatigue and performance (Olofsen *et al.*, 2004; Van Dongen, 2004).

Finally, the present study made use of an ANOVA structure of the fixed effect, treating the KSS as a nine-level factor variable. This allowed the slope of the KSS to vary between all levels of the scale. It would be possible to estimate a more restricted model that describes the relation between the KSS and the dependent variable as a function of a fewer number of linear and/or non-linear parameters. However, any miss-specification of the parameters in such models may inflate the estimates of individual differences. Because exploring individual differences was one of the main objectives of the present study, a less restrictive and more explorative approach was chosen. The results suggest, though, that the association between the KSS and both dependent variables describes a curvilinear function. Further research is needed to establish the exact shape of a more parsimonious function of the association between the KSS and SDLAT/BLINKD. The findings of the present study suggest that such models should make use of a random intercept and probably also a random coefficient of the slope of the KSS to account for individual differences.

In conclusion, the present study has demonstrated a relation between subjective sleepiness measured with the KSS and driving performance as well as 'objective' indicators of sleepiness in a highly controlled situation without disturbing physical activities or other environmental changes. With higher KSS levels, the SD of the lateral position increased and eye blinks became longer in duration. Furthermore, this relation was observed for all subjects in the present study. However, large individual differences were also observed that needs to be taken into account if predictions are to be made for individual subjects. These individual differences were complex and the mechanisms behind them are not yet understood. Further research is needed that explicitly addresses these issues with proper designs and statistical methods.

ACKNOWLEDGEMENT

The results presented in this paper are based on the research work being performed at the European co-funded, 6th FW, Integrated project SENSATION (IST, 507231).

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