Effects of chronotype and time of day on the vigilance decrement during simulated driving

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Submitted to: **Accident Analysis and Prevention** on 14/08/13

First revision submitted on 21/01/2014

Second revision submitted on 25/02/2014

Paper accepted for publication: 25/02/2014

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[1] The current work was based on the Master Doctoral Dissertation by Enrique Molina, defended in 2010 in the University of Granada. Partial results of this research were presented in the 2011 TIMELY Workshop on the "Psychophysical, Computational, and Neuroscience Models of Time Perception" (Groningen, Netherlands). Video and slide presentation can be downloaded here: http://www.timely-cost.eu/sites/default/files/videos/2ndTrSc/correa.mp4. http://www.timely-cost.eu/sites/default/files/ppts/2ndTrSc/Correa.pdf

Abstract

The current study tested for the first time the effect of individual differences in circadian rhythmicity (chronotype) on both driving performance and its evolution along time on task. Morning-type and evening-type female participants were tested in morning (8 am) and evening (8 pm) sessions, in which we controlled for prior sleep duration and prior wake. Measures of body temperature, subjective activation and affect, reaction times (RT) in the Psychomotor Vigilance Task (PVT), behavioral performance (error position) and EEG alpha power during simulated driving were collected. The main result showed strong linear increments of mean and standard deviation of error position along time on task (vigilance decrement) when evening-type participants drove at their non-optimal time of day, that is, during the morning session. In contrast, driving performance in the morning-type group remained stable over time on task and was not affected by time of day. This finding can be due to differences in personality traits (e.g., conscientiousness, sensation seeking) and task appraisal associated to extreme chronotypes. The consideration of chronotype in vigilance and driving tasks can enhance safety and human performance by promoting work schedules and countermeasures to prevent failures in the accomplishment of tasks under non-optimal circadian conditions.

Keywords: neuroergonomics; circadian; morningness; time on task; PVT; EEG

1. Introduction

Performance in vigilant attention tasks after 18 hours of extended wakefulness declines until levels equivalent to those produced by the ingestion of the legal maximum amount of alcohol (0.05% blood alcohol concentration) allowed for driving in many countries (Dawson and Reid, 1997). This finding emphasizes the relevance of research on sleep and circadian rhythms in driving. The aim of the current research was to study the influence of several circadian and time-related factors (chronotype, time of day and time on task effects by controlling for prior sleep duration and prior wake) on performance during a simulated driving task.

Circadian rhythms set the timing for basic biological and physiological functions on a daily basis, such as sleeping and feeding, body temperature, hormone production and brain activity, thus influencing behavioral and cognitive functions (Berendes et al., 1960; Kleitman, 1933). Performance in cognitive tasks measuring simple reaction time (RT), attention and vigilance shows circadian rhythmicity, which indicates that the amount of prior wake and the time of day at which a task is accomplished are major influences (reviewed by Blatter and Cajochen, 2007; Lim and Dinges, 2008; Valdez et al., 2010; Wright et al., 2002).

Time of day is a key factor in tasks demanding vigilance such as driving, as highlighted by statistics on traffic accidents (Di Milia et al., 2011; Folkard, 1997). Specifically, traffic accidents occur most frequently when both body temperature and vigilance levels are at minimum, that is, around 3 to 5 am. Time of day effects in driving performance have also been demonstrated by laboratory experiments (Akerstedt et al., 2010; Baulk et al., 2008; Lenné et al., 1997). However, most of these studies have not considered the negative impact that extending duration of prior wake exerts upon driving performance, which can be exacerbated at specific times of day when vigilance is low, for example at 4 am (Matthews et al., 2012).

Individual differences in profiles of circadian rhythmicity, i.e. "chronotype", can be another relevant factor for studies addressing time of day effects on cognitive and driving performance. The chronotype reflects inter-individual differences in the phase (or amplitude) of circadian rhythms, such as body temperature and sleep cycle (for a recent review see Adan et al., 2012; Kerkhof and Van Dongen, 1996). Morning-type people tend to wake up and to go to sleep earlier, and show more arousal and activity during the morning, than evening-type people. This tendency can be measured by a questionnaire (Horne and Östberg, 1976) and has been related to genetic factors (Katzenberg et al., 1998). Morning-type individuals also show optimal performance on many cognitive tasks in the morning, whereas evening-type individuals show best performance in the evening. This interaction between chronotype and time of day is known as the "synchrony effect" (May and Hasher, 1998).

Chronotype has been acknowledged as a crucial factor in research on fatigue and accident risk (Di Milia et al., 2011). However, the influence of chronotype on driving performance remained to be tested. The few available evidence that measured chronotype has controlled rather than manipulated this factor by testing only participants with intermediate chronotype (e.g., Matthews et al., 2012). A recent study reported that morning-type participants showed higher cortisol levels (indicating higher arousal), reported both less subjective workload and reduced sleepiness than evening-type participants during a simulated driving task (Oginska et al., 2010). Unfortunately, however, the Oginska et al.'s study did not focus on driving performance so that measures related to the driving task were not reported. Therefore, the current study aimed to investigate the influence of chronotype on driving performance, by simultaneously considering time of day and prior wake factors.

Task duration ("time on task") is another relevant factor influencing cognitive performance (Mackworth, 1948), and therefore the level of vigilance during driving. Many studies on real and simulated long driving have reported performance decrements, for example, by showing that the lateral position of the car becomes more variable (i.e., SDlat measure) and less accurate along time on task (e.g., Brookhuis and de Waard, 1993). The time on task effect has been related to increased fatigue and sleepiness, and to decrements in vigilance, which can be indexed by self-report and electroencephalographic (EEG) measures (Otmani et al., 2005; Ranney et al., 1999). For example, subjective sleepiness and EEG alpha activity have been shown to increase concomitantly with time on task (Kecklund and Akerstedt, 1993).

Given that vigilance fluctuates across time of day, it is reasonable to expect that the vigilance decrement during driving can be affected by time of day. This issue was addressed by a recent study, but no interaction between time of day and time on task was reported (Akerstedt et al., 2010). Since chronotype was not measured in this study, it is possible that variability due to individual differences in chronotype might have precluded the finding of clear interaction between time of day and time on task. Hence, the current study tested for the first time (as far as we know), whether the vigilance decrement during driving depends on chronotype and time of day. We have recently found that the vigilance decrement during a task measuring vigilance and response inhibition (the Sustained Attention to Response Task –SART-; Robertson et al., 1997) can be prevented by testing morning-type and evening-type individuals at their respective optimal times of day (Lara et al., 2014). Thus, we expected to extend this finding to a simulated driving task, in order to counteract the impairments in performance during long driving.

To summarize, the current study tested morning-type and evening-type participants performing a simulated driving task in morning and evening sessions. Effects of the manipulation of chronotype and time of day were additionally tested by measuring subjective activation (Monk, 1989), vigilance during the Psychomotor Vigilance Task (PVT; Dinges and Powell, 1985), and the slow alpha frequency range of the EEG (Kecklund and Akerstedt, 1993; Klimesch, 1999) before and during simulated driving. These variables were further analyzed by multiple regression (see Supplementary Material 2.2) in order to model and predict driving performance.

On the basis of the literature reviewed above, we expected to find a reduced vigilance decrement in driving performance when participants were tested at the optimal rather than non-optimal time of day according to their chronotype. We also predicted higher subjective activation, faster RTs in the PVT and lower alpha power in the EEG, at optimal compared to non-optimal times of day.

2. Material and methods

2.1. Participants

Twenty-nine participants with extreme chronotype were contacted from a database of students from the University of Granada who completed the Spanish reduced version of the Morningness-Eveningness Questionnaire (Adan and Almirall, 1991) to take part in the experiment voluntarily. Data from four participants were excluded from the study as they either crashed the car (two of them were driving at their non-optimal time of day) or missed one session. Data from eleven participants who either slept less than 6 hours the night prior to the experiment, did not complete any of the tasks or their EEG recording was excessively noisy, were replaced by testing new participants.

Summing up, data from twenty-five participants (age range 18-26 years old, Mean age = 21.09, SD = 2.46), all of them female, right-handed, with normal or corrected to normal vision, were finally included in the analyses. Testing only females was not particularly intended and was due to practical reasons regarding higher availability of this specific sample. There were no male participants in the rejected sample described above. Thirteen participants with scores of 17 and above were assigned to the morning-type group, whereas twelve participants with scores of 9 and below were assigned to the evening-type group. The study was conducted in accordance with both the ethical guidelines of the University of Granada and the standards laid down in the 1964 Declaration of Helsinki. Participants gave informed written consent before the study and they were rewarded with course credits for their participation.

2.2. Apparatus and Stimuli

Participants' body temperature was measured by means of an electronic thermometer placed under the armpit. The reduced version of the Spanish adaptation of the Morningness-Eveningness Questionnaire (rMEQ, Adan and Almirall, 1991; Horne and Östberg, 1976) was developed to measure participants' chronotype on the internet (available at http://wdb.ugr.es/~molinae/rmeq/). Scores in this questionnaire can range in a continuous between 4 (extreme eveningness) and 25 (extreme morningness). Subjective activation and affect were measured by an electronic version of the Visual Analogue Scale developed by Monk (1989). Scores can range from 0 (minimum activation/positive mood) to 100 (maximum activation/positive mood).

The simulated driving task and the PVT were run on the same PC laptop (Intel Core 2 Duo at 1.8 GHz with 2 GB of RAM, 15.6'' LCD screen). The PVT task was programmed with E-Prime software (Schneider et al., 2001). The target stimulus was a black circle with a red edge (diameter: 9.15 degrees of visual angle at a viewing distance of 50 cm). As simulated driving task we used the Racer software (http://www.racer. nl/; version 0.8.9), which is free, customizable through ASCII files and it generates a log file on driving performance that can be analyzed with Matlab (Mathworks Inc.).

The track used in our study was the Speedest2 (http://www.racer-xtreme.com/), a road forming a big ovaled-rectangle (approximately 3,000 x 1,750 m, with a bend radius of 850 m), which was specifically selected to study time on task effects on vigilance by simulating monotonous driving on a highway. Sharp bends involving high driving skills were thus avoided. The car was a model of the Lexus IS350 to improve simulation of physical behavior in real conditions. The display showed a green line near the center of the track, and a velocity gauge on the bottom left corner of the screen (Figure 1, top). The car was controlled through a

Logitech Momo Racing wheel and pedals set. Auditory feedback of the engine was provided through loudspeakers (Figure 1, bottom).

Figure 1. Display presented to the participant in the driving task (top) and experimental setup for the driving task (bottom).

Participants were instructed to drive the car following the green line drawn on the center of the road. The task involved keeping the car both as centered on the line as possible and at a constant velocity of 60 miles per hour (i.e., 96.56 km/h). The surface of the road was irregular, thus causing smooth but unpredictable deviations of the car position. Hence, the task demanded continuous attentional tracking of the car trajectory which participants had to correct with the steering wheel constantly. That is, they had to maintain attention both to the speed and position of the car.

EEG activity was recorded only during the simulated driving task with a 128-electrode net (Electrical Geodesics Inc.; Tucker et al., 1994). E-Prime was used to synchronize the driving task with the EEG data acquisition.

2.3. Procedure

Each participant completed identical 2-hour sessions in two consecutive days, one at 8 am and one at 8 pm. The time of day of the first session was counterbalanced across participants. At the beginning of the session, the experimenter registered the participant's amount of experience with both real driving and videogames, body temperature, amount of sleeping during the previous night, waking time and consumption of coffee or other stimulant substances during that day. Then, the participant completed the Monk's activation-affect scale, performed the PVT task for 10 minutes and a go no-go temporal orienting task (Correa et al., 2010) for another 10 minutes that was counterbalanced with the PVT (this task was part of another study to be reported elsewhere).

In the PVT task, participants were instructed to pay attention to the red empty circle and to press a key as soon as the circle started to fill up in red (in a counter-clock wise manner, and at an angular velocity of approximately 0.011 degrees per second), which happened every trial after a random interval ranging between 2 and 10 seconds. Participants were encouraged to respond as quickly as possible while avoiding anticipations.

After that, the electrode net was placed on the participant, who stayed five minutes with the eyes open and five minutes with the eyes closed, in order to measure the individualized alpha frequency (IAF). The IAF was used as an anchor point to calculate the different frequency bands. Then the driving task was administered for approximately one hour. The experimenter remained in the room while the participant drove the first straight of the circuit to ensure accomplishment of task instructions. Participants completed a lap in 3-4 minutes, and each participant completed a minimum of 9 laps (i.e., 18 hemi-laps). Finally, after the driving task, participants completed the Monk's activation-affect scale again.

2.4. Design and Data Analysis

The general design consisted of a repeated-measures analysis of variance (ANOVA) with Chronotype (morning-type, evening-type) as between-participant factor and Time of day (morning: 8am, evening: 8pm) manipulated within-participants. However, given that evening-type participants had slept significantly longer at the evening session (see details below in 3.1), the analyses focused on testing the effect of chronotype only in the morning session, and the effect of time of day only in the morning-type group, in order to control for the influence of prior sleep (Matthews et al., 2012). Further analyses of covariance (ANCOVA) tested for the synchrony effect on our main measures by including Prior sleep to the evening session as a covariate in the full Chronotype x Time of day design (see Supplementary Material 2.3).

The analyses of the PVT task included the median RT of responses above 100 ms, amount of anticipations (responses below 100 ms) and lapses (RTs above 500 ms). The design of the driving task additionally included Type of stretch (straight, curve) and Hemi-lap (1 to 15), which was used to study the effect of time on task (i.e., the vigilance decrement). Two additional hemi-laps were first completed as practice and were therefore not included in the analyses. The analysis of driving performance included the mean error in the position of the car corrected by the velocity. That is, we scaled the absolute values of the position error with an index of the velocity error, as difficulty of driving could vary with velocity. The velocity error was the absolute value of the difference between the instructed (60 miles per hour) and the actual velocity. The position error could take values from -0.5 to 0.5, but was later rectified so that position error ranged from 0 to 0.5 (i.e., 0 meaning perfect execution). We also analyzed the standard deviation of the corrected position error (SDlat; see Supplementary Material 2.1), a measure commonly used in the literature (e.g., Akerstedt et al., 2010; Baulk et al., 2008; Matthews et al., 2012).

Electrophysiological activity was recorded from a 128-electrode Electrical Geodesics system, off-line preprocessed using FASTER (Nolan et al., 2010), and then analyzed by Fast Fourier Transform using EEGLab (Delorme and Makeig, 2004). The band frequencies were defined in relation to the IAF following the method described by Klimesch (1999). We then focused in the lower alpha band, defined as the frequency between IAF minus 4 and IAF, on the cluster of electrodes with the highest activation on the alpha frequency band, located in posterior sites (see Supplementary Material 1, for further details on EEG methods).

Effect sizes of significant results in the ANOVA are reported as partial eta-squared (ηp^2), which quantifies the proportion of the variability in the dependent variable that is explained by the effect. The Greenhouse-Geisser correction was applied, and corrected probability values and degrees of freedom are reported, when sphericity was violated (Jennings and Wood, 1976).

3. Results and Discussion

3.1. Questionnaires

In the evening session, five participants (2 morning-type and 3 evening-type) reported having had a nap after lunch. Five participants (3 morning-type) drank coffee within the four hours prior to the morning session, and three of them (1 morning-type) drank coffee before the evening session. Thus, both nap and coffee intake were reasonable balanced for both chronotype and sessions.

The ANOVA of the rMEQ scores with Chronotype as between-participants factor confirmed that the morning-type group scored significantly higher in morningness (M = 18.15, SD = 1.34) than the evening-type group (M = 9.17, SD = 0.83), $F\ (1, 23) = 394.84$, $p < 0.001$, $\eta p^2 = .94$. The two chronotype groups were matched in terms of age, number of years with driving license and experience with videogames (all $F < 1$). However, the ANOVA on the sleep duration in the night prior to the experiment (“Prior sleep”) revealed a significant interaction between Chronotype and Time of day, $F(1, 23) = 6.66$, $p = .017$, $\eta p^2 = .22$. Post-hoc Fisher LSD comparisons showed that evening-type participants slept longer in the night prior to the evening session (M = 7.83 hours, SD: 1.11) than: 1) evening-types before the morning session (M = 6.46, SD = 0.50), 2) morning-type participants before the morning session (M = 6.58, SD = 0.53), and 3) morning-types before the evening session (M = 6.96, SD = 0.78), all $p < .01$. Importantly, participants in these three latter conditions were balanced in sleeping duration: morning-type morning-session compared to morning-type evening-session, $p = 0.16$; morning-type morning-session compared to evening-type morning-session, $p = .70$. Therefore, subsequent ANOVAs tested for the effect of Chronotype only in the morning session, and the effect of Time of day only in the morning-type group, whereas an ANCOVA including Prior sleep as covariate tested for synchrony effects as revealed by an interaction between Chronotype and Time of Day (ANCOVA results are described in Supplementary Material 2.3).

3.2. Effect of Chronotype in the morning session

The analysis on the amount of ***time awake*** before the morning session did not show significant differences between morning-type (M = 1.15, SD = 0.32) and evening-type (M = 1.00, SD = 0.37) groups, *F*(1, 23) = 1.26, *p* = .27. Similarly, body temperature in the morning session did not differ between morning-type (M = 36.24, SD = 0.47) and evening-type (M = 36.49, SD = 0.44) participants, *F*(1, 23) = 1.80, *p* = .19.

The Chronotype (morning-type, evening-type) x Pre-post (before driving, after driving) ANOVA on ***subjective activation*** in the morning session showed a significant main effect of Chronotype, *F*(1, 23) = 9.88, *p* < .01, $\eta p^2 = .30$, such that morning-type reported higher activation (M = 55.45, SD = 15.54) than evening-type (M = 38.06, SD = 11.65) participants. The Pre-post effect was also significant, *F*(1, 23) = 5.16, *p* = .03, $\eta p^2 = .18$, leading to reduced activation at the end (M = 43.21, SD = 16.05) as compared to the beginning (M = 51, SD = 20.14) of the session. The analysis on subjective affect did not show significant main effects or interactions (all *F* < 1).

The analysis of the ***PVT* performance** in the morning session did not show significant differences between chronotypes in terms of median RTs, lapses or anticipations (all *F* < 1).

The Type of stretch (straight, curve) x Chronotype (morning-type, evening-type) x Hemi-lap (1 to 15) ANOVA on the **mean *position error*** during the driving task in the morning session revealed a significant main effect of Hemi-lap, *F*(3.36, 77.30) = 3.52, *p* = .02, $\eta p^2 = .13$. Specifically, the position error followed a significant linear increment across hemi-laps (*r* = 0.89, *p* < .001), that is, the vigilance decrement. Most relevant was the significant interaction between Chronotype and Hemi-lap, *F*(3.36, 77.30) = 3.89, *p* < .01, $\eta p^2 = .14$ (Figure 2). Further analyses revealed that the vigilance decrement was present in the evening-type group (r = 0.91, p < .001), but it was absent in the morning-type group (r = -0.14, p = .63).

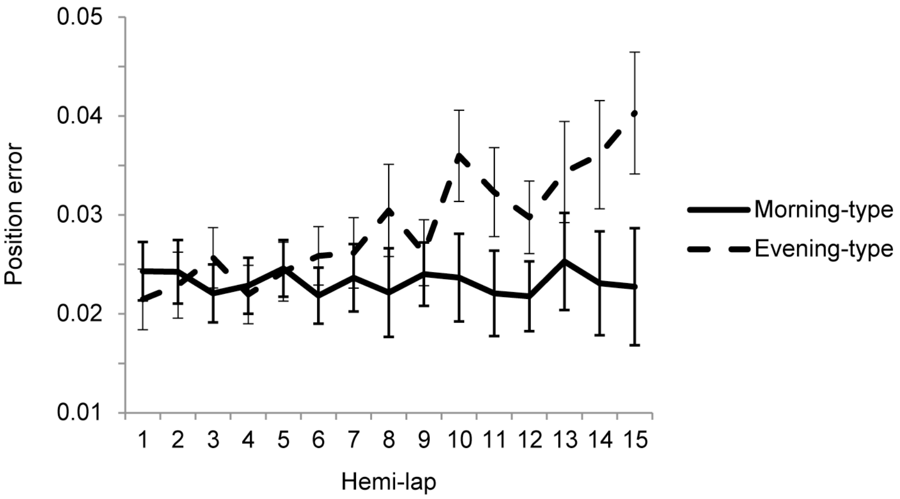

Figure 2. Mean position error (in distance units) as a function of Hemi-lap for morning-type (solid line) and evening-type (dashed line) groups driving in the morning session. Error bars represent the standard error of the mean.

The remaining effects were not close to the significance level (all p > .2), except for a marginally significant main effect of Type of stretch, F(1, 23) = 3.75, p = .07, suggesting that participants tended to drive more accurately in straights than in curves.

The analysis of ***slow alpha*** (*IAF - 4* Hz to *IAF* Hz) frequency power during eyes closed did not show significant differences between chronotypes, F < 1. In the driving task period, the Type of stretch x Chronotype x Hemi-lap ANOVA on the slow alpha power revealed a main effect of Type of stretch, F(1, 23) = 9.59, p < .01, ηp^2 = .29, leading to higher alpha power on curves (M = -1.69) than on straights (M = -1.91), and a main effect of Hemi-lap, F(3.67, 84.33) = 23.04, p < .001, ηp^2 = .50, showing a significant linear increment of alpha across hemi-laps (r = 0.96, p < .001), which suggests a vigilance decrement. In contrast to the behavioral data, this decrement did not differ between chronotypes (F < 1; Figure 3). No other significant terms in the ANOVA reached statistical significance (all p > .23).

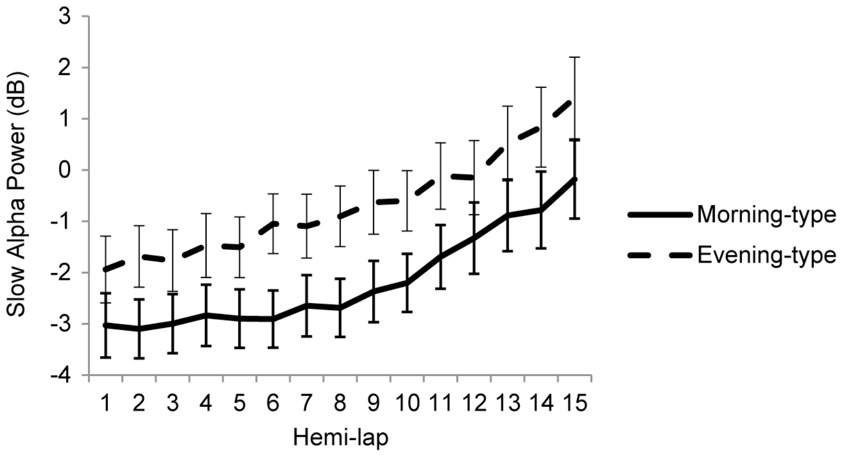

Figure 3. Mean slow alpha power (in dB) as a function of Hemi-lap for morning-type (solid line) and evening-type (dashed line) groups driving in the morning session. Error bars represent the standard error of the mean.

Altogether, the results of the morning session replicated the typical effects associated to the vigilance decrement by showing reduced subjective activation after driving, decreased accuracy and higher variability of the car position along hemi-laps (in the evening-type group), and linear increments in EEG alpha power as a function of hemi-lap (Brookhuis and de Waard, 1993; González et al., 2009; Kecklund and Akerstedt, 1993; Otmani et al., 2005; Ranney et al., 1999). The analyses further showed that morning-type and evening-type participants did not differ in terms of sleeping duration the night prior to the experiment, time awake, body temperature, vigilance as measured by the PVT and EEG alpha power. In contrast, the chronotype groups differed in both subjective activation and the vigilance decrement function related to driving performance. In the morning session, morning-type participants reported to be more active and indeed did not show any vigilance decrement as compared to evening-type participants, who could not attenuate it. This finding extends our previous research indicating that the vigilance decrement in attentional functions related to response inhibition as measured by the SART can be prevented by performing the task at the optimal time of day according to chronotype (Lara et al., 2014).

At first, the lack of chronotype differences in body temperature, PVT performance and alpha activity was unexpected on the basis of previous research (reviewed by Adan et al., 2012), but it can be attributed to the balance of sleep duration and prior sleep between the groups. In that sense, the simulated driving task was more sensitive to individual differences based on chronotype than the other measures of vigilance. The EEG data further showed that slow alpha activity followed a linear increment across the driving task, but it was not sensitive to the additional influence of chronotype.

3.3. Effect of Time of day in the morning-type group

The analysis on the amount of ***time awake*** confirmed that the morning-type group had spent less time awake between the waking-up time and the beginning of the morning session (M = 1.15, SD = 0.32) as compared to the beginning of the evening session (M = 11.35, SD = 1.30), $F(1, 12) = 938.42$, $p < .001$, $\eta p^2 = .99$. Likewise, body temperature was lower in the morning (M = 36.24, SD = 0.47) compared to evening (M = 36.55, SD = 0.53), $F(1, 12) = 5.25$, $p = .04$, $\eta p^2 = .30$.

The Time of day (morning, evening) x Pre-post (before driving, after driving) ANOVA on ***subjective activation*** showed a significant main effect of Time of day, $F(1, 12) = 8.40$, $p = .01$, $\eta p^2 = .41$, such that the morning-type group reported higher activation in the morning (M = 55.45, SD = 15.54) than in the evening (M = 43.25, SD = 14.29). Similarly to results reported in Section 3.2, the Pre-post factor was significant, $F(1, 23) = 5.63$, $p = .04$, $\eta p^2 = .41$. The analysis on subjective affect did not show significant main effects or interactions (all $p > .16$).

The ***PVT*** performance of the morning group did not show significant differences between morning and evening sessions in terms of median RTs, lapses or anticipations (all $p > .12$).

The Type of stretch x Time of day x Hemi-lap ANOVA on the ***position error*** during the driving task in the morning-type group did not show significant effects either with the mean (all $p > .15$) or the *standard deviation* (all $p > .12$).

S*low alpha* power during eyes closed did not differ between morning and evening sessions in the morning-type group, $F < 1$. The Type of stretch x Time of day x Hemi-lap ANOVA on the slow alpha power during driving replicated the results described in 3.2, that is, a main effect of Type of stretch, $F(1, 12) = 13.75$, $p < .01$, $\eta p^2 = .53$, and a main effect of Hemi-lap, $F(1.61, 19.32) = 13.78$, $p < .001$, $\eta p^2 = .53$. None of the remaining terms in the ANOVA reached statistical significance (all $p > .15$).

To summarize, the analysis of the time of day effect in morning-type participants revealed stable performance across sessions in both the PVT and the driving task, although they reported to be more alert and body temperature was lower in the morning compared to the evening. In this group, the lack of a decline in driving performance in the evening session may have been achieved at the cost of higher effort and workload, as previously suggested (Oginska et al., 2010). Although we did not measure subjective workload, this explanation is consistent with our finding of time on task effects on alpha EEG, suggesting that morning-type participants driving at their non optimal time of day also showed the typical neural consequences associated to the vigilance decrement. Another possibility considers that the evening session was not late enough to capture clear effects of time of day on behavior, as it fell within the "forbidden zone for sleep" or "wake maintenance zone"(between 8 and 10 pm), when the alertness level is particularly high (Lavie, 1986).

4. Conclusions

The current study tested for the first time the combined influence of chronotype and time of day on driving performance, and its evolution as a function of time on task, by controlling for the effects of sleeping duration and prior wake. The main finding showed a strong linear decrement in driving performance across time on task in evening-type participants, which was not present in morning-type participants. This result was found in the morning session, when both chronotype groups were tested under similar conditions, that is, at the same time of day and with balanced doses of sleeping duration and prior wake.

The main question then concerns the mechanisms underlying the differential driving behavior of morning-type compared to evening-type individuals. Different personality traits associated to chronotype can play a role, as evening-type participants usually show extraversion, low conscientiousness, high impulsivity and sensation seeking, which have been related to poor vigilance and increased accident risk (reviews by Di Milia et al., 2011; Finomore et al., 2009). Previous findings of both higher arousal as indexed by cortisol level and reduced subjective workload in morning-type compared to evening-type participants when driving in the morning has been interpreted as differential appraisal of the simulated long driving task. This suggests that the task was more challenging and motivating for morning-type than evening-type participants (Oginska et al., 2010). Therefore, further research about the influence of both chronotype and personality factors on fatigue, accident risk and driving should help explain the bases of our main empirical finding (see also Di Milia et al., 2011 for a similar suggestion).

The current study presented several limitations that should be addressed in future research. Despite the multiple inclusion criteria required to participate in the experiment, sleeping duration in the evening session could not be entirely controlled in the final sample, thus making it difficult to analyze the data from evening-type participants in the evening session (the synchrony effect was nevertheless studied by means of analyses of covariance). This circumstance might be a normal consequence of testing under ecological free-living conditions as compared to more controlled experimental settings typically used in circadian rhythm research, such as procedures involving forced-desynchrony and the measurement of circadian variables during the week prior to the experiment (Matthews et al., 2012). Another aspect susceptible of improvement concerned the sample, which could have been larger and include male participants. It is not uncommon, however, to find studies focusing on one sex, male in this case (Matthews et al., 2012; Oginska et al., 2010), so we do not have strong reasons to expect different results as a function of sex in our experiment. We also focused on testing extreme chronotypes in order to optimize the finding of chronotype effects. Further research could also test intermediate chronotypes, who represent about the 60% of the population. Nevertheless, our selection criteria assured the balance of other several key variables for circadian research (see also Akerstedt et al., 2010; Oginska et al., 2010). Finally, we acknowledge that our study was limited to the use of a simulated driving task. The generalization of the current findings to real driving settings should be further supported by future experiments on the field and demographic studies (Di Milia et al., 2011) on the relationship between chronotype, time of day and traffic accidents.

To conclude, the current research contributes to further understanding of main circadian and time-related factors by emphasizing the relevance of chronotype, an under-studied but influential variable with regard to performance in vigilance and driving tasks. The consideration of individual variability in chronotype in combination with time of day and sleep-related factors can provide practical implications for the design of work schedules to enhance human performance and prevent accidents during activities involving health risks. Future research on the interactive effects of circadian and sleep factors should inform the design of effective countermeasures to prevent declines in performance for tasks executed under non-optimal circadian conditions.

5. Acknowledgments

This work was supported by the Spanish Ministerio de Ciencia e Innovación (Ramón y Cajal programme: RYC-2007-00296, PLAN NACIONAL de I+D+i: research grant PSI2010-15399) to AC, by a predoctoral grant (FPI, MICINN) to EM, and by the Junta de Andalucía (research grant: SEJ-6414) to DS and AC. The authors are grateful to Dr. Juan Antonio Madrid and Dr. Mercedes Atienza for their helpful advice on the design and analysis of this research.

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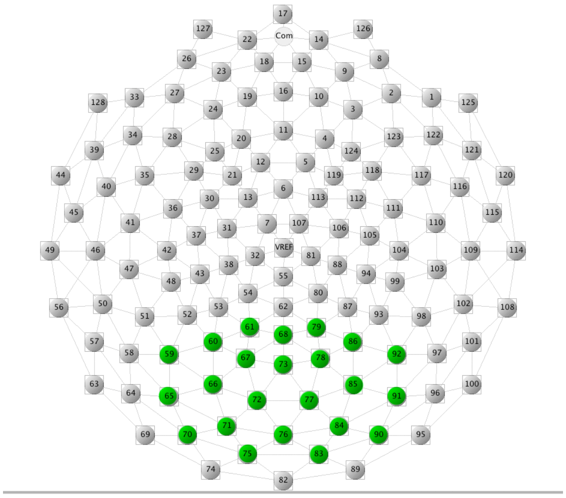
Supplementary Material.

"Effects of chronotype and time of day on the vigilance decrement during simulated driving".

1. Supplementary Methods

Electrophysiological activity was recorded from 128 electrodes referenced to the vertex. The electrodes located above and beneath the eyes, and to the left and right of the external canthi of the eyes were used to detect blinks and eye movements. The EEG net was connected to an AC-coupled high-input impedance amplifier (200 MΩ), and impedances were kept below 50kΩ, as recommended for the Electrical Geodesics high-input impedance amplifiers. While registering, the signal was amplified, filtered (0.1 to 100 Hz band pass) and digitized with a sampling rate of 250 Hz using a 16 bits A/D converter. EEG data from all periods (eyes opened, eyes closed and driving) was off-line preprocessed using FASTER version 1.2.3. (Nolan et al., 2010). Data were re-referenced to average and band-pass filtered between 0.5 and 40 Hz. Before epoching, bad channels were interpolated. Data were divided in 4-second epochs. A new interpolation of bad channels within each epoch was performed. The continuous EEG frequency power in the alpha band was analyzed by Fast Fourier Transform of 256 points using EEGLab software (Delorme and Makeig, 2004). The band frequencies were defined in relation to the IAF following the method described by Klimesch (1999). We analyzed the power of the eyes-closed period in two posterior electrodes, O1 and O2. The average power of those two channels was then used to find the peak between 9 and 12 Hz for each subject and session. This peak was defined as the IAF for that subject in that session. We then focused in the lower alpha band, defined as the frequency between IAF minus 4 and IAF. After averaging data from all participants, a channel spectra map was then generated for the eyes-closed period, which was used to select the cluster of electrodes with the highest activation on the alpha frequency band. This cluster comprised the posterior region of the brain on both hemispheres (Figure 2). We used this cluster for all the analyses.



Supplementary Figure 1. Electrode location of the 128-channel net. Green electrodes represent the cluster chosen for the EEG analyses during the simulated driving task.

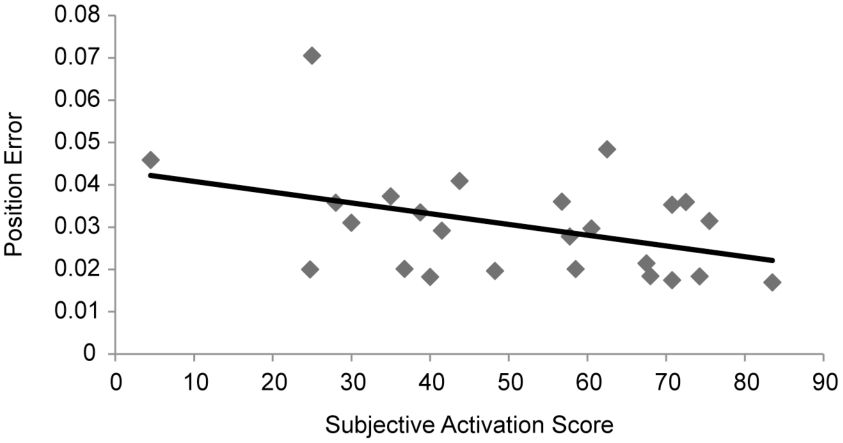
2. Supplementary Results

2.1. Effect of Chronotype in the morning session: Analysis of the standard deviation of the position error.

The Type of stretch x Chronotype x Hemi-lap ANOVA on the *standard deviation of the position error* replicated the pattern of results described above for the mean position error. That is, we found a significant main effect of Hemi-lap, $F(4.33, 99.63) = 2.83$, $p = .03$, $\eta p^2 = .11$, and a significant interaction between Chronotype and Hemi-lap, $F(4.33, 99.63) = 2.54$, $p = .04$, $\eta p^2 = .10$, which revealed increasing variability of driving performance across time on task (i.e., the vigilance decrement) only for evening-type but not morning-type participants. The main effect of Type of stretch, $F(1, 23) = 6.58$, $p = .02$, showed higher variability of driving performance in curves than in straights.

2.2. Multiple regression analysis in the morning session.

A multivariate stepwise regression analysis was performed to predict mean error position of driving performance in the morning session, which included rMEQ scores, subjective activation and affect before the driving task, RT performance in the PVT and alpha power during driving. A significant model was obtained, *F*(1,23) = 4.34, *p* = .049, which included subjective activation (beta = -.41, R^2 = .16, adjusted R^2 =.13) as the only significant predictor. As can be observed in Figure 5, higher scores of self-reported activation just before the driving task were associated to lower position errors in driving performance.



Supplementary Figure 2. Mean position error plotted against scores of subjective activation before the driving task in the morning session.

The regression analysis did not find a correlation between slow alpha EEG and driving performance, which did not confirm our hypothesis based on previous research (Akerstedt et al., 2010; Kecklund and Akerstedt, 1993; Lal and Craig, 2002), but it is consistent with other studies (Otmani et al., 2005a). The behavioral measures provided by the PVT were not able either to reliably predict driving performance in our experiment, which suggests that simple RT short tasks are not sufficient to predict performance of complex tasks like driving (Baulk et al., 2008; see also Matthews et al., 2012; but see recent evidence by Jackson et al., 2013). On the other hand, subjective activation showed a significant correlation with driving performance, which is congruent with multiple studies (Akerstedt et al., 2010; Ingre et al., 2006; Otmani et al., 2005b; Reyner and Horne, 1998). The fact that the correlation was rather weak and it did not explain much variance in the data could be improved by increasing sample size.

2.3. Analysis of the synchrony effect by ANCOVA

The analysis including prior sleep to the evening session as a covariate revealed a synchrony effect on *subjective activation* which was reflected by a significant interaction between Chronotype and Time of day, *F*(1, 22) = 17.72, $p < .001$, $\eta p^2 = .45$. Planned comparisons showed that the morning-type group reported higher activation in the morning (M = 55.45, SD = 19.86) than in the evening (M = 41.85, SD = 19.69), *F*(1, 22) = 8.59, $p < .01$. In contrast, the Evening-type group reported higher activation in the evening (M = 53.92, SD = 20.58) than in the morning session (M = 40.23, SD = 20.76), *F*(1, 22) = 10.96, $p = .003$.

The ANCOVA on the reaction time data from the PVT also confirmed the synchrony effect by a significant interaction between Time of day and Chronotype, *F*(1, 22) = 12.35, $p = .002$, $\eta p^2 = .36$. Planned comparisons in the evening-type group showed that RT was slower in the morning (M = 309, SD = 39) than in the evening (M = 287, SD = 30), *F*(1, 22) = 13.36, $p = .001$. No significant difference was found for the morning-type group, *F*(1, 22) = 2.30, $p = .14$.

Most relevant was the finding of synchrony effects on the vigilance decrement during driving performance as revealed by a significant interaction between Time of day, Chronotype and Hemi-lap, *F*(3.32, 73.09) = 3.00, $p = .002$, $\eta p^2 = .18$. Further analyses revealed a significant interaction between Chronotype and Hemi-lap in the morning session, *F*(3.34, 73.53) = 4.31, $p < .01$, $\eta p^2 = .16$, but not in the evening session, *F*(3.16, 69.60) = 1.24, $p = .30$.

The ANCOVAs on the alpha EEG data did not reveal any significant results (all $p > .1$).

To sum up, covariate analyses further confirmed the finding of a synchrony effect in driving performance, indicating that the vigilance decrement can be counteracted by driving at the optimal time of day according to the chronotype.