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Sleep quality and comfort in fully automated vehicles: A comparison of two seat configurations

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A R T I C L E I N F O

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A B S T R A C T

As autonomous driving technology advances, the possibility of using vehicles as sleeping environments becomes increasingly relevant. To investigate the feasibility of this concept, a sleep study was conducted with twelve participants who were given a 4-h opportunity window to sleep in both reclined and flat seat configurations. The evaluation involved both objective measures, including polysomnographic (PSG) data analysis, and subjective measures through questionnaires, assessing sleep quality and comfort. While the sleep quantity results were comparable between the two sleeping positions, the reclined position showed a slight advantage in sleep quantity (TST and WASO). Interestingly, a trend highlighting a possible difference was found between the seat positions regarding non-rapid eye movement stage 3 (NREM 3). NREM 3 tended to be in a higher proportion of total sleep time in the flat seat position. Sleep onset latency (SOL) also showed a trend of a shorter latency by participants in the flat position. Additionally, most participants reported a preference for the flat position over the reclined position. These findings suggest that a flat seat configuration could offer a more comfortable and restful sleep environment for passengers in autonomous vehicles.

1. Introduction

Increasingly higher levels of vehicle automation are currently being developed (Audi, 2023, Moia, 2023, Nissan Motor Co., 2023, Tesla, 2023; Daimler, 2023; SAE, 2021). With the upcoming release of fully automated vehicles, there will be plenty of new opportunities for occupants. In this context, several studies have explored alternative use cases that people wish to engage in while travelling in these vehicles (Becker et al., 2018; Cyganski et al., 2015; Kyriakidis et al., 2015; Östling and Larsson, 2019), with sleeping being identified as one of the most popular priorities.

Sleep is one of our fundamental daily activities. It takes up a third of our daily time; and good sleep is essential for health, well-being and quality of life (Institute of Medicine, Committee on Sleep Medicine and Research, 2006; Watson et al., 2015). Moreover, daily performance depends highly on sleep quality (Barnes and Watson, 2019; Miyata et al., 2013; Vyazovskiy, 2015). Adults are recommended to sleep seven to 9 h daily, although adults often sleep less than recommended (Alonzo et al., 2021; Alsaggaf et al., 2016; Peltzer and Pengpid, 2017; Quick et al., 2016; Steptoe et al., 2006). Short sleep durations have been often associated with poorer health (Franceschini et al., 2020; Steptoe et al., 2006; Wells and Vaughn, 2012; Zee and Turek, 2006). In particular, during the day after a night of poor or abnormal sleep, there are immediate negative physical and cognitive effects, such as concentration and vigilance detriments, memory blanks and irritability (World Health Organization, 1998).

An optimal sleep environment is key to achieving good sleep quality (Caddick et al., 2018). In a car interior, accomplishing this ideal sleeping environment is troublesome due to limited space and car movement. However, one of the opportunities in this scenario is the high level of control over the sleep environment. This includes lighting (Albahri, 2012; Bertolini, 2017; Garcia et al., 2019; Heuer et al., 2002; Lam et al., 2015; Schofield et al., 2016; Solari, 1997; Tonar et al., 2012), temperature and air quality, as well as the creation of a specific car seat for the purpose of sleeping, addressing the seat angles, as it is one of the main differences between today's car seat and a bed.

In the context of travelling in a car, a few studies have investigated

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Abbreviations

EEG	Electroencephalography: an electrodiagnostic technique to measure the electrical activity produced by the brain
EMG	Electromyography: an electrodiagnostic technique to measure the electrical activity produced by skeletal muscles
EOG	Electrooculography: an electrodiagnostic technique to measure the electrical activity produced by eye movements
PSG	Polysomnogram/polysomnographic: multiparameter diagnosis and study technique in sleep medicine. It monitors many body functions, including brain activity (EEG), eye movements (EOG) and muscle activity (EMG)

sleep and seating positions. Stanglmeier et al. (2020) argue that a reduced seat tilt is the most optimal solution for sleeping in a vehicle in order to reduce space use. This reclined position, of 40° seat pan and 65° backrest with respect to the horizontal and vertical, respectively, was also optimal regarding biomechanical quality, i.e. the interface pressure score. However, when participants were asked about their preferred position for sleeping, they chose the flattest option of 20° seat pan and 75° backrest. People choosing the seat position closer to a flat lying position for sleeping or relaxing were also observed by Smulders et al. (2016) and Bohrmann and Bengler (2020).

PSG has been defined as the gold standard of sleep evaluation yet, there is limited literature including PSG in the evaluation of sleep in the car context. Roach et al. (2018) evaluated through PSG the quantity and quality of sleeping in three different seat positions, upright (20° backrest from the vertical), reclined (40° backrest) and flat (87° backrest). The study findings revealed that sleep quality improved with the increase of backrest angle, but no significant differences were found between the reclined and flat seat positions.

In the present study, the effect of two different seat positions, reclined (60° backrest from the vertical, 20° seat pan from the horizontal) and flat (87° backrest and 90° seat pan from the vertical) on sleep quality is investigated. The experiment includes objective sleep evaluation techniques (PSG including EEG, EOG and EMG), as well as subjective methods, which are based on sleep medicine and previous established research framework (Caballero-Bruno et al., 2022a, 2022b). Based on preceding research, the main hypothesis is that the quantity and quality of sleep in a seat increase as the seat tilt increases towards horizontal.

2. Material and methods

2.1. Participants

Twelve participants (7 women, 5 men) volunteered to be part of the study (Table 1). Exclusion criteria included neurological, psychiatric or psychosomatic diseases, sleep disorders, intake of central nervous substances, increased alcohol, caffeine and/or taurine consumption, pregnancy, prone position sleep preference, uncomfortable feeling to sleep in a vehicle, back problems and/or definite or moderate evening chronotypes according to Horne and Östberg (1976). These criteria aimed to minimize the risk of poor sleep due to external factors during the testing as well as avoiding poor electrode readings. Moreover, due to prototype seat limitations, only participants with a height in range between 160 cm and 185 cm and weight under 100 kg were recruited. Finally, due to the COVID-19 pandemic, COVID risk groups according to RKI definition (Rommel et al., 2021) were also excluded.

A pre-screening was implemented, including demographic questions, questions regarding sleeping habits, like the Pittsburgh Sleep Quality Index (PSQI) (Buysse et al., 1989) and the Morningness–eveningness questionnaire (Horne and Östberg, 1976). No sleep deprivation was used to observe a more natural sleep behaviour.

This study was approved by Ethics Committee of the Medical Faculty of the Eberhard Karls University Tübingen (Number: 184/2022BO2) and followed the guidelines of the Declaration of Helsinki. Informed consent has been obtained from all the participants prior to the experiment.

Table 1
Anthropometric measurements of the participants.

Participants [n = 12]	Mean	SD
Age (years)	25.9	4.6
Height (cm)	172.3	6.6
Body weight (Kg)	66	10.6

2.2. Test conditions

The seat prototype used in the study was positioned inside of a Volkswagen T6.1 Multivan. The interior surrounding of the seat prototype (Fig. 1) was built to be a comfortable, private space, resembling that of a first-class long-distance airplane cabin. For the testing purpose, the belt system visible in the picture was not used.

The purpose of the study was to compare the sleep achieved in two different seat positions, a reclined and a flat seat position. The reclined position at 60° from the vertical, close to position prior described and studied by Smulders et al. (2016) and Stanglmeier et al. (2020), and a lying position at 87°, resembling a flat bed angle (Fig. 3). The researchers conducted pilot tests to determine the most comfortable angles for the seat pan and leg support for each backrest position. The seat pan angles were set at 20° and 0° relative to the horizontal, while the leg support angles were adjusted to 65° and 90° from the vertical, for the reclined and the flat position, respectively. Therefore, the seat could be set up in those two positions as illustrated in Fig. 2.

Previous studies (Caballero-Bruno et al., 2022a, 2022b) suggest that foam stiffness might be one of the critical aspects when it comes to improving sleep quality. Therefore, a foam optimization process was executed by experts, considering previous studies comfort evaluation and participants' feedback comments. The result of this process was a two layered surface with different foam characteristics (Fig. 3). The under layer is made from a traditional foam of 3.9 kPa and 20 mm thickness and the over layer is made from viscoelastic foam of 1.6 kPa of 30 mm thickness.

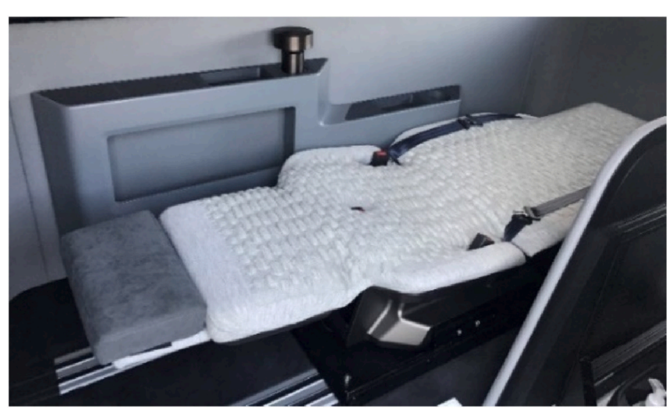

Fig. 1. Prototype seat and environment inside the vehicle in the flat position.

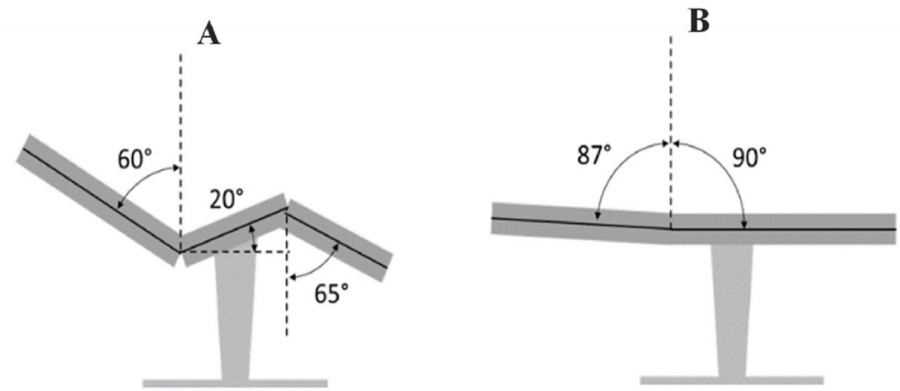

Fig. 2. Configurations for reclined and flat seat conditions. (A) Reclined (B) Flat.

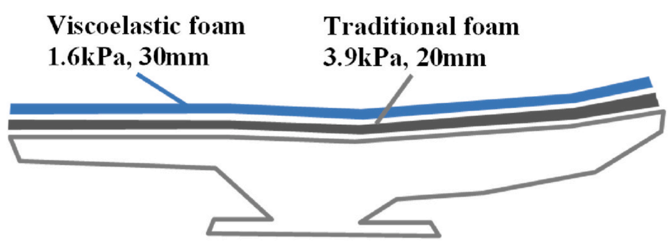

Fig. 3. Side view diagram of seat prototype in flat condition. Blue area represents the 1.6 kPa layer of foam and grey area represents the 3.9 kPa layer of foam. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

2.3. Sleep environment

The Volkswagen T6.1 Multivan vehicle, containing the seat prototype, was located inside a laboratory. In order to get a clean and good electrode signal for the objective sleep assessment, the vehicle was static during the experiment (Benbadis, 2005).

In order to provide a comfortable and comparable temperature inside of the vehicle, the laboratory was cooled with an air conditioning unit before the start of the test sessions. The temperature inside the room and inside the vehicle was measured and recorded at the start time of each trial. Temperature inside de car had a mean (±ST) of 20.6 (±2.59 °C).

To ensure a realistic simulation of the driving experience, the car windows were covered to prevent the participants from seeing outside of the vehicle. The light sources from the room and the vehicle were turned off, to provide a dark light situation in the vehicle that is suitable for sleeping (<10 lx).

In addition, a realistic acoustic environment was provided by playing audio from a real vehicle driving at 100 km/h on a smooth road surface through the car's speakers. This audio was played throughout all sessions, including the familiarization phase, and helped to create a sense of immersion for the participants. To minimize any external disruptions, sound from outside the vehicle was kept to a minimum. Any environmental disturbances, such as loud noises from outside the vehicle, were recorded.

2.4. Subjective measurements

Sleep diaries are widely used as a powerful tool for subjective sleep assessment (Buysse et al., 1989). In this study sleep diaries were used as an instrument to understand influencing factors, such as special sleep events previous to the data collection. Participants started recording sleep diaries two days before the first data collection and continued until the date of the second data collection. The sleep diary was based on the extended version of the consensus sleep diary (Carney et al., 2012). When relevant, notes on subjective data related to sleep specific rare events were done. Furthermore, the PSQI was used to determine the sleep quality at home before the study (Buysse et al., 1989).

On the day of the study session, a collection of subjective questionnaires was done before and after sleeping. The goal of these questionnaires was to find out the opinion of the participant, as well as subjectively evaluate the sleep and the seat position. This was of special importance when interpreting the objective sleep parameters and identifying the underlying reason of possible discomfort and disturbances. Participants rated five items on a 7-point Likert scale as to how comfortable or uncomfortable they felt (−3 = strong discomfort, 0 = neutral, +3 = strong comfort). The five items were head/neck, back, buttocks, legs/feet and general comfort. Participants rated their comfort initially before lights out time and again 4 h later after waking up while sitting/lying on the seat.

Other relevant factors that might influence the quantity and quality of sleep are sleepiness and mood. Therefore, the Karolinska Sleepiness Scale (KSS) (Akerstedt and Gillberg, 1990; Kaida et al., 2006) and the Multidimensional Mood Questionnaire (MDMQ) (Steyer et al., 1994) were also provided before and after sleeping. To explore participants' perception regarding their experienced sleep in the car, a self-reported sleep timeline was filled by the participants retrospectively. This method was used in previous research (Caballero-Bruno et al., 2022b) to compare the self-reported and PSG-based sleep hypnograms.

A final questionnaire was requested after participants have tested both of the conditions. This final questionnaire includes: seat condition preference, the extension of the User Experience Questionnaire (UEQ+) (Laugwitz et al., 2008; Schrepp and Thomaschewski, 2019) and the opportunity to give general remarks about the study, the sleep and/or the seat.

2.5. Objective sleep measures

In this study, PSG was included as the main way to evaluate sleep objectively, by determining the sleep phases. PSG is current gold standard, as it provides the most accurate information on sleep architecture (Rundo and Downey, 2019). The neurophysiological data obtained from PSG allows for a more in-depth understanding of sleep quality, which cannot be achieved through subjective methods alone, making it a preferred method in sleep medicine (Ibáñez et al., 2018).

Sleep recording and evaluation followed the American Academy of Sleep Medicine rules (Berry et al., 2012a, 2012b, 2017). However, since the objective of the study was not the diagnosis of sleep related disorders, electrocardiogram and pulse oximetry were excluded. EEG signals were recorded from eight scalp electrodes (F3, F4, C3, C4, P3, P4, TP9 and TP10 according to the 10–20 system). The Fz was used as common reference and EEG was grounded to AFz. EOG was recorded from 4 channels which were bilaterally referenced (left HEOG-right HEOG2, left VEOG1-right VEOG2). EMG was collected using two bilaterally referenced electrodes at the chin (EMG1-EMG2) (Fig. 4). All the signals were digitized at 1 kHz, high pass filtered with a time constant of 10 s and stored. High-quality Ag/AgCl gel-based passive electrodes and amplifier from Brain Products (Brain Products GmbH, 2022) were used for this purpose.

To identify the different sleep and wake stages, the automated sleep algorithm YASA (Vallat, 2018; Vallat and Walker, 2021) was used, instead of traditionally manually human scoring, which is often related with human errors (Berthomier et al., 2020; Fiorillo et al., 2019; Rosenberg and van Hout, 2013). This algorithm is an unsupervised machine learning which has demonstrated a median accuracy of 87.46% using a dataset of 585 full-night manually scored sleep hypnograms (Vallat and Walker, 2021). Vallat and Walker (2021) suggested choosing a central electrode for the scoring. Neurophysiological signals were down sampled to 100 Hz and a single central EEG channel C4, the EOG channels and EMG channel were used for the automated sleep scoring. Previous to the automated sleep scoring, EEG signals were re-referenced to the electrode on the mastoid TP9, opposite to C4, and the signals were bandpass-filter with 0.40 and 30 Hz as cutoffs (Vallat, 2018; Vallat and Walker, 2021). The YASA-based hypnograms were manually reviewed for misclassifications by two trained technicians using 30 s windows of the down-sampled, filtered PSG signals. Hypnograms were inspected individually and any anomalies that could be observed in the plots were identified and noted. To objectively evaluate sleep quality, various sleep parameters (Table 2) were obtained using the YASA-based hypnograms.

2.6. Familiarization phase

To familiarize participants with the study setup and ensure their compatibility with the study requirements, a familiarization protocol was conducted. During this familiarization phase participants were informed about the study, as well as experienced the interior, the seat and electrodes setup.

After the participant signed the informed consent and data protection agreement, demonstration and explanation of the sleeping environment and the measuring equipment followed. Moreover, further explanation of the EEG, EMG, EOG were also done by the test experimenter. To create an inviting, calm and relaxing atmosphere, relaxing ambient music (Entspannungsmusik für Schlaf, 2017) was used while the attachment of the electrodes on the scalp. Earlier studies revealed that such music can reduce anxiety and improve subjective sleepiness (Cordi et al., 2019; Dickson and Schubert, 2019; Holm and Fitzmaurice, 2008; La Torre-Luque et al., 2017). After the electrodes were set up and while sitting in the test environment, participants were instructed to relax, try to rest and imagine sleeping 4 h in the car for 5–10 min. Finally, the participants were asked if they could imagine sleeping inside the vehicle while wearing the electrodes. If the participants agreed and no issues were detected during the familiarization, they were scheduled their data collection appointments for the first and second session.

2.7. Experimental procedure

To ensure participants experienced both test conditions (Chapter 2.2.), two experimental sessions were conducted for each participant, separated by a wash-out period of at least one week. To avoid sequence effects, the order of sessions was systematically changed between participants, with one half of the participants starting in condition A and the other in condition B. Participants were scheduled to arrive at the location of the study at around 18:30 h and had a 4-h long opportunity to sleep, from approximately 20:00 h to 00:00 h, during each session.

In each session, initial participant's state and opinion were first gathered through questionnaires regarding the current comfort, mood and sleepiness. The attachment of electrodes was done as in the familiarization session while relaxing music was playing.

At that time, vehicle audio was turned on and participants could start their sleep. The precise time of lights out was noted for each participant. For safety, participants could at any point communicate with the test experimenter through a provided baby-phone. Furthermore, the experimenter was always in the adjacent room monitoring the EEG, EMG and EOG signals.

After 4 h, participants were awoken by the experimenter through the baby-phone and the light was turned on. Once the participants were awake and ready, they answered the post sleep questionnaire consisting of current comfort, mood, sleepiness and sleeping experience and timeline questions.

Once participants completed the two sessions in both seat positions, the final questionnaire was submitted as an online questionnaire the morning after the second data collection session.

2.8. Statistical analysis

R Studio version 1.2.5042 (RStudio Team, 2020) was used to perform all the statistical analysis. ANOVAs were performed using the package *rstatix*, while *t*-tests, Wilcoxon tests and Pearson correlations were calculated using the R packages *stats* and *coin* (Hothorn et al., 2021). All visualizations of the data were created using the R package *ggplot2* (Wickham, 2011). Data assumptions were checked before the significance tests were performed. Statistically significant differences in this study refer to a $p < 0.05$.

Wilcoxon tests were performed regarding comfort and discomfort evaluation. Wilcoxon tests were used to compared pairwise two factors: seat position (60° vs. 87° from the vertical) and time (0 min vs. 240 min).

Paired t-tests were performed in all normally distributed sleep parameters, including TST, W, N1, N2, N3, R, %N1, %N2, %N3, %R, SE and SME. The rest of sleep dependent variables (i.e., SPT, SOL, N3L, REML, WASO, WASF and SS), which were non-normally distributed,

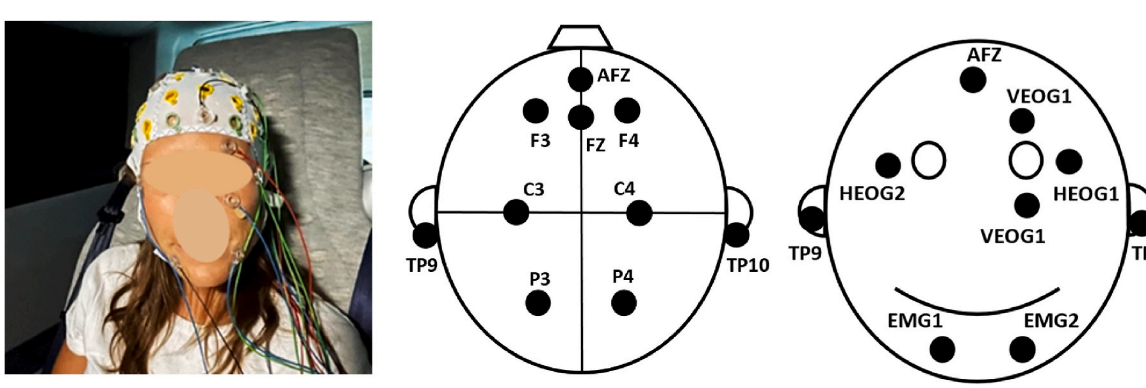

Fig. 4. Participant wearing the electrodes set up and top and front view diagrams of electrode placement.

Table 2
Sleep parameters used to evaluate sleep quantity and quality from the PSG data. Good sleep quality characteristics are included as reference (Boulos et al., 2019; Carskadon and Dement, 2005; Carskadon and Rechtschaffen, 2005; Dykierek et al., 1998; Ohayon et al., 2017; Shrivastava et al., 2014).

Acronym	Sleep Parameter	Meaning	Good sleep quality criteria
SPT	Sleep Period Time	Duration from first to last period of sleep	A longer SPT is generally better. It can also be the indication of other sleep issues, such as fragmentation or long Wake After Sleep Offset (WASF).
TST	Total Sleep Time	Total time spent in any of the stages of sleep during SPT TST = NREM1 + NREM2 + NREM3 + REM	Longer TST is better.
W, N1, N2, N3, REM	Sleep stages total times	Total time in each individual sleep stage	Each sleep stage has a function. Healthy sleeps include all of them, in specific proportions and orders (typically: W, N1, N2, N3, REM) during a full night sleep.
%W, %N1, %N2, %N3, %REM	Percentage of sleep stages	Proportion of the sleep stage of TST in % E.g.: (N3/TST) * 100	During a full night sleep N1 accounts for 2–5%, N2 for 45–55%, N3 for 10–20% and REM for 20–25%. A larger %N3 and smaller %REM is expected due to shorter study time.
SOL	Sleep Onset Latency	Time taken after lights out to start sleep activity	Shorter SOL is better. Less than 30 min is considered good sleep quality.
N3L	N3 Latency	Latency to first N3 Stage from the lights out	A normal, healthy N3L ranges from 10 to 70 min.
REML	REM Latency	Latency to first REM Stage	A normal, healthy REML ranges from 50 to 100 min.
WASO	Wake After Sleep Onset	Duration of wake periods within SPT	Shorter WASO is better. ≤20 min is considered good sleep quality, >40 min is considered bad sleep quality.
WASF	Wake After Sleep Offset	Duration of wake period after sleep offset	Shorter WASF is better, ideally 0 min.
SE	Sleep Efficiency	TST/TIB (Time in Bed) * 100 (%) TIB ≈ 240 min	Higher SE is better.
SME	Sleep Maintenance Efficiency	TST/SPT *100 (%)	Higher SME is better.
SS	Sleep Stability	Average of the transition probability of N1, N2, N3 and REM	Higher SS is better.

Wilcoxon tests were performed. Due to the small number of participants in this study ($N = 12$), type II errors are quite likely. To provide an indication of the size of the difference between conditions, Cohen's d was calculated for each dependent variable (Cohen J., 1988; Sawilowsky, 2009). Effect sizes were taken into consideration when they exceeded a moderate level ($d > 0.40$).

Finally, additional analysis was done to find possible explanations of different results, as well as validate subjective methods. Data comparison was done through the creation of Pearson correlation matrices. Significant moderate, strong or very strong correlation coefficients ($r > 0.4$) (Schober et al., 2018; Taylor, 1990) were identified for further exploration. Boxplots or scatter plots were used in order to find plausible explanations and, if appropriate, possible causalities.

3. Results

3.1. Self-reported assessment

3.1.1. Comfort

The subjective comfort and discomfort ratings for general and the different body parts comfort were plotted and visually examined (Fig. 5). Generally, the ratings indicated a positive experience, and the participants did not report strong discomforts (−3) at any point. Wilcoxon tests were performed to find significant differences. In terms of the seat position, there were no significant effects present. However, time was shown to have a significant effect on the back area, where comfort rating improved with time for both seat positions. ANOVAs for KSS and MDMQ scores did not reveal differences between the positions.

3.1.2. Self-reported sleep

Participants' perception of their own sleep resulted in different subjective sleep data (Fig. 6). In general terms, reported sleep was similar among the two conditions and large standard deviations can be observed. Although visually we can observe differences in the SOL and WASF between the conditions, there were no significant effects found between the positions (Table 3). Nonetheless, *t*-test and Cohen's d test showed that there is a trend for the reported SOL to be shorter in the flat position.

3.1.3. Preference

A final evaluation after both sessions included the question regarding the preference of the condition for sleeping (Fig. 7 - A). Although the reported sleep TST and quality was similar for both positions, most of the participants, 9 out of 12, chose the flat seat position as their preferred one for sleeping while travelling. The preference regarding the seat position seems to be related to the reported subjective TST and sleep quality. Participants chose the seat position in which they perceived longer and higher quality sleep (Fig. 7 - B).

3.2. Objective neurophysiological data

Several sleep parameters were calculated for evaluation (Table 4). Compared to ideal sleep parameter values (Table 2), TST and SE are slightly reduced. Regarding sleep stage proportion, a slightly elevated %N1 was observed. Stages %N2 and %N3 show expected proportions and %REM levels are slightly low. Regarding latencies, SOL was for most participants healthy and a sign of good sleep quality. N3L was elevated in the case of the reclined position and within the good sleep quality range for the flat position. REML was mostly within the range of good sleep quality, yet some participants showed reduced or prolonged REML. WASO and WASF are quite elevated especially for the flat condition, with three participants with WASF of over 90 min in this

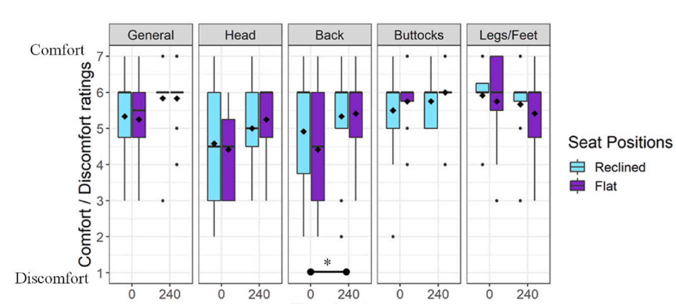

Fig. 5. Boxplot with different body part comfort ratings for flat and reclined seat conditions over time ($N = 12$, ◆ mean, ● outliers). Time in minutes. Main effects in Wilcoxon (*<0.05).

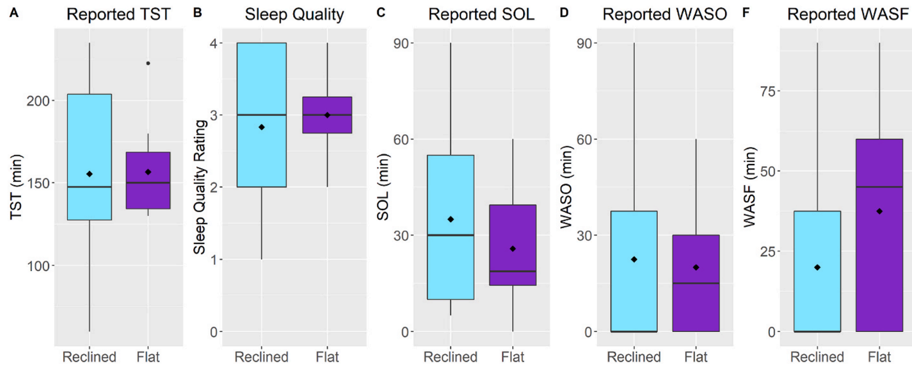

Fig. 6. Reported perceived sleep parameter boxplots for the reclined and flat seat conditions. ($N = 12$, ◆ mean, ● outliers).

Table 3
Effects of seat angle and time on dependent variables related to reported sleep. * indicates significant effects ($p < 0.05$) and+indicates tendency ($p < 0.1$).

Dependent variables	Significance		Effect Size	
	Two-sided unpaired *t*-test		Cohen's	95% Confidence Interval
	t	*p*	*d*	[lower, upper]
Reported TST	0.062	0.951	0.027	[-0.83, 0.96]
Reported SOL	−1.941	0.078⁺	−0.559	[-1.25, 0.29]
	Two-sided, unpaired Wilcoxon test		Cohen's	95% Confidence Interval
	z	*p*	*d*	[lower, upper]
Sleep Quality	3.9937	0.664	0.185	[-0.61, 1.03]
Reported WASO	1.6947	1	−0.090	[-0.92, 0.9]
Reported WASF	1.6958	0.357	0.509	[-0.26, 1.62]

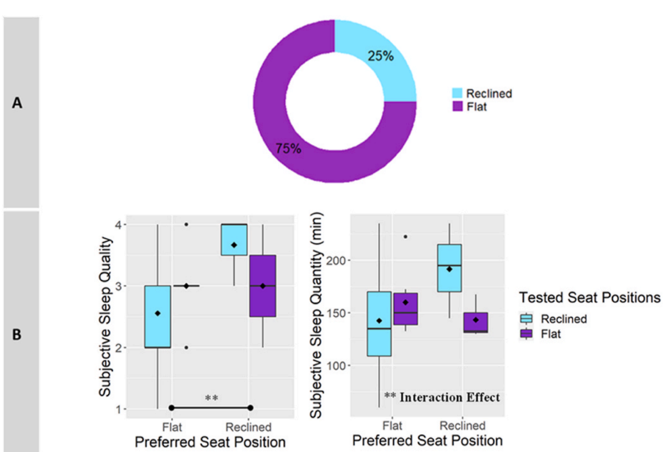

Fig. 7. (A) Preferred seat position for sleeping according to the participants (N = 12) (B) Subjective sleep quantity and quality by preferred seat position for sleeping boxplots as reported by participants (N = 12, ◆ mean, ● outliers). Significant main effects in ANOVA (*<0.05, **≤0.01).

condition. SS was optimal, except for one participant. Regarding individual hypnograms, most of them (91.67%) presented a normal, healthy stage progression and fragmentation of sleep stages for a 4-h sleep opportunity, though individual differences were present.

Sleep parameters were plotted for further examination (Fig. 8). On one hand, SPT, TST and WASF graphs indicated that the sleep quantity was slightly higher in the reclined position. On the other hand, the parameters related to slow wave sleep, %N3 and N3L, indicated a higher proportion and an earlier latency of this stage in the flat position. Moreover, it is also apparent that SOL tended to be shorter in the flat position. Nevertheless, there were no significant effects found (Table 5). Through *t*-tests, Wilcoxon test and Cohen's *d*, trends were identified for %N3 and SOL (Table 5). Both the %N3 and SOL trends indicated that participants obtained better sleep quality in flat position, with higher %N3 and a lower SOL than in the reclined position.

Reported sleep graphs were visually compared with the corresponding real sleep hypnograms (Fig. 9). Some participants reported quite accurate simplified hypnograms (Fig. 9 - A). 5 out of 12 participants had visually similar hypnograms in the reclined positions and 3 out of 12 in the flat position. While other participants' self-reported hypnograms had less in common with the real sleep hypnogram estimated from the PSG (Fig. 9 - B). It was observed that generally participants (91.67%) correctly reported whether they were mostly asleep or awake during the last time slot (minute 210–240). It was also perceived that SOL was generally (75%) reported longer, with a mean of (±ST) 23.6 min (±26.09) longer of reported SOL compared with real SOL. Some of the reported SOLs (41.67%) were closer to N3L time than to real SOL time. Lastly, participants would report if they were on longer period of wake between sleep periods, but not always at the correct time. To confirm these visual similarities between the sleep hypnograms, correlations between the objective and reported parameters were obtained. TST, SOL and WASF sleep parameter were moderately correlated with the PSG-based objective data (Table 6).

4. Discussion

4.1. Main findings

The evaluation of sleep quality in vehicles is an emerging area of research and the present study represents a pioneering effort in this field. To comprehensively assess sleep quality, a multi-method approach was used, combining both subjective and objective data. The analysis of sleep metrics such as SPT, TST, and WASF revealed a non-significant marginal increase in sleep quantity for individuals adopting the reclined position. However, objective data also showed statistical trends in the %N3 and SOL measures, indicating that sleep quality might have been better in the flat position than in the reclined position. Specifically, %N3, representing the percentage of slow-wave sleep (SWS), was higher in the flat position, while SOL, representing the time taken to fall asleep, was lower in the flat position. These specific differences were not observed in previous research (Ogata et al., 2022; Roach et al., 2018). SWS is essential for adequate cognitive functioning, immune system strengthening and memory consolidation (Diekelmann and Born, 2010; Halson and Juliff, 2017; Léger et al., 2018; Maquet, 1995). The role of this stage in sleep is crucial and its presence is necessary to achieve good quality sleep (Datta and O'Malley, 2013). Therefore, these findings suggest that the flat position may be more contributing to achieving deeper and more restful sleep.

In addition to objective data, subjective evaluation of comfort,

Table 4
Descriptive statistics for objective sleep quantity and quality ($N = 12$, except $N = 11$ in REM Latency in the reclined position due to lacking REM stage).

Variables (min, unless specified)	Reclined seat position (60°)				Flat seat position (87°)			
	mean	SD	min	max	mean	SD	min	max
Sleep Period Time (SPT)	222	15	189	235	201	47	120	236
Total Sleep Time (TST)	173	35	115	228	156	42	85	212
WAKE (W)	67	35	14	126	84	42	29	156
N1	25	17	9	64	23	23	6	86
N2	93	29	44	141	79	31	37	140
N3	35	22	5	69	38	18	13	78
REM	19	13	0	46	16	13	1	36
Proportion of NREM1 (%N1)	15%	10%	4%	36%	15%	13%	4%	48%
Proportion of NREM2 (%N2)	54%	12%	38%	81%	50%	9%	38%	67%
Proportion of NREM3 (%N3)	20%	11%	3%	34%	26%	12%	7%	40%
Proportion of REM (%REM)	11%	8%	0%	25%	10%	8%	0%	25%
Sleep Onset Latency (SOL)	15	11	6	41	11	6	5	23
N3 Latency (N3L)	73	58	20	196	50	31	21	130
REM Latency (REML)	101	41	55	197	91	70	9	208
Wake After Sleep Onset (WASO)	53	36	7	108	74	43	16	147
Wake After Sleep Offset (WASF)	4	10	0	36	28	48	0	111
Sleep Efficiency (SE)	72%	14%	48%	94%	65%	18%	35%	88%
Sleep Maintenance Efficiency (SME)	78%	15%	51%	97%	79%	17%	37%	98%
Sleep Stability (SS)	85%	14%	46%	94%	85%	10%	61%	95%

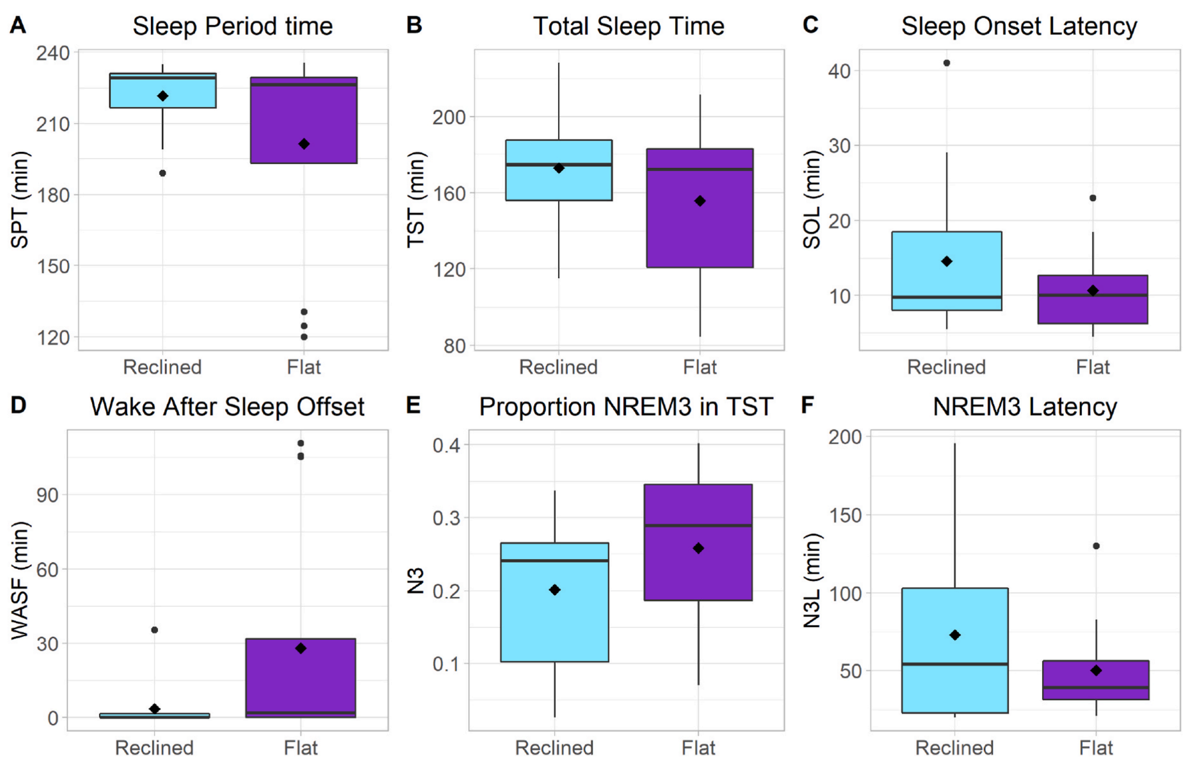

Fig. 8. Sleep parameter boxplots for the reclined and flat seat conditions gathered by PSG ($N = 12$, ◆ mean, ● outliers).

preference, and experience was also conducted. Prior to the study, the comfort of the seat prototype had already been assessed for sleeping use (Caballero-Bruno et al., 2022b), and the results were used to optimize the seat design. The comfort and discomfort evaluation was conducted both before sleep and after the 4-h session. The long-term comfort evaluation in this study indicates the accomplishment of the optimization since ratings were improved in both reclined and flat positions compared to previous results.

Notably, the majority of participants (75%) preferred the flat sleeping position after trying both of the positions for sleeping. The higher %N3 observed in the flat position could have contributed to the participants' preference for this position. Moreover, this result supports the understanding that subjective factors also influence sleep experience, and sleep should not only be evaluated objectively.

4.2. Secondary findings and methodology

Overall, the sleep quantity and quality of participants were found to be adequate, despite the short duration of sleep chance and early bedtime, i.e. ~20:00. The participants slept generally similar amounts in any of the seat positions, with a mean (±ST) 173 min (±35) in the reclined and 156 min (±42) in the flat position. This results were consistent with previous research (Caballero-Bruno et al., 2022b; Roach et al., 2018). Marginally reduced sleep parameters, such as TST and SE, show an acceptable quantity for a 4-h sleep opportunity without sleep deprivation, at an earlier than usual bed time (Roach et al., 2018). While

Table 5
Paired t-tests, Wilcoxon tests and effect size analyses for sleep parameters gathered by PSG ($N = 12$). * Indicates significant effects ($p < 0.05$) and+indicates tendency ($p < 0.1$).

Dependent variables	Two-sided paired t-test		Cohen's	95% Confidence Interval
	t	*p*	*d*	[lower, upper]
SPT	−1.327	0.211	−0.59	[-1.26, 0.26]
TST	−0.939	0.368	−0.45	[-1.28, 0.41]
N1	−0.382	0.709	−0.07	[-1.15, 0.67]
N2	1.498	0.162	−0.49	[-1.59, 0.28]
N3	0.363	0.724	0.13	[-0.81, 1.03]
R	−0.770	0.457	−0.25	[-1.17, 0.57]
%N1	−0.140	0.891	−0.03	[-0.96, 0.76]
%N2	−1.722	0.113	−0.37	[-1.21, 0.46]
%N3	2.140	0.055+	0.50	[-0.35, 1.35]
%R	−0.615	0.551	−0.18	[-1.19, 0.66]
SE	−0.966	0.355	−0.45	[-1.35, 0.36]
SME	0.233	0.820	0.07	[-0.69, 1.10]
SS	−0.033	0.974	−0.01	[-1.03, 0.70]
	Two-sided paired Wilcoxon test		Cohen's	95% Confidence Interval
	z	*p*	*d*	[lower, upper]
SOL	4.288	0.071+	−0.45	[-1.17, 0.43]
N3L	4.287	0.266	−0.49	[-1.34, 0.33]
REML	4.197	0.607	−0.18	[-1.14, 0.70]
WASO	4.286	0.850	−0.09	[-1.15, 0.65]
WASF	0.101	0.194	0.71	[-0.21, 1.35]

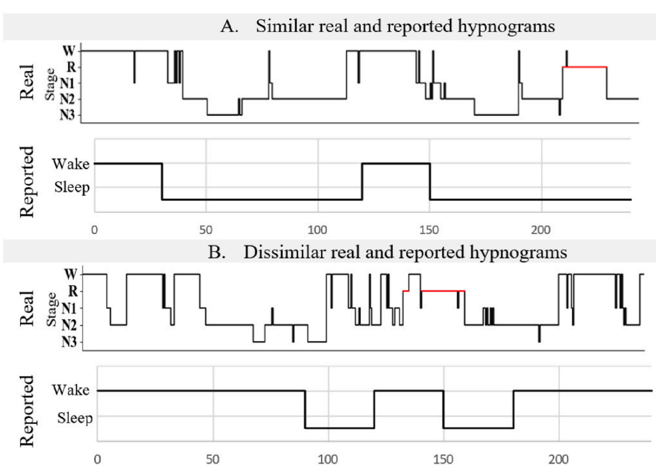

Fig. 9. Examples of a similar (A) and a dissimilar (B) comparison between real and reported sleep hypnograms. X axis: Time (min).

Table 6
Correlations between the objective and reported parameters. Significant correlations indicated as * $p < 0.05$.

Variables	Pearson Correlation	
	r	p
TST	0.57	<0.001*
SOL	0.59	<0.001*
WASO	0.25	0.005*
WASF	0.62	<0.001*

slightly elevated N1 and reduced REM levels were observed, these findings were expected given the reduced sleep duration and environmental conditions.

The evaluation of long-term comfort and discomfort revealed an uncommon behaviour in which the comfort/discomfort score tended to remain stable or even improve over time, as opposed to the usual trend of discomfort increasing over time (El Falou et al., 2003; Lantoine et al., 2022; Vink et al., 2017). This trend could be attributed to the improved seat design and lack of vibration and movement in the car.

The subjective evaluations of sleep were found to be moderately correlated with objective sleep measures. Specifically, self-reported TST, SOL, and wake after sleep onset (WASO) were significantly moderately correlated with their PSG counterparts. These results are consistent with previous studies (Argyropoulos et al., 2003; Matthews et al., 2018). However, it is noteworthy that participants consistently reported longer SOL than objectively measured, even though self-reported TST was within the real TST parameters.

4.3. Limitations and outlook

Environmental factors that could influence sleep were carefully considered in this study. Discomfort points and sleep disturbances caused by real driving movement were excluded from the study. By minimizing the impact of such factors, the focus was able to be on the sleep quality of participants and the differences between the seat positions. The current testing setup with a real car, modified interior and driving sound was designed to give the participants the opportunity to imagine themselves in a real-world scenario. Some participants declared feeling "like the car was really driving". Since the participants had no visual stimuli, this was probably due to the addition of the driving sound. However, the lack of movement and vibration in the scenario probably had an impact on psychological factors, such as trust (Paddeu et al., 2020; Payre et al., 2014) and comfort (Basri and Griffin, 2013; Bubb and Bengler; Chen and Gao, 1990). Specifically, vibration has been classified as one of the main comfort influencing factors when travelling (Mellert et al., 2008). Presumably, normal driving movement would also affect sleep and possibly induce motion sickness (Iskander et al., 2019). Future studies could investigate the impact of a dynamic scenario on sleep quality, comfort, trust and other psychological factors.

One of the main sleep-influencing factors of this study is the early starting time of the sleep opportunity. The starting time was chosen to better represent a realistic driving scenario and due to organizational advantages. However, this was not the usual sleep time for any of the participants. Circadian and homeostatic process are responsible for regulating sleep (Borbély and Achermann, 1999; Saper et al., 2005). The homeostatic process is the process that increases the propensity to sleep during waking time and dissipates it during sleep. This means that participants, who woke up between 06:00AM and 8:00AM, would have had a relatively low sleep pressure at 08:00PM (Cajochen et al., 2006). Also, the circadian process, which reflects the time-of-day-dependent variations of different body functions and correlates closely with sleepiness, was probably in a phase during the sessions that did not provide optimal conditions for the participants to fall asleep (Halberg and Stephens, 1959). Possible solutions for future research include scheduling testing sessions later in the evening or inducing sleep deprivation.

Additionally, to establish a sleep neurological baseline (Gusnard and Raichle, 2001) in a naturalistic setting, including aspects such as habitual bedtime, sleep surface, ambient noise, and light levels, could offers valuable insights for future research. By facilitating a comparison between study sleep hypnograms and typical sleep patterns in home environments, further understanding of the subject can be achieved.

The use of the YASA toolbox as an automated scoring method in this study has demonstrated great potential. These type of methods reveal great potential due to high classification accuracy (Vallat, 2018). Automated methods are user-friendly, less time-consuming and reduce the chances of human error, compared to traditional manual scoring methods. Although automated methods are not yet established as a standard in the research field (Fiorillo et al., 2019; Vallat, 2018), the use of YASA toolbox in this study provides significant benefits in applied sleep research. Therefore, the YASA toolbox could be a valuable tool in future studies.

The study's small sample size may have contributed to the lack of significant effects of seat positions on sleep parameters. Additionally, the study's limited age range, which consisted of a young population free from factors that could potentially influence sleep and comfort evaluations, represents a limitation. Therefore, it is uncertain whether similar results could be obtained from other potential users, including older populations or individuals with impairments.

To further investigate and obtain a more targeted evaluation of comfort and discomfort, future studies could consider using separate rating scales for comfort and discomfort (Looze et al., 2003; Vink and Hallbeck, 2012; Zhang et al., 1996). Furthermore, the seat comfort evaluation could be based on mattress comfort methodology (Buckle and Fernandes, 1998; Naddeo et al., 2015; Wong et al., 2019), which may provide more detailed insights into the comfort level of the seat. It should also be noted that this study only assessed the comfort level during one designated use case: sleeping. However, as seats are often designed for a range of use cases, future research should investigate how other uses for a vehicle seat affect comfort evaluation.

Even though majority of the participants favoured the flat position for sleeping and this result is in line with previous research on this topic (Caballero-Bruno et al., 2022b; Östling and Larsson, 2019; Smulders et al., 2016; Stanglmeier et al., 2020; Yang et al., 2019), the reason for this preference cannot be fully justified by the objective results. This preference seems to be influenced by other factors, beyond those found by objective sleep analysis (Kaplan et al., 2017). Making adjustments to your body position is essential to avoid putting excessive pressure on soft tissues and to prevent your muscles from becoming stiff (Haex, 2004; Koninck et al., 1992). It is crucial to adjust your posture to a reasonable and natural extent to ensure a positive and comfortable sleep experience. The preference for the flat seat position is likely influenced by this factor as well. Previous experience and expectation may also have a significant impact on preference (Naddeo et al., 2015), as most participants chose the angle they already knew for sleeping. Therefore, the study highlights the need for further research in this area and emphasizes the importance of considering both subjective and objective data when evaluating sleep quality.

Overall, this study contributes to the understanding of sleep quality in vehicles and its evaluation. The use of a multi-method approach enabled the collection of comprehensive data from different sources, providing a more complete picture of sleep quality in this context. Subsequent studies can expand on this knowledge by investigating the variables that impact sleep quality in vehicles. Specifically, future research should explore alternative backrest angles, seat pan angles, and different foam materials and hardness. Through this investigation, there is potential for the development of improved ergonomic designs and better sleep quality, which could provide valuable insights in promoting enhanced sleep comfort and alleviating discomfort. Additionally, as new seat angles and body positions are introduced, it is imperative that safety and restraint systems are adapted and updated accordingly.

5. Conclusion

In summary, this study provides a comprehensive understanding of sleep quality and quantity in the context of travelling in a fully automated car. By using a real environment instead of a typical lab, the study provided a more realistic view of sleep in this new context. The study's multi-method approach combining subjective evaluations based on questionnaires and multimodal neurophysiological recordings evaluated with machine learning provided a holistic picture of individual comfort and sleep quality. The findings of this study fill some current knowledge gaps in the field of sleeping while travelling by car and have important implications for the development of new technologies and design of car seats. While this study represents a first step towards a better understanding of sleeping while travelling by car, future research is needed to explore the factors that influence sleep quality in vehicles and develop interventions to improve it.

In conclusion, this study has contributed to the understanding of sleep quality in vehicles and its evaluation. Sleep quality was generally within optimal sleep ranges in both seat positions, with the flat position resulting in deeper sleep and quicker sleep onset for participants. The findings suggest that the flat position may be more conducive to achieving deeper and more restful sleep. Moreover, each participant had the opportunity to sleep in both tested seat positions. The majority of participants preferred the flat position for sleeping in the travelling context.

These findings may have implications for future car seat designs, suggesting that a flat position may be more conducive to sleep quality while travelling. A future where people can comfortably sleep inside a car while commuting or going on holidays might be possible with further developments in car seat designs and technology.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: This manuscript is part of the PhD research of ICB, who is enrolled at the University of Las Palmas de Gran Canaria, Spain: ICB is initiator of the study. She designed the user study and is responsible for the conceptualization, methodology, formal analysis, resources, data curation, writing the original draft, visualization and project administration. ICB, MW and TW are employed by Volkswagen AG, Wolfsburg. KL, DP and MV are employed by Fraunhofer Institute of Industrial Engineering, Stuttgart. NT and DP are employed by Institute of Human Factors and Technology Management, Stuttgart. The objective of this paper was to define the best seat configuration for sleeping during a car journey. Data were collected by and at the Fraunhofer Institute of Industrial Engineering (IAO) in Stuttgart, Germany. This study was financially supported and leaded by Volkswagen AG. The results, opinions and conclusions expressed in this article are not necessarily those of Volkswagen Aktiengesellschaft.

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