How to Work in the Car of the Future?

A Neuroergonomical Study Assessing Concentration, Performance and Workload Based on Subjective, Behavioral and Neurophysiological Insights

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ABSTRACT

Autonomous driving provides new opportunities for the use of time during a car ride. One such important scenario is working. We conducted a neuroergonomical study to compare three configurations of a car interior (based on lighting, visual stimulation, sound) regarding their potential to support productive work. We assessed participants‘ concentration, performance and workload with subjective, behavioral and EEG measures while they carried out two different concentration tasks during simulated autonomous driving. Our results show that a configuration with a large-area, bright light with high blue components, and reduced visual and auditory stimuli promote performance, quality, efficiency, increased concentration and lower cognitive workload. Increased visual and auditory stimulation paired with linear, darker light with very few blue components resulted in lower performance, reduced subjective concentration, and higher cognitive workload, but did not differ from a normal car configuration. Our multi-method approach thus reveals possible car interior configurations for an ideal workspace.

CCS CONCEPTS

• Human-centered computing~HCI design and evaluation methods

KEYWORDS

Multi-method HCI evaluation, autonomous driving, workload, EEG, neurergonomics

ACM Reference format:

Kathrin Pollmann, Oliver Stefani, Amelie Bengsch, Matthias Peissner & Mathias Vukelić. 2019. How to Work in the Car of the Future? A Neuroergonomical Study Assessing Concentration, Performance and Workload Based on Subjective, Behavioral and Neurophysiological Insights. *In 2019 CHI Conference on Human Factors in Computing Systems Proceedings (CHI 2019), May 4–9, 2019, Glasgow, Scotland, UK.* ACM, New York, NY, USA. 14 pages. https://doi.org/10.1145/3290605.3300284

1 INTRODUCTION AND MOTIVATION

Technological innovations are accelerating the advance of autonomous vehicles, which will fundamentally change the way we interact with and use our cars. In the near future, people will no longer have to actively engage in a driving task and will become passive passengers. Consequently, they will have some free time during the car ride that could be used for personal activities. Although travelling in autonomous vehicles can generally be compared to riding a train or a cab, a self-driving car offers some additional advantages. It was shown that the main constraint inhibiting work in trains and planes is space [24]. A car is a restricted, closed space that provides privacy, quietness, and enough room for a single passenger and office tasks [24]. The space available in a car can even be extended when parts of its current interior (e.g. steering equipment) become obsolete. At the same time, this opens new opportunities for the spatial layout and interior design of future cars. The interior could not only be better tailored to individual preferences, but also provide features that support the activity that the passenger carries out in the car such as relaxing, playing a game or working [27, 31]. Since our working styles and habits are becoming more flexible

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CHI 2019, May 4-9, 2019, Glasgow, Scotland, UK.

ACM ISBN 978-1-4503-5970-2/19/05...$15.00.
DOI: https://doi.org/10.1145/3290605.3300284

and independent of time and location, using the car as an office appears to be of special interest. Working during the car ride on a business trip, on the way to work or even to our holiday destination can increase efficiency, and at the same time provide us with an undisturbed environment tailored to our own needs. Will cars ultimately become our new offices?

From the design perspective, various propositions have been made for how cars can be transformed into functional and stylish offices [e.g. 26, 36]. While these designs appear to be relevant, car manufactures are currently still rather focused on the technical developments of autonomous driving than on time usage in self-driving cars. The scientific community, on the other hand, has put some emphasis on the importance of the concrete design and user experience of autonomous driving or, more precisely, the *experience of being driven by a car*. Main research constructs are for example level of autonomy, loss of control, uncertainty, trust, acceptance, and driving fun [37]. Some attempts have also been made to capture people's visions of self-driving cars and activities they might want to engage in during a car ride [3, 27, 31, 45]. These studies do, however, only *identify* certain activities and do not examine or propose any *guidelines* on how the design of the car can actually facilitate these activities.

In order to build future autonomous cars that are well accepted and can be used with pleasure, it is crucial to take a closer look at concrete activities and consider the related design options. We therefore conducted a neuroergonomical study to investigate how working in the car of the future might look like. Specifically, our research question is: *To what extent do possible car interior configurations affect the passenger's concentration and performance levels as well as cognitive workload?*

In order to investigate this research question we let passengers work on two different concentration tasks during a simulated self-driven car ride. We designed three possible interior design configurations and integrated them in an autonomous driving simulator: a *normal configuration*, a *concentration-focused configuration*, and a *leisure-oriented configuration* (see section 4). Each configuration consisted of a defined set-up of lighting conditions as well as visual and auditory stimulation in the car interior.

1.1 Research Approach

It has been argued that investigating future scenarios and technologies is not straightforward [45]. In a lot of future-oriented research, interviews and surveys are employed to assess people's attitudes and visions. However, this very theoretical and hypothetical approach is limited when it comes to examining people's experiences *in or with* future scenarios. Simulations and virtual environments can be used for such evaluations. Hence, the first step to prepare our study was to design a driving simulator that allows our participants to experience traveling and working in a self-driving car. The driving simulator also included a technical set-up that enabled us to change the interior to let participants experience our three different interior configuration and to investigate how they influence participants' performance during concentration-demanding tasks.

We used a multi-method approach combining subjective, behavioral, and neurophysiological insights for investigating subjective concentration, performance, and cognitive workload. Our multi-method approach allows us to examine the influence of different car interior configurations from different perspectives. Thus, we can obtain comprehensive, holistic answers and increase the robustness of our understanding about different aspects of the phenomena under investigation [38]. With the multi-method approach we are hence able to gain a broad as well as deep understanding of the factors that affect the subjective, behavioral, and neurophysiological state of the participant, while offsetting the weaknesses inherent to using a unimodal approach.

While subjective and behavioral measures are well established in automotive and working contexts, neurophysiological methods are still emerging. Research in the area of neuroergonomics has flourished in the past decades with the rise of non-invasive and mobile neurophysiological measurement techniques. The goal of this new research domain is to study aspects of human behavior and performance in relation to the interaction with technology, working environments, and in operating vehicles such as cars by monitoring brain and physiological functions [42]. Measuring neurophysiological signals can be regarded as a valuable, additional source of information about people's cognitive state and activities to complement subjective and performance measures. The most common method for measuring brain activity in neuroergonomical studies are electroencephalographic (EEG) recordings. EEG devices are portable, non-invasive and allow participants to be in their natural and comfortable positions while performing any given task. [42]. EEG has already been used to assess different dimensions of cognitive workload in various studies in automotive and work contexts (compare section 2), justifying it as our preferred neurophysiological method in our multi-method approach.

1.2 Contribution

With this study, we combine the two current research domains of *autonomous driving* and *future work*. The goal is to investigate the feasibility of self-driving cars as workplaces and gain insights that help better tailor them to the passenger's needs and activities. In a nutshell, our main contributions are:

- Providing a detailed investigation of the activity of working in a self-driving car using a driving simulator that is especially designed for this purpose
- Proposing three potential car interior configurations (taking into account lighting, sound, and visual stimulation) that can be used to set optimal workplace conditions in a self-driving car
- Conducting a neuroergonomical evaluation of the three interior configurations with the goal to provide evidence which interior configurations support and impede productive and focused work in a self-driving car
- Employing a multi-method approach that combines subjective, behavioral and neurophysiological data recordings under close-to real autonomous driving conditions

2 RELATED WORK

Concentration, cognitive workload, and performance are common constructs of investigation in automotive research. Some studies have already considered a multi-method approach for their empirical work in this research area [43, 52]. With increasing automation in automotive contexts, it is increasingly relevant to investigate different cognitive states, e.g. attention, task engagement and cognitive workload [14, 49, 53, 58]. However, current work always focusses on detecting cognitive workload *during the task of driving* and examining the effects of the present situation or the environment, e.g. traffic complexity [43] or road layout [57]. Neuroergonomical studies have researched, for example, the detection of the driver's movement intentions via EEG to support car breaking assistance systems, or drowsiness level and mind wandering during simulated driving scenarios [2, 8, 22]. To our knowledge, the futuristic scenario of working in a self-driving car has not yet been experimentally investigated.

Working scenarios in general, and cognitive workload assessment in particular, are one of the main areas of interest in neuroergonomic research. Studies have extensively documented the impact of increasing cognitive workload on human behavior and proposed approaches for the quantification of cognitive workload with EEG measures [4, 7, 17]. Their findings show that cognitive workload is a complex multidimensional construct. Naturally, cognitive workload increases when an individual engages in a task. The cognitive workload level is, however, not only dependent on the task itself, but can also be influenced by environmental factors. We base our EEG measurements on these insights. We hypothesize that the cognitive workload of a passenger performing a task in a car can be deliberately influenced by changing the interior design.

3 SET-UP OF THE DRIVING SIMULATOR

Any effects or experience of the passenger during autonomous driving can only be investigated safely in a simulated setting. The set-up of such driving simulators requires careful consideration. In particular, it needs to be assured that it is sufficiently immersive to allow the transfer of the conclusions acquired in the simulated environment to a real-world driving context.

Besides the simulation of the surrounding landscape, it needs to be considered which interior design, and thus which vision of autonomous driving, participants should be exposed to.

3.1 Simulation of the Self-driving Mode

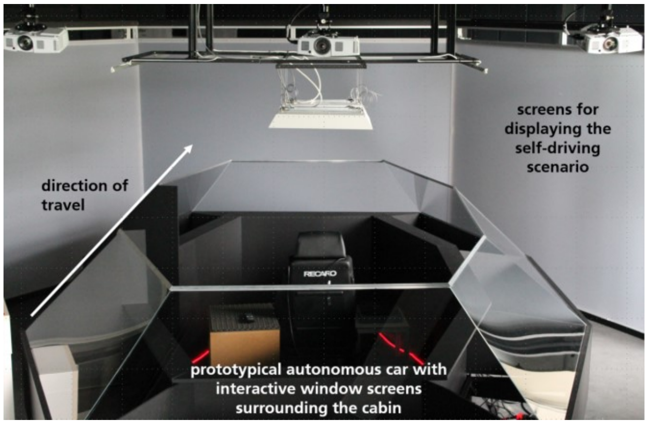

Figure 1: Set-up of the stationary driving simulator (©Audi AG).

Figure 1 shows the stationary car mock-up in front of three large screens that display the virtual visual simulation of the self-driving mode. Since the participants were seated face-forward, we made sure that the three screens completely covered their field of vision. Thus, there was no need to enclose the complete car with screens. On the large screens, we displayed the surrounding landscape that moved past the car to simulate the impression of driving. The setting for the simulation of the self-driving mode was a slow car ride with a tempo limit of 30 km/h through a cityscape of Barcelona at night time (e.g. a drive home from work), as this sets a suitable stage for our interior configurations. Participants were told that the car mock-up was a simulation of a fully automated level 5 vehicle. Before the experiment started, participants completed a test ride through the virtual environment to ensure that they did not feel any discomfort or sickness due to the motion of the cityscape. None of the participants reported any motion sickness.

3.2 Possible Interior Design Set-up

In future cars, the new role of the human as a passenger - rather than a driver - offers new opportunities to redesign the interior layout of the car. Different seating layouts have been proposed and investigated, suggesting that passengers prefer a spacious, comfortable layout with their seat facing forwards [27, 29]. This position enables them to monitor the behavior of the car better, thus giving them a feeling of security.

Autonomous driving also requires human-machine interface experts to redefine the way we interact with the car. Conventional interaction and steering mechanisms become redundant. This results in an open design space and various opportunities to integrate new emerging technologies in the car interior. Some previous work points out that people envision future cars not only to be more luxurious and comfortable, but also to feature large screens [29, 45]. Several possible suggestions of design set-ups have been made to alter cars into office environments [26, 36]. For the design of our future car we decided to incorporate this vision and equipped our car prototype with four interactive screens as windows similar to the ones proposed by Toyota ([28]). We placed one screen in front of the passenger's seat, two to the front-right and right of the passenger and one to the front-left (Figure 1). No screens were placed to the left where the entrance to the car was located or behind the seat as the passenger would not look at this direction during the ride.

The car prototype had a size of 180x500 cm to resemble a rather spacious upper-class car. Due to experimental purposes the car neither had a roof nor a door. Instead, two LED-Panels (2x Illuxtron MLMC 595X595 with 5950 lm) and three LED Stripes were installed above the passenger's seat (on the left and right side 1800 mm x 8 mm, front 1000 mm x 8 mm Barthelme Bardolino LLFlex Profile with frosted diffuser) to allow us to set-up the specific lighting conditions for our three car configurations.

4 THREE SCENARIOS OF WORKING IN A CAR AND RELATED INTERIOR CONFIGURATIONS

The presented driving simulator formed the basis for the design of three car interior configurations that can be used to let participants experience three different scenarios of working in a self-driving car. For each interior configuration, defined concepts for lighting, as well as visual and auditory stimulation are proposed.

4.1 The Normal Configuration

The normal configuration (NC) is based on the current experience of a car ride with no specific lighting, monotonous traffic noise from the environment and a few visual distractors being displayed on the interactive windows.

4.2 The Concentration-focused Configuration

The concentration-focused configuration (CC) presents a set-up which, based on related research, can be expected to have a positive effect on the passenger's productivity and focused working style (Figure 2). In this configuration, distractors from the outside were decreased by turning the interactive windows opaque and reducing the traffic noise. Based on existing light research, we also implemented a light set-up that should help people concentrate and be more productive (Figure 2).

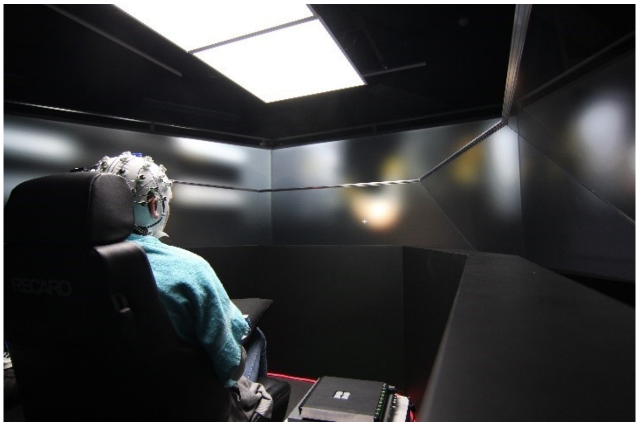

Figure 2: Concentration-focused interior configuration of the self-driving car prototype: large-area, bright light with high blue components and blurred window screens (©Audi AG).

Previous research has shown that bright light can acutely increase attention [10, 19, 47, 61] and improve cognitive performance [1, 11, 13, 34]. Furthermore exposure to blue-enriched light induces enhanced attention, subjective alertness and leads to significantly faster reaction times [13, 56]. Thus, it can be concluded that there is a positive correlation between correlated color temperature (CCT) and alertness (blue-enriched light with higher CCT results in higher alertness and vice versa). The same applies for illuminance (higher illuminance results in higher alertness and vice versa). This is predominantly caused by the recently discovered melanopsin containing retinal ganglion cells, photoreceptors that, besides rods and cones, are photosensitive as well [5, 15, 21]. These photosensitive ganglion cells project to several nuclei in the brain that are responsible for non-image-forming functions and are furthermore known to be involved in alertness and vigilance [15]. Provencio et al. [46] reported to the Nature magazine, that a roughly resolved network of photosensitive ganglion cells extends over the entire retina of mice. Since those melanopsin containing ganglion cells are distributed over large areas of the retina, we assumed that the concentration effect of light is greatest when the light comes from a large spatial light source, such as shown in Figure 2. Therefore, we investigated if spatial light has different effects compared to linear light. We hypothesized that, if only a small area of the retina is illuminated from a linear light with less blue components (as shown in Figure 3), a weaker non-image-forming effect can be expected than by illuminating the entire retina. To do so, two LED-Panels (2x Illuxtron MLMC 595X595 with 5950 lm), installed above the passenger's seat, provided a large-area, bright light (vertical illuminance at the eye was 48 lx) with high blue components (CCT was 6070 K).

4.3 The leisure-oriented configuration

Studies show that many people imagine the car of the future to be designed like a living room [29, 45], which inspired us to include a leisure-oriented configuration. We were curious to examine whether such an environment could also be suitable for working or whether future cars will have to provide interior configurations tailored to specific activities of the passenger.

In the leisure-oriented configuration (LC) we designed an environment which mirrors notifications and digital distractors that we are familiar with from our smartphones. These are displayed on the interactive windows surrounding the car (see Figure 5). Environmental noises are still present in this configuration, while the light is optimized to support a relaxing passenger state. In congruence with the research reported above this can be achieved with a low CCT and low illuminance.

The lighting setup for the LC therefore features linear, darker light with very few blue components and with 4.8 melanopic lux. The linear light came from the three LED Stripes installed above the passenger's seat (on the left and right side 1800 mm x 8 mm, front 1000 mm x 8 mm Barthelme Bardolino LLFlex Profile with frosted diffuser). They were set to a correlated color temperature of 2630 K and a vertical illuminance at the eye of 11 lx (Figure 3).

Figure 3: Lighting concept for the leisure-oriented configuration of the prototypical self-driving car: linear, darker light with very few blue components (©Audi AG).

5 NEUROERGONOMICAL STUDY

For our study, we implemented the three interior configurations described above in our driving simulator. We then designed an experiment to systematically investigate to what extent different configurations affect a participant's perceived concentration (questionnaire), behavioral performance (reaction time and error rate) and cognitive workload (EEG) during two controlled concentration tasks.

5.1 Participants

We recruited 30 participants (*M* = 28.5 years, *SD* = 6.4, 14 female) for this study. The participants had no habitual drug or alcohol consumption, cognitive or psychiatric impairments, neurological disorders, metal implants or pregnancy. Seven participants were excluded because they did not complete the protocol or because no artifact-free EEG signal could be obtained, resulting in a total of 23 participants in the analysis. Participants were monetary compensated for their participation and gave their written, informed consent before participation. The study protocol was approved by the local ethics committee.

5.2 Experimental Design

We used a within-subject block design with the three experimental blocks representing the three interior car configurations. The block order was randomized across participants. Each block contained two iterations of the two different concentration tasks (see Figure 4), followed by the assessment of the subjective concentration. Behavioral task performance and cognitive workload were recorded continuously throughout the experiment.

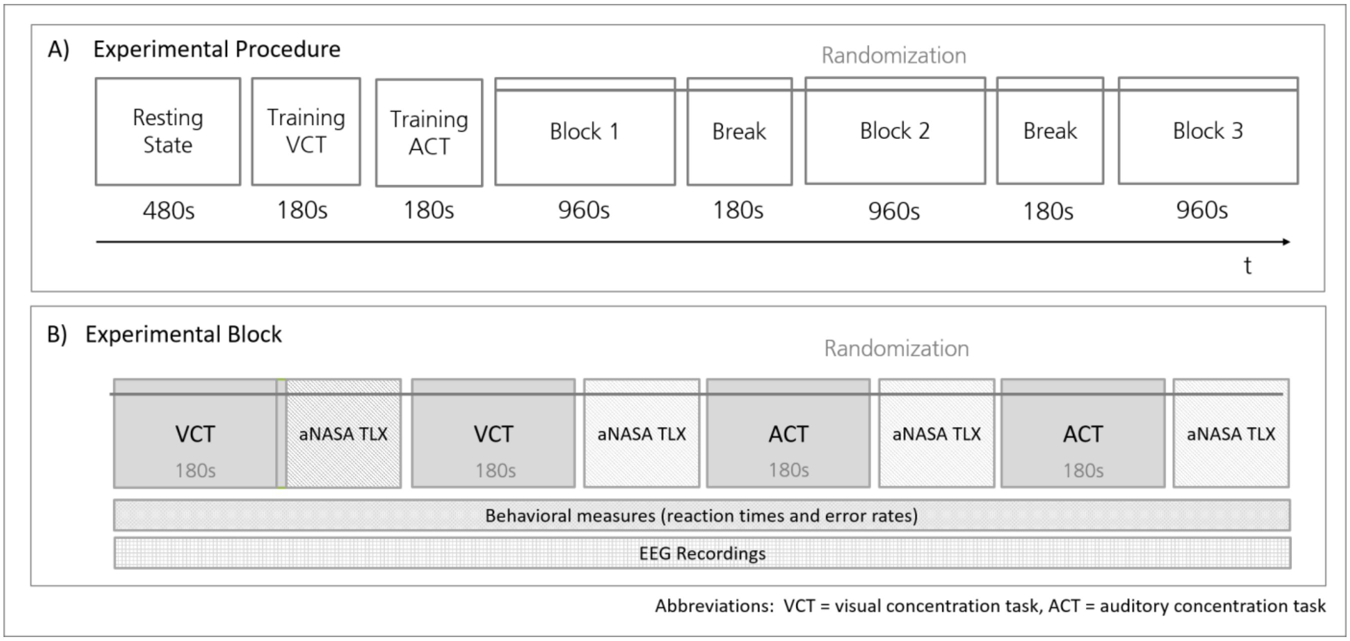

Figure 4: A) Experimental Procedure. In each of the three blocks one of the interior configurations is applied to the driving simulator. B) Experimental Block. Participants had to carry out two iterations of each of the concentration tasks in randomized order

5.3 Concentration Tasks

To put participants in a scenario of working, they were asked to carry out two different concentration tasks focusing on the visual and auditory human sensory system. Both tasks were taken from psychological research and are well suited to induce different concentration levels in the participants. Furthermore, they have been used in accordance with simultaneous EEG recordings. This gave us the opportunity to investigate specifically, the effect of different environmental conditions on the concentration level of the participants. Based on [25], we used a modified version of a combined go/no-go task with a memory task, here called visual concentration task (VCT). VCT requires people to concentrate on and react to visual stimuli. In a 10-second memorization phase, participants are shown a sequence of four different letters on a screen. Their task is to memorize these letters and identify them again in a longer sequence of letters presented to them in the subsequent testing phase (one letter after the other in 3-second time intervals). If a letter is shown that they recognize from the memorization phase, participants are instructed to press a "Yes" button and otherwise a "No" button. The visual stimuli were shown on the middle front interactive car window and participants' provided their input through a touch panel containing the "Yes" and "No" buttons.

The auditory concentration task (ACT), a modified version of the auditory vigilance task presented by Pang and colleagues [41], is similar to the VCT, but based on auditory stimuli. In the memorization phase, participants first hear a sequence of four words ("left", "up", "right", "down") and have to memorize the words and their order. In the testing phase, more sequences of the four words in different orders are played to them in 2-second intervals. Participants are instructed to react to the correct order of words by pressing the "Yes" button and by discarding the wrong word order by pressing the "No" button. The auditory stimuli were played over speakers installed in the car. Participants provided their input with the same touch panel used for the VCT.

5.4 Assessing Subjective Concentration, Task Performance and Cognitive Workload

Our multi-method approach is based on the idea of combining insights from different sources that complement each other, to better understand the passenger's concentration experience and performance for the three interior configurations.

5.4.1 Subjective Insights. The subjective concentration experience was assessed using a four-item questionnaire based on the National Aeronautics and Space Administration-Task Load Index (NASA - TLX, [20]). Since not all of the items proposed by the NASA-TLX were applicable to the tasks and set-up in our study, we only included the items "mental effort" and "frustration" in the questionnaire and added the items "concentration" and "distraction" (adjusted NASA-TLX; aNASA-TLX). As proposed for the original version of the NASA-TLX, the items were rated on a seven-point Likert scale ranging from "low" to "high". Given the modification of the scale in the context of this study, the second step of pairwise comparisons between items proposed by [20] is not applicable.

5.4.2 Behavioral Insights. Performance is assessed using reaction times (RTs) for both concentration tasks. They reflect the time it took participants to press the correct button. The error rates (ERs) represent the proportion of incorrect responses.

5.4.3 Neurophysiological Insights. EEG measures the temporal and frequency characteristics of brain activity by monitoring electromagnetic processes, i.e. the synchronization processes between populations of thousands of neurons at the cortical surface, with electrodes placed on the scalp of the participants [40]. These synchronization processes are related to different measurable oscillatory frequency bands in the brain that are associated with different cognitive functions [51]. We used the EEG recordings to capture a specific cognitive state of the participant that is important within our context: the change in working memory load in relation to the different car interior configurations. Working memory load (also called cognitive work-load) can be understood as the amount of mental resources that are used to execute a particular task [18, 33] (in our case the VCT and ACT). Cognitive workload related changes in the EEG are associated with changes in the theta-band power (4-7Hz) at frontal brain areas and in the alpha-band power (8-14 Hz) at parieto-occipital brain areas [4, 7, 44]. We hypothesized, that additional cognitive demands (e.g. increased memory load capacities) would be occupied depending on the interior configurations while participants perform the two different concentration tasks. This cognitive demand can be measured by analyzing changes in frontal theta-band and parieto-occipital alpha-band EEG power [9-10]. In this study we used the workload index as previously introduced in [18, 30]. The index is defined by the ratio of frontal (FR) theta-band (θ) power divided by parieto-occipital (PO) alpha-band (α) power in the EEG:

$$workload\ index = \frac{FR\ (\theta)}{PO(\alpha)}$$

This measures the participants mental effort or cognitive workload.

Scalp EEG potentials were recorded (BrainAmp, Brainproducts GmbH, Germany) from 32 positions, with Ag/AgCl electrodes (actiCAP, Brainproducts GmbH, Germany) from: Fp1, Fp2, F7, F3, Fz, F4, F8, FC5, FC1, FCz, FC2, FC6, T7, C3, Cz, C4, T8, CP5, CP1, CP2, CP6, TP10,P7, P3, Pz, P4, P8, PO9, O1, Oz, O2, PO10. The left mastoid was used as common reference and EEG was grounded to AFz. All impedances were kept below 20 kΩ at the onset of the experimental session. EEG data was digitized at 1 kHz, high-pass filtered with a time constant of 10 seconds and stored for offline data analysis using the Brain Vision Recorder Software (Brain Products, Munich, Germany).

5.5 Experimental Procedure

Participants were seated in the car seat in the center of the driving simulator. At the beginning of the experimental procedure, the initial resting state EEG was measured. We recorded brain activity for six minutes with alternating tasks to "relax with eyes open" (EO; fixation on a cross displayed on the middle interactive window screen) and "relax with eyes closed" in intervals of 15 seconds [6]. A beep indicated the switch between the tasks. This data was later used for normalization of the EEG signals for statistical comparison between different participants. Subsequently, the participants performed a six-minute training phase that introduced the participants to the VCT and ACT they were to perform during the experiment.

Participants then completed the three testing blocks. Within each block, a visual cue between the concentration tasks (180 seconds) indicated the task to perform. Furthermore, this gave the participants a short break of 60 seconds to switch between the different tasks. Between the blocks, participants received a short break of 180 seconds (see also Figure 4). This accounted for potential sequential impact of the changes in light conditions.

Figure 5: Experimental set-up: The participant is in the center of the prototypical car wearing the mobile EEG device and performing the visual concentration task (displayed on the front window screen) in the leisure-oriented condition (©Audi AG).

5.6 Data Analysis

Subjective, behavioral, and neurophysiological data were analyzed separately. For each of the three data sets, individual analyses were conducted for the two concentration tasks, the VCT and ACT.

5.6.1 Subjective Evaluations based on aNASA-TLX. For each effort, concentration task, the ratings of the aNASA-TLX were analyzed separately. First, the two ratings for each item of the aNASA-TLX within one experimental block were grouped together and the mean was calculated. The obtained values were then entered into four Repeated-Measures Analyses of Variance (rmANOVA) with post-hoc pairwise comparisons, one for each item. Thus, the statistical difference between the subjective evaluations of mental frustration, concentration and distraction for the NC, CC and LC could be explored for the VCT and ACT, respectively.

5.6.2 Behavioral Performance based on RTs and ER. We removed all error trials from the data set prior to the statistical analysis. Error trials were defined as RTs above 1500ms and non-response trials. Moreover, all RTs below the threshold of 200ms were excluded from further analysis, as this is the minimum time needed for stimulus perception and motor responses [59]. For each participant, the remaining RTs within one experimental block were grouped together, the mean was calculated and the effect of experimental block on RTs was examined using the rmANOVA and post-hoc pairwise comparisons. The same process was used to analyze the effect of experimental block on error rate.

5.6.3 Cognitive Workload Index based on EEG recordings. Further data analysis uses EEG signals that were recorded during the blocks of the concentration tasks and the EEG data during the EO condition [6] from the initial resting state measurement. Several pre-processing steps were performed to remove artefacts from the EEG data (e.g. environmental noise or other non-brain related processes) before analysing the data for differences in the workload index. All data analysis was performed with custom written or adapted scripts in MATLAB®.

5.6.3.1. EEG pre-processing. For the EEG analysis during the concentration tasks, we grouped the EEG data of each 180s task block per condition, resulting in a total of 6-minutes EEG recording for the VCT and ACT during each of the three experimental blocks. The EEG signals were de-trended, zero-padded and re-referenced to mathematically linked mastoids [2]. Next, we band-pass filtered the EEG signals between 0.5 to 45 Hz for calculation of oscillatory frequency band power. The filtering procedure was performed with a first order zero-phase lag FIR filter. The whole dataset of 6 minutes per condition was divided into non-overlapping epochs of 2 seconds. Epochs were rejected when they contained a maximum deviation above 200 µV in any of the frontal EEG channels (Fp1, Fp2) accounting for heavy eye-movement artifacts superimposed in the EEG signals. For the remaining epochs we further performed an independent component analysis (ICA) using the logistic infomax algorithm as implemented in the EEGlab toolbox [16], and removed further cardiac, ocular and muscular artifacts. This was done by careful visual inspection of the topography, times course and power spectral intensity of the ICA components [12, 23].

Similarly for the EEG data acquired during the resting state measurements we grouped each 15s of EO condition together, resulting in a data stream of 3 minutes per participant. Here again, the EEG signals were de-trended, zero-padded and re-referenced to mathematically linked mastoids [40]. Next, we band-pass filtered the EEG resting state signals between 0.5 to 45 Hz for calculation of oscillatory frequency band power, using a first order zero-phase lag FIR filter. Afterwards the whole dataset of 3 minutes was divided into non-overlapping epochs of 2s. Furthermore, amplitude-based rejection and ICA method was used to remove cardiac, ocular movement and muscular artifacts, as described in detail above.

5.6.3.2. Estimation of the EEG-based Workload Index. We estimated the oscillatory frequency band power of the EEG signals by applying the Welch's method of spectral averaging [50] to each valid epoch (artefact-free EEG data). This was done separately for the concentration tasks during the three different configurations and the resting state measurements. Next, for each configuration and resting state data we averaged the spectral power across all epochs. Since the spectral power of the scalp EEG can vary between different participants due to several factors (including anatomical, age and gender characteristics or unspecific noise characteristics), the EEG data from the different conditions has to be normalized before the workload index can be calculated. The EEG power for the concentration tasks for each interior configuration was divided by the power of the resting state measurement per participant. Finally, as defined in 5.4.3 we calculated the workload index [18, 30] by taking the mean spectral power of the θ-band (4-7Hz) from bi-lateral frontal electrodes (Fz, F3, F4) divided by the mean spectral power of the α-band (8-14Hz) from bi-lateral parietal electrodes (Pz, P3, P4).

5.7 Results

5.7.1 Perceived Concentration. For the VCT the rmANOVA revealed statistical effects of *interior configuration* on the items "concentration" (*F*(2,46) = 4.83, *p* = .012), "frustration" (*F*(2,46) = 8.05, *p* = .001) and "distraction" (*F*(2,46) = 12.05, *p* < .001). Participants reported higher concentration efforts, higher frustration, and higher distraction for the LC than the CC. The values for the mean (*M*) and standard deviation (*SD*) for all blocks and items can be found in Table 1. No difference was found between the NC and either of the other configurations. In addition, no effect was found for the item "mental effort" (*F*(2,46) = 2.43, *p* = .10) which received ratings between 3 and 4 (out of 7) for all three conditions, indicating a medium level of perceived mental effort for the VCT.

Table. 1: Participants' mean ratings for the VCT on the four items of the aNASA-TLX for the three car interior configurations.

configuration	aNASA-TLX items	*M* (VCT)	*SD* (VCT)
Normal (NC)	concentration	3.56	1.49
	frustration	2.48	1.32
	Mental effort	3.31	1.66
	distraction	3.00	1.56
Leisure-oriented (LC)	concentration	3.99	1.21
	frustration	2.86	1.30
	Mental effort	3.77	1.46
	distraction	3.69	1.51
Concentration-focussed (CC)	concentration	3.21	1.51
	frustration	2.10	1.12
	Mental effort	3.27	1.64
	distraction	2.04	0.87

For the ACT a statistically significant effect was found for "distraction" (*F*(2,46) = 16.35, *p* < .001). Distraction was rated significantly lower for CC than for NC (*p* = .02) and LC (*p* < .001). LC received significantly higher distraction ratings than NC (*p* = .003). Table 2 shows the values for *M* and *SD* for all blocks and items. No effects were found for "concentration", "frustration", and "mental effort". For these two items, the mean ratings were low to medium for all three configurations (all *M* between values of 2 and 3.6). This indicated that participants generally perceived the ACT to be little frustrating, to require little mental effort, and a medium level of concentration.

5.7.2 Task Performance. The statistical analysis revealed an effect of *interior configuration* (i.e. the experimental block) on RTs for the VCT (*F*(2,42) = 47.53, *p* < .001). RTs were found to be significantly shorter for CC (*M* = 974.04, *SD* = 92.26) than for NC (*M* = 1059.51, *SD* = 90.03) and LC (*M* = 1084.02, SD = 89.12; all *p* < .001; see Figure 6). RTs for NC and LC did not differ significantly (*p* > .05).

For the ACT, the rmANOVA also revealed an effect of interior configuration (i.e. the experimental block) on RTs for the ACT (F(2,44) = 6.51, p = .003). We found significantly lower RTs for CC (M = 648.66, SD = 148.66) as compared to NC (M = 699.45, SD = 155.59; p = .43) and LC (M = 716.41, SD = 187.40; p = .016; see Figure 7). RTs were slightly lower for NC than for LC, but this difference did not reach significance.

For neither the VCT nor the ACT, an effect of interior configuration on error rate could be detected (*F*(2,42) = .85, *p* = .434 and *F*(2,44) = .30, *p* = .743, respectively).

Table. 2: Participants' mean ratings for the ACT on the four items of the aNASA-TLX for the three car interior configurations.

configuration	aNASA-TLX items	*M* (ACT)	*SD* (ACT)
Normal (NC)	concentration	3.17	1.43
	frustration	2.19	1.47
	Mental effort	2.81	1.57
	distraction	2.83	1.32
Leisure-oriented (LC)	concentration	3.58	1.44
	frustration	2.25	1.70
	Mental effort	3.13	1.45
	distraction	3.83	1.88
Concentration-focused (CC)	concentration	2.90	1.49
	frustration	2.00	1.44
	Mental effort	2.63	1.67
	distraction	1.98	0.74

5.7.3 Cognitive Workload. For the statistical comparisons of the EEG-based workload index we analyzed the results with a two-way ANOVA, to test the factors *interior configuration* (NC, LC, and CC) and *concentration task modality* (ACT and VCT) followed by a post-hoc performed paired t-test (corrected for multiple comparisons by using the Bonferroni correction method). The result for the two-way ANOVA revealed a main effect for the factor *interior condition*, F(2, 0.2417) = 12,17, p < .0001, but not for the factor *concentration task modality* F(1, 0.2417) = 0,55, p = 0.45 and for the interaction between these factors F(2, 0.2417) = 1,32, p = 0.27.

For both concentration tasks, the participants showed a significantly lower workload index when the task was performed under the concentration-focused configuration as compared to the other two interior configurations (see Figure 8; p-values indicate the results from the post-hoc performed paired t-test).

5.8 Discussion

Our multi-method approach combines subjective, behavioral and neurophysiological insights. These insights coincide and, combined, reveal a positive effect of the CC

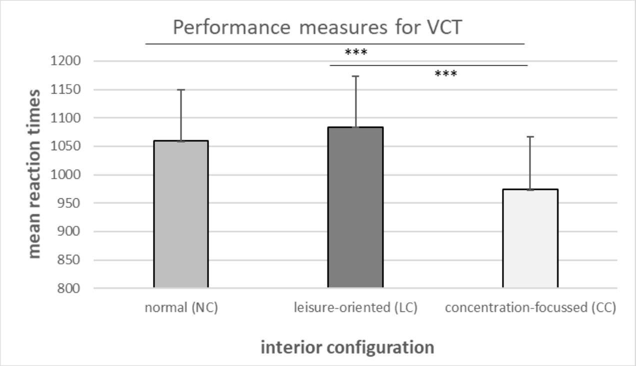

Figure 6: Mean RTs for the VCT for the three interior configurations. Statistically significant differences with $p < .001$ are marked with **.

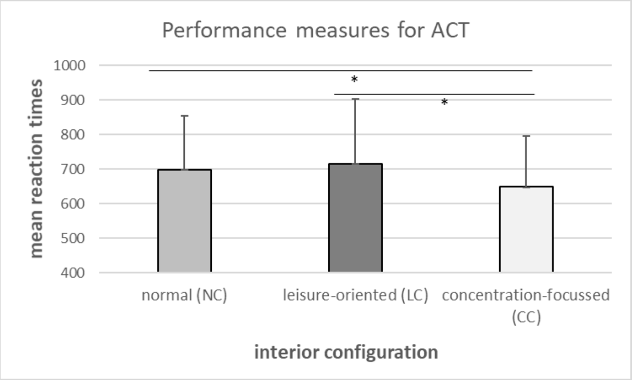

Figure 7. Mean RTs for the ACT for the three interior configurations. Statistically significant differences with $p < .05$ are marked with *.

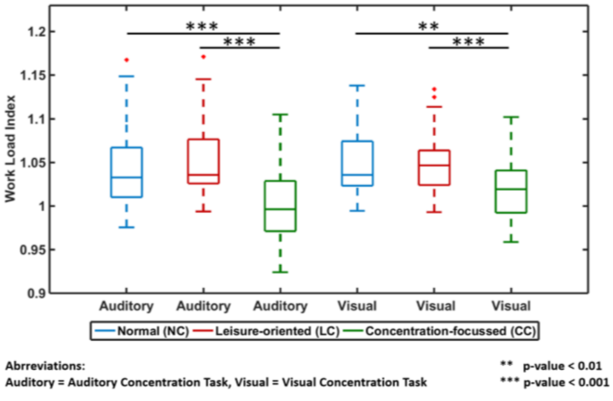

Figure 8: Boxplots representing the EEG-based workload index for the three configurations. Statistically significant differences with $p < .01$ are marked with ** and with $p < .001$ with ***.

on the participants' concentration, performance and cognitive workload levels and uncover a main difference between the CC and the LC as well as NC.

In the CC participants experienced the concentration effort and the distraction as assessed by the aNASA-TLX to be much lower than in the other two configurations. Moreover, their task performance for the two concentration tasks was better in the CC in terms of quantity (RTs), but not regarding quality (error rates). The EEG-based workload index was able to detect variations on a neurophysiological level that converge with results from the subjective and performance level. Our findings indicate a lower need for performance and cognitive load when participants performed the concentration tasks during CC as compared to LC and NC. The EEG-based index helped us to differentiate between physical-based parameters (performance-based metrics) that represent an indirect measure of the process of mental capacity, and cognitive-based parameters (EEG-based mental workload index) as a direct measure of mental process capacities [35]. Generally, task performance and mental workload are inversely related to each other. However, the mental resource theory by Wickens [60] states that under certain circumstances, one can maintain a high level of performance despite high mental workload. This is achieved by adopting information processing strategies that may direct attention to the primary tasks rather than to a secondary task, or as in our case environmental distractors. This ambiguity can be effectively accounted for by using neuronal measures of cognitive load, such as EEG. Furthermore, our results highlight that the brain's working memory resources were unaffected by the modality, e.g. visual or auditory human sensory system, which cannot be deduced using performance based metrics alone. Hence, it can be concluded that the effect of interior configuration is quite similar for both, the visual and auditory system of the participants. Our EEG-based index that takes into account the relation between changes of theta-band activity in electrodes overlying FR brain regions and alpha-band activity in electrodes overlying PO brain regions proved to be a valuable measure to objectively quantify cognitive workload. It furthermore highlights the involvement of a specific fronto-parietal brain network that was consistently shown to be involved in workload estimations in other studies as well [4, 7, 25, 30, 44].

Differences between NC and LC could not be found. This finding suggests that a more leisure-oriented car interior neither supports nor interferes with concentrated working. On the other hand, a light, sound, and visual design as proposed for the CC can be used to configure a car to deliberately support a productive and concentrated working style. It suggests itself that our findings can be put into relations with these findings. Offices are not necessarily the same size as a car. However, factors that inhibit productive work during transportation such as limited space, environmental noise and time constraints [24] are also valid for office environments. There are several studies demonstrating the effect of lighting on humans under lab-conditions and possible office settings [9, 54]. Light-related studies showed that light applied during night time affects alertness in a dose- and spectrum dependent manner. Studies investigating light exposure during daytime found inconclusive results. Especially, the effect of lighting on the cognitive workload, and more specifically on the brain level, has not yet been systematically addressed. Our findings are in line with results of another recent study that shows that spectral properties of light can influence mental effort [32]. Furthermore, it demonstrated that this effect occurs after 15 minutes of light exposure and can be detected with cardio-vascular measurements. We thus conclude that our findings can be extrapolated not only to other commuting workplace conditions but also to office environments and extends the existing body of research in this area. We could demonstrate how a multi-method approach including EEG can be used to better understand the concepts of subjective concentration, performance and mental workload and how they are affected by certain environmental factors. Still, more research needs to be conducted in this direction, especially with regards to substantiating the assumptions about the connection between lighting and mental workload.

To our best knowledge, comparable studies in automotive scenarios are scarce. Taillard et al. [55] presented implications of using specific light configurations in a car. They could show that interior blue light enhances driving performance during night time, thus providing evidence on how to transfer findings from lab-settings into real-world driving scenarios. Although findings about optimal lighting in offices could generally also be applied to an automotive setting, there are some differences that might require further investigation: In cars there are some factors that could potentially produce glare such as the placement of lighting devices, brightness and contrast. Other major differences are continuously moving visual cues and g-forces. In our study we explicitly tested moving cues in addition to the effect of spatial versus linear light. We therefore consider the development of a specific, human-centered lighting concept for the interior of a self-driving car as an important contribution of the present study.

Still, our study also has some limitations: First, we restricted our participants to a young population (mean age 28.5 years) free from any diseases or other possible cognitive and perceptual impairments that might compromise their EEG activity, concentration or performance level. Hence, it is not known whether similar effects on the cognitive resources can be found for an elderly population or individuals with compromised cognitive or perceptual capabilities.

Moreover, although the simulated virtual environment appeared to be the best choice for our experimental set-up, it is, naturally, not identical with a real-world situation. Our results were obtained under carefully controlled experimental conditions and tasks. Higher variability in both neurophysiology and behavior might occur for real-world working tasks and environments.

Sadeghian Borojeni et al. [48] investigated the influence of motion on take-over-responses (TOR) in highly automated vehicles, comparing moving and non-moving driving simulators. They could show that motion had an effect on take-over-responses (TOR), depending on road contexts. However, they did not find an effect on perceived mental workload, even for non-driving task performance. Thus, the perception of real motion seems to influence situational awareness and TOR, but does not necessarily have an impact on concentration and non-driving tasks, such as the concentration tasks in our study. Our motivation was to find empirical evidence that, by manipulating the configuration of the interior design, participants experience different levels of concentration and workload. We present a baseline for future work, which can include other possible influences from the external environment, e.g. motion.

6 CONCLUSION AND FUTURE CHALLENGE

Our neuroergonomical study shows that self-driving cars have the potential to serve as a workplace and that the interior design of light, sound and visual stimulation can be configured to support concentrated working. The multi-method approach helped us examine possible interior design set-ups and to come up with a holistic picture on the influences on concentration and workload. Our results are cumulative, which increases their robustness and extends our understanding of the constructs under investigation.

We proposed three different variants of interior configurations for a workplace in a self-driving car and set-up a driving simulator. We designed an experimental study that allowed us to investigate to what extent these configurations support a productive working style. The LC features relaxing light and enables the passenger to receive notifications and media content from their mobile phone on the interactive window screens of the car, thus combining the task of working with a more leisure-oriented environment. Our study shows that in this environment, subjective concentration, behavioral performance, and cognitive workload are comparable to the NC, the regular set-up of a car with standard lighting, traffic sound and a few visual distractors. The third interior variant (CC) was designed to deliberately boost the passenger's concentration and productivity with an activating lighting concept, blurred window screens and reduced environmental sounds. The results of our study indicate that participants did indeed perform better in this set-up, while their perceived workload and actual cognitive workload were significantly lower than for the other design variants. The CC may be used as a guideline on how to adjust certain configurations in future autonomous cars in order to make them productive workplaces. By understanding the relationship between car configuration modes and cognitive workload, car manufacturers can design future interiors that adequately address human cognitive limitations, skills, and needs by providing optimal working conditions.

To arrive at this conclusion, we used a multi-method approach combining subjective evaluation based on a questionnaire, behavioral measures capturing RTs and error rates, and EEG recordings assessing neurophysiological processes in the brain. The results of our study show that these methods complement each other well and, taken together, can provide a holistic picture about a participant's experience and cognitive state in the context of working in an automotive setting.

The study presented in this work should be regarded as a first step towards concrete design propositions for using cars as mobile offices. We ensured that - although being placed in a mock-up car - in all three configurations participants had the impression of being in an automated car (level 5). Thus, we offer an ecologically valid setup for inducing different mental workload and concentration levels by manipulating the interior design configuration. We based our design variants on the configuration of light, sound and visual stimulation. This is, quite obviously, only a subset of the interior features that can be configured. Future studies can build upon our initial design propositions and include other aspects such as temperature or seating configuration.

Interestingly, we found that the leisure-oriented set-up did not have a negative effect on participant's concentration, performance or workload. Still, in this study, the display of notifications and media on the interactive window screens was limited to a medium level. For future studies, it would be interesting to investigate the threshold of the amount of displayed media content for causing a cognitive overload and consequently impeding productive work.

The next big step for future research would be to take this, and similar work out of the lab, and apply it to real-world scenarios. In our case, this might entail conducting similar investigations with more realistic office tasks and ultimately apply our findings to commercial self-driving cars. There are also attempts to improve real-time cognitive state assessment with neurophysiological measures and integrate respective sensors in the car interior [39]. This research fuels the design of adaptive in-car interfaces that are able to tailor interior configurations to the individual passenger based on data recorded during the car ride. For working scenarios, EEG-based quantification of workload, as demonstrated in our study, may become a valuable technique. The idea of a system adapting to the individual based on the current cognitive workload requires a robust estimation and user model that collects relevant information about the user during runtime. Our study provides an initial evidence that EEG is a valid approach to disentangle context-based influences on user's mental workload capacities. We will therefore promote future research on real-time cognitive state assessment based on EEG for adaptive lighting conditions as well as visual and auditory information displays.

ACKNOWLEDGMENTS

This research was funded by Audi AG as part of the 25th Hour project. We would like to thank Daniel Duwe, Frederik Diederichs, and Sven Bischoff for their support in setting up the driving simulator and conducting the study.

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