EFFECTIVE PATTERNS OF SLEEP WARNINGS BASED ON THE PHYSIOLOGIC AND BEHAVIOURAL REACTION OF USERS

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ABSTRACT: This paper presents a study of the efficacy of different types of sleep warnings sequences over heart rate, lane keeping, and the subjective opinion of the user. We used a fixed-base driving simulator and a multimodal sleep warning system with four types of signals: visual, acoustic, speech, and vibrotactile. These signals were differently combined, in order to create two sequences of different intensities. 14 drivers in different sleep conditions (normal, poor sleep and deprived of sleep for more than 20 hours) participated in the experiment. Heart Rate Variability and Standard Deviation of Lane Position decreased just after triggering the warning. This was a positive effect of the warning, which was more marked as the events were repeated on, when their intensity increased over time, and for the group of participants that had been deprived of sleep. These results contribute in learning the best way of counteracting sleepiness at the wheel.

1 INTRODUCTION

Driver sleepiness is one of the major safety problems that ITS attempt to address. In recent years, many studies have been devoted to develop devices for detecting and counteracting driver fatigue. Most systems in the market are based on the control of driving performance. These techniques assess variables recorded by CAN, like the position of the vehicle on the lane, its speed, and steering wheel movements [1]. The Standard Deviation of Lane Position (SDLP) is the indicator most consistently associated with drowsiness, although it should be complemented with other measures, since its reliability decreases for moderate levels [2, 3].

Drowsiness detection experiments usually combine performance indicators with subjective ratings and objective physiological measurements, like electroencephalography (EEG), percent of eye closure (PERCLOS), and electrocardiography (ECG) [2, 4–6]. The latter is an important, robust indicator of the driver's state. Heart activity varies depending on the person's activity, and it is possible to identify the lack of attention by analyzing heart rate variability (HRV). A person focused on performing some task usually shows a more regular heart rate, and as the focus on the task decreases, heart rate becomes more irregular and HRV increases [7].

However, up to now, most studies on this matter have been oriented to detect the symptoms associated to or preceding sleep, and little is yet known of the most adequate strategies to design sleep warnings. Human-Machine Interfaces (HMI) may use different modalities. Visual displays are the most common type of devices, since they may provide a great amount of information immediately. However, the visual channel is usually overloaded, so multimodal interfaces are encouraged. Multimodal systems have several benefits, like synergy, redundancy, and an increase bandwidth of information transfer [8]. Some studies have evaluated the influence of different types of signals on the effectiveness of HMI functions, like speed control [9], collision warnings [10], or lane departure warnings [11–12]. Besides visual information, haptic and auditory signals have been assessed in those studies, with similar objective results for both modalities [13] or combinations of them [14]. The efficacy of a vibrotactile collision warning in a haptic pedal has been found to depend on the characteristics of the vibration [15]. Likewise, the effectiveness of acoustic warnings may depend on the type of sound: speech warnings provide more information, and thus may be better suited for certain situations [16]. Multimodal warnings with a combination of acoustic, visual and haptic output signals have been used for sleep and hypovigilance prevention systems [17].

This paper is aimed to evaluate how different sequences of sleep warnings affect driver's behaviour, and user preferences on different types of sleep warnings. Various modalities and sequences were tested. The attention level was measured in terms of driving performance and physiological activity, and by self-evaluation. The results have been used to provide some guidelines for counteracting drowsiness at the wheel.

2 MATERIAL AND METHODS

2.1 Subjects

14 people (7 men and 7 women) aged between 20 and 45 were recruited to participate in the experiment. They were licensed drivers, who used their vehicles daily. 2 subjects (1 man and 1 woman) were sleep deprived: they had remained awake for more than 20 hours. On the other hand, 2 further subjects (1 man and 1 woman) had slept normally the night before. The remaining 10 subjects were people with poor sleep, who had slept less than 4 hours the night before. None of them had drunk or eaten stimulating substances during the day preceding the test sessions. They were external volunteers, who were not professionally nor personally involved in the project, and were paid for their participation.

2.2 Laboratory, simulator and instruments

We used a fixed-base driving simulator in a room with ambient light, sound and temperature set to simulate a night, warm scenario (dim lights, monotonous road noise, and 24-26 ºC). All the computers were placed behind the simulator bench, which was surrounded by panels to create a closed environment. To further prevent distraction, the experiment was monitored with roof-mounted cameras from a control room out of the participant's sight, so that the subjects should not feel themselves accompanied or observed.

The simulator incorporated a sleep warning system, in order to alert and stir the driver, triggered by an external observer. That warning consisted in the following signals:

- Visual warning: an image displayed on the screen as a Head-Up Display (HUD) (see 0).
- Auditory tone warning: a 0.5 s tone at 1 Hz.
- Speech warning: a spoken message, telling "Please rest for your safety".
- Vibrotactile warning: a vibrating torque from 0 to 50 mNm in the accelerator pedal, controlled by a haptic device.

Fig 1 : Example of the "red" visual warning

All these signals were triggered simultaneously, with the exception of the speech warning, which followed the auditory tone. These signals were differently combined, in order to create two warning combinations:

"Yellow" warning: the visual signal was a yellow icon indicating moderate fatigue, the auditory warning tooted once; there was no speech message, and the pedal vibrated at 2.5 Hz.

"Red" warning: the visual signal was a red icon indicating strong fatigue, the auditory warning tooted three times, the speech message was on, and the pedal vibrated at 5 Hz.

The characteristics of the visual and acoustic signals were designed according to recommendations for driver information systems and hypovigilance warning systems in particular [18–19]. The vibrotactile pedal was the haptic device used in [15], and the vibration characteristics were chosen to achieve an adequate balance between effectiveness and nuisance, depending on the level of the alarm, and according to the results of that study.

The simulator recorded driving-related variables continuously, like elapsed distance, vehicle speed, lateral position, steering wheel angle, and vehicle controls manipulation.

The electrocardiographic activity of the participants (ECG) was also measured continuously, with a medical monitor that was synchronised with the simulator, so that the timeline of the ECG recording coincided with the simulator output. ECG sampling rate was 255 Hz, whereas the simulator recorded driving data at 10 Hz.

2.3 Test procedure

Participants first made an adaptation trial between 5 and 15 minutes long, in which they got themselves familiarised with the simulator, and then the measurement session began. During that session, their physiological signals were constantly monitored while they drove in a highway with low traffic density and smooth curves, in a night scenario.

The experimenter monitored the test out of the participant's sight. The first 55 minutes of the session were dedicated to "tire" the subject, and no important event happened in the road, unless his or her behaviour showed evident symptoms of drowsiness (eyes closed for more than 2 seconds, excursions off the lane, or unusual reduction of speed). When this occurred, or when the 55 minutes had passed, the experimenter triggered a "red" warning. Whenever the participant showed again drowsiness symptoms, or every 5 minutes, the experimented triggered another warning, until 9 events had occurred. Thus, we had the same number of measurements for all subjects.

Both types of warnings were presented in different order, depending on the subject: a "yellow-red" sequence was applied to seven participants, with four "yellow" warnings followed by of four "red" warnings. An inverted "red-yellow" sequence was applied to the remaining seven participants (0). This distribution was balanced across the three groups of participants according to their sleep condition.

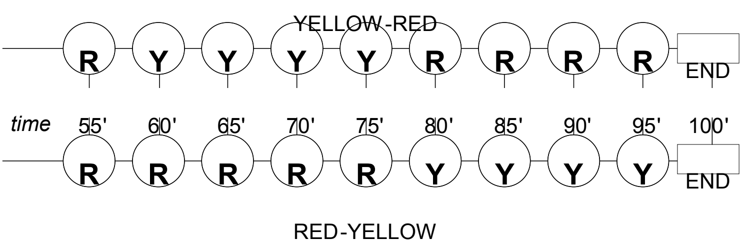

Fig 2 : Warning sequence types

Immediately after every event, a speech message instructed the participants to press one button of the steering wheel if they felt themselves wakeful, in order to gather a subjective impression of their state. After finishing the test, all subjects were asked to fill a questionnaire to gather further subjective information about: (a) the preferred or least preferred warning signals, and (b) the subjective drowsiness condition as the test progressed.

2.4 Analysis

Two objective variables were analysed: beat-to-beat Heart Rate Variability (HRV) and SDLP. HRV was measured as SDNN, the standard deviation of the R-R intervals (the intervals between peaks of the ECG signal) [20]. SDLP was likewise the standard deviation of the lateral position of the vehicle with respect to lane boundaries. Both variables were measured in 1 minute intervals before and after the event. They both are indicators of driver's inattention or fatigue, so we expected them to increase immediately after the events. ANOVA tests were performed to compare if those variables actually changed as a consequence of the warning activation, and the differences of those changes depending on the type of warning ("yellow" vs. "red"), the type of sequence ("yellow-red" vs. "red-yellow"), the number of previous events, and the sleep condition ("deprived" vs. "poor sleep" vs. "normal").

The self-perception of driver's fatigue was gathered during the test from their reaction to the spoken instruction (pressing a button if they felt wakeful), and after finishing the test. The former variable was analysed just as the objective variables. The frequencies of the different answers to the questionnaire were statistically compared with a likelihood ratio test, in order to find significantly prominent answers.

3 RESULTS

3.1 Objective variables

Around the warning activation instants, drivers' heart rate (HR) was 76.4 beats per minute (bpm) on average, with a standard deviation equal to 6.1 bpm. HRV decreased every time the warning was triggered ($p < 0.05$). In HR units, its variability decreased 2.9 bpm after the warning. 0 there is an example represented in a Poincaré plot, where each R-R interval is plotted against the next interval [21]. The observations after the event (black dots) were gathered in a smaller cloud of points than before the event (empty squares). This meant that the R-R intervals became more homogeneous after the warning; the R-R typical variation decreased 29 ms on average when the warning was triggered.

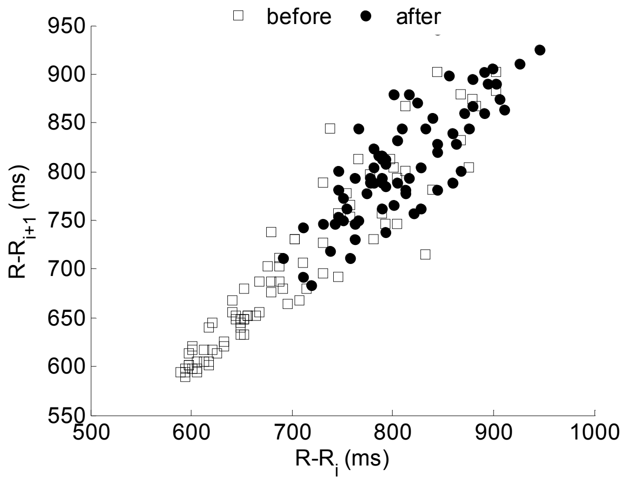

Fig 3 Poincaré plot of the R-R intervals (ms) before the warning (empty squares) and after the warning (dots). Data for subject #11, warning #5.

The reduction of HRV indicated that warnings generally stimulated the driver's attention [7]. Moreover, this effect was significantly greater for the "yellow-red" warning pattern than for the "red-yellow" sequence, as well as for the group of participants who had not slept the night before ($p < 0.05$).

Fig 4. plots the values of SDLP before the event against their values after the event, for all the cases. There were more cases in which SDLP decreased after the warning as well (there is a greater amount of points below the 1:1 line), and this reduction of SDLP was also significant (average reduction = 0.1 m, $p < 0.05$). This improvement increased significantly as the events were repeated (0, $p < 0.05$), and was also greater for sleep-deprived participants ($p < 0.05$).

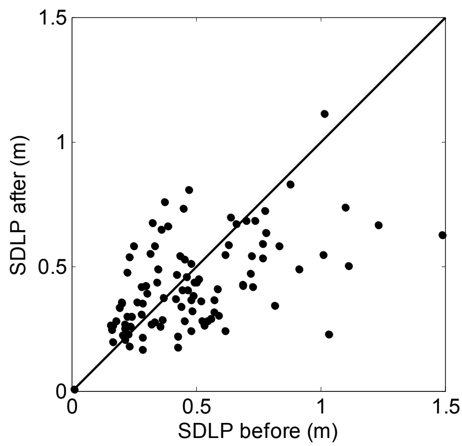

Fig 4 Relation of SDLP before and after the warnings

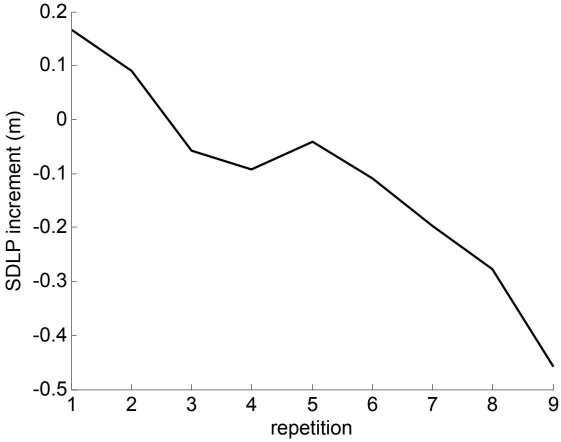

Fig 5 Average values of the SDLP increment (SDLP after the event minus SDLP before the event) as a function of repetition

3.2 Subjective variables

The feeling of "tiredness" or "wakefulness" that the participants reported by their interacting with the HMI, was not significantly different depending on their sleep condition, the type of warning, or the number of times that it had been repeated. However, it did differ according to the type of sequence: the "yellow-red" sequence yielded more frequent "wakeful" reactions than the "red-yellow" sequence (79% of cases vs. 33%, $p < 0.05$).

According to the questionnaires that the participants responded after the test had finished, the vibration was the most adequate modality (by 54% of users), and the worst one was the visual symbol (according to 46% of users, see 0). A likelihood ratio test over their answers revealed that the positive bias towards vibration was significant ($p < 0.05$), but the negative bias against the visual signal was not.

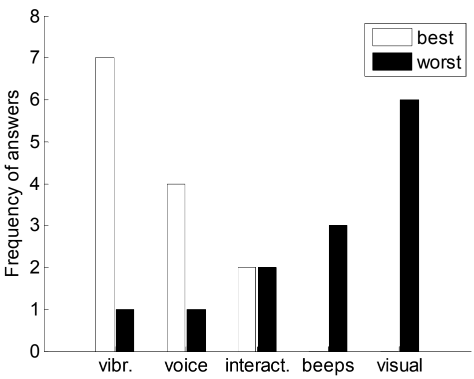

Fig 6 Best and worst modalities according to the users

4 CONCLUSIONS

The experiments confirmed that the sleep warnings were effective for arousing drivers and enhancing their attention, and this effect depended on the design of the warning sequence, the moment of the test, and the initial state of the participants. Successive repetitions of the warning improved the reaction of drivers in terms of SDLP, and both the physiological signal and the subjective self-evaluation revealed a greater increment of attention for the “yellow-red” sequence (moderate warnings followed by stronger warnings). These effects were always more marked for the group of participants that had been deprived of sleep for 20 hours before the experiment. The different modalities also received dissimilar ratings: the best-rated one was the vibration, and the visual display received the worst score.

There are some limitations to these conclusions: the number of participants was small, and this could be the cause of failing to find further differences. The different warning modalities were always displayed together, so their impacts could have been added up, and the participants’ subjective ratings of each modality could have been influenced by the effect by the other ones.

These findings are a useful contribution for the design of effective patterns of sleep warnings, which do not only caution the drivers about their state, but also enhance their awareness, so that they may gain time to look for a resting place safely.

5 ACKNOWLEDGMENTS

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6 REFERENCES

[1] Wright, N.A., Stone, B.M., Horberry, T.J., and Reed, N.: ‘A review of in-vehicle sleepiness detection devices’, TRL Limited, Published Project Report PPR157, 2007.

[2] Liu, C.C., Hosking, S.G., and Lenné, M.G.: ‘Predicting driver drowsiness using vehicle measures: Recent insights and future challenges’, Journal of Safety Research, 2009, 40, (4), pp. 239–245.

[3] de Rosario, H., Solaz, J.S., Rodríguez, N., and Bergasa, L.M.: ‘Controlled inducement and measurement of drowsiness in a driving simulator’, 16th ITS World Congress, 21–25th September 2009, Stockholm, Sweden, paper no. 3003.

[4] Boyle, L.N., Tippin, J., Paul, A., Rizzo, M.: ‘Driver performance in the moments surrounding a microsleep’, Transportation Research Part F: Traffic Psychology and Behaviour, 2008, 11, (2), pp. 126–136.

[5] Dinges, D.: ‘F. PERCLOS: A valid psychophysiological measure of alertness as assessed by psychomotor vigilance’, Tech. Rep. MCRT-98-006, Federal Highway Administration, Office of motor carriers, 1998.

[6] Lal, S.K.L., Craig, A.: 'A critical review of the psychophysiology of driver fatigue', Biological Psychology, 2001, 55, (3), pp. 173–194

[7] Oron-Gilad, T., Ronen, A., and Shinar, D.: 'Alertness maintaining tasks (AMTs) while driving', Accident Analysis & Prevention, 2008, 40, (3), pp. 851–860.

[8] Sarter, N.B.: 'Multimodal information presentation: Design guidance and research challenges', International Journal of Industrial Ergonomics, 2006, 36, (5), pp. 439–445.

[9] Adell, E., Várhelyi, A., & Hjälmdahl, M.: 'Auditory and haptic systems for in-car speed management – A comparative real life study'. Transportation Research Part F: Traffic Psychology and Behaviour, 2008, 11(6), pp. 445–458.

[10] Hoffman, J. D., Lee, J. D., & Hayes, E. M.: 'Driver preference of collision warning strategy and modality'. In 2nd International driving symposium on human factors in driver assessment, training and vehicle design, 2003.

[11] Stanley, L. M.: 'Haptic and auditory cues for lane departure warnings'. Human Factors and Ergonomics Society Annual Meeting Proceedings, Surface Transportation, 2006, 4, pp. 2405–2408.

[12] Suzuki, K., & Jansson, H.: 'An analysis of driver's steering behaviour during auditory or haptic warnings for the designing of lane departure warning system'. JSAE Review, 2003, 24(1), pp. 65–70.

[13] Lee, J.D., Hoffman, J.D., and Hayes, E.: 'Collision warning design to mitigate driver distraction', in Dykstra-Erickson, E., and Tscheligi, M. (Eds.): 'Proceedings of the ACM CHI 2004 conference on Human Factors in Computing Systems April 24–29, Vienna, Austria (ACM, 2004), pp. 65–72.

[14] Navarro, J., Mars, F., and Hoc, J. M.: 'Lateral control support for car drivers: A human–machine cooperation approach', in Brinkman, W.P., Ham, D.H., and Wong, B.L.W. (Eds.): 'Proceedings of the 14th European conference on cognitive ergonomics, August 28–31, London, UK (ACM, 2007), pp. 249–252.

[15] de Rosario, H., Louredo, M., Díaz, I., Soler, A., Gil, J.J., Solaz, J.S., and Jornet, J.: 'Efficacy and feeling of a vibrotactile Frontal Collision Warning implemented in a haptic pedal', Transportation Research Part F: Traffic Psychology and Behaviour,2010, 13(2), pp. 80-91.

[16] Martens, M., and van Winsum, W: 'Effects of speech versus tactile driver support messages on driving behavior and workload', SAE technical papers 2001-06-0080, SAE International, 2001.

[17] Polychronopoulos, A., Amditis, A., and Bekiaris, E.: 'Information data flow in AWAKE multi-sensor driver monitoring system', 2004 IEEE intelligent vehicles symposium, Parma, Italy, 14-17 June 2004, pp. 902–906.

[18] Green, P., Levison, W., Paelke, G., Serafin, C.: 'Suggested Human Factors Design Guidelines for Driver Information Systems', Technical

Report UMTRI-93-21, 2003 (Revised August, 1994).

[19] Bekiaris, E.D., Nikolaou, S.I.: ‘Towards the development of design guidelines handbook for driver hypovigilance detection and warning - the AWAKE approach’, Proc. 12th IEE International Conference on Road Transport Information and Control, RTIC 2004, 20-22 April, London, UK, 2004, pp. 314–320.

[20] Malik, M.: ‘Standard Measurement of Heart Rate Variability’, in: Malik, M., Camm, J. (ed.): Dynamic electrocardiography, NY: Blackwell Futura, 2007, pp. 13-21.

[21] Mäkikallio, T.H.; Perkiömäki, J.S.; Huikuri, H.V.: ‘Nonlinear Dynamics of RR Intervals’, in: Malik, M., Camm, J. (ed.): Dynamic electrocardiography, NY: Blackwell Futura, 2007, pp. 22-30.