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Evaluation of biologically effective light in the vehicle interior in terms of subjective and objective parameters of the driver's state

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Abstract

The automotive sector is a safety relevant domain for a majority of people. Despite all innovations, accidents still occur frequently. The effort to reduce accidents has gained a new dimension in the last years: The application of biologically effective light is supposed to increase attention, human performance, alertness, and vitality. Blue and bright white light can evidently elicit these effects. Only a few published studies broached that issue in the vehicle interior. The studies attesting a positive impact of blue or bright light on the driver's state were mainly conducted under circumstances in which the driver was particularly demanded, e. g. sleep deprived. Therefore, the question whether light ameliorates the driver's state in everyday life situations is still open. The thesis at hand aims to answer this question by expounding a controlled within-subjects study. Subjects were exposed to blue light while driving in a driving simulator in the morning. Subjective as well as objective parameters of the driver's state were assessed with regard to the light treatment compared with the control condition without any additional light. The results showed consistently that neither the subjective nor the objective measures were affected by light application. Nonetheless, the insights gained from the thesis at hand are able to propose directions for potential future research.

Index of abbreviations

ADTF	Automotive Data and Time-Triggered Framework
BL	Blue light (test condition)
CBT	Core body temperature
cd	Candela
CTB	Core body temperature
ECG	Electrocardiography
EEG	Electroencephalography
EMG	Electromyogram
HR	Heart rate
HRV	Heart rate variability
ipRGC	Intrinsically photosensitive retinal ganglion cell
K	Kelvin
KSS	Karolinska Sleepiness Scale
LED	Light emitting diode
LER	Light-Emitted Rejuvenation
lm	Lumen
lx	Lux
M	Mean
MCTQ	Munich Chronotype Questionnaire
MDMQ	Multidimensional Mood State Questionnaire
MEQ	Morningness-Eveningness Questionnaire
NL	No light (test condition)
nm	Nanometer
RSS	Residual sum of squares
RT	Reaction time
SCN	Suprachiasmatic nuclei
SD	Standard deviation
SDLP	Standard deviation of lateral lane position
VTD	Virtual test drive
WT	Wrist temperature

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1. Introduction

Being part of everyday life, the automotive sector is a safety relevant domain for a majority of people. Despite efforts to ensure this safety, accidents occur frequently, especially when attention and alertness are impaired. Numerous authors report that about 15 – 20%, or even more, of all road crashes are related to sleepiness (Anund, Kecklund, & Åkerstedt, 2011; Cleaver, Simpson, De Roos, Henry, & Peden, 2009; Hartley, et al., 2013; Hammoud & Zhang, 2008). In Germany in 2015, 24% of all road accidents occurred in darkness or twilight (Statistisches Bundesamt, 2016), which are periods of the day predestinated to reduced attention and sleepiness at the wheel. An investigation of road crashes on Bavarian highways revealed that a similar amount of road crashes occur at night (10 pm to 6:30 am) as by day (Dinich, 2003). Hartley et al. (2013) report a peak of fatal highway accidents between 2 am and 7 am, which coincides with the nadir of the circadian rhythm. According to Taillard et al. (2012), nocturnal driving impairment corresponds to a blood alcohol concentration of approximately 0.1‰ and is therefore a noteworthy risk. Fighting this impairment by enhancing attention and alertness is a promising approach in order to reduce the number of road crashes.

But how to reduce sleepiness and sleepiness related accidents, increase human performance and vitality? In order to answer this question one might first think of a substance based intervention such as the consumption of caffeine or a medication. However, it is much easier: The exposure to light of certain characteristics can cause these wholesome effects. "[L]ight affects our circadian rhythms more powerfully than any drug" (Czeisler, 2013, p. S13). Beside the fundamental function of light as "zeitgeber" (Skene, 2003, p. 438; Scheer, Van Doornen, & Buijs, 1999, p. 203), it is able to exert multilayered effects on the human organism.

Blue and bright white light have shown to be effective in enhancing alertness, comfort and performance under certain circumstances. In the last 20 to 30 years, research in that area flourished to unveil the probable benefits of its application but there is still work to do (Van Bommel & Van den Beld, 2003): "[A]n important challenge for lighting research today is to establish the alerting and vitalizing potential of light in everyday life, over and above the rich set of stimuli already experienced there" (Smolders, De Kort, & Van den Berg, 2013, p. 271), especially when considering that the effect is often rather minor[1]. The foundations have been laid, albeit the practical use – particularly in risk involving domains like aviation and road traffic – needs further investigation.

Taillard et al. (2012) succeeded to show that sleep-deprived drivers performed better in the driving task when exposed to blue light at night compared to drivers in the placebo condition. Shekari Soleimanloo (2016) was able to show that blue-green light improved the drivers' subjective sleepiness and driving performance in comparison to the placebo condition. A study conducted by Leger, Philip,

[1] E. g., an improvement of one scale point rounded (alertness) or 3.3 % (speed of cognitive processing) in Lehrl, Gerstmeyer, Jakob, Bleich, & Kornhuber (2007)

Jarriault, Metlaine & Choudat (2009) revealed that the combination of a nap and a bright light pulse reduced both objective and subjective sleepiness independent of the time of the day in professional shift work drivers. These results from the automotive context illustrate that exposure to light can be a measure to improve driver sleepiness and drowsiness, respectively, as well as driving performance. The use of light application is not limited to common vehicles driven by the driver: In autonomous vehicles, the occupants can be prepared for their workday as the light, besides alertness, increases also concentration, cognitive performance, sustained attention, and mood.

However, as nearly all studies attesting the effectiveness of light, the mentioned studies were conducted under conditions which are rather far away from everyday life; e. g., participants were sleep-deprived (Taillard, et al., 2012; Hartley, et al., 2013; Figueiro, Nonaka, & Rea, 2014; Popp, 2005; Shekari Soleimanloo, 2016), shielded from any zeitgebers (Rüger, Gordijn, Beersma, de Vries, & Daan, 2006; Rahman, et al., 2014) or the light was applied at night (Taillard, et al., 2012; Cajochen, Zeitzer, Czeisler, & Dijk, 2000; Cajochen, et al., 2005). It might well be possible that humans only profit from targeted light application in such extreme settings; the results of internal studies point into that direction. One exemption constitutes the study by Farkas, Leib, Betz, & Rothe (2015): They succeeded to prove the effect of blue light in a real drive with truck drivers. Similar to the study at hand, reaction time and alertness were measured as well as driving efficacy and acceptance. A major difference to the study at hand is that the probes were carried out in daylight.

Therefore, one of the questions to be answered is whether light exposure helps to increase drivers' attention, mood and alertness as well as to reduce drowsiness under realistic conditions – such as the commute to and from work – in darkness. The thesis at hand aims to answer this question. A controlled simulator study testing the impact of blue light on objective and subjective parameters of the driver's state was conducted. To achieve a high ecological validity, a setting imitating routines of the target group of an in-vehicle light device – professional drivers and communters who drive longer distances in a monotonous environment with a prolonged time on task and on potential performance nadirs – was created. None of the outcome measures displayed the expected biological light effect. Nonetheless, for the big picture, the thesis at hand provides some insights that should be considered for future research on biologically active light.

2. Theoretical foundations

The biological effect of light on the human organism depends on numerous, mutually entangled factors which make the investigation of this effect highly complex. For example, seemingly banal things like eye color can exert an influence on the effect of light (Beaven & Ekström, 2013). Thus, a thorough review of the relevant literature is necessary in order to extrapolate hypotheses about the effect of light treatment and create a proper experimental design.

2.1. Sleepiness and related constructs

Sleepiness, which is operationalized as *sleep propensity* (Popp, 2005), is defined as the "subject's tendency to doze off or to fall asleep" (Cluydts, De Valck, Verstraeten, & Theys, 2002, p. 83). It reflects a physiological need for sleep caused by a shortage of sleep. S*ubjective sleepiness* is the subjective perception of feelings or symptoms associated with the need for sleep; it is equivalent to *drowsiness* and *tiredness* (Cluydts, De Valck, Verstraeten, & Theys, 2002; Popp, 2005). As opposed to this, *fatigue* "can be considered as a gradual process of disinclination towards effort which may not be directly observable or measured, but eventually impairs performance on a range of cognitive and psychomotor tasks" (Shekari Soleimanloo, 2016, p. 22). Acute fatigue is a condition resulting from physical effort and prolonged activity while sleepiness does not imply any prior effort (Cluydts, De Valck, Verstraeten, & Theys, 2002; Craye, Rashwan, Kamel, & Karray, 2016). Sleep reverses the sleepy state; fatigue can be fought by resting (Cluydts, De Valck, Verstraeten, & Theys, 2002). Sleepiness and alertness are opposed two states. Beside the circadian rhythm, a number of additional factors contribute to the current state of sleepiness; there are different models (Appendix C: Models of sleepiness) which explain the synergy of these factors.

Résumé Light is only one of numerous factors influencing the current sleepiness state. A potential sleepiness reducing effect can only be proved doubtless in a within-subjects design due to individual sleepiness levels among others. Further, state sleepiness can be deliberately stemmed as well as created through situational features.

2.2. Circadian rhythm

The circadian rhythm expresses the daily rhythm of sleep and wakefulness, associated physiological parameters, and nutrition intake. The circadian rhythm is of relevance for the thesis at hand, because it is highly dependent on the processes of the non-image forming system (next section). A mechanism of the non-image forming system regulates wakefulness in relation to the light condition. This mechanism called entrainment, denotes the property of the circadian system by which the biological clock is synchronized to external time giving cues (Duffy & Wright, 2005). Not only the solar clock, but also a "social" clock is a zeitgeber for the circadian system (Roenneberg, Wirz-Justice, & Merrow, 2003). The social clock is aligned with working times and timing of social commitments and needs. When theses time giving cues are incongruent, e. g. after a trans-meridian flight or shift work, the circadian system must adapt to the new daily rhythm. The temporary realignment takes some time – approximately one hour of time lag can be compensated per day – and the adaptation period is coined by insomnia, daytime sleepiness, worsened mood, gastrointestinal disturbances, poor performance, poor concentration and an increased probability of road traffic accidents (+ 8 %; Burgess, 2011; Burgess, 2011a; Dinich, 2003).

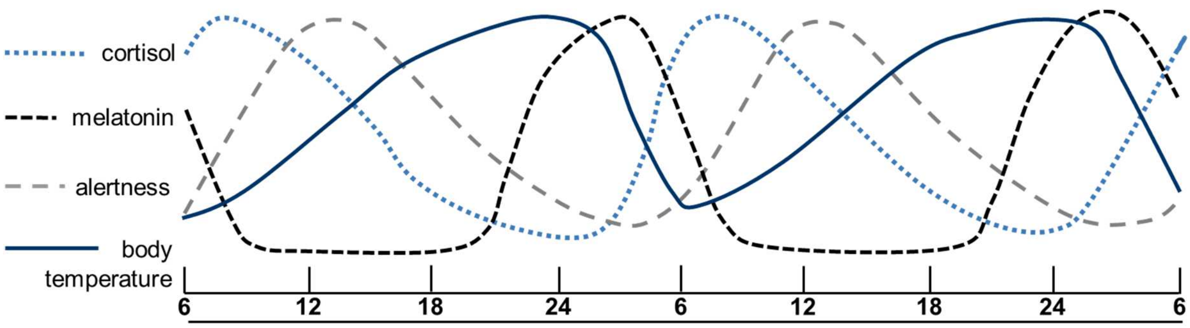

Figure 1: Double plot (2 x 24 hours) of typical daily rhythms of body temperature, melatonin, cortisol, and alertness in humans for a natural 24-hour light/dark cycle (adapted from Van Bommel & Van den Beld, 2003)

In the course of the biological day, melatonin and cortisol concentration as well as the (core) body temperature (CBT) and other physiological parameters oscillate (Figure 1). Melatonin and cortisol can be viewed as antagonists: Melatonin induces sleepiness while cortisol triggers alertness. Both neurotransmitters are controlled by the suprachiasmatic nuclei (SCN), the circadian pacemaker. Cortisol concentration reaches a peak around awakening and is related to heart rate variability (HRV) and heart rate (HR), respectively (Rüger, Gordijn, Beersma, de Vries, & Daan, 2006). These systematic oscillations can be used to determine the circadian phasing. Table 1 provides an overview of the measures which give some indication of the circadian phasing.

Table 1: Physiological parameters of the circadian rhythm and their indications

Measure	Indication
Body temperature (Sarabia, Rol, & Madrid, 2008; Cajochen, Zeitzer, Czeisler, & Dijk, 2000; Figueiro, Nonaka, & Rea, 2014; Rüger, Gordijn, Beersma, de Vries, & Daan, 2006; Cajochen, 2007; Kantermann, et al., 2012; Weisgerber, Nikol, & Mistlberger, 2016; Martinez-Nicolas, Ortiz-Tudela, Madrid, & Rol, 2011; Natale & Cicogna, 2002; Kraneburg, Franke, Methling, & Griefbahn, 2017)	In general, a decrease in *CTB* indicates sleepiness, resulting in a nadir in the circadian rhythm, while an increase in CBT proves advancing alertness. However, the elevation of CBT is also an indicator for non-circadian effects of light: Light given after the CBT nadir advances the phase of circadian rhythms, whereas light given before the CBT nadir induces delays. Additionally, the *body temperature* shows different time courses for the chronotype manifestations. The *wrist temperature* (WT), recorded on the radial artery of the non-dominant hand, has an inverse phase relationship with CBT and has shown to be an easily measureable index of the circadian system; WT shows a circadian rhythm with higher values during sleep and lower values during waking hours.
Cortisol (Rüger, Gordijn, Beersma, de Vries, & Daan, 2006; Rothert, Wieland, Niedling, & Völker, 2015)	An increasing cortisol level is associated with alertness and stress while a low cortisol level indicates sleepiness. With regard to light exposure, the research results are inconsistent.
HR/HRV	The *HR* rises with growing activity and is low in a relaxed state. Influenced by (blue) light, an elevation of HR can be observed.

(Figueiro, Nonaka, & Rea, 2014; Rüger, Gordijn, Beersma, de Vries, & Daan, 2006; Cajochen, 2007)	In contrast to the HR, the *HRV* increases with drowsiness and is more synchronous and therefore lower in alert states.
Melatonin (Cajochen, Zeitzer, Czeisler, & Dijk, 2000; Benloucif, et al., 2008; Sülflow, 2013; Chellappa, et al., 2011; Skene, 2003)	Melatonin is the best marker for the actual phase position and for chronodisruption (temporary misalignment of the circadian rhythm). Additionally, it can give some indication of the chronotype. The release of melatonin initiates tiredness, a low melatonin concentration hints at wakefulness. Melatonin is suppressed in response to light and can reduce the core body temperature.

A further measure indirectly estimating the circadian phasing are the alpha and theta waves of the electroencephalography (EEG) which are sensitive to light exposure (Okamoto & Nakagawa, 2016; Cajochen, Zeitzer, Czeisler, & Dijk, 2000). But because they are only an indirect measure and highly dependent on other factors, they are not reflected more detailed.

The circadian rhythm is not synchronous in all humans; a shift of approximately two hours differentiates between morning- ("larks") and evening-types ("owls") (Dinich, 2003). The preferences in the timing of sleep and wake are presumably partly based on genetics (Roenneberg, Wirz-Justice, & Merrow, 2003). These different manifestations of the circadian rhythm are called chronotypes. The chronotype does not only cohere with the measurement of the circadian phasing but may also be crucial for the biological effect of light (Sülflow, 2013). Early chronotypes feel fit and recovered in the mornings while evening types have their wellness and performance peak in the evening when extreme morning types are already getting tired. Systematic differences in wellbeing, vigilance, performance and alertness arise from the different chronotype manifestations for a certain time in the day (Kantermann, et al., 2012; Dinich, 2003; Sülflow, 2013).

Résumé The chronotype is a factor substantially influencing in the investigation of the impact of light on the human organism. Therefore, some studies specifically excluded late or both kinds of extreme chronotypes (Figueiro, Nonaka, & Rea, 2014; Chellappa, et al., 2011; Cajochen, et al., 2011; Figueiro, Bierman, Plitnick, & Rea, 2009). On one side, for the study at hand, it might be useful to exclude persons with an extreme early or morning type manifestation of the chronotype. On the other hand, accounting for ecological validity, there should not be a prioritization of indifferent and late types. Additionally, the extreme chronotypes are rare anyway (Natale & Cicogna, 2002; Dinich, 2003).

Changes in the circadian rhythms due to light exposure occur after hours or even days. Changes in body temperature have been found to occur after a delay of two hours (Lehrl, Gerstmeyer, Jakob, Bleich, & Kornhuber, 2007; Cajochen, et al., 2005). Accordingly, physiological indicators of the chronotype can be a useful supplement in order to capture the biological effect of light.

2.3. Non-image forming visual system

The visual perception is one of the most important senses, especially for the driving task, as 95% to 98% of information relevant for the driving task is perceived visually (Gramberg-Danielsen, Hartmann, & Giehring, 1984). Apart from the obvious image forming properties (Appendix B: Image forming system) of the (healthy) visual system, it exerts a second, non-image forming function of a biological nature.

Beside the rods and cones, the retina contains a third photoreceptor type, the intrinsic photosensitive retinal ganglion cells (ipRGCs). Originally, it was only known that retinal light exposure phase shifts the circadian clock accompanied by an acute suppression of melatonin (Zeitzer, Dijk, Kronauer,

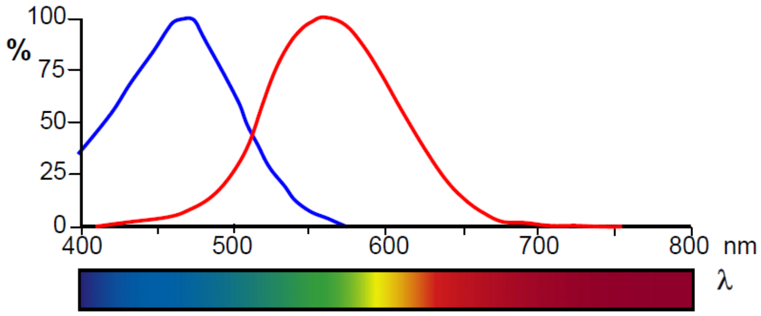

Figure 2: Spectral biological action curve (based on melatonin suppression), in blue, (source: Brainard [6]), and the visual eye sensitivity curve, in red (Van Bommel & Van den Beld, 2003)

Brown, & Czeisler, 2000). With the discovery of the ipRGCs, the secret of how the non-image forming response to light is regulated was lifted: The ipRGCs have an action spectrum with a peak sensitivity of approximately 465 nm[2] (Figure 2). Light of that wavelengths – which is perceived blueish – suppresses melatonin most effectively (Brainard, et al., 2001; Thapan, Arendt, & Skene, 2001). Melatonin is neurotransmitter produced by the pineal gland which is known to induce sleepiness. Like in the other types of photoreceptors, light hitting the retina of the eye launches the process of photopigment release, in this case melanopsin. Contrary to the image forming system, the ipRGCs have neural connections (retinohypothalamic tract) to the SCN – the site of the principal mammalian pacemaker or biological clock – and direct and indirect projections to brain areas implicated in the regulation of arousal (Cajochen, 2007). Efferent signals from the SCN are transmitted to the pineal gland which causes the suppression of melatonin (Thapan, Arendt, & Skene, 2001).

Because the ipRGCs are not distributed equally on the retina, light exposure must be applied in a certain angle of light incidence. Irradiation of the lower, mid and nasal parts of the retina leads to the suppression of melatonin, while the lateral and upper parts of the retina seem to be rarely occupied by ipRGCs (Weber & Schulmeister, 2004). Consequently, the exposure must follow in an angle of

[2] The relevant physical measures are explained in Appendix A: Physical measures.

maximal 60° to be effective; the optimal angle of light incidence lies between 0° and 45° (Figure 3; Heske, 2013).

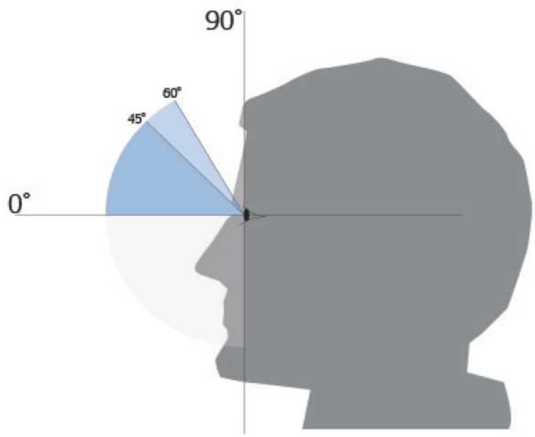

Figure 3: Optimal angle of light incidence for stimulation of the ipRGCs (internal illustration)

2.4. Non-visual light effects

Humans possess two different light-sensitive pathways: the circadian system and the visual system (Kretschmer, Schmidt, & Griefahn, 2012). Therefore, the non-visual action spectrum of light is twofold: On the one hand, light entrains the circadian rhythm and on the other hand, it exerts a direct influence on experiencing and behavior.

Light administered after the nadir of CBT can advance the phase of circadian rhythm whereas light given before the temperature nadir can induce delays (Cajochen, Zeitzer, Czeisler, & Dijk, 2000; Cajochen, et al., 2005; Benloucif, et al., 2008; Kantermann, et al., 2012). This means that light exposure in the late afternoon to early night causes the suppression of sleepiness accompanied by a later than usual CBT nadir. When light is applied in the morning hours, the circadian clock is reset back to an earlier circadian time.

The direct light effect on experience and behavior is very complex: Numerous authors report diverse reactions succeeding light exposure; Table 2 provides an overview of proved light effects including the detailed references. One commonality of the cited studies is that the light applied was essentially similar: Bright white, blue-enriched white or blue light was used for the investigation of potential light effects. Beside the peak sensitivity of the ipRGCs for blue light, light of that kind is closest to daylight which may be another reason for its effectiveness. However, single studies proved an activating effect of red light, for example Figueiro, Bierman, Plitnick, & Rea, 2009; Figueiro, Nonaka, & Rea, 2014; and Choi, Kim, Kim, Kim, & Choi, 2011.

2.4.1. Alertness

The most prominent positive effect of light is the capability to reduce sleepiness and enhance alertness at the same time. Both sleepiness and alertness can be assessed subjectively and objectively; the measurements are not necessarily correlated. This incongruency is also reported for subjective and objective measures of sleepiness unrelated to light exposure (Cluydts, De Valck, Verstraeten, & Theys, 2002). Indeed, it is certain that the effectiveness of light on subjective sleepiness is independent of the time of day in laboratory as well as real-world settings, such as workplaces. Some studies could successfully show that effect within minutes. Nevertheless, there are indicators that light can only operate when a respective psychological state is given: The subjects' alertness can only benefit from light exposure when they are tired or at least not explicitly alert (Sülflow, 2013). Subjects with high night-time melatonin levels who in general showed stronger subjective and performance-related impairment benefited primarily from the light exposure. In another study, feelings of sleepiness are only affected positively when fatigue occurs (Smolders & de Kort, 2014). This is comparable to a medication against headache; it can only operate when a headache is present. Therefore, the majority of studies induced a certain sleepiness in participants to achieve an observable increase in alertness. Further, it is reported that evening fatigue is reduced when subjects were exposed to bright light on the day.

Objective sleepiness improved with regard to reduced theta sleep episodes, a reduction of driving asleep and a suppression of the evening rise in melatonin. As with the subjective data, there are controversial findings.

With regard to the research question, behavioral measurements such as the yawning frequency, head movements, eye closing, and performance measured by means of reaction time (RT) and driving performance are eligible indicators beside the subjective rating scales. Complementing the overview by Cludyts et al. (2002), the following illustration will highlight indicators which are applicable for the driving context. First of all, the driving performance reflects the alertness state of the driver (Craye, Rashwan, Kamel, & Karray, 2016; Platho, Pietrek, & Kolrep, 2013; Taillard, et al., 2012; Shekari Soleimanloo, 2016; Hartley, et al., 2013; Weisgerber, Nikol, & Mistlberger, 2017). Physiological parameters like electrocardiography (ECG), EEG and their secondary parameters such as HR and HRV are good indicators of driver fatigue (Craye, Rashwan, Kamel, & Karray, 2016). Hammoud & Zhang (2008) additionally name the decline of muscle tone and body temperature, and the electromyogram (EMG) shift to lower frequencies and higher amplitude.

The eyes of the driver also reveal a lot about his sleepiness state; slow eyelid closures, increased number and duration of eye blinks as well as the percentage of eye lid closure indicate drowsiness (Sun & Yu, 2014; Hammoud & Zhang, 2008; Platho, Pietrek, & Kolrep, 2013; Craye, Rashwan, Kamel, & Karray, 2016; Wiegand, McClafferty, McDonald, & Hanowski, 2009). According to Hargutt (2001) the duration of eye lid closures corresponds to sleepiness while the frequency of eye lid closures is related to task variables, information processing and attention. Beside this objective measures, Filtness et al. (2014) identified four sleepiness related eye symptoms which are sensitive to driver sleepiness: "eye strain", "difficulty focusing", "heavy eyelids" and "difficulty to keep the eyes open".

Résumé One can assume that the exposure to light of blue wavelengths enhances the subjective as well as objective alertness. There are numerous opportunities to measure alertness; many of these are rather indirect. However, subjective alertness can be directly assessed using rating scales. An increase in objective alertness is associated with physiological parameters. Since these may compromise the experimental setup, many studies get by with indicators of alertness like shorter RTs, less frequent and shorter eye lid closures as well as enhanced performance.

2.4.2. Attention

The alertness state influences other parameters such as performance, attention and well-being. "Safe driving requires an adequate level of attention allocated to the driving task" (Hammoud & Zhang, 2008, p. 302). Attention is a very complex concept with diverse operationalizations. Mostly, task performance and RT measures are used as observable manifestation. Generally speaking, derivatives of attention take advantage of light exposure, albeit there are a few exemptions. On one hand, light exposure was shown to have a negative impact on selective attention in terms of accuracy while reaction times were unaffected. The number of correct and false reactions was unaffected in selective attention tasks. However, other authors were nonetheless able to show faster RTs using the same task (psycho-motor vigilance task) under blue and bright light.

On the other hand, divided attention profits from light exposure: Participants committed less omission errors, showed more correct responses, and higher accuracy, but RTs remained the same. Additionally, reduced attentional lapses were reported; according to Cheyne (2010) and Smallwood et al. (2004) these are an indicator of sustained attention. Sustained attention was improved in a LED screen (6953 K) compared to the non-LED screen condition. The effect of bright light on sustained attention seems to be dependent on the duration of exposure. However, blue light is able to enhance sustained attention.

Sustained attention is of particular significance for the driving task, especially with respect to the main target group of an in-vehicle light device. Longer trips with relatively low task demands and sparse variability require enduring sustained attention. Especially after sleep deprivation, monotonous conditions affect attention negatively ("monotony intolerance"; Popp, 2005).

Résumé The different kinds of attention apparently are not equally influenced by light exposure. Sustained attention is commonly measured by RT. Hypothetically, blue light exposure should enhance sustained attention which would result in faster reactions.

2.4.3. Vitality and well-being

One parameter directly related to attention is vitality; experiencing vitality presumes availability of mental resources. The allocation of resources is an essential requirement for establishing and maintaining attention. Hence, vitality is interrelated with the driving task as well. Only a few studies broached the issue of vitality but these could confirm the beneficial effect of daytime light exposure on experienced vitality. This effect can be observed after long term exposure as well as after a short duration of light exposure.

Many authors mention that light generally has a positive effect on well-being but without further specification (Van Bommel, 2006; Hoffmann, et al., 2008; Figueiro, Nonaka, & Rea, 2014; Ferlazzo, Piccardi, Burattini, Barbalace, & Giannini, 2014). Chellappa et al. (2011) found an increased well-being resulting from light exposure in the evening. Other authors report no change on daytime of physical well-being.

Résumé With regard to well-being and vitality, the biological effect of light could be further specified. In general, a positive effect is likely. However, since some studies attest the contrary for well-being, light devices should be evaluated concerning well-being and vitality.

2.4.4. Performance

The parameters illustrated above all impact the most important variable for the automotive context, the driving performance. Performance is a very vague formulation whose definition is only precise in relation to a task or a goal to be accomplished. For the driving task, it lies at hand to use the vehicle operation data to estimate the quality of performance. Participants performed better in the driving task after exposure to light of different characteristics insofar that some or all of the chosen measures showed a better outcome in comparison of the baseline. However, the cited studies investigated the light effect in “extreme” settings. Moreover, it must be noted that the effect partly did not occur immediately.

The results concerning performance in other tasks like cognitive and visual tasks are ambiguous: Faster or unaffected RTs are reported. Performance on complex and higher cognitive tasks (performed on screens) tapping executive functions, working and declarative memory, and visual-spatial abilities might be enhanced. In paper-based tasks, no improvement in relation to the experimental light treatment could be found. Most studies could not prove a beneficial effect of the light treatment on visual performance compared to normal lighting conditions, except from the finding of a carryover effect of daylight on nighttime performance and a relative best performance under light of 6500 K.

Résumé Performance measures in general are not easily distinguished from other interrelated constructs like attention. Nonetheless, there are a few reliable indicators of driving performance which have been proven to be sensitive to the biological effect of light.

2.4.5. Mood

In laboratory and real-life settings at daytime, targeted light enhances self-reported mood towards a more positive mood. This beneficial effect can be proven in healthy individuals and also in persons with mood disorders insofar that the intensity of depressive symptoms is reduced. High color temperatures cause lower depression ratings in terms of valence. Light impacts the amygdala and the hippocampus, which might explain its impact on mood (Vandewalle, et al., 2006).

An aspect not explicitly mentioned in Table 2 but nonetheless important for the road traffic is aggression. Unfortunately, there is only one study available which directly addresses that issue:

Wessolowski (2014) conducted observational ratings of aggressive behavior in school children and stated that there is a tendency that dynamic light advances pro-social behavior and aggressive behavior is not shown.

Résumé

Concerning the mood state, one can hypothesize that exposure to light of blue wavelengths enhances the current mood.

Due to the interrelatedness of all the parameters potentially being affected by light exposure, the measurement of an effect has to be planned and carried out very thoughtfully: Most authors combine physiological, subjective and objective data in order to make statements about the light effect. Circadian oscillations, sleep and wake times, the time of the day, and the individual chronotype must always be considered. Individual levels of neurotransmitters, age, and gender among others might mediate the light effect (Popp, 2005; Rüger, Gordijn, Beersma, de Vries, & Daan, 2006; Weber & Schulmeister, 2004). The same holds for the design of a potential placebo light condition: Red light, for example, is not the right choice because single studies reported effects similar to those of blue light.

Table 2: Overview of the light effect on selected parameters (The parameters are not independent of each other; overlaps occur)

Parameter & studies	Light effect	Specification of parameter	Measurement
Alertness		Alertness is one of the most prominent indicators for the biological effect of light; it can be distinguished between *subjective* and *objective* alertness. In general, alertness is a construct associated with high levels of environmental awareness. Alertness correlates with speed of information processing and is generally associated with higher performance.	Indicators of *objective* alertness are for example short response times, fast and more accurate tests of mental capacity, EEG correlates of alertness (increase in alpha and beta activity[3], respectively) as well as hormone production (cortisol) and correspondingly suppression (melatonin). *Subjective* alertness is evaluated in self-ratings.
Viola, James, Schlangen, & Dijk, 2008	⇒ Subjective alertness benefits from longtime (4 weeks) exposure to blue-enriched white light (17000 K, ~ 310 lx during working hours).		
Figueiro, Bierman, Plitnick, & Rea, 2009	⇒ Subjective sleepiness ratings were not strongly affected by the lighting (max. 470 nm, 40 lx, 45 min).		
Lehrl, Gerstmeyer, Jakob, Bleich, & Kornhuber, 2007 Gerstmeyer, Lehrl, Bleich, & Kornhuber, 2008	⇒ Subjective alertness was elevated from "relaxed" to "full alertness" by blue light (2 min, 1400 lm, 455 nm).		
Leichtfried, et al., 2015	⇒ Brief exposure (30 min) to bright light (6500 K, max. 1500 cd/m²) in the morning hours can improve subjective measures of alertness.		
Rahman, et al., 2014	⇒ Daytime and nighttime light exposure (460 nm, 6.5 h, 2.8 × 1013 photons/cm²/s) improved objective alertness. However, subjective alertness was only improved at night.		
Attention		Attention is a general concept that refers to the ability to allocate cognitive capacity and finite processing resources as a function of arousal and effort. Several subconcepts can be distinguished: *Selective attention* is the competence to focus the attentional resources on relevant stimuli while ignoring irrelevant ones. It contributes to	According to Kretschmer, Schmidt, & Griefahn (2012), RT tasks are a common measure for sustained attention/vigilance. Psychomotor vigilance test (PVT), which can be carried out auditory or visual, is widely used. Other methods of measurement are the Go-NoGo-task and the
Kretschmer, Griefahn, & Schmidt, 2011 Kretschmer, Schmidt, & Griefahn, 2012	⇒ Divided attention profits from light exposure (3000 lx, 4 h, night shift): Participants committed less omission errors, showed more correct responses, and a higher accuracy, but reaction times remained the same. Only divided attention, but not selective attention benefits from bright light.		

[3] "Alertness is associated with [...] low power densities in the alpha frequency range (812 Hz) and high power densities in the beta frequency range (1230 Hz) in the electroencephalography (EEG)" (Figueiro, et al., 2009, p. 2) Controversially, it is stated that "EEG high-frequency alpha activity [...] is a specific marker of the circadian drive for alertness" (Rahman, et al., 2014, p. 279).

Parameter & studies	Light effect	Specification of parameter	Measurement
Leichtfried, et al., 2015	⇒ Intense illumination (6500 K, 1500 cd/m², 30 min) negatively impacts sustained attention.	mental/cognitive performance and is therefore decisive for work efficiency and safety. *Sustained attention* terms a prolonged wakefulness over a longer period of time dealing with a certain task. (*Vigilance* – a state of wakeful monitoring of particular stimuli in a monotonous environment with low task demands – is in the most publications treated as equal to sustained attention; the psychomotor vigilance task is commonly used to assess one or both.) *Divided attention* is the capability to attend two different kinds of demands simultaneously ("multi-tasking").	sustained attention test of the Vienna Test System.
Beaven & Ekström, 2013	⇒ Blue light exposure (~ 40 lx, max. 470 nm, 1 h) improved the accuracy in a sustained attention task. Reaction times only improved in blue-eyed participants.		
Rahman, et al., 2014	⇒ Exposure to 460-nm monochromatic light for 6.5 h improved auditory performance in a sustained attention task and reduced attentional lapses.		
Cajochen, et al., 2011	⇒ 5-h evening exposure to a white LED-backlit screen enhanced sustained attention compared to a non-LED-screen.		
Smolders & de Kort, 2014	⇒ "While performance on a simple reaction time task benefited from bright light exposure, performance on the other more complex tasks appeared to be affected adversely by brighter light" (200 vs. 1000 lx, 30 min, 4000 K).		
Chellappa, et al., 2011	⇒ Blue-enriched light (6500 K, 40 lx, 2 h in the evening) leads to faster reaction times in tasks associated with sustained attention.		
Hartley, et al., 2013	⇒ Bright light (30 min, 10000 lx) applied at night time did not change indicators of objective and subjective vigilance.		
Cognitive Performance		The term cognitive performance is unprecise; in this work it will be used to summarize different kinds of mental performance which may involve other aspects of working memory (e.g., spatial, verbal) and speed of information processing. Some authors measure cognitive performance in terms of sustained attention which is not included in the definition but treated as a distinct parameter. However, cognitive performance and attention are linked to each other.	To name some examples of tasks measuring cognitive performance, the Digit-Symbol Association Test (subtest of the WAIS), Purdue Visualization Rotations Test (subtest of the Purdue Spatial Visualization Test Battery), task switching, word (-pair) learning, auditory sequence monitoring tasks, verbal event planning tasks, spatial map study tasks and n-back tasks can be enumerated.
Ferlazzo, Piccardi, Burattini, Barbalace, & Giannini, 2014	⇒ "Performance on complex tasks tapping executive functions and visual-spatial abilities are modulated by exposure to a cooler light" (p. 98; ~ 3500 lm, 4000 K).		
Cajochen, et al., 2011	⇒ Participants achieved a better performance during higher cognitive tasks involving working and declarative memory systems when exposed to a white LED-backlit screen compared to a non-LED-backlit screen.		
Smolders & de Kort, 2014	⇒ "While performance on a simple reaction time task benefited from bright light exposure,		

Parameter & studies	Light effect	Specification of parameter	Measurement
	performance on the other more complex tasks appeared to be affected adversely by brighter light" (200 vs. 1000 lx, 30 min, 4000 K).		
Hawes, Brunyé, Mahoney, Sullivan, & Aall, 2012	⇒ Faster reaction times as a function of higher color temperature (3345 – 6029 K, 1.5 h) are reported. The lighting-induced improvements in participant mood state reliably predict faster cognitive task performance.		
Chellappa, et al., 2011	⇒ Blue-enriched light (6500 K, 40 lx, 2 h in the evenings) improves performance in tasks associated with sustained attention, but not in tasks associated with executive function. The improvement in cognitive performance related to attenuated melatonin levels.		
Lehrl, Gerstmeyer, Jakob, Bleich, & Kornhuber, 2007	⇒ Speed of information processing increases by 3.3% corresponding to an increase of about 5 IQ-points.		
Kretschmer, Griefahn, & Schmidt, 2011 Kretschmer, Schmidt, & Griefahn, 2012	⇒ Unaffected reaction times in a working memory task but more correct responses due to bright light (3000 lx, 4 h, night shift) exposure were observed.		
Driving performance		Driving performance is the extent to which a driver is able to fulfill requirement of the driving task like lane tracking etc. There are numerous measures from the vehicle operation data which can be employed to operationalize the driving performance.	Concrete indicators of driver drowsiness identified via an expert study are: amplitude of steering correction, standard deviation of steering correction, time during which a set steering angle, and/or steering speed is exceeded, relation of fast and slow steering corrections, deviation from lane middle, standard deviation of lateral lane position (SDLP), time to lane crossing and touching and overrunning the lane border, respectively (Platho, Pietrek, & Kolrep, 2013). There are numerous other operationalizations of driving performance: number of inappropriate line crossings, longitudinal and lateral velocity, mean/absolute lateral lane position, the
Taillard, et al., 2012	⇒ The exposure to blue light (468 nm, 20 lx, 2 h) reduced the number of inappropriate line crossings and the standard deviation of the lateral position of the car in a real driving study at night.		
Shekari Soleimanloo, 2016	⇒ The study investigated the effect of light in comparison with caffeine as well as the combination of both treatments. In general, blue-green light (500nm, 506 lx, 230 μW/cm², 30 min exposure on daytime) improved indices of driving performance. The absolute value of steering wheel angle was found to be the most sensitive index of driving performance to sleep deprivation. Light alone improved speed exceedance and steering wheel angle indices.		

Parameter & studies	Light effect	Specification of parameter	Measurement
	However, the combination of light and caffeine is most effective.		longitudinal acceleration due to the brakes, mean/absolute speed, mean/absolute steering wheel angular rate, the minimum time to collision, the minimum range between ego vehicle and other vehicles/pedestrians, speed exceedances, speed deviation, and the number road crashed/collisions.
Hartley, et al., 2013	⇒ Exposure to bright light (10000 lx, 30 min) at night time decreases lane drifting and speed deviation while driving in a driving simulator. However, this effect did not occur immediately.		
Weisgerber, Nikol, & Mistlberger, 2016	⇒ Bright light (5000 K, 5600 lx, 45 min) results in fewer incidents and accidents overall when sleep deprived subjects drive in a high fidelity driving simulator. Additionally, the time-on-task effect was attenuated.		
Mood		Mood, or the emotional state, can be divided into the two dimensions valence and arousal. *Valence* describes the negative to positive continuum, while *arousal* describes the high (e.g., excitement) to low (e.g., sleepiness) continuum. Mostly, the mood assessment in the reviewed literature follows unidimensional. Since arousal is highly associated with subjective alertness, it is treated as a distinct construct (apart from Hawes, Brunyé, Mahoney, Sullivan, & Aall, 2012).	Beside visual analogue scales, the Positive and Negative Affect Scale (PANAS), the Profile of Mood States (POMS), the Seasonal Pattern Assessment Questionnaire (SPAQ), the Multidimensional Mood State Questionnaire (MDMQ) and the “Befindlichkeits-Skala” (Bf-S) were used in the cited studies.
Viola, James, Schlangen, & Dijk, 2008	⇒ Blue-enriched light enhances self-reported mood towards a more positive mood (17000 K, ~ 310 lx during working hours).		
Borisuit, Linhart, Scartezzini, & Münch, 2015	⇒ The authors found that an improvement of mood is associated with a higher correlated color temperature (at 4 pm, 4000 K, 1000 – 2000 lx).		
Hoffmann, et al., 2008	⇒ Variable light (500–1800 lx, 6500 K) exerts a potential advantage in indoor office accommodations with respect to subjective mood: the variable lighting enhanced ratings of the dimensions of “activity” (on day 1 of the study).		
Leichtfried, et al., 2015	⇒ Bright light (6500 K, 1500 cd/m^2, 30 min) in the morning leads to an increase in self-reported mood.		
Hawes, Brunyé, Mahoney, Sullivan, & Aall, 2012	⇒ Higher color temperatures lead to increased arousal states and lower rated depression relative to the lower color temperatures (3345 – 6029 K, 1.5 h). “[H]igher color temperatures produced an increase in vigor/activity and decreased fatigue scores, allowing participants to experience extended periods of arousal” (p. 127).		

Parameter & studies	Light effect	Specification of parameter	Measurement
Partonen & Lönnqvist, 2000	⇒ Exposure to bright light (6500 K) has a beneficial effect on mood in healthy adults working in an office environment insofar that it reduced the intensity of depressive symptoms in healthy adults.		
Sülflow, 2013	⇒ The results of a blue light intervention in the evening are positive, although this effect seems to be dependent on the chronotype and gender (460 nm, 12.15 μW/cm²).		
Physical performance		Physical performance equates to sporting prowess which is to the individual's internal time.	Physical performance is operationalized as total work (kJ), changes in blood lactate, HR, body temperature, oxygen uptake and carbon dioxide expiration.
Kantermann, et al., 2012	⇒ Timed according to the chronotype, light exposure (4420 lx) augments physical performance with a concomitant increase in individual strain.		
Deutscher Skiverband, 2015 OSRAM, 2016	⇒ The light device developed by OSRAM simulates the course of daylight and there is an additional "light shower". The light application is said to improved responsiveness, enhance physical performance and counteract jetlag.		
Sleepiness		Since sleepiness is the counterpart to alertness, there are a few overlaps with respect to the measurement and empirical evidence. One can distinguish between *subjective* and *objective* sleepiness. Objective sleepiness can be operationalized as performance deterioration or physiological parameters are utilized as indicators. A detailed definition of sleepiness is provided in the section 2.1.	Cluydts, De Valck, Verstraeten & Theys (2002) provide following overview: *Behavioral measures* ⇒ Behavioral observation: Yawning frequency, oculomotor activity, eye closing, head movements, facial expression, actigraphy ⇒ Performance tests: Reaction time tests, psychomotor vigilance test, driving simulator *Subjective rating scales* ⇒ Acute level of sleepiness: Stanford Sleepiness Scale (SSS), Karolinska Sleepiness Scale (KSS), Visual analogue scales of sleepiness/alertness ⇒ Global level of sleepiness: ESS, Sleep–wake activity inventory (SWAI)
Figueiro, Bierman, Plitnick, & Rea, 2009	⇒ Physiological correlates of sleepiness (ECG, EEG, and melatonin) are positively affected by blue light (470 nm, 40 lx) at night; but HR and EEG data were also affected by red light. Controversially, performance and subjective sleepiness rating do mirror this effect.		
Figueiro, Nonaka, & Rea, 2014	⇒ Subjective sleepiness ratings were compared after 1 h exposure to blue (max. 470 nm, 40 lx) and red (max. 630 nm, 40 lx) light; there is no difference between the lighting conditions. However, in a second study, subjective sleepiness was attenuated after exposure to blue light at night under sleep deprivation.		
Rüger, Gordijn, Beersma, de Vries, & Daan, 2006	⇒ Bright light (5000 lx) has a time-dependent effect on heart rate and core body temperature; i.e., bright light exposure at night, but not in daytime, increased heart rate and enhanced		

Parameter & studies	Light effect	Specification of parameter	Measurement
	core body temperature. It had no effect on cortisol. The effect of bright light on the psychological variables is time independent, since nighttime and daytime bright light reduced sleepiness and fatigue similarly.		*Electrophysiological measures* Multiple sleep latency test (MSLT), Maintenance of wakefulness test (MWT), polysomnography, pupillometry, cerebral evoked potentials Supplementary, parameters set forth in Table 1, brain activity derived from the EEG or electrical potential oscillations of an EOG are widely used as objective determinants of sleepiness.
Leger, Philip, Jarriault, Metlaine, & Choudat, 2009	⇒ Bright light (5000 lx, 10 min) after a nap of 20 min reduces subjective sleepiness in shift working professional drivers. Further, the percentage of driving asleep is reduced as well as episodes of theta sleep. Unfortunately, no information concerning the driving behavior of the participants is reported.		
Popp, 2005	⇒ Blue light (460 nm, 2500 lx) fights symptoms of sleepiness (vigilance, pupillography) exclusively at night; this effect is mostly pronounced in subjects with a high nocturnal melatonin concentration.		
Cajochen, et al., 2005	⇒ Light of 460 nm wavelength caused a suppression of salivary melatonin compared to 550 nm wavelength light starting after 30 min of exposure; a parallel effect can be observed for subjective sleepiness. CTB and HR were also affected by the blue light. The light application followed in the evening.		
Beaven & Ekström, 2013	⇒ Blue light (~ 40 lx, max. 470 nm, 1 h) did not affect subjective sleepiness.		
Brown, et al., 2014 Brown L. , et al., 2014a	⇒ Flight crew members who were daily exposed 30 min to 465 nm light over two weeks, showed a higher "behavioral alertness" (measured by the PVT) and lower subjective sleepiness.		
Kaida, Takeda, & Tsuzuki, 2012	⇒ A short nap is a powerful countermeasure against sleepiness compared to bright light (> 2000 lx) exposure in the afternoon.		
Smolders & de Kort, 2014	⇒ Exposure to bright light (1000 lx, 4000 K) had an effect on subjective sleepiness mainly when participants felt fatigued; the effect is		

Parameter & studies	Light effect	Specification of parameter	Measurement
	dependent on the individuals' psychological state.		
Shekari Soleimanloo, 2016	⇒ The application of blue-green light (500nm, 506 lx, 230 μW/cm², 30 min exposure on daytime) decreased subjective sleepiness scores from "some signs of sleepiness" to "not sleepy" or even to "rather alert". Light alone did not improve objective sleepiness, only light and caffeine in combination improved reaction times.		
Kraneburg, Franke, Methling, & Griefahn, 2017	⇒ Illuminations with higher correlated color temperatures (> 3900 K) are associated with lower melatonin levels. Though, the subjective sleepiness ratings do not decrease correspondingly.		
Cajochen, et al., 2011	⇒ Evening exposure to a LED-backlit computer screen resulted in attenuated sleepiness levels compared to a non-LED-backlit screen.		
Viola, James, Schlangen, & Dijk, 2008	⇒ Blue-enriched white light (17000 K) decreases subjective sleepiness when participants are regularly exposed to the light (during working hours).		
Shamsul, Sia, Ng, & Karmegan, 2013	⇒ Artificial daylight (6500 K) during lecture leads to the lowest sleepiness ratings compared to white light.		
Sleep-quality		Factors like the number of awakenings etc. determine the sleep quality.	Sleep quality was assessed via self-report regarding awakenings, inability to sleep, sleep duration, feeling after awakening and depth of sleep in the studies at hand; e. g. a standardized questionnaire is the Pittsburgh Sleep Quality Index (PSQI).
Viola, James, Schlangen, & Dijk, 2008	⇒ The quality of subjective nocturnal sleep was improved under blue-enriched white light (17000 K, ~ 310 lx during working hours).		
Aries, 2005	⇒ An improved sleep quality after bright light (17000 K during daytime workhours; 2000 lx) exposure during the day is reported.		
Visual (task) performance		Visual task performance means that the given task is based on visual perception and accurate visual perception is necessary to succeed in the task, respectively. Ideally, visual performance tasks do not commingle	Several standardized, computer based tasks can be used to assess visual task performance. In two studies, Landolt rings were used as paper based procedure. Further tests are color recognition tasks
Sivaji, Shopian, Nor, Chuan, & Bahri, 2013	⇒ Under cold withe light (4000 K), the highest typing speed is achieved but the differences in CCT of lights do not affect workers performance involving the use of computer.		

Parameter & studies	Light effect	Specification of parameter	Measurement
Hawes, Brunyé, Mahoney, Sullivan, & Aall, 2012	⇒ Performance on a visual perception task involving color recognition showed faster performance with lighting of higher color temperatures (3345 – 6029 K, 1.5 h).	with cognitive performance tasks. The comparison of performance in visual tasks is a common way to assess the light effect.	(pseudoisochromatic plates, Farnsworth-Munsell 100 color hue test), visual acuity tasks (Snellen Eye Chart), numerical verification and matching tasks.
Kaida, Takeda, & Tsuzuki, 2012	⇒ The study examined effects of a short afternoon nap (20 min) and/or bright light (2000 lux) on visual search and implicit learning. Only sleepiness, but no performance measure is affected by light.		
Kraneburg, Franke, Methling, & Griefahn, 2017	⇒ Color discrimination is worse under illuminations with correlated color temperatures under 2000 K than for correlated color temperatures higher than 2000 K.		
Shamsul, Sia, Ng, & Karmegan, 2013	⇒ Computer-based task performance is best under artificial daylight (6500 K) compared to white light. In a paper-based task, no differences between the lighting conditions occur.		
Wilhelm, Weckerle, Durst, Fahr, & Röck, 2011	⇒ Visual performance was investigated with regard to visual acuity, color vision and contrast sensitivity. During the dayshift, increasing the illuminance from 500 lux to 1500 lux or 2500 lux has no effect on the parameter of visual performance.		
Vitality		Vitality describes the positive feeling of having energy or resources available to the self. Vitality is related to alertness, mood and the chronotype. The term is used here synonymous to activity, energy and fitness.	Standardized self-assessment scales for vitality are among others the Activation-Deactivation checklist (“energetic”, “lacking in energy”, “alert”, “sleepy”), the RAND general health rating index and selected items of the Short Form 36 Questionnaire (SF-36).
Viola, James, Schlangen, & Dijk, 2008	⇒ Regular exposure (4 weeks during work) to blue-enriched white light (17000 K) enhances feelings of vitality in white-collar workers.		
Partonen & Lönnqvist, 2000	⇒ Partonen & Lönnqvist (2000) report improved vitality ratings for all participants after exposure to bright light (6500 K) in winter time in the office.		
Smolders & de Kort, 2014	⇒ Participants felt more vital after exposure to bright light of 1000 lx.		

Parameter & studies	Light effect	Specification of parameter	Measurement
Smolders, De Kort, & Van den Berg, 2013	⇒ The field study revealed that the amount of light received is related to vitality insofar that persons exposed to more light feel more vital. This effect is especially pronounced in the morning, during winter and when a person feels hardly vital.		
Mills, Tomkins, & Schlagen, 2007	⇒ The self-reported vitality of subjects increased by 28.4 % compared to the baseline after regular exposure to light of 17000 K in an office environment.		
Well-being		Chellappa et al. (2011) operationalize well-being as a function of mood, tension and physical comfort.	Simple unidimensional scales are mostly used for the self-assessment of well-being. Physical well-being is also evaluated as one dimension (physically comfortable – physically uncomfortable).
Wilhelm, Weckerle, Durst, Fahr, & Röck, 2011	⇒ In this study, well-being under different lighting conditions (500/1500/2500 lx) in the dayshift was investigated; no improvement compared to the normal illuminance of 500 lx could be found.		
Borisuit, Linhart, Scartezzini, & Münch, 2015	⇒ The physical well-being of the participants did not change in the course of the afternoon in relation to the light exposure (1000 – 2000 lx, ~ 4500 K).		
Chellappa, et al., 2011	⇒ When comparing subjective well-being during light exposure to pre-light levels, light at 6500K (40 lx, 2 h in the evenings) resulted in an increase of 1.1 ± 3.1%.		

3. Light in the vehicle interior

Nowadays, vehicle interior design is not only an issue of usability but does also address user experience. Classical ambient lighting is of a primarily decorative nature but it additionally provides "a better orientation in the car, an improved sense of spaciousness, an impression of safety, value, and comfort" (Caberletti, 2013, p. 1). Light in the vehicle interior can be called ambient light when the light is active while driving (Grimm, 2002). "Performing not only conventional and ambient illumination functions, lighting is now taking part as a safety function as well" (Bizal & Wambsganß, 2015, p. 587). E. g., ambient light can be used to guide the driver's attention in a certain direction or to inform the driver during assisted driving (Barthel, Thomschke, Koether, & Neumann, 2015; Bizal & Wambsganß, 2015).

3.1. Biologically effective light

As already mentioned in the preceding sections, there are some studies which investigated the effect of light in terms of driver sleepiness in the vehicle interior (Table 2). The positive effect of light can be seen as proven with the limitation that the driver was in a state of diminished alertness before light application due to experimental settings or shift work. Daimler's TopFit Truck was developed based on research concerning sleep, vitalization and fitness in trucks; it possesses beside different wellness and fitness features an ambient lighting called "Daylight+" (Figure 4) installed at the ceiling of the driver's cabin (Daimler, 2013). The lighting concept consists of red light for relaxation in the break and blue light to keep the driver alert (trucker.de, 2014). It is reported that a sufficient amount of light reaches the driver's eye to successfully suppress the release of melatonin (trucker.de, 2014). Farkas et al. (2015) were able to show for the first time that an in-vehicle, biologically effective light like the Daylight+ has a stimulating, activating and performance enhancing effect on truck drivers. The effect of blue light (460 nm) was compared to low levels of red light with regard to vigilance, alertness, driving skills and acceptance. The measurements were taken before and after a drive in the truck equipped with the Daylight+. Due to the within-subjects design, every participant completed the subjective ratings and the objective vigilance test four times. Subjective ratings for vigilance and alertness increased after exposure to blue light compared to the placebo light. No differences in reaction times were evident but the accuracy of reactions increased as a result the blue light treatment. They even reported that the biological effective light leads to a more economical driving style. However, the statement made above about the limitations of evidence for the light effect cannot totally be proved wrong because the active light condition in the Daylight+ study was paired with a high natural luminance.

KIA presented an in-car lighting concept called "Light-Emitted Rejuvenation (LER) system" which is design to provide "therapeutic light" (KIA, 2016). It consists of "LEDs surrounding the moonroof that glow in a "pattern of therapeutic light," supposedly to reduce drowsiness", treat jetlag and improve the passengers' energy levels (Atiyeh, 2016). Unfortunately, no information on the empirical testing of the LER system is available.

Figure 4: Daylight+ (left; trucker.de, 2014) and Light-Emitted Rejuvenation system (right; KIA, 2016)

Analogous to the vehicle interior, Brown et al. (2014, 2014a) applied light therapy with blue light on flight crew and cabin crew members for a duration of two weeks. The working environment of the target group is not only coined by high safety demands but also by personal strains on the operators such as jetlag. The blue light led to a decreased self-reported sleepiness and fatigue as well as reduced physiological indications of sleepiness.

3.2. Prototype vehicle

The Volkswagen Group did also undertake research in the area of biologically active light. To evaluate the actual effect of an in-vehicle light device designed to increase the driver's alertness, a prototypical ambient light was constructed. The ambient light was already subject of an evaluation (Appendix D: Pilot study). The vitalizing light device "V-Light" is installed in a passenger car of the model Audi Q7 (automatic gearbox) over the driver's seat at the headliner (Figure 5). It consists of six horizontal

Figure 5: Interior lighting V-Light

aligned LED bars which reach from the sun shield to the full height of the roof. This array is supposed to emit light in an angle from 0° to 60° in the peripheral visual field of the driver to warrant an optimal angle of light incidence at the driver's eye. The light bars are equipped with two and four Power-LEDs per bar, respectively, which provide white light of a relatively high intensity. Additionally, the LED bars contain RGB-LEDs which emit among others blue light of 475 nm wavelength. The actual dominant wavelength of the blue light which hits the driver eye is 468 nm; the dominant wavelength is slightly shifted because of a dot matrix layer.

The V-Light concept intends that the driver is alerted by the blue light in darkness and twilight, e. g. in the morning on the ride to work, and that daylight (environment brightness above 400 lx) is reinforced by white light. In addition, the driver can be exposed to orange light inspired by dawn which is supposed to have a calming effect (Fördergemeinschaft Gutes Licht, 2014; Noguchi & Sakaguchi, 1999). Overall, the prototype is designed to support the driver's routine in a circadian appropriate way.

Résumé

Recently, new dimensions of interior lighting design for vehicles were exploited; one of them is the application of biologically effective light. Beside the studies mentioned in the Theoretical foundations section, two lighting concepts, the LER system and the Daylight+, were made public. Only the Daylight+ was empirically tested with promising results. Nonetheless, the research focus of the thesis at hand is not covered yet: The study by Farkas et al. (2015) concentrated on daylight reinforcement while the study exposed in the next section focused on light application at the interior of a passenger car in darkness at the morning hours.

4. Method

To examine the research question, a trade-off between ethical issues and a realistic setting had to be made. To guarantee the security of participants and comparability of environmental light conditions, a simulator study was conceptualized. In the following sections, the setup and procedure of the study will be outlined.

4.1. Ethics

The study was conducted according to the Declaration of Helsinki and approved by the Volkswagen Group (Wolfsburg, Germany) internal Ethics authority. Dealing with a simulator study, there is no noteworthy risk; the probability of the participants becoming simulator-sick is minimal in the chosen setting. Due to the fact that the light exposure happens in the morning hours, there are no inadvertent consequences such as a delayed falling asleep to be expected.

4.2. Participants

The participants were all employees of the Volkswagen Group, Wolfsburg and participation in the study was restricted to subjects who fulfilled following criteria:

- No journeys over one or more time zones within the last two weeks, since a jetlag "produces a temporary misalignment between the timing of the central circadian clock and the desired sleep times" (Burgess, 2011, p. 152) which in turn causes insomnia, daytime sleepiness etc. (Burgess, 2011); due to the testings on different days, measures of participants suffering from jetlag would lack comparability;
- No shift workers, because the schedule is not compatible with the study schedule; the early shift is currently working while exposing night shift workers to the blue light in the morning would be unethical;
- Not older than 50 years, because older people tend to be early chronotypes and additionally, the absorption of short-wavelength light increases with the age due to the age related macular degeneration, while the pupil diameter decreases with increasing age (Dinich, 2003; Gerstmeyer, Lehrl, Bleich, & Kornhuber, 2008; Weber & Schulmeister, 2004);
- Taller than 1.70 m, in order to ensure an appropriate angle of light incidence;
- No participation in the pilot study, because subjects were informed about the non-visual effect of light;
- No wearers of glasses and no optical aid with color screen to assure reception of the blue wavelength light;
- No eye diseases which could lead to a diminished absorption of blue wavelength light (dyschromatopsia was no exclusion criterion because normal trichromatic vision is not necessary for light-mediated neuroendocrine regulation (Beaven & Ekström, 2013));
- Ownership of a driver's license.

The acquisition of subjects followed through the Volkswagen internal subjects' pool. Of the N = 23 subjects, n = 15 were male and n = 8 female. The mean age was M = 32.27 years (SD = 9.78) with the youngest participant being 22 years old and the oldest 49 years old. As participation was restricted to persons taller than 170 cm, the mean height was M = 181.5 cm (SD = 6.49) ranging from min = 171 cm to max = 196 cm. On average, the subjects traveled to work M = 37.05 min (SD = 39.92, min = 10, max = 200) and hold their driving license M = 14.89 years (SD = 9.21, min = 5, max = 33). The majority of the participants was driving 10000 to 20000 km per years. 16 participants corresponded to the intermediate chronotype and 7 to the moderately morning type.

Initially, the sample consisted of 33 subjects; 7 female participants needed to be excluded due to their height. One participant was not included because he did not return the questionnaire containing the demographic data. Further, two trials could not be completed due to technical difficulties.

4.3. Design of study

The design of the study addressed in this thesis is based on a few lessons learned from a pilot study (Appendix D: Pilot study): First, the subjects in the pilot study were not tired at all. To observe a vitalizing effect, the participants must necessarily be sleepy at the initial state (Sülflow, 2013). The same applies to the current mood state. Possibly, the choice of the time slots was not ideal and did not match the circadian nadirs of the participants. Another reason may been the season; the study was conducted from May to June 2016. As it is known that daylight and sunlight, respectively, do have an effect on the current state (seasonal affective disorders), a study conducted in the winter months has a greater potential to show a light induced effect.

Second, the LED strip in the sunshield which was designed to ensure that smaller drivers receive the light in an appropriate angle of incident was not enlightened but at the same time there were no restrictions regarding the size of participants. Although the position of the driver's seat was standardized the amount of light hitting the retina may have varied due to different heights of subjects.

Third, a RT task was carried out every 10 minutes. There is empirical evidence that tasks like counting backward result in stress related changes in physiological parameters (Allen, Blascovich, Tomaka, & Kelsey, 1991; Kaiser, Altmann, Bledowski, & Naumer, 2007; McNulty, Gevirtz, Hubbard, & Berkoff, 1994). The same effect might occur with a RT task: Since the participants are stressed every 9 to 10 minutes, they might have been aroused permanently and therefore could not reach a pronounced state of sleepiness. Chellappa et al. (2011) were able to prove shorter RTs due to light exposure but the interval between the measurements was much longer (90 min) or in other studies, participants were sleep deprived and/or the duration of light exposure was longer. Therefore, intervals larger than 10 min between the measurement points seem useful.

Fourth, some participants reported that they enjoyed the secondary task. Probably, the visual search task was too pleasurable to be eligible as secondary task. This would have a similar contorting effect like the RT task executed every 10 min. Addionally, the chosen visual search task is not comparable to a realistic driving scenario.

The study at hand was designed as a repeated measures within-subjects design with one test condition (no light – NL, blue light – BL) per day. The order of test conditions was randomized by means on the sample function of R (The R Foundation for Statistical Computing, version 3.3.0, 2016). The participants were instructed to choose the time slot for the trial corresponding to their regular daily routine so that no notably shift in the wake-up time was induced. The time slots for the testing were 6:30 – 8:00 a.m. and 8:00 – 9:30 a.m. on workingdays. Since one can see it as proven that a certain level of drowsiness is necessary to achieve an observable effect of light (Sülflow, 2013), the only ethically conductible way was to invite participants in the morning hours. This time span is due to its relevance in daily life and the corresponding nadir in the circadian rhythm especially of interest.

4.3.1. Independent variables

The manipulation in the study follows through the variation of the lighting conditions via the light device implemented in the prototype vehicle (Prototype vehicle section): no light (NL) versus blue light (BL). Each testing lasted 61 minutes. In the no light condition, no light except for the illumination of the cockpit instruments and the beamers used for the scenario projection was administered. Participants were exposed to blue monochromatic light of 468 nm wavelength with an illuminance of 22 lx[4] for 40 minutes after a darkness period of 20 minutes. The darkness prior to the blue light was used to neutralize a potential light exposure before the trial and to establish a certain level of drowsiness in the participants.

4.3.2. Dependent variables

The effect of the manipulation was measured in relation to the parameters current mood state, subjective as well as objective alertness, and attention. Figure 6 displays schematically the different measurement points in the course of the trial. The measurement time point t0 was at the beginning of the study, prior to the NL- or BL-condition. During and after the test condition, measurements were taken (t1, t2). The last measurement point (t3) was on the following day. After the testing, a paper-pencil survey in an addressed envelope was given to the participants with the instruction to complete it on the following day and to send it back to the experimenter. The post-trial questionnaire serves to assess the sustained light effect.

Multidimensional Mood State Questionnaire: The current mood state was assessed by means of the German version of the Multidimensional Mood State Questionnaire (MDMQ; Steyer, Schwenkmezger, Notz, & Eid, 1997). The current mood state is operationalized through three dimensions on a five-point Likert scale: good-bad ("content"), awake-tired ("rested") and calm-nervous ("restless"). The short versions A and B consisting of 12 items (four items per dimension) was used in a randomized

[4] Vertical luminance measured at eye level of a driver of 1.80 m height

manner. The internal consistency of the short version lies between Cronbach's Alpha $r = .73$ and $r = .89$ (Steyer, Schwenkmezger, Notz, & Eid, 1997a). In order to calculate the overall score per subscale, the scores of the single items are added. The possible range for each dimension is from 4 to 20. The lower the score, the worse is the evaluation; a sum of 12 indicates a neutral state.

Karolinska Sleepiness Scale: To measure the subjective sleepiness, the Karolinska Sleepiness Scale (KSS; Åkerstedt & Gillberg, 1990; German translation by Popp, 2005) was applied. The scale allows an assessment of the alertness state ranging from "extremely alert" (score = 1) to "extremely sleepy – fighting sleep" (score = 9). According to Åkerstedt & Gillberg (1990), the KSS score is validated against physiological sleepiness indicators. Further, the KSS score is known to predict performance (Gillberg, Kecklund, & Åkerstedt, 1994).

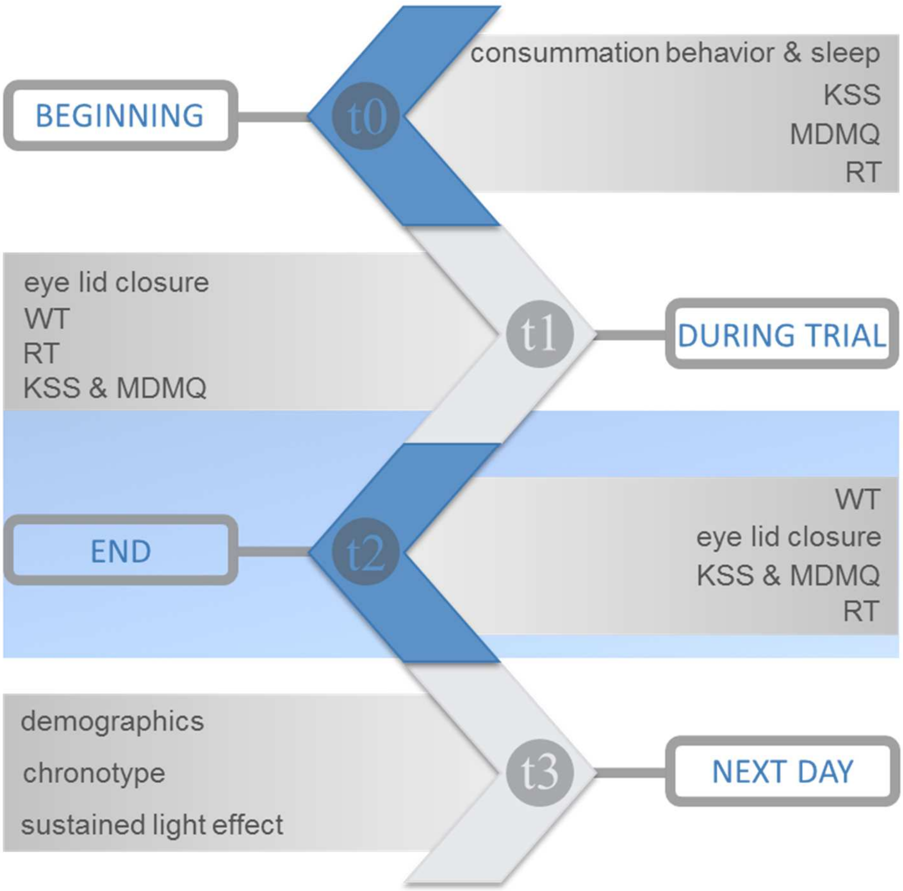

Figure 6: Schematic overview of the measurement time points (t0 – t3) and measured parameters; the blue bar indicates the light application in the BL-condition

Eye lid closure: "Drowsy drivers typically have problems to control their eyes [...]. Physiologically this behaves as rapid blinking at the on-set of drowsiness and slow blinking as the drivers are deeply affected" (Sun & Yu, 2014, p. 1936). Hargutt (2001) ascertains that the duration of the eye lid closure hints at sleepiness while the frequency of eye lid closures is related to task variables, information processing, and attention. "Eye closures with a duration of over 300 - 500 milliseconds are typically coded as slow eyelid closures [...] and eye closures with a duration of under 300–500 milliseconds are coded as normal eye blinks" (Hammoud & Zhang, 2008, p. 308).

In the study at hand, a contact less eye tracking system was used to avoid any barriers in front of the eye which might reduce the light incidence of the ambient light. During the whole drive, an infra-red camera (1280 * 1024 pixels) recorded the subjects via the ADTF developer (Automotive Data and Time-Triggered Framework, Elektrobit, version 2.13.3) with a sampling rate of approximately 13 Hz. Two additional infra-red spotlights (850 nm) were installed at the cockpit. Infra-red light is not visible for the human eye; the spotlights served to enhance the quality of the video recording. The videos were further processed with the landmark detection algorithm by OpenCV (Open Source Computer Vision, http://opencv.org/). This algorithm contains a model of the human head which is adapted for every participant automatically from the video data. Based on the model of the head, 65 landmarks in the face are detected (colored dots in Figure 7). Six landmarks define each eye (Figure 8). By means of the middle distance between correlating eyepoints, the algorithm calculates the eye lid closure in pixels.

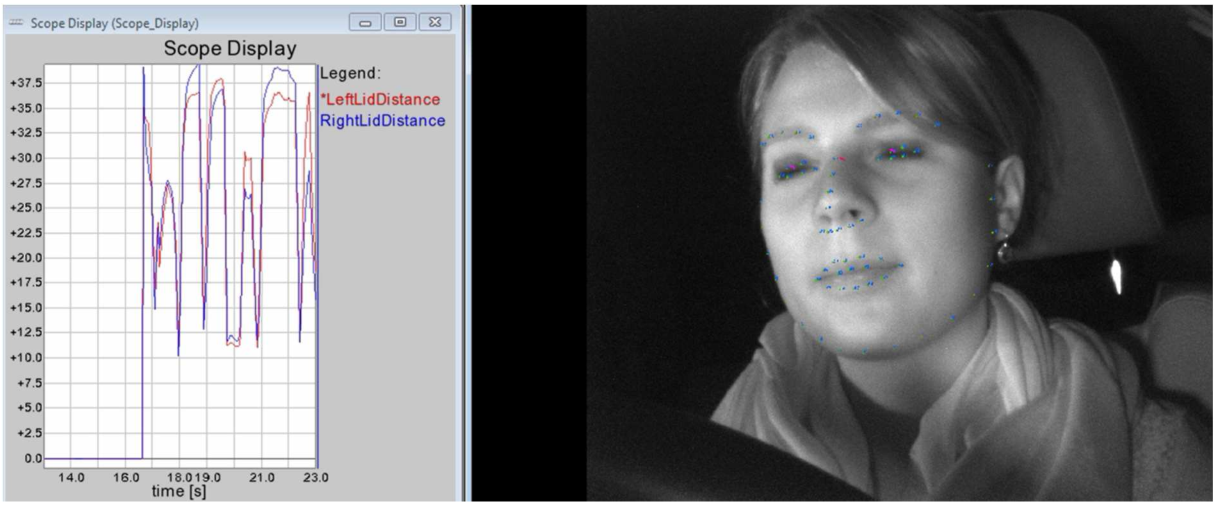

Figure 7: Screenshot of the software to extract the eye lid closures from the video recordings

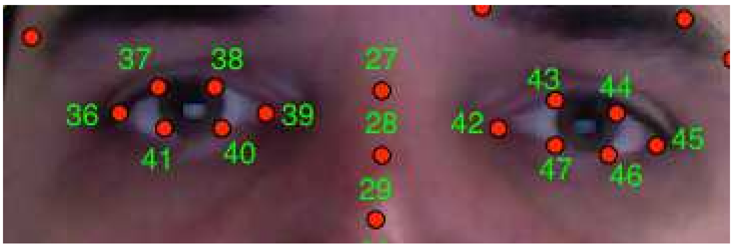

Figure 8: Landmarks for eye detection (Face Analysis SDK by CI2CV, 2013)

Wrist temperature: Additionally, the wrist temperature (WT) was tracked. The peripheral skin temperature was shown to be sensitive to light and is therefore a reliable measure of the circadian phase in humans (Martinez-Nicolas, Ortiz-Tudela, Madrid, & Rol, 2011; Sarabia, Rol, & Madrid, 2008). Through the determination of the circadian phasing, not only the effect on circadian phase associated parameters like alertness and cognitive performance can be investigated but also the direct light effect. The wrist temperature was logged by a mobile measurement data capture system (Krah & Grote, Measurement Solutions, Gewerbering 9, 83624 Otterfing, Germany). It measures the temperature on a range of - 20° C to + 60° C with an accuracy of ± 0.5° C in the range of body temperature. Volkswagen internal investigations showed that the sensors are very sensitive to changes in skin temperature; the relative accuracy is convenient to illustrate the course of the WT. Two sensors – one for validation – were fixed for the duration of the trial at the participant's wrist of the non-dominant hand with medical tape (Hansaplast Sensitive Fixierpflaster). An additional sensor was used to control the environmental temperature. The record interval was set to 5 sec. The DataPilot Manager, also provided by Krah & Grote, was used for data analysis and adaptation of settings.

Reaction times: Whether the light application affected the attention was tested using a RT task implemented in the driving scenario. While driving, an "X" appeared on the front view screen of the driving simulator which the subjects had to respond to as quickly as possible (Figure 9). The participants were instructed to react by pressing a button on the steering wheel ("Next"-button on the right hand side) before the testing began. On each measurement point, the task was explicitly announced. Per measurement point, six trials were taken. The time span between the reaction to the previous stimulus and onset of the new stimulus varied randomly between 3 and 7 sec (Chellappa, et al., 2011; Kretschmer, Schmidt, & Griefahn, 2012). The stimulus disappeared as soon as the right button was pressed.

Sustained light effect: The sustained light effect was evaluated using a short, self-developed paper-pencil questionnaire consisting of 9 items (Table 3) which were assessed on a 5-point Likert scale. The items were cumulated to a total score that ranged from 9 to 45; a high score points to a positive mood state succeeding the trial. The scale was part of the survey which was handed out to the participants after the trial. An expert review of the scale within the pretest did not reveal any concerns. Finally, Table 3 provides a summary of all dependent variables and the construct they reflect.

Table 3: Overview of the dependent variables and the underlying latent constructs

Construct	Operationalization	Indication
Mood	MDMQ ⇒ good – bad ⇒ awake – tired ⇒ calm – nervous	the higher the score, the more positive the current mood state
Alertness	KSS	the higher the score, the less alert
	WT	the higher the temperature, the less alert
	Eye lid closure: duration	the longer the duration, the less alert
Attention	RT	the higher the RT, the less attentive
	Eye lid closure: number	the higher the number, the less attentive
Sustained light effect	⇒ Wake, vital, unproductive, fit, powerful, comfortable, tired, attentive and sleep quality	the higher score, the more positive

4.4. Experimental setup

The study took place at the HMI laboratory of the Volkswagen Group Research, Wolfsburg, from February to March 2017. The laboratory is shielded from any natural light and the walls as well as the floor are black. Monotonous settings which require participants to drive in a stimulus lean environment for a longer time with low task demand were successfully used to induce fatigue (Hartley, et al., 2013; Matthews & Desmond, 2002; Popp, 2005).

4.4.1. Driving simulator

The Audi Q7 Prototype vehicle (Prototype vehicle section) was embedded in the static driving simulator. The headlights, backlights, and the direction indicators were covered. The driving simulator consists of a control room and the test room. The test room is equipped with three screens of 3 x 1.80 m (width x high) to enable approximately 160° horizontal vision. The vertical vision is approximately 17° down and approximately 18° up measured from the middle of the front view screen. Measured from the eye of the subject while seated in a middle seat position, the distance to the front screen is about 3.20 m. The simulated environment is projected on the screens through beamers installed at the ceiling, one per screen. Moreover, tree monitors placed beside and behind the vehicle serve to realize the scenario in the side and back mirrors. According to Caberletti (2013) the luminance level of a simulated night drive track corresponds to measured real street luminance levels.

Figure 9: Experimental setting: left: experimental setting from participants' perspective in BL-condition, right top: start screen, right bottom: view during the RT task

The chosen scenario (Figure 9) was a night drive at a highway with hardly any traffic. It was realized with Virtual Test Drive (VTD, Vires, version 1.4.3). The track was mostly straight with few environmental features. All in all, the goal of the scenario design was to be as realistic and as monotonous as possible at one time. The vehicle operating data were logged with ADTF with a sampling rate of approximately 60 Hz.

4.4.2. Procedure

After participants were picked up at the meeting point and accompanied to the laboratory, they were welcomed and asked to sign the consent form after reading it (the form was signed on the day of the first testing). Afterwards, they received a short explanation about the course of the trial without revealing the true purpose of the investigation. Subsequently, the participant took a seat at the driver's seat of the prototype vehicle. The sensors for the wrist temperature measurement were placed after asking for the non-dominant hand. The participants could configure the position of the seat and the mirrors according to their individual needs. Before the actual drive started, the participants completed the KSS and MDMQ scales as well as questions concerning the consumption of stimulating substances. On the start screen, the stimulus for the RT task was faded in so that the subjects knew the target stimulus. The experimenter explained the RT task and showed the button on the steering wheel the participants had to press in order to react to the stimulus.

The participants were instructed to drive maintaining a speed of approximately 90 km/h and to ignore the speed indication traffic signs to prevent them from focusing their attention on the speed too much. The current speed was displayed in a simulated head-up display. Additionally, they were instructed to comply with the obligation to drive on the right. The subjects were asked to blink long (about 1 sec) twice before they started driving to set a marker in the eye tracking recording. After a short habituation phase of 5 minutes, the subjects executed for the first time the RT task.

After 20 minutes and the second RT task, the participants again completed the assessment of sleepiness and the current mood state which required that they interrupted the driving by a short stop on the breakdown lane. The surveys were filled out digitally on a Windows Surface tablet computer on which a blue light filter (f.lux®) was installed. The questionnaires were implemented in LimeSurvey (LimeSurvey GmbH, Survey Services & Consulting, Barmbeker Str. 7a, 22303 Hamburg, Germany) using a black template with white font color. The brightness of the screen was adapted the extent that the font was easily readable but participants were not dazzled.

In the BL-condition, the blue light was turned on incrementally before the participants were driving again after the questionnaires (t1). After 60 minutes, the participants completed the RT task a third time. The light exposure ended after approximately 61 minutes (duration 40 min) and after stopping the driving task the sleepiness and mood assessment were filled a third time. At the end of the trial, the sensors were removed and the participants received the post-trial questionnaire to be filled out the next day. After the first test day, the post-trial survey was extended with a chronotype questionnaire, items concerning the demographics and potential influencing factors of the light effect (Appendix E: Potential influencing factors). After the second testing, the participants were debriefed concerning the true intention of the study and the effect of the blue light. Finally, they received a present as acknowledgement for participation (after the second trial).

4.5. Data analysis

The data analysis was conducted using R (The R Foundation for Statistical Computing, version 3.3.0, 2016). To explore the data set, the dependent variables were visualized using separate boxplots per condition and measurement point if applicable (ggplot2; Wickham, 2009). Additionally, the continuous measurements wrist temperature and eye lid closure were plotted as point and line graphs per condition, respectively. The first data cleaning and reorganization was done using Microsoft Excel 2010. Prior to the investigation of the effects, the associations between the dependent variables were investigated using the “ggpairs” function of the R package GGally (Schloerke, et al., 2016).

4.5.1. Dependent variables

MDMQ and KSS: Since the current mood state was assessed on the three dimensions good – bad, awake – tired, and calm – nervous, these dimensions were considered separately but a total mood score was calculated also. The items “restless”, “bad”, “worn-out”, “tired”, “uneasy”, “uncomfortable”, “sleepy”, “unhappy”, “discontent”, “tense”, “nervous” and “exhausted” were inverted (1 was transformed to 5 etc.).

Reaction times: The RTs were extracted from the log-files containing all data recorded via the driving simulator. The boxplots partly showed massive outliers; extreme values whose reason was known (e. g., one subject did not press the right button the steering wheel) were removed as well as the first measurement per measurement time point. Therefore, only five measurements per measurement time point remained for the further analysis. Due to technical difficulties in one trial, the number of data sets was reduced to $n = 22$.

Wrist temperature: After combining the data of both trials per subject, a baseline per subject was established for the visualization. Afterwards, the data was plotted to visually assess the quality of the data. In some cases, the measurement of one sensor was removed, e. g. when it was obvious that the sensor became detached or the participant reported that it loosened. When data quality was very poor for a whole test condition, all data of the subject was excluded from the analysis. A sample of $n = 20$ remained. Moreover, it was checked whether the room temperature was constant; it varied between 23 ° and 25 ° C approximately. To enable a comparison of measurement time points t0 – t2, means of 1.5 minutes-intervals (2.5-4; 17.5-19; 57.5-59 min) were calculated.

Eye lid closure: The size of the eye is individually different, thus it is inevitable to ascertain a reference size for every subject, separately for right and left eye. The exploration of the data additionally showed that the detected size of the eye even varied between the trials due to a non-uniform distance to the camera, e. g. caused by a different seat position. The reference eye size is needed for the blink detection. According to Hargutt (2001), one can assume that the eye is closed when the lid covers 80 % of the eye. Correspondingly, the eye is detected as closed when 20 % or less of the reference eye size are recorded. 20 % of the individual eye size were set as threshold for the minimum detection carried out with the “findpeaks” (pracma) function of R (Borchers, 2017). The function returns the number of peaks as well as the duration. The duration of a peak is defined as the distance between two conversions. The number of eye lid closures, the sum of the duration and the mean duration of eye lid closures were calculated for intervals of approximately 2 minutes (2-4; 17-19; 57-59 min).

Sustained light effect: The internal consistency for the self-developed light effect scale was calculated. To evaluate the sustained light effect, single item scores were accumulated (commutated scores for the inverse items "unproductive" and "tired"). The data of one participant was excluded because there was strong indication for a fixed response set in one of the questionnaires.

4.5.2. Reference regression model

Due to the outcome variables of various types from different measurement time points and the repeated measures design, the independence of observations assumption for classical statistical tests is violated. The reference regression model based on generalized linear models proposed by Schmettow, Schnittker & Schraagen (2017) meets the requirement of the experimental design at hand. The model allows an estimation of the fixed effects as well as random effects. The fixed effects defined in the reference regression model postulate three effects: First, an effect of the test condition which is the impact of the blue light treatment versus the control condition. Second, of the time course and third, an interaction between the test condition and the measurement point since only at the end of the trial a difference should emerge. Random effects on participant level were set for the variation between participants, the variation of interaction between participant and test condition and the measurement point. For all outcome variables (expect sustained light effect), treatment contrasts were set for measurement time point with the first measurement (t0) as reference level. The NL-condition was always used as reference test condition.

MDMQ: The original reference regression model (Gaussian) was not used for every dependent variable; but for the effect estimation for the MDMD score with the subscales as task equivalent. In that case, task-level random effects were used to capture differences between the subscales and differences between the subscales in response to the treatment.

KSS: For the outcome measure KSS, the model was adapted leaving out the task level random effects. As with the MDMQ scores, a Gaussian regression was fitted.

Reaction times: Due to the special characteristics of the RT data distribution, the RT data was not analyzed with the reference regression model described previously. However, by means of the "brms" package for Bayesian multilevel model calculation in R (Bürkner, in press) an exgaussian regression was adjusted. The structure of fixed and random effects was the same like in the reference regression model.

Wrist temperature: Again, the reference regression model with Gaussian family was used. For validation purposes, the variation between the sensors was implemented as task level random effect.

Eye lid closure: For the eye lid closure prediction, the underlying distribution of the reference regression model was changed to Poisson (number of eye lid closures) and exponential (duration), respectively. Random effects were adopted from the Gaussian estimations. The potential variation between right and left eye was again set as task level random effect.

Sustained light effect: Since there is only one measurement time point for the sustained light effect, a mixed effects model with a fixed effect for condition and random effects for subjects was fitted. The "lmer" function of the lme4 package (Bates, Mächler, Bolker, & Walker, 2015) for R was used.

5. Results

The results of the data analysis described above will be explained for each dependent variable in the following sections, starting with the descriptive statistics. There were no remarkable associations between the dependent variables, expect from the moderate correlation between the KSS rating and the MDMQ score (Appendix F: Additional diagrams). The fixed as well as random effects results (posterior distributions and 95% certainty) are illustrated in detail in Appendix G: Regression results tables.

5.1. MDMQ

As is can be seen in Table 4, at the beginning of the trial, the participants were on average in a slightly positive mood which deteriorated over the course of the trial. The visualization of the individual scores per subject by measurement point can be found in Appendix F: Additional diagrams. The reference regression model was fitted with a Gaussian regression, which is defined by the characteristic that "the linear predictor has the same scale as observed values, such that parameters could be interpreted as differences" (Schmettow, Schnittker, & Schraagen, 2017, p. 123).

Table 4: Mean (*M*) and standard deviation (*SD*) of the empirical MDMQ subscales per condition and measurement time point

t	Subscale	BL *M*	BL *SD*	NL *M*	NL *SD*
t0	awake – tired	14.33	2.91	14.21	3.12
	calm – nervous	16.25	1.98	16.33	2.46
	good – bad	17.46	1.72	16.25	2.94
t1	awake – tired	12.30	3.51	13.58	3.41
	calm – nervous	15.35	2.81	16.17	2.88
	good – bad	16.00	2.28	16.42	2.47
t2	awake – tired	11.08	3.35	11.17	3.06
	calm – nervous	14.66	3.39	14.96	3.29
	good – bad	14.96	3.25	14.58	3.41

The intercept $\beta_0 = 15.62$ represents the average MDMQ score in the NL-condition at measurement time point t0. Figure 10 visualizes locations and 95% credibility intervals of fixed effects. The location mirrors the central tendency of the posterior distribution and indicates the most likely region for the true value.

It becomes apparent that the blue light has a negligible effect ($\beta_{t|C[2]} = -.45$) on the mood which additionally is relatively uncertain. The strongest effect is the deterioration of the MDMQ score over the course of the trial, being worst at the end of the trial ($\beta_{t[2]} = -2.04$). It would seem that worsening of mood is attenuated by the blue light condition ($\beta_{t|C[2]} = -.45$). However, this is a result of the coincidental difference between $\beta_{t[1]} = -.22$ and $\beta_{t|C[1]} = -1.16$ and uncertainty.

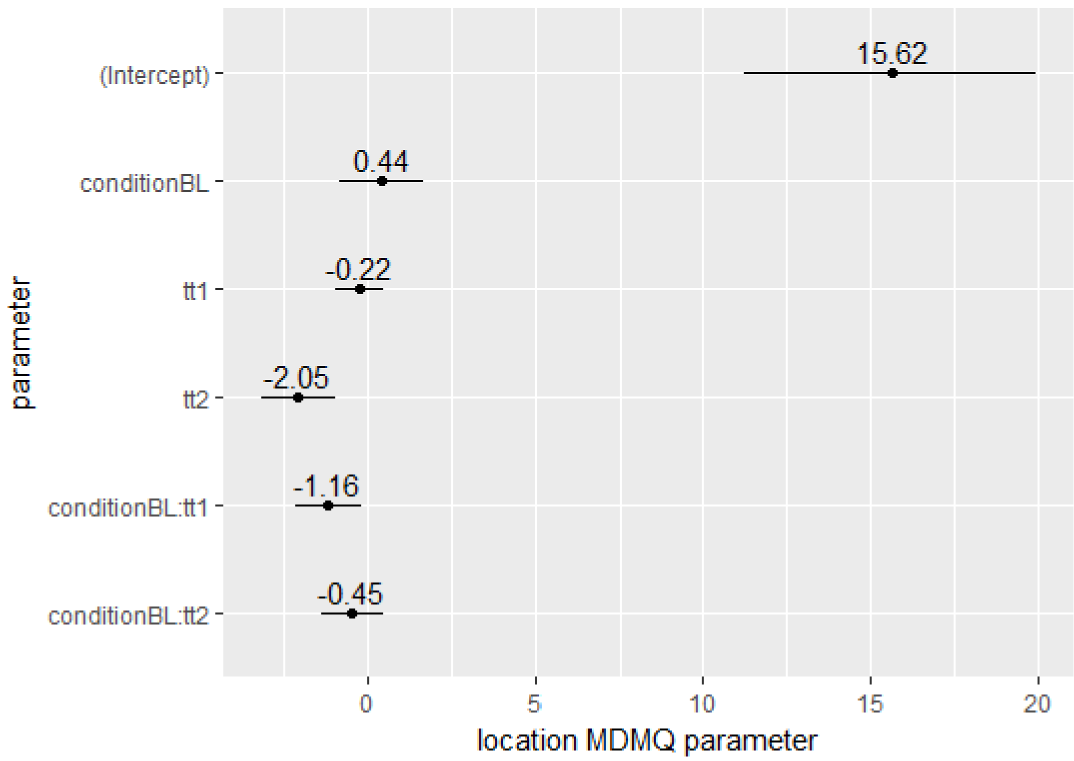

Figure 10: Location and 95% credibility limits of fixed effects for the MDMQ score

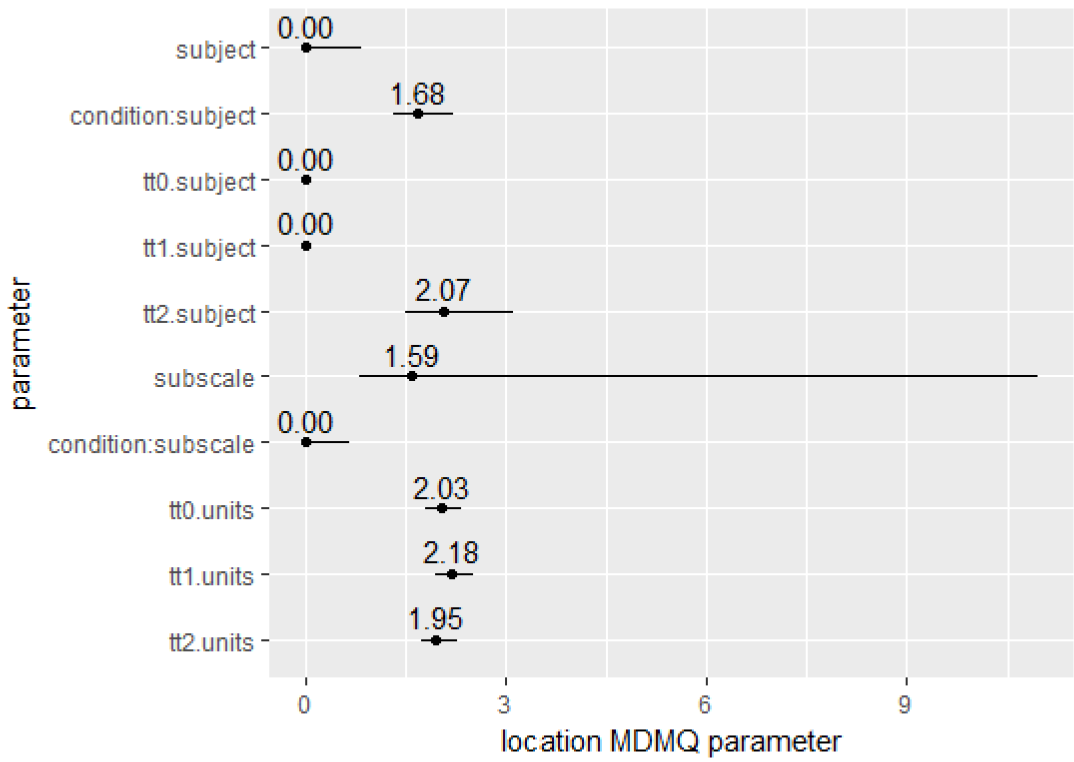

Figure 11: Location and 95% credibility limits of random effect variation (*SD*) for the MDMQ score

Figure 11 displays the magnitude of random effect variation and residuals including the credibility intervals. With regard to the measurement time point, the MDMQ scores only vary at the last measurement ($\sigma_{S|t[3]}$ = 2.07). As it can be expected, there is some variance (σ_{Su} = 1.59) in the ratings between the subscales, most likely due to the proportionally high decrease on the subscale awake –

tired. It has to be noted that the uncertainty of this variance is extremely high. The differences caused by the subscales affect both conditions consistently ($\sigma_{Su|C}$ = .00). Lastly, the measurements seem to be noisy as the variation on observation-level is relatively strong. To sum up, it can be said that the blue light has a void effect on the mood state. This is visualized in the regression plot (Figure 12).

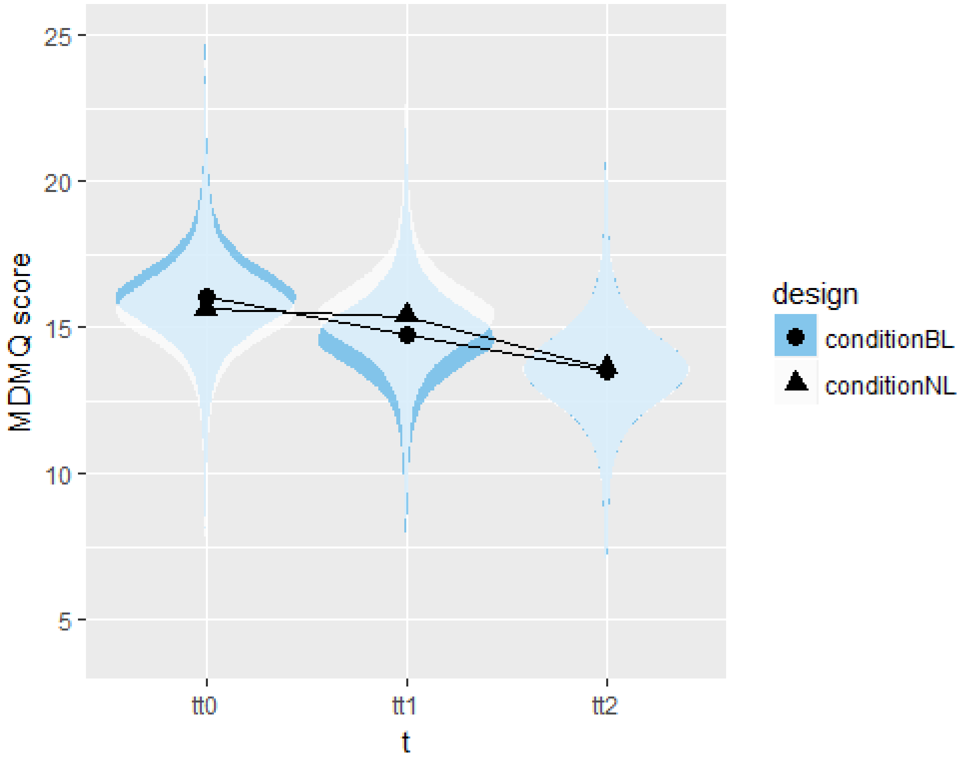

Figure 12: Posterior distribution by measurement point and condition for the MDMQ score

5.2. KSS

Prior to the trial, the subjects were on average in a neutral alertness state which diminished over the time; Table 5 displays the KSS scores per condition. The purely visual exploration (diagram can be found in Appendix F: Additional diagrams) does not prompt a difference between the test conditions.

Table 5: Mean (*M*) and standard deviation (*SD*) of the empirical KSS scores per condition and measurement point

Condition	t	*M*	*SD*
BL	t0	4.33	1.88
	t1	5.29	2.18
	t2	6.50	1.91
NL	t0	4.33	1.97
	t1	4.79	1.69
	t2	6.33	2.04

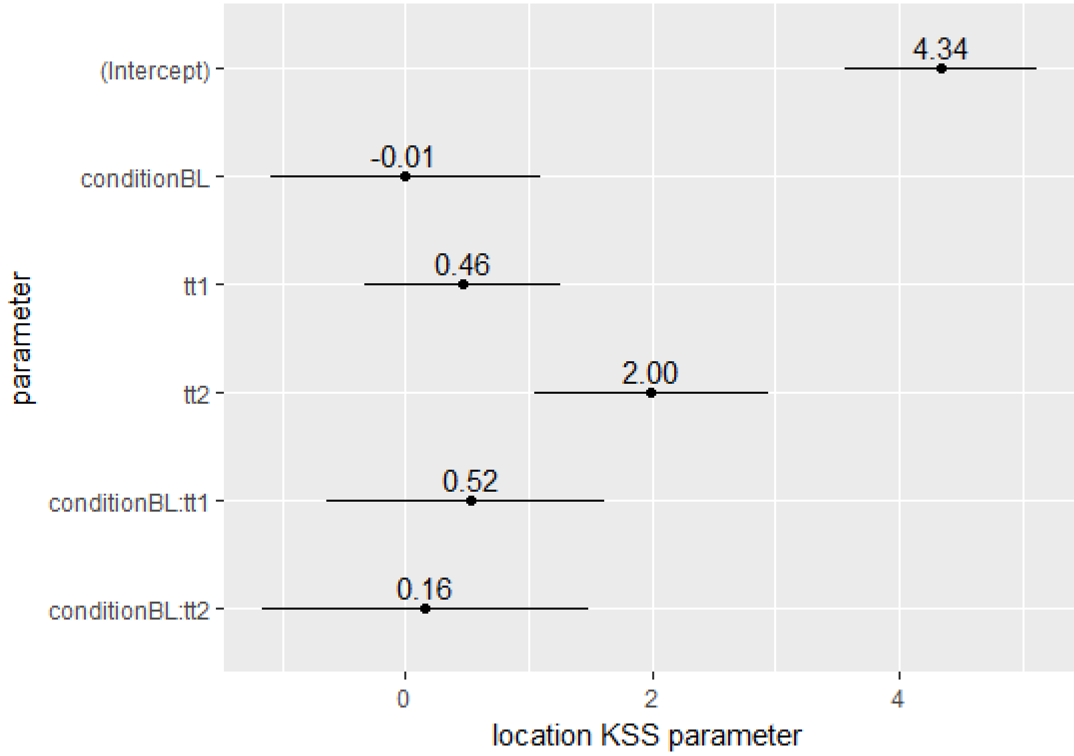

Figure 13: Location and 95% credibility limits of fixed effects for the KSS ratings

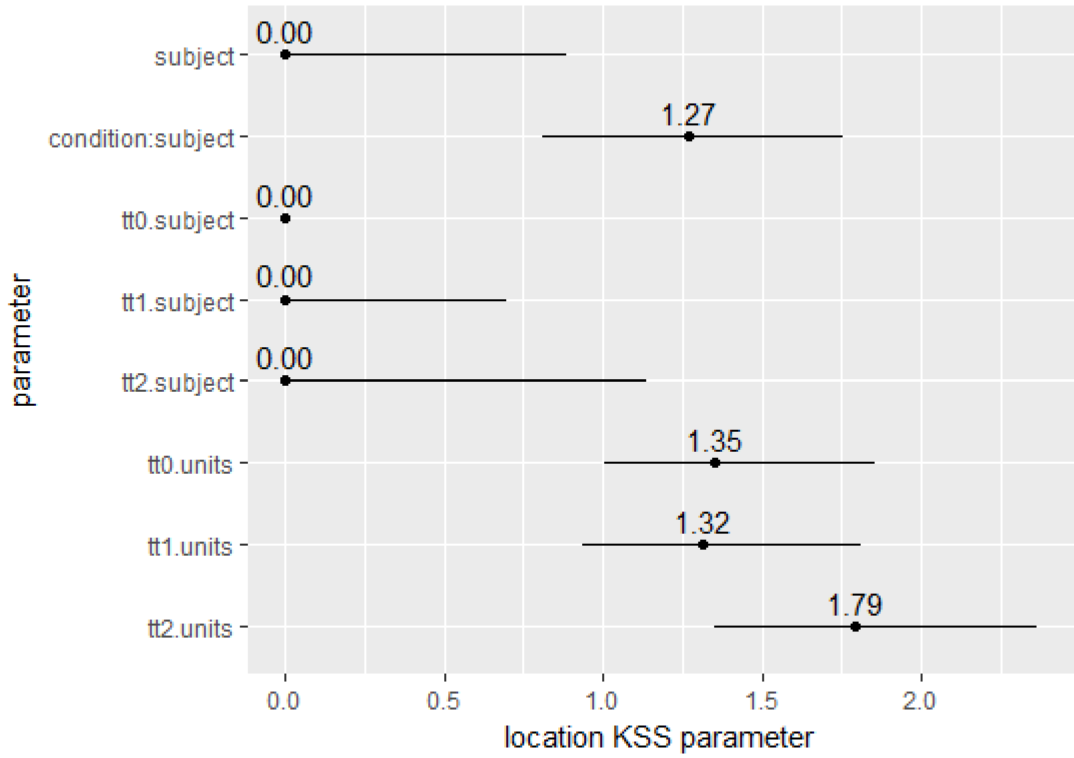

Figure 14: Location and 95% credibility limits of random effect variation (SD) for the KSS ratings

The determined intercept $\beta_0 = 4.34$ corresponds to the initial sleepiness score in the NL-condition which is essentially the same for the BL-condition ($\beta_C = -.01$). However, uncertainty is noticeable as can be learned from Figure 13. The fixed effect for t2 $\beta_{t[2]} = 2.00$ is the strongest. However, as for all fixed effects for the KSS ratings, credibility intervals are huge. The blue light treatment has a neglectable effect $\beta_{t|C[2]}$ = .16 on the alertness rating. Figure 14 illustrates the magnitude of random effect variation and residuals including credibility. Again, as σ_ϵ is proportionally strong, the measurements are noisy. In the BL-condition, there is some variance (σ_S = 1.27) in the KSS scores which is not observed in the NL-condition (σ_S = .00). Figure 15 shows the interaction plot.

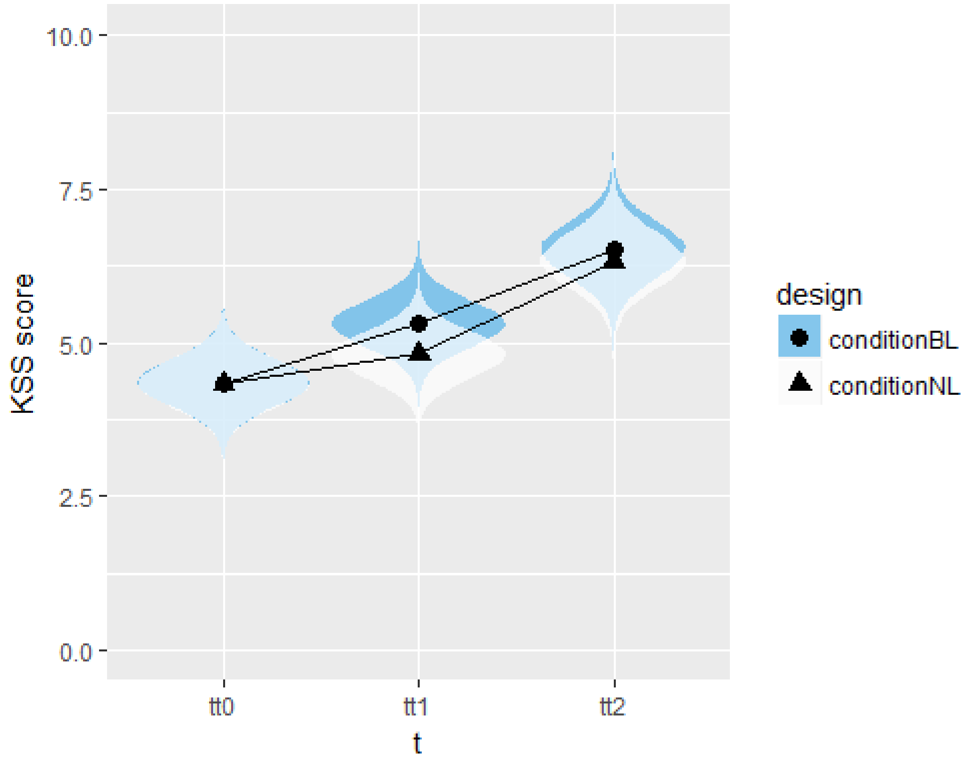

Figure 15: Posterior distribution by measurement point and condition for the KSS score

5.3. Wrist temperature

The mean WT and the corresponding *SD* is given in Table 6 (a descriptive diagram is given in Appendix F: Additional diagrams). Starting from the baseline measurement, the temperature rose about approximately 1° C during the trial. The results of the regression resemble the ones of the MDMQ and KSS prediction: First, the intercepts (β_0 = 30.67 and β_C = 30.69 –.12) are fundamentally identical (Figure 16). Second, there is a clear increase in WT with a maximum at time point t2 ($\beta_{t[2]}$ = 1.06) which is even, albeit only marginal, reinforced by the blue light treatment ($\beta_{t|C[2]}$ = .49; Figure 16). Third, there is a certain noise within the measurements ($\sigma_{\epsilon[0]}$ = .54, $\sigma_{\epsilon[1]}$ = .33, $\sigma_{\epsilon[2]}$ = .88; Figure 17). Figure 18 displays the interaction plot.

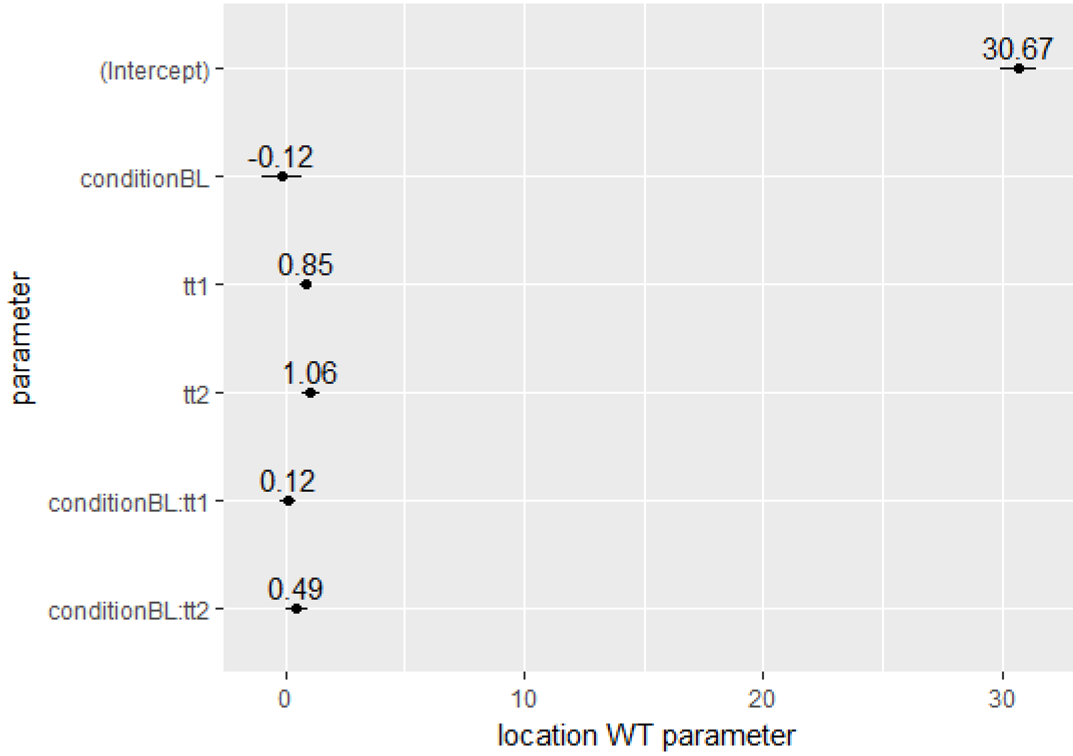

Figure 16: Location and 95% credibility limits of fixed effects for WT

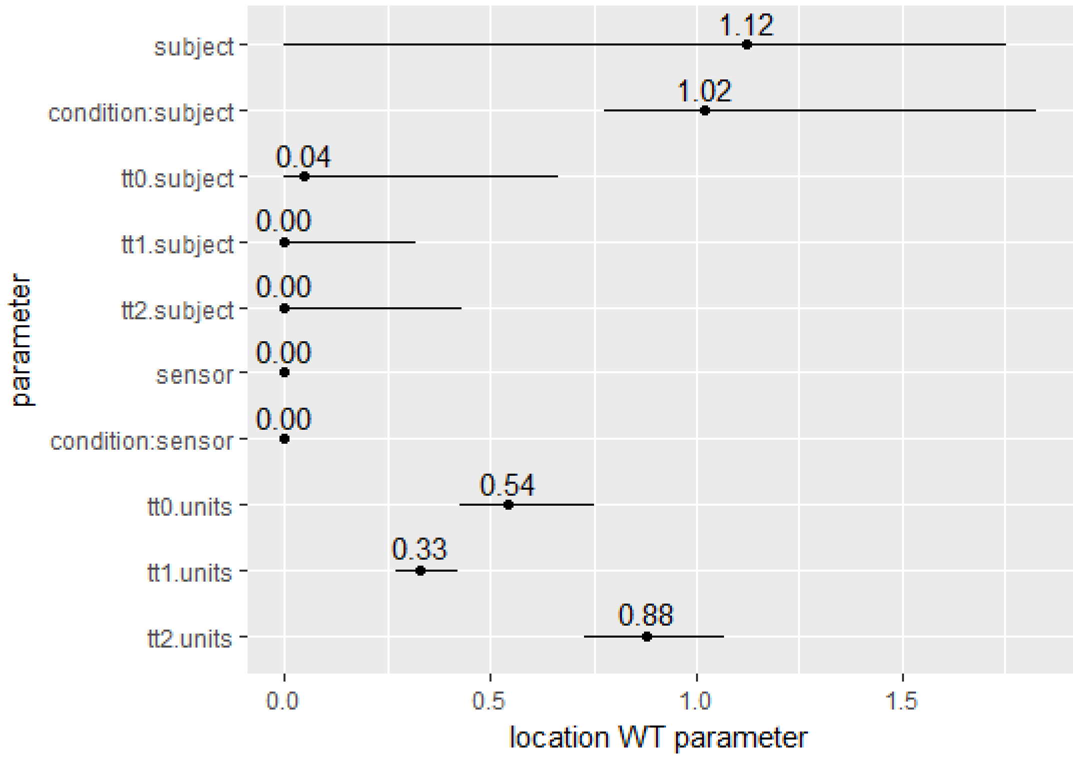

Figure 17: Location and 95% credibility limits of random effect variation (*SD*) for WT

Table 6: Mean (*M*) and standard deviation (*SD*) of the empirical WT per condition and measurement point

Condition	t	*M*	*SD*
BL	t0	30.51	1.57
	t1	31.51	1.42
	t2	32.07	1.32
NL	t0	30.64	1.89
	t1	31.49	1.82
	t2	31.69	1.53

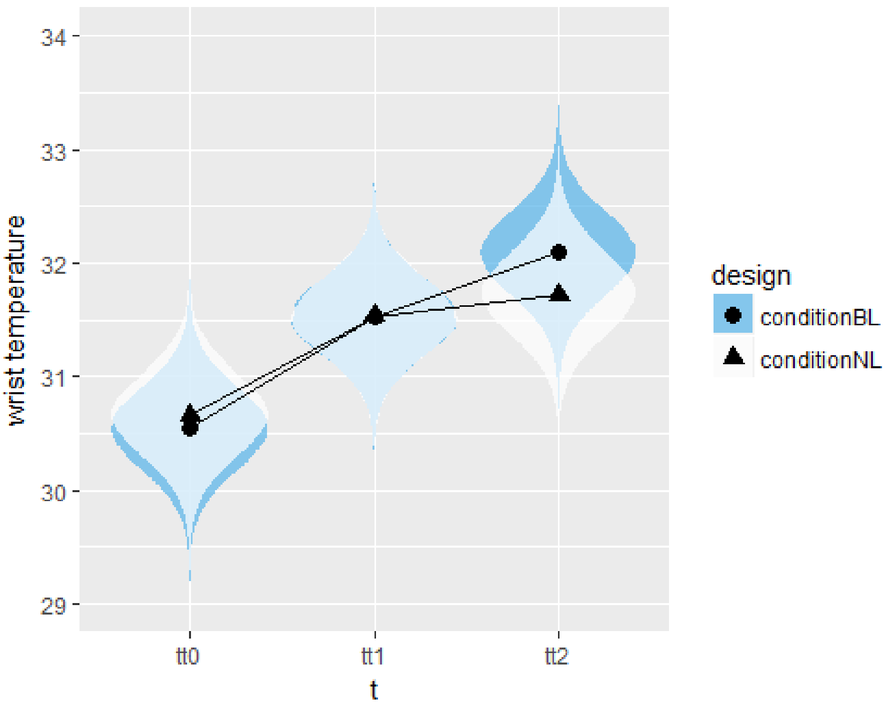

Figure 18: Posterior distribution by measurement point and condition for WT

5.4. Reaction times

The mean RTs per measurement time point are given in Table 7; it becomes apparent that there are a lot outliers upwards causing a large standard deviation (boxplot can be found in Appendix F: Additional diagrams). The visual exploration prompts that no meaningful differences between the conditions occurred.

Table 7: Mean (*M*) and standard deviation (*SD*) of the empirical RTs per condition and measurement point

Condition	t	M	SD
BL	t0	565.08	195.32
	t1	549.80	162.22
	t2	546.90	129.30
NL	t0	515.30	74.83
	t1	525.66	113.69
	t2	541.18	104.58

The regression results are provided in Table 8 and Table 9. As it was expected due to the heterogeneous distribution of the measurements, uncertainty for the estimated parameters is very high. Therefore, the validity is limited. Nonetheless, one can assume that RTs did not differ according to the test condition since the predicted difference for t2 is less than 5 ms ($\beta_C = 1.32$ and $\beta_{t|C[2]} = -2.13$). The regression plot is given in Figure 19.

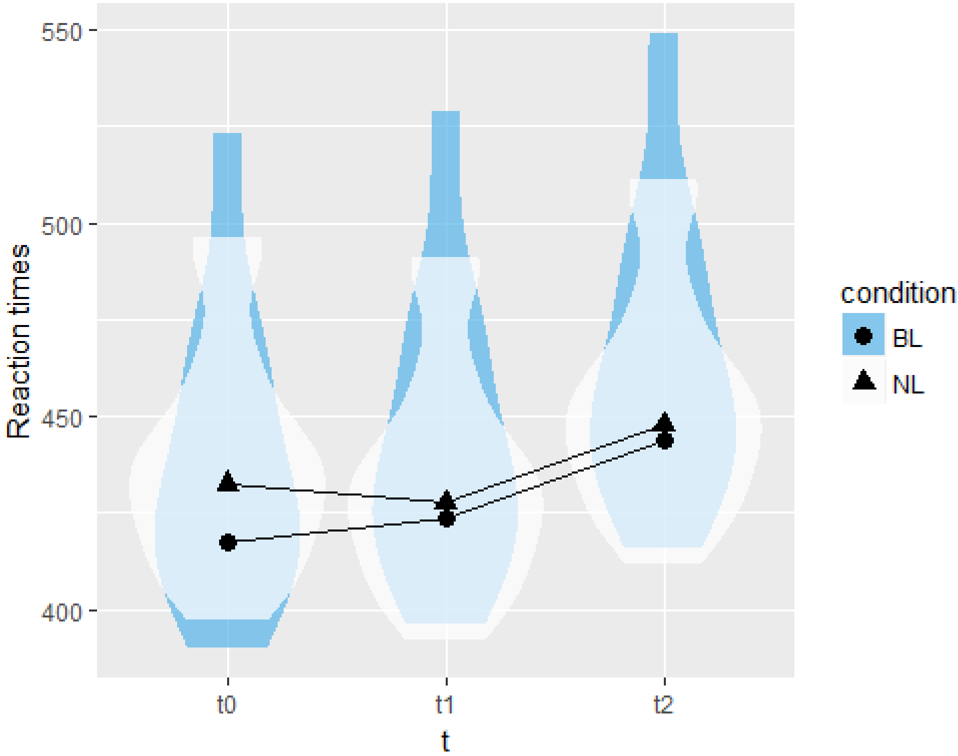

Figure 19: Posterior distribution by measurement point and condition for RT

Table 8: Fixed effects results for RT, posterior distributions summarized as mode (location) and 95% certainty

Beta	Parameter	Location	CI.025	CI.975
β_0	(Intercept)	467.86	449.24	486.61
β_C	conditionBL	1.32	-15.93	18.90
$\beta_{t[1]}$	t1	-7.87	-21.40	5.51
$\beta_{t[2]}$	t2	10.300	-3.48	23.88
$\beta_{t\|C[1]}$	conditionBL:t1	6.77	-13.13	26.30
$\beta_{t\|C[2]}$	conditionBL:t2	-2.13	-22.15	17.95

Table 9: Subject-level variation (*SD*) of RT, posterior distributions summarized as mode (location) and 95% certainty

Sigma	Parameter	Location	CI.025	CI.975
σ_S	Subject	33.77	22.72	49.35
$\sigma_{S\|C}$	Condition: subject	27.11	12.15	44.72

5.5. Eye lid closure

The descriptive statistics for the number, mean duration and summed duration of eye lid closures are given in Table 10. Boxplots for duration and sum of eye Appendix F: Additional diagrams. The number of eye blinks increase from approximately 23 times per minute (t0) to approximately 34 times per minute (t2). For the parameters number and duration mean a regression each was run. The random effects are not reported because they are effectively not existent. Table 12 gives the regression coefficients for the fixed effects for the number of eye blinks. For the initial measurement, the number of eye lid closures per minute is predicted as approximately 18.59 (exp(β_0= 3.62)/2) and 18.69 (exp(β_0) * exp(β_C = .01)/2), this increased to 19.52 and 19.28 per minute, respectively, at the end of the trial. The uncertainty of the prediction is considerably high. There is a huge variation in the number of eye lid closures (Table 10) but the variation is equally high between condition and subjects.

For the duration of eye lid closures, uncertainty is even more present than for the number of eye lid closures prediction. Figure 21 shows the predicted values transformed to the original scale (units of time), the parameter estimates are given in Table 12. As with the number of eye blinks, the duration varies but there are no differences in the variation between subjects and conditions. It seems like the duration of eye lid closures would increase less strong in the blue light condition (Figure 20) which would theoretically indicate an advantage of the blue light treatment. However, due to the massive uncertainty and the small effect, no reliable statement can be made.

Table 10: Mean (*M*) and standard deviation (*SD*) of the empirical number and duration of eye lid closures per condition and measurement point

Condition	**t**	***M* number (*SD*)**	**Sum duration (*SD*)**	***M* duration (*SD*)**
BL	t0	46.84 (29.71)	354.50 (193.15)	8.07 (1.93)
	t1	48.52 (31.74)	372.50 (184.89)	8.14 (1.71)
	t2	64.33 (42.87)	504.33 (242.80)	8.31 (2.13)
NL	t0	44.31 (28.25)	343.22 (165.70)	8.55 (2.08)
	t1	51.21 (25.23)	428.73 (180.32)	8.63 (2.04)
	t2	72.52 (45.97)	563.75 (269.31)	8.39 (1.70)

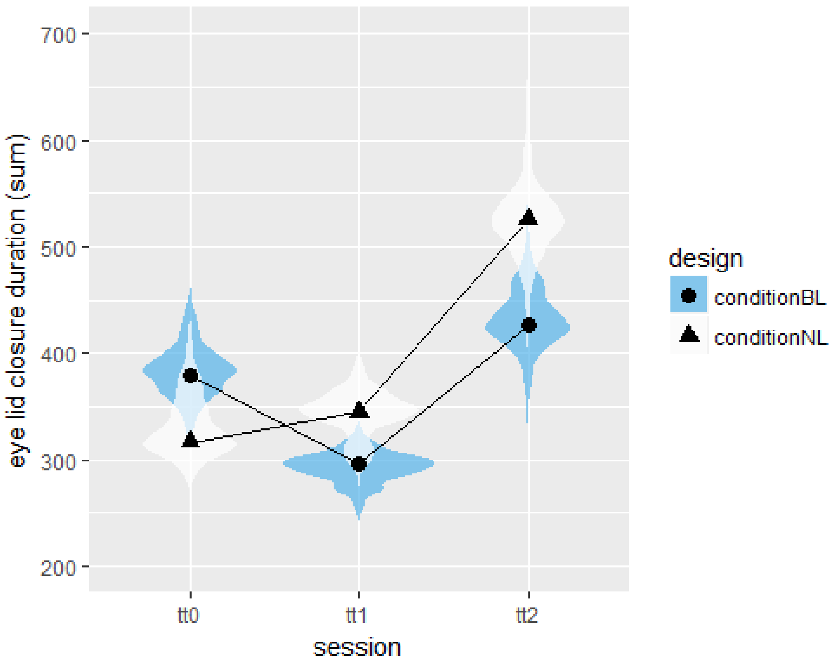

Figure 20: Posterior distribution by measurement point and condition for the duration of eye lid closures

Table 11: Fixed effects results for the duration of eye lid closures, posterior distributions summarized as mode (location) and 95% certainty

Parameter	Location	CI.025	CI.975
ConditionNL:t0	-5.76	-6.00	-5.67
ConditionBL:t0	-5.94	-6.08	-5.81
ConditionNL:t1	-5.84	-5.95	-5.69
ConditionBL:t2	-5.69	-5.76	-5.56
ConditionNL:t2	-6.27	-6.40	-6.12
ConditionBL:t2	-6.05	-6.21	-5.92

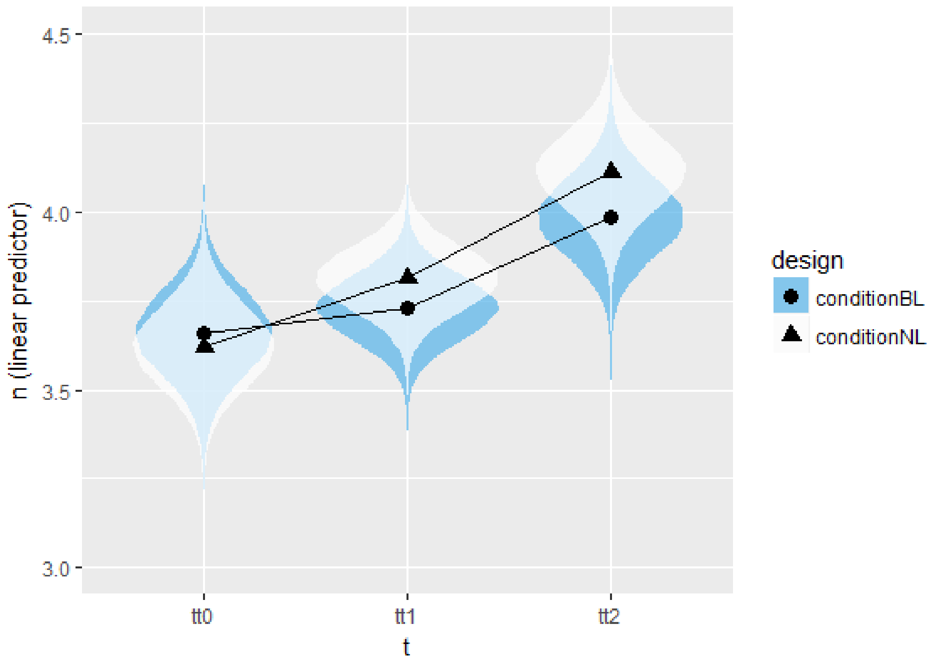

Figure 21: Posterior distribution by measurement point and condition for the linear predictor of the number of eye lid closures

Table 12: Fixed effects results for the number of eye lid closures, posterior distributions summarized as mode (location) and 95% certainty

Beta	Parameter	Location	CI.025	CI.975
β_0	(Intercept)	3.62	3.38	3.86
β_C	conditionBL	0.00	-0.19	0.26
$\beta_{t[1]}$	t1	0.02	-0.07	0.46
$\beta_{t[2]}$	t2	0.05	0.19	0.79
$\beta_{t\|C[1]}$	conditionBL:t1	-0.01	-0.40	0.16
$\beta_{t\|C[2]}$	conditionBL:t2	-0.02	-0.45	0.11

5.6. Sustained light effect

Since the sustained light effect was assessed with a row of self-developed items concerning the general mood state, the internal consistency was calculated. The inter-item correlation was 0.57 (without the item “sleep” 0.60; without the items “sleep” and “unproductive” 0.60). The sustained light effect was only assessed once after each test condition; consequently, the only fixed effect was for the condition. The mean score in the BL-condition was M_{BL} = 33.00 (*SD* = 6.58) and M_{NL} = 30.95 (*SD* = 6.91); other location parameters are illustrated in Figure 32. A table listing the mean scores per item can be found in Appendix H: Sustained light effect. One could additionally assume that the order of conditions affects the sustained light effect rating because the second rating was completed after debriefing. However, this did not provide any further insights; the analysis can be found in Appendix H: Sustained light effect. The regression coefficients for the linear model are given in Table 13 and is visualized in Figure 22. There is a slight positive tendency in the blue light condition β_C = 2.05. However, uncertainty is too high to assume a real advantage of the blue light treatment and the impact is too small with regard to the overall scores.

Table 13: Fixed effects results for sustained light effect summarized as mode (location) and 95% certainty

Beta	Parameter	Location	CI.025	CI.975
β_0	Intercept	30.96	28.13	33.78
β_C	conditionBL	2.05	0.34	5.54

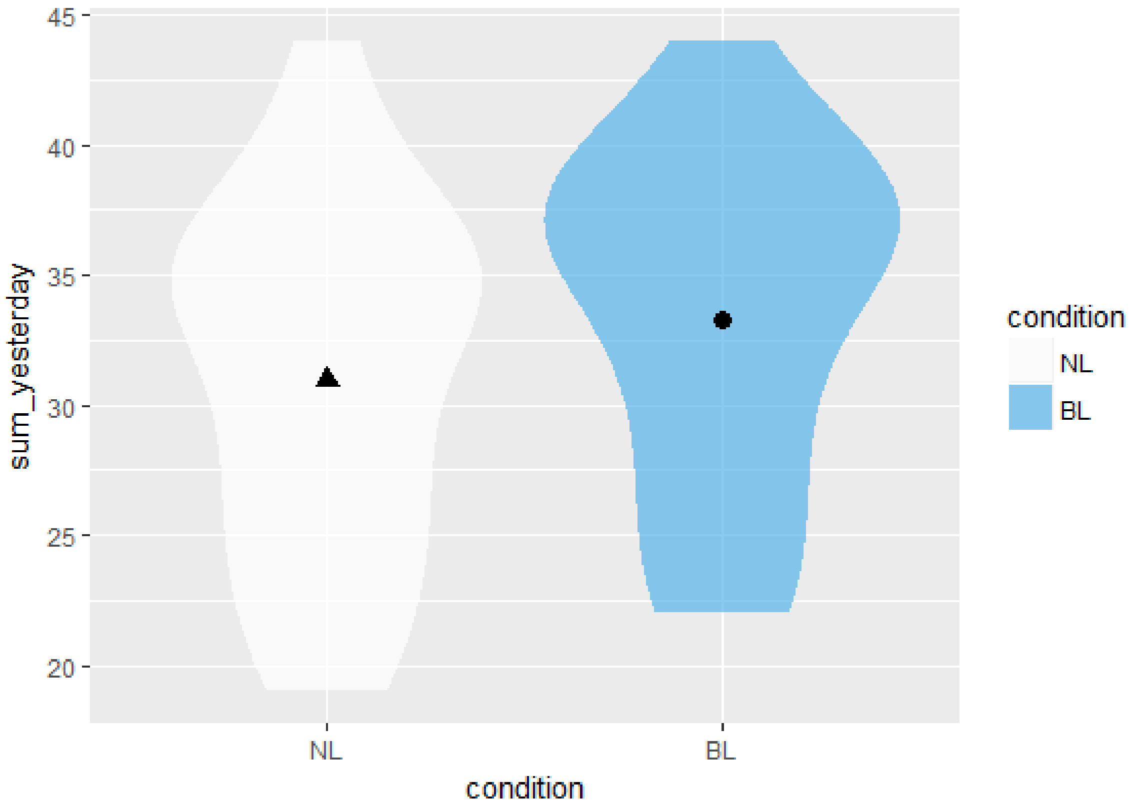

Figure 22. Distribution and mean of the sustained light effect scores by condition

6. Discussion

The major finding of the study at hand is that the blue light treatment did not affect any of the measured variables as hypothesized. The homogeneity of results between the different measures suggests that there is no practical relevant advantage of blue light application in the given setting. However, due to the relatively large credibility intervals of the estimates for the outcome variables, one cannot state with high certainty that there is no effect.

The thesis at hand was motivated by the trend in the automotive sector to design a vehicle interior exceeds to support functional goals but to create an extended user experience. Common countermeasure to drowsy driving are insufficient (Appendix I: Countermeasure to drowsy driving). Therefrom emerges the need to find alternatives ways to keep the driver alert. Beside the alertness promoting function of blue light, it might enhance attention, mood, vitality, and well-being of the passengers. A rich body of theory led to the following assumptions: Light application would enhance alertness, attention, and current mood state. More precisely, the MDMQ score, indicating the current mood state would increase while the KSS score, measuring alertness, would decrease as a response to the blue light treatment compared to the control condition. Since a rise in WT hints at a decrease in the circadian alertness component, it was expected that under blue light exposure, WT would be diminishing or show at least a less steep slope relative to the control condition. Reactions were supposed to be faster under blue light. The number and the duration of eye lid closures, signaling the sleepiness and the attentional state were thought to be less frequent and of a minor duration in the BL-condition in comparison to the control condition. In order to investigate these assumptions, a controlled driving simulator study was conducted. The absence of an observable effect may have myriads of reasons, e. g. individual characteristics of the participants and the position of the light source; these will be elaborated divided into results and method in the following.

6.1. Interpretation and reflection of the results

The key finding which is consistent for all measures, is the fact that neither subjective nor objective parameters of the driver's state were affected by the blue light exposure. The fixed effects for the measurement time points t1 and t2 were universally the strongest effects observed (expect for the RTs). These are especially pronounced for the subjective ratings scales. The phenomenon that subjective sleepiness symptoms are found more easily than objective ones seems commonplace (Matthews & Desmond, 2002). The effect of time means that the intended reduction of alertness accompanied by decreasing current mood state etc. over the course of the trial was successful, despite the light treatment. Therefore, one can exclude that the biological light effect was not detected because the subjects were too alert. However, uncertainty of the measurement point effect should be considered. The decline of alertness after 20 min and more expressed by the effects is in accordance with other studies (Shekari Soleimanloo, 2016; Matthews & Desmond, 2002).

Starting with a moderate positive mood (MDMQ score ≈ 16), the current mood state of the participants declined at the end of the trial towards a slight positive mood (MDMQ score ≈ 14). Since the scores of the two test conditions do not differ, the assumption that blue light exposure would increase the mood cannot be confirmed. However, the variance in the MDMQ scores at t2 could be interpreted as differences in response to the blue light, meaning that some participants were positively affected; visual exploration of the scores separately for each subject supports that hypothesis. This assumption would be further supported if there was a higher variance of the BL-condition ($\sigma_{S|C}$) and additionally of t2 ($\sigma_{S|t[2]}$) for other outcome measures. Unfortunately, if this pattern is solely observed for one dependent variable, it is not sufficient to hold that inference. An alternative explanation would be that some participants are especially sensitive or insensitive to the drowsiness induction resulting in more extreme ratings at t2, as addressed in the Critical reflection of the method section. The worsening of mood as an effect of time was also present in other studies investigating light effects (Borisuit, Linhart, Scartezzini, & Münch, 2015; Hoffmann, et al., 2008). Additionally, Borisuit et al. (2015) found a moderate negative correlation between sleepiness and mood. Like indicated in Table 2, Hoffmann et al. (2008) were able to demonstrate an improved mood with respect to the dimension „activity“ but this effect disappeared after the first test day.

A similar pattern like the mood state course became apparent for the KSS ratings: the initial alertness state changed from rather alert (KSS score ≈ 4) to some signs of sleepiness (KSS ≈ 6). The assumption that some individuals are very sensitive to the monotonous setting holds only for the MDMQ scores since there is essentially no variation between the subjects. The variance in the BL-condition can therefore only be by chance. More generally, the light treatment did not improve the alertness ratings. In other studies, the KSS was equally applied to assess sleepiness and alertness as opposing constructs. Figueiro et al. (2009), for instance, found a similar time effect on the sleepiness ratings and even higher scores in the light condition compared to the dark condition (although objective sleepiness measures were positively affected, like in Kraneburg, et al., 2017). In Figueiro, Nonaka, & Rea (2014), only the effect of time was significant but not the effect of the lighting condition (experiment 1).

The WT increased over the duration of the trial by approximately 1° C with a difference of 0.38° C between the blue light and the control condition. The higher predicted mean WT at the end of the trial could be a result of the variance between subjects in the BL-condition, if there were different variances for the measurement time points. Here too, the variation can be only random. Since the WT measurement was an exploratory approach, no reference results are available.

For the RTs, the uncertainty for the regression results was extremely high; interpretation is therefore hardly possible, but it seems like there is no difference between the blue light and the control condition. The apparent fixed effect for the time observed for the outcome measures already discussed is barely present. This might hint to the fact that RTs are not sensitive to attentional changes in relation to the lighting conditions. This is supported by the finding of Weisgerber, Nikol,

& Mistlberger (2016) who did not find an effect of light treatment on RT although salivary melatonin was suppressed. Comparing the results at hand with other studies, there is consensus with unaffected RTs (Kretschmer, Schmidt, & Griefahn, 2012; Kretschmer, Griefahn, & Schmidt, 2011; Farkas, Leib, Betz, & Rothe, 2015). Beaven & Ekström (2013) report that only a subgroup of participants showed faster responses after light treatment.

The frequency as well as the duration of eye lid closures was compared regarding the effect of the test condition. Unfortunately, the uncertainty of the fitted models was extremly high due to the strong variation in the observed values. Statements about an beneficial effect of the blue light on alertness and attention in terms of eye lid closures cannot be made. Additionally, it has to be noted that as with the WT data, there was some information loss because of the data aggretation to three measurement points. Hargutt (2001) observed similarly strong variations in eye lid closure duration during simulated night drive. Although the eye lid closures are a common measure to assess alertness, no published study used it to assess the biological effect of light.

The scale assessing the sustained light effects has no huge but still an acceptable internal consistency. The comparision between groups revealed that the predicted score is about 2 points higher in the blue light condition. Vividly said, it means that the subjects rated one item about two points higher or two items each one point higher on a scale of nine items. However, dealing with a possible range of 9 to 45 points and notable uncertainty, this cannot be interpreted as a true impact of the blue light. Additionally, rating might be affected by the retrieval bias causing the slight advantage in the scores after the blue light exposure.

6.2. Critical reflection of the method

The successful induction of tiredness, proven by the effect of time shows that the experiment itself was functioning. The chosen outcome variables (except RT) were sensitive enough to record changes in the driver's state and a driver's state with potential for improvement was established. Although this confirms the strength of the experimental design, there are some aspects of the methodology to be discussed.

6.2.1. Light application

The blue light of 468 nm wavelength was applied for a period of 40 min with a luminance of 22 lx. Compared to other studies, the light intensity in the experimental condition was relatively low. A trade-off between a luminance level which could be administered safely in real road traffic and a high luminosity in favor of the biological effect had to be made. Beside the acceptance aspect, blue light has a special damage potential for the retina ("blue hazard") when the intensity is too high[5] (Hünig,

[5] The blue hazard potential of a light source depends on size and luminance of the light source; the light source at hand is harmless because of the extensive distribution of the LEDs (ZVEI-Fachverband Licht in

2008). A luminance not restraining the view of the driver was implemented. Indeed, there is evidence that very low doses of light can alert humans. An exposure period of 40 min was chosen because it should be longer than in the pilot study (30 min) but should still be realistic for the daily commute to work. Partly, the participants reported that they initially felt alerted by the light but that this effect diminished over the course of the probe. The paper-pencil questionnaires contained the opportunity to utter free comments; one participant wrote that experience down. This hints to the hypothesis that either the light exposure, the trial or a combination of both was too long. Concerning that issue, Shekari Soleimanloo (2016) wrote that „time-on-task effect or fatigue from driving is highly likely to emerge after 30 min driving [...]. It remains quite possible that a longer driving time could reveal greater alerting effects of light" (p. 334). One can only guess whether another time span would have revealed other results but in general the chosen duration of 40 min seems appropriate for once-only light exposure.

Despite the expert rating and the pilot study (Appendix D: Pilot study), a few subjects announced that they felt glared by the blue light and adopted therefore a relieving posture preventing the light incidence into the eyes. This was also noted in the free comments of the post-trial questionnaire by one subject. The fact is challenging for two main reasons: It is possible but not very clear whether is caused the lack of an observable effect. If anticipated, one would have documented that behavior systematically. Further, it is a definite signal that the applied light intensity is not suited for the road traffic in darkness; especially when considering the fact that the user group (elderly people) who is most sensitive to glare did not participate in the study (Lachenmayr, 1995). The extent of the glare was not foreseen in the deviance of careful trade-off and pretesting. For the study at hand, it must be accepted but is it a valuable insight for potential future investigations.

A contrary hypothesis to the beforehand explanation is that the setup of the prototype may have contributed to the absence of the biological light effect. Like it was mentioned in the Non-image forming visual system section, not all parts of the retina are equally sensitive to the biological effect of light. Obviously, the structure of passenger cars limits the design space; the light device cannot be implemented directly in the driver's field of view. The concept of the prototypical lighting aimed at considering the optimal angle of light incidence but probably not all possible seat and driver position configurations are uniformly covered. While some participants felt glared by the blue light, others might have neglected the light on eye level.

6.2.2. Experimental setup

To account for ethical issues and to warrant a standardization of environmental conditions, a simulator study was favored over a real drive study. This allowed for constant environmental lighting

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Zusammenarbeit mit dem VDE Prüf- und Zertifizierungsinstitut, Fachgebiet Licht: Autorenteam Fotobiologische Sicherheit von Leuchten und Lichtquellen, 2014).

and no disturbances through varying weather conditions. However, simulator studies in general do have disadvantages: Sleepiness appears faster in driving simulator studies and an earlier and more pronounced decline in performance can be observed compared to real drive studies (Shekari Soleimanloo, 2016; Filtness, et al., 2014; Cluydts, De Valck, Verstraeten, & Theys, 2002). Additionally, driving simulators maximize the amplitude of the effects of sleep deprivation (Hartley, et al., 2013). These effects are beneficial for the study at hand but limit the ecological validity. With regard to the research question, it should be noted that Weisgerber et al. (2017) assert that "[a]lthough simulators are a validated tool for measuring the effects of sleep loss on driving, they might be less sensitive to countermeasures, due to the lack of consequences for driving errors" (p. 18). This statement is related to the vehicle operation data but might also hold for other measures taken in the context of simulated driving. A specific problem in the study at hand was the steering behavior: Because the prototype light device is integral in a series vehicle, the vehicle had to be integrated into the simulator. This influenced the steering behavior insofar that the servo steering was inactive and could not be simulated. Consequently, the participants had to perform more steering movements with a higher resistance than usual. For that reason the vehicle operation data was not included in the analysis; many participants claimed that they had a significantly worse lane keeping than usual. Apart from the issue concerning the vehicle operation data, it has to be mentioned that many subjects communicated that the steering behavior was perceived as straining further promoting sleepiness and fatigue. One can only guess which impact that exerted. Basically, there are two options: First, the lack of an observable biological light effect is independent of the deepened drowsiness induction. Second, the deepened drowsiness induction covered the biological light effect. The latter seems unlikely because the literature (e. g., Sülflow, 2013) points more into the direction that the light effect is more present when sleepiness and other adverse states are pronounced.

A certain state of diminished alertness was deliberately induced through the monotonous setting: the situational components in combination with time of the day successfully attained that state. Of course, this is not wanted in the real road traffic. Still, it is realistic whereby – as already mentioned above – this drowsiness inducing effect is more pronounced in driving simulators than in real road traffic. It seems like some participants were especially sensitive to the fatigue induction; a few participants displayed a steep decline of mood and alertness in both conditions and communicated that feeling expressively.

The testings were conducted separately on two days, one test condition each. This has the advantage that the experimental conditions did not interfere with each other. Disadvantages like variations in the sleep duration the night before must be accepted because the with-in subjects design is inevitable for the given research question. In general, a within-subjects design is always to be preferred over a between-subjects design since it reduces the unexplained variance.

The participants were informed before the first trial that the aim of the study was to assess the driver's state in relation to different ambient lighting scenarios and that they would encounter one lighting condition and a control condition without light. After the second trial, they were debriefed and asked if they knew the biological effect of light in advance. There were controversial arguments for the decision whether to inform participants about the light effect before the trial or not. Contra arguments against keeping the participants uninformed were that the biological effect of light is relatively known and that a potential customer would know about the function of an in-vehicle light device he/she buys. However, the arguments that the light device might have a sole placebo effect and participants would respond according to social desirability outweighed the other ones because the validity of the results would be impaired. Additionally, it was assumed that some participants would know the effect anyway, so the knowledge of the light effect might be a covariate. 10 of the 23 participants confirmed that they at least had a rough idea about the effect of blue light or concluded it from the experimental set-up. Only seven of the 10 knew the effect concretely.

6.2.3. Dependent variables

As the literature review illustrated, there are numerous aspects of human physiology, behavior and cognition which profit from blue light. However, not all of them are suited for measurement in the setting at hand. The research question was investigated with regard to parameters which are at one hand feasible to measure while driving, and on the other insightful for the driving setting. Rating scales are the easiest applicable measure available in user research. The problem with self-ratings that they are susceptible to deliberate distortions or unconscious biases has a special aspect in terms of sleepiness assessment: "[S]ome individuals struggle to comprehend the exact nature of their increasing sleepiness" (Filtness, et al., 2014, p. 568). As this study is not only based on subjective ratings but both subjective and objective ratings, a reliable interpretation of the result should be ensured.

Two standardized self-report questionnaires were chosen. The KSS was deployed in numerous probes evaluating the biological effectiveness of light, and, as already mentioned it was validated against physiological parameters and is able to predict performance. For the MDMQ, no information about the validation is available. One might criticize that the MDMQ subscales were aggregated into an overall mood score although they cover different dimensions and the subscale awake – tired apparently seems to show deviating scores. The summary of the subscales into an overall mood state score is legitimate because the correlations (.70) are remarkable (Hinz, Daig, Petrowski, & Brähler, 2012).

The WT is a marker for the circadian phasing; currently, there are no publications in which WT recordings were used as an indicator for an acute response to biologically effective light. "Acute changes in light intensity exhibit an inverse relationship with WT" (Martinez-Nicolas, Ortiz-Tudela, Madrid, & Rol, 2011, p. 625). Sarabia, Rol & Madrid (2008) state that subjective and objective sleepiness are linked to WT. Therefore, the idea to use the distal body temperature as an indirect measure to evaluate the light effect emerged. Clearly, to use the WT in this context must be seen as an exploratory approach which is underpinned by the other measures. Measuring the WT is a comfortable, easy and economical way to investigate circadian processes. Other measure like the melatonin levels bear much more challenges: They require laboratory equipment and are inconvenient for participants. Melatonin levels, for example, are in some individuals generally low and decrease naturally after getting up in the morning. However, WT measurement was previously only used for long-term monitoring of circadian rhythms. If it would approve to be suited to gather short term changes, it might a valuable measurement process for the scope of research of biological light effects. Unfortunately, there were some factors that might restrict the validity of the results of the WT measures: Although the measurement process was pretested, sometimes the tape used for fixing the sensors at the wrist loosened. Likely, the proportional high skin humidity of some participants and fitful movements were the causes. If only one sensor was impacted, the erroneous data set could be removed. In the other cases, the original data set was maintained. The relative accuracy of the sensors might be given; however, the absolute accuracy is poor. The measurement device is equipped with eleven sensors which can only be disabled or activated as a whole. The variation between the sensors that were not actively used was about 1° C for one sampling point. Logically, the same measurement inaccuracy pertains for the sensors attached at the subject's wrist. Further, for most subjects there were quite unequal baselines, probably because the body temperature is influenced through factors like colds etc. which were not systematically documented. The data was strongly aggregated to obtain scores corresponding to the measurement points; obviously, some information is lost. However, this was necessary to fit the data to the reference regression model.

RT was commonly used to evaluate the light effect albeit it is operationalized as manifestation of different latent variables such as divided and sustained attention, and cognitive task performance. Likewise, RT could be seen as a distinct parameter, at least in the study at hand, because the target was a simple stimulus not involving any deeper processing. RT was selected as dependent variable mainly for three reasons: First, it is a task easy to implement and conduct which is nonetheless very relevant for the driving task. Second, as a simple RT task was used in the pilot study, comparability is achieved. Third, it was known in advance that the vehicle operation data might not be insightful due to the problematic of the steering behavior; but to reach some meaningfulness for the driving situation, a measure directly related to the driving task needed to be included. Nevertheless, on has to be aware of the fact that only few studies found faster RT in response to the light treatment (Kretschmer, Schmidt, & Griefahn, 2012).

The eye lid closure belongs to the most valid indicators of drowsiness (Platho, Pietrek, & Kolrep, 2013). Only a contactless eye tracking system was qualified for the study because a head-mounted eye tracking system would have entailed the same difficulties as glasses (shielding of the blue light). Further advantages are that the contactless system is comfortable and does not impair the participants. At the same time, it bears the disadvantages that it is relatively unprecise and prone to measurement errors because there is no fix distance between the eyes and the camera. Additionally, a baseline for the eye size and the threshold for eye lid closures needed to be determined post hoc.

Another difficulty which was not detected in the pretest was that if the participants changed their seat position during the trial, this lead to a shift in the reference eye size. Therefore, the calculated baseline needed to be adjusted manually for some recordings. The camera was installed on the left side of the cockpit causing beside the natural difference a slight difference in ascertained eye size between right and left and probably also in accuracy. In the percentage of eye lid closure system (PERCLOS), only eye lid closures with a duration greater than 300 ms are counted (Hargutt, 2001). For the data at hand, this threshold was not implemented because the time stamp in the data frame is no metric time unit; the duration in microseconds varies between the frames. Hargutt (2001) likewise did not implement a lower threshold and concluded from his observations that short eye lid closures have a different dynamic that longer eye lid closures. Only the differences in duration and frequency of eye lid closures between the conditions were compared because of non-uniform time stamps. A classification of the drowsiness state is not necessary anyway with regard to the research question.

As last outcome measure the sustained light effect was assessed in a self-developed questionnaire. No statement about the validity can be made but the reliability was estimated regarding the inter-item correlation. The subjects were instructed to complete the survey the day after the trial because one item concerned the sleep quality. The survey was handed out to the participants as paper-pencil survey; thus, no verification when it actually was filled in was possible. Surveys requiring the subjects to recall their experiences are always susceptible to memory biases. Consequently, the interpretation of the results needs to be done with care. The scale answers just a minor part of the research question; therefrom, it seems to be legitimate to apply it. Other authors like Viola, James, Schlangen & Dijk (2008) also used self-developed scales without considerable objections.

6.2.4. Sample

Originally, based on experience, a sample size of N = 25 was strived for. Unfortunately, this size was not achieved due to technical difficulties and violations of imperative requirements (height) of participants. Other constraints for the participation are indeed remissible; for example, shift workers and travelers over more than one time zone were excluded. These groups could be part of the main target group for biologically effective lighting because it might help to re-entrain the circadian rhythm. Notwithstanding, in terms of comparability of the two test conditions, it was simply not possible to include such individuals. The impact of a jetlag is equalized within a few days; the shift work and therefore the personal schedule shifts every week. Further, as mentioned in the Participants section, the shift work schedule was not compatible with the study schedule. Another point to be discussed is the age limitation. For reasons already explained, the maximal age of subjects was set to 50 years. Apparently, this narrows the general validity of the results, especially under the aspect of the increasingly aging population. There are also indices for an age-independent effect of blue light (Gerstmeyer, Lehrl, Bleich, & Kornhuber, 2008). Nonetheless, the age limitation was useful because age is associated with factors like chronotype, medication and optical aids. Concerning the chronotype it must be said that a bias in the sample cannot be excluded: Late chronotypes might not have participated because the study schedule was not compatible with their personal schedule. The chronotype attribution was done according to Horne & Östberg (1976) but there is an alternative attribution scheme for the MEQ scores (Taillard, Philip, Chastang, & Bioulac, 2004). The chronotype classification by Taillard et al. (2004) is adapted for middle aged (33 – 58 years) employees. According to that classification, 16 participants corresponded to the intermediate type, four to the moderately evening type and two to the definitely evening type (the distribution classified after the original scheme was 16 intermediate type, seven moderately morning type). So the concern that composition of the sample significantly influenced the results of the study seems not to be justified, especially since according to both classification schemes, the majority of subjects belonged to the intermediate type.

There are indications that only a subgroup of the population is susceptible to the effect (Sülflow, 2013; Popp, 2005). An a priori selection of participants was not undertaken. Potential indicators for the responsiveness to the biological light effect, such as the nocturnal melatonin rise, were not measured in the study at all. There are also many intra-personal factors which can distort the measurements. Beside practical reasons, this was not an issue of the study at hand because the utility of an alertness increasing measure should not be limited to a subgroup of users. Another reason not to analyze the listed influencing factors on the biological light effect (Appendix E: Potential influencing factors) systematically was that uncertainty was already pronounced for the regressions conductioned; the small size of the subgroups would have led to even more unprecise coefficiencts hardly interpretable. In case of the light actually affecting the driver's state in only a subgroup, the sample was likely too small to capture that effect. One participant wrote in the paper pencil questionnaire "The drive without lighting was substantially more exhausting and very tiring" (translated from German), supporting the hypothesis.

6.3. Conclusion and outlook

The theory convincingly demonstrated that light of blue wavelengths can increase alertness, mood, vitality, and different kinds of performance in humans. A driving simulator study was conducted to test whether its beneficial effect appears in a realistic driving scenario which was not the case for the chosen measurements. It might well be possible that humans only profit from a targeted light exposure when they are in an amendable mood state. Studies attesting the insensitivity of humans to light in the context of biologically effective light are hardly found; however, e. g. Wilhelm et al (2011) support the assumption that human expericence is rather insensitive to different lighting conditions. The insights found in the study at hand are limited to the light application in the dark. Potentially, a real driving study would yield other results. The transfer of the findings to real life is not totally possible in a congruent way: The ecological validity is a little limited by the peculiarities of the simulator setup at hand. However, findings concerning the glare and avoidance behavior are highly relevant and not limited to a specific setting.

Why the vitalizing effect could not be observed is ambiguous. One could further investigate the data from the study at hand with regard to potential factors that modulate the light effect, e. g. gender, age and chronotype. The identification of the true and valid determinants of the biological light effect in humans under realistic conditions in general could be subject of another investigation.

For the everyday life application, a further refinement of the right dosage would be of greater interest. From the state of art it seems that the right formula to bringing blue light into non-autonomous vehicles on the road is yet to be. For the scope of an in-vehicle light device, a long-term study might be meaningful for usage in daylight as well as darkness. This would be especially insightful for the sustained light effect which was only present as a vague tendency in the study at hand. On daytime, the vitalizing light can be implemented as daylight reinforcement like in Farkas et al. (2015). In autonomous vehicles and for passengers other than the driver, different requirements apply for a vitalizing lighting which need to be refined. Finally, a proportionally small target group like professional drivers could benefit from the light device in the vehicle interior in extreme situations as proven by Taillard et al. (2012).

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Appendix

Appendix A: Physical measures

The light flux describes the radiation flux of a light source; it is measured in lumen [lm]. This radiation flux is perceived through the eyes in a spectrum of 380 nm to 780 nm [nm: nanometer]. The light intensity candela [cd] defines the relation of the light flux, its solid angle and the size of the solid angle. The luminance can be explained as the subjective impression of brightness resulting from the lighting of a surface which is stated in candela per m^2. Lastly, the illuminance refers to the relation of the light flux hitting a surface and the size of the illuminated surface. The illuminance is given in lux [lx]. Table 14 provides an overview of the explained photometric measures.

Table 14: Overview of photometric measures

Measure	Unit
Light flux	lm = cd · sr
Light intensity	cd
Luminance	cd/m^2
Illuminance	lx = lm/m^2

To clarify the connection between the photometric measures, it can be said that a standard lamp of 100 watt with 230 volt line voltage emits a light flux of approximately 1380 lm. Correspondingly, the light intensity amounts to approximately 250 cd. If the implied lamp is on a height of 1.5 m, the illuminance at the ground is approximately 100 lx (Haferkorn, 2003).

Another relevant measure is the color temperature which is given in kelvin (K). Low color temperatures are perceived as orange-red (ca. 1000 – 3000 K), like candle light or sunset, while high color temperatures appear blueish (> 6000 K) like a cloudless sky.

Appendix B: Image forming system

The image forming system draws its input basically from the rods and cones located at the retina. These photoreceptor cells are due to their different tasks not distributed equally: The highest density of the color sensitive cones can be found in the fovea centralis (point of sharpest vision) while the rods are at the peripheral parts of the retina (Grimm, 2002). Depending on the brightness proportions, the eyes adapt to photopic, scotopic or mesopic vision. Photopic vision occurs at lighting conditions like at the day (luminance range > 3 cd/m^2); the cones allow for accurate color vision (Rea, Bullough, Freyssinier-Nova, & Bierman, 2004; Schierz, 2007). When adapted to scotopic vision (luminance range < 0.001 cd/m^2), perception is solely based on the rod cells which don't produce color sensation (Rea, Bullough, Freyssinier-Nova, & Bierman, 2004; Schierz, 2007). In the luminance range between darkness and daylight (> 0.001 cd/m^2 and < 3 cd/m^2), mesopic vision, the transition between day vision and night vision, occurs. Mesopic vision corresponds to an adaptation level at which both rods and cones are interacting to enable vision. However, the signal input and combination of rods and cones is not linear: "[M]esopic spectral sensitivity depends on environmental luminance, colours, solid angle under which the objects are seen, and their position on the retina" (Caberletti, 2013, p. 12).

Mesopic vision is for the scope of the blue light at darkness especially relevant because the environmental luminance is not high enough to trigger adaptation to photopic vision (Grimm, 2002; Caberletti, 2013). In that context, Caberletti (2013) noted that under conditions of mesotopic vision (luminance between 0.01 cd/m² and 0.1 cd/m²), blue ambient light must be of a lower luminance level than green or red light for the same comfort. This can be explained by the Purkinje effect; blue is perceived brighter in mesoptic vision an in photopic.

The spectral eye sensitivity curve for photopic vision (V_λ) builds the basis for all lighting units explained in Appendix A: Physical measures (Van Bommel, 2006; Van Bommel & Van den Beld, 2003): As already mentioned above, the photometric system is based on the relative luminous efficiency function V_λ (which is also called spectral eye sensitivity curve; λ: wavelength) for photopic vision. Essentially, the function displays that the human eye is not very sensitive to blue and red light under daylight conditions, but has a maximal sensitivity for green-yellow light (Figure 23). In turn, the rod system is more sensitive to light of blue wavelengths (V'_λ, Figure 23) which explains why blue light glares more than light of the same intensity but other colors (Caberletti, 2013; Caberletti, Elfmann, Kummel, & Schierz, 2010). There is no determined sensitivity function for mesoptic vision; it lies between those for photopic and scotopic vision. The spectral sensitivity curves changes as a function of age resulting from the age-related macular degeneration: With increasing age, stimuli containing proportions of blue are perceived darker (Schierz, 2007). Older people are dazzled at lower light intensities than younger ones (Schiller, Sprute, Haferkemper, & Bodrogi, 2009).

When rods and cones are stimulated by light, they initiate the release of photopigments. These again trigger the complex reaction of image forming. The input from the retina is transduced via the optic nerve to the visual cortex, the part of the brain responsible for visual processing.

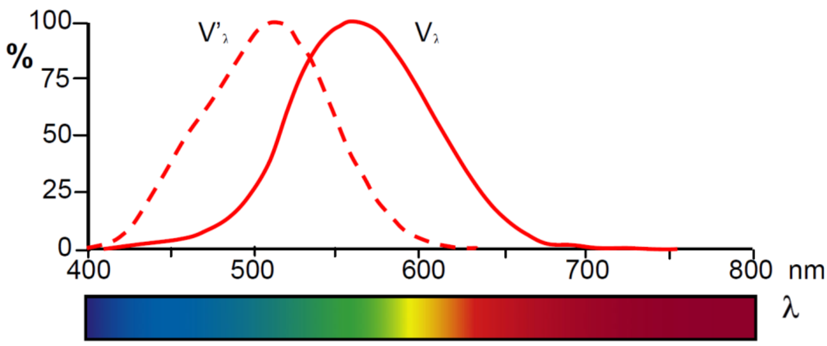

Figure 23: Spectral eye sensitivity curves, V_λ for the cone system (photopic vision: solid line) and V'_λ for the rod system (dotted line; Van Bommel & Van den Beld, 2003)

Appendix C: Models of sleepiness

Early models like the two-process model of sleep regulation (Borbély, 1982) build the basis for newer models but were due to some shortcomings further adapted (Cluydts, De Valck, Verstraeten, & Theys, 2002). Essentially, sleepiness is determined by two components: state and trait sleepiness.

State sleepiness: State sleepiness describes short-term changes in sleepiness due to situational conditions. These are characterized by the *process C*, which is the circadian-rhythmic component and *process S*, the homeostatic-monotonic component. Process S reflects the preceded sleep duration and time awake. A third *process W* represents sleep inertia, the state of stupor after awakening (Folkard & Åkerstedt, 1987). The *sleep drive* or *sleep pressure* rises with increasing time wake and a sleep deficit (Popp, 2005; Sülflow, 2013). The sleep drive consists of a primary component regulated by central-nervous activity in certain brain regions and a secondary component (Johns, 1993). The secondary component corresponds to process S. The *wake drive* is "composed of chronobiological factors [...] and of environmental factors, such as posture and physical activity" (Cluydts, De Valck, Verstraeten, & Theys, 2002, p. 85). Likewise, the two factors characterize the wake drive: First, the primary wake drive which is essentially equal to process C, but accentuates the alerting rises of the circadian rhythm. Second, the sensomotoric input influenced by posture, behavior, physical activity, feelings and mental activity that leads to an increment in central-nervous activation, which composes the secondary wake drive. *Process A* describes the situation specific sensory input to the central nervous system. Process A corresponds to the secondary wake drive. E. g., in a modest and maybe routine driving scenario the secondary wake drive may be restrained.

Trait sleepiness: Trait sleepiness, which can be understood as an analogy to a personality trait; it is a "particular baseline level of sleep drive in each individual" (Cluydts, De Valck, Verstraeten, & Theys, 2002, p. 87). The trait sleepiness is a product of the interaction of the individual need for sleep and an individually specific level of arousal. The combination of trait and state sleepiness determines the actual sleepiness (Cluydts, De Valck, Verstraeten, & Theys, 2002). Figure 24 provides a summarizing overview of the factors determine the individual sleepiness state.

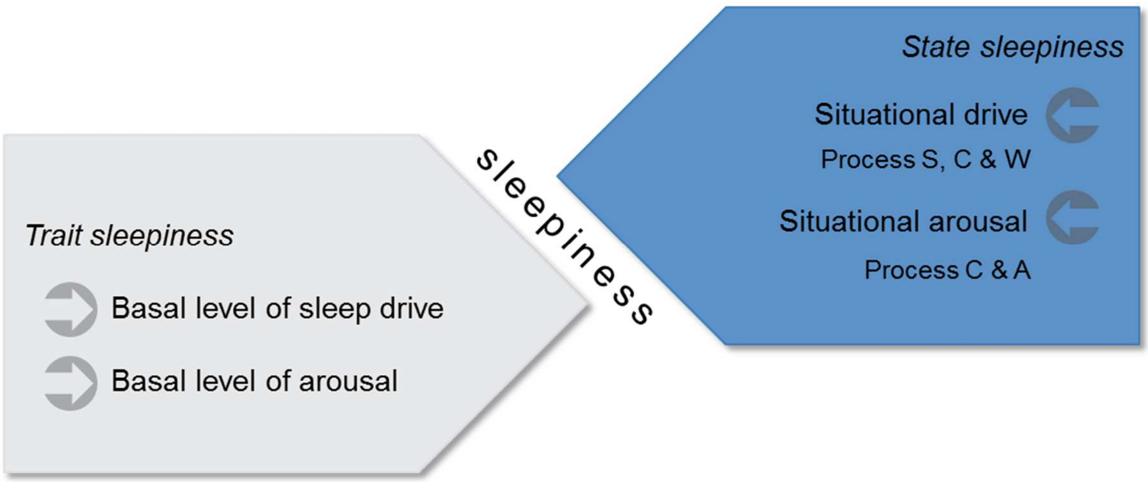

Figure 24: Summarized model of sleepiness (own illustration)

Appendix D: Pilot study

Expert rating

Prior to the user study, an expert rating took place to evaluate the maximal light intensity without dazzling and the most comfortable light intensity. The sample consisted of n = 8 experts whose mean age was M = 28.1 years (SD = 3.98). The participants were seated on the driver's seat with a standardized seat position in the vehicle equipped with the ambient light. The vehicle was located at a dark light channel with turned on dimmed headlights. The subjects were instructed to determine their preferred light intensity at which they felt most comfortable and deemed they were able to drive the vehicle safely. Furthermore, the maximal tolerable light intensity at which the participants had the impression to have an adequate sight to maintain safe driving was assessed. The experimenter adjusted light intensity via pulse-width modulation (possible range: 0 – 255) on a tablet computer so that the subjects were not exposed to another light source than the ambient light.

A mean of M = 16.3 (SD = 7.69) which corresponds to 4 lux is calculated as maximal light intensity without dazzling. The optimal light intensity is 1.3 lx which corresponds M = 5.63 (SD = 4.50) on the pulse-width modulation scale. From the comments of the participants, it became clear that the rating of the light intensities was so low due to the LED (short for "light emitting diode") beam implemented at the sun shield. Therefore, a second expert rating without the LED beam in the sun shield was carried out.

N = 5 participants (all participants of the first expert rating; age M = 26.6, SD = 3.44) were asked to indicate the maximal light intensity without dazzling and the most comfortable light intensity under the same conditions as in the first expert rating, except from the disabled light in the sun shield. A maximum of 19 lx light intensity (corresponding to M = 99.6, SD = 56.8 on the pulse-width modulation scale) and an optimum of 3 lx (corresponding to M = 14.4, SD = 5.03 on the pulse-width modulation scale) were detected. As conclusion, the participants of the user study were exposed to a light intensity of 19 lx with a disabled LED beam at the sun shield.

User study

The user study aimed at investigating the hypothesis that blue light in an otherwise dark surrounding enhances the scores in the subjective as well as objective variables measured. In the within-subjects design with two inquiry points of time, the independent variable was the exposure to blue light via the light device for 30 min versus no light exposure. The effect of the treatment was evaluated through subjective sleepiness (Karolinska Sleepiness Scale, KSS), current mental state (Multidimensional Mood State Questionnaire, MDMQ), concentration (d2-R), mental workload (reaction-time task with visual stimuli) and user acceptance (Van der Laan Scale, semantic differential). Additionally, the participants completed a questionnaire to specify the chronotype (Morningness-Eveningness Questionnaire, MEQ). Because the study took place in a laboratory setting, the participants performed a secondary task (visual search task) instead of the driving task. The visual search task was projected via a 78 inches display in front of the vehicle (Figure 25). Thereby, the same illuminance levels (0.2 – 0.5 lx) like in a night drive were established. Since participants are most likely to be tired in the morning or when they have finished work, time slots were set at 8:00/9:00 a. m. and 3:00/4:00 p. m. lasting for one hour. Every subject had to register for two time slots each at the same time. Before the blue light exposure, the participants received an information sheet explaining the impact of blue light on the human. Like in the expert ratings, the sample consisted of Volkswagen employees. The participation was restricted to employees who fulfilled following criteria: maximum age of 50 years, no shift work, no consummation of caffeine-containing beverages or nutrition within two hours before the trial, no wearers of glasses, no optical aid with color screen and no sleep disorders or intake of sleep-regulating medication. A sample size of $n = 33$ (male: 17, female: 16) with the average age $M = 33.3$ years ($SD = 8.77$, range: 19 – 50) was achieved. The participants travel on the average $M = 30.2$ minutes ($SD = 25.5$, min. = 5, max. = 120) to work and possess their driver's license $M = 15.6$ years ($SD = 8.35$, min. = 3, max. = 33). Three subjects had dyschromatopsia and four stated to smoke. Concerning the chronotype, it can be noted that none of the participants had an extreme tendency towards morningness or eveningness. 11 subjects were attributed to the moderate morning type (male: 6, female: 5) while the other 22 subjects correspond to the indifferent type (male: 11, female: 11; the raw scores were interpreted as proposed by Horne & Oestberg, 1976).

Figure 25. Experimental setup in the blue light condition (left) and exemplary visual search task (right).

At each of the four measurement points (0 min, 10 min, 20 min, 30 min) the surveys as well as the reaction time task were completed. Regarding the KSS scores, the blue light had no effect on the sleepiness. In general, it could be observed that the participants were not sleepy at all; independent of the following treatment or time of the day the mean KSS score was $M = 3.1$ ($SD = 1.98$). The subscale Good-Bad-Mood of the MDMQ indicated that the participants were at the beginning of the trials in a neutral mood which did not change in the course of the trial independent of the condition. The participants also remained awake and tired, respectively, at the same level during the trial in both conditions. Additionally, there were no changes in the scores for the subscale Calm-Nervous of the MDMQ.

Concerning the concentration measured by the d2-R test, it can be reported that in the baseline as well as in the light condition significantly higher test scores (meaning less errors) were achieved after the trail compared to the ones before the trial. The improvement of performance in the concentration test in the baseline condition is against expectations and can be explained by the occurrence of a learning effect (Rothert & Völker, 2016). Therefore, a potential increase in concentration performance evoked by the blue light application might be overlaid by this learning effect (Rothert & Völker, 2016). Reaction times (RT) were measured with a traffic light task; the traffic light changed from yellow as indicator for the preparation time (2 sec) to red and afterwards to green (1000/5000 ms). Participants were instructed to press a button as soon as the traffic light changed to green. No differences in RT could be found between the experimental conditions.

Appendix E: Potential influencing factors

In this section, factors which are known to influence the effect of light on the human organism, but cannot be randomized as experimental factor, will be explained. Smolders & de Kort (2014) list following potential confounding variables: time awake, minutes of sleep, time spent outdoors, traveling time outdoors prior to the experiment, gender, age, light sensitivity, chronotype, global sleep quality, trait vitality, general health and subjective light sensitivity.

Gender: Some studies investigating the influence of light excluded females as participants for following reasons: the effects of menstrual cycle phase on cognitive performance during sleep deprivation and on sleep quality (Taillard, et al., 2012; Hartley, et al., 2013); due to the influence of menstrual phase and the use of oral contraceptives on, for instance, melatonin secretion (Cajochen, et al., 2011); slower reaction times (Hartley, et al., 2013); because likely no women were in the job (Leger, Philip, Jarriault, Metlaine, & Choudat, 2009); physical performance was measured as outcome variable (Kantermann, et al., 2012) or for reasons not further explained (Chellappa, et al., 2011; Cajochen, et al., 2005; Okamoto & Nakagawa, 2016; Rahman, et al., 2014). However, there are numerous studies which could show an effect for female participants. For the application in everyday life it is inevitable to include female participants in the studies.

Age: In terms of non-visual light effects, the age of participants must be considered for reasons already explained above (Participants section). Beside the reduced permeability of blue wavelength light, the diameter of the pupil decreases with increasing age which leads to a mitigation of the irradiance at the retina compared to younger subjects (Weber & Schulmeister, 2004; Turner & Mainster, 2008). Further, the age may modulate the effect of time on task and cause differences in the driving performance (Popp, 2005; Shekari Soleimanloo, 2016).

Chronotype: The chronotype was specified though the validated German version of the Morningness-Eveningness Questionnaire (MEQ; Griefahn, Künemund, Bröde, & Mehnert, 2001). It distinguishes between definitely morning type, moderately morning type, neither type, moderately evening type and extreme evening type. The self-assessment questionnaire contains items concerning sleep-wake-pattern, subjective mental state and physical performance (Horne & Östberg, 1976). The higher the score, the more related is the subject to the morning type (Horne & Östberg, 1976).

Knowledge of light effect: A placebo effect owning to the knowledge of the alerting effect of blue light was avoided by excluding participants of the pilot study. Nonetheless, it cannot be completely averted that subjects already learned about the blue light impact or anticipated it from the experimental setup. Thus, after the debriefing on the day of the second measurement, the participants were orally asked if they had an idea about the effect of the light application.

Caffeine, nicotine and alcohol consummation: Caffeine and alcohol are known to have a stimulating effect (Popp, 2005; Gershon, Shinar, & Ronen, 2009; Beaven & Ekström, 2013; Schwarz, et al., 2011). The effect of nicotine seems to be ambivalent (Popp, 2005). The participants were instructed to restrain from caffeine and alcohol in the night and the morning before the trial. No instructions concerning smoking were given. To ascertain compliance, a single item each was used asking for the last caffeine and alcohol intake, and to check for consummation of nicotine.

Eye color: The effect of blue light is mediated by the eye color insofar as blue and light eyed participants, respectively, show greater responses to the blue light exposure (Beaven & Ekström, 2013; Higuchi, Motohashi, Ishibashi, & Maeda, 2007). To account for this potential source of variance, the eye color was inquired in the paper-pencil survey.

Appendix F: Additional diagrams

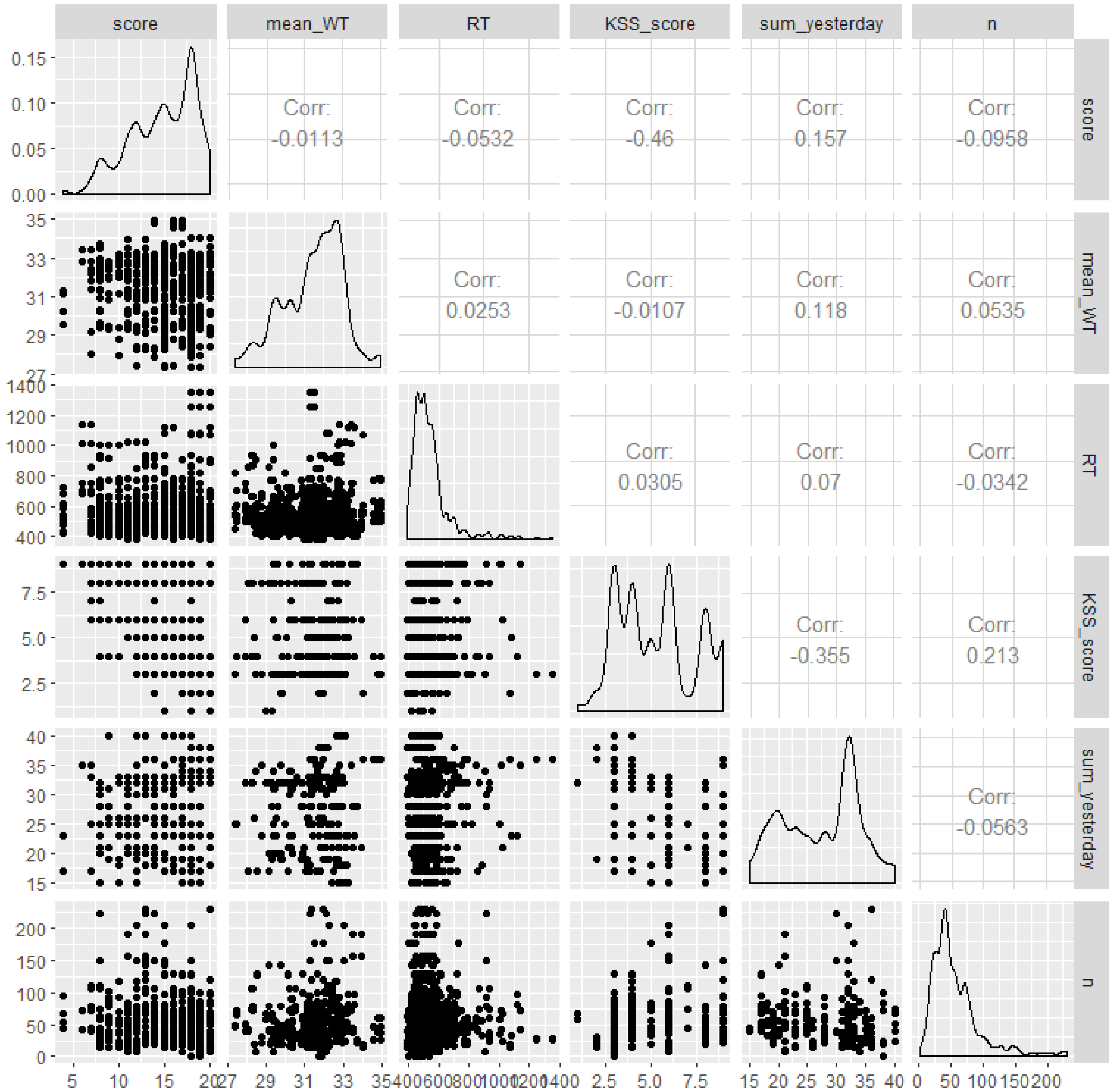

Figure 26: Dependencies between the outcomes measures and distribution

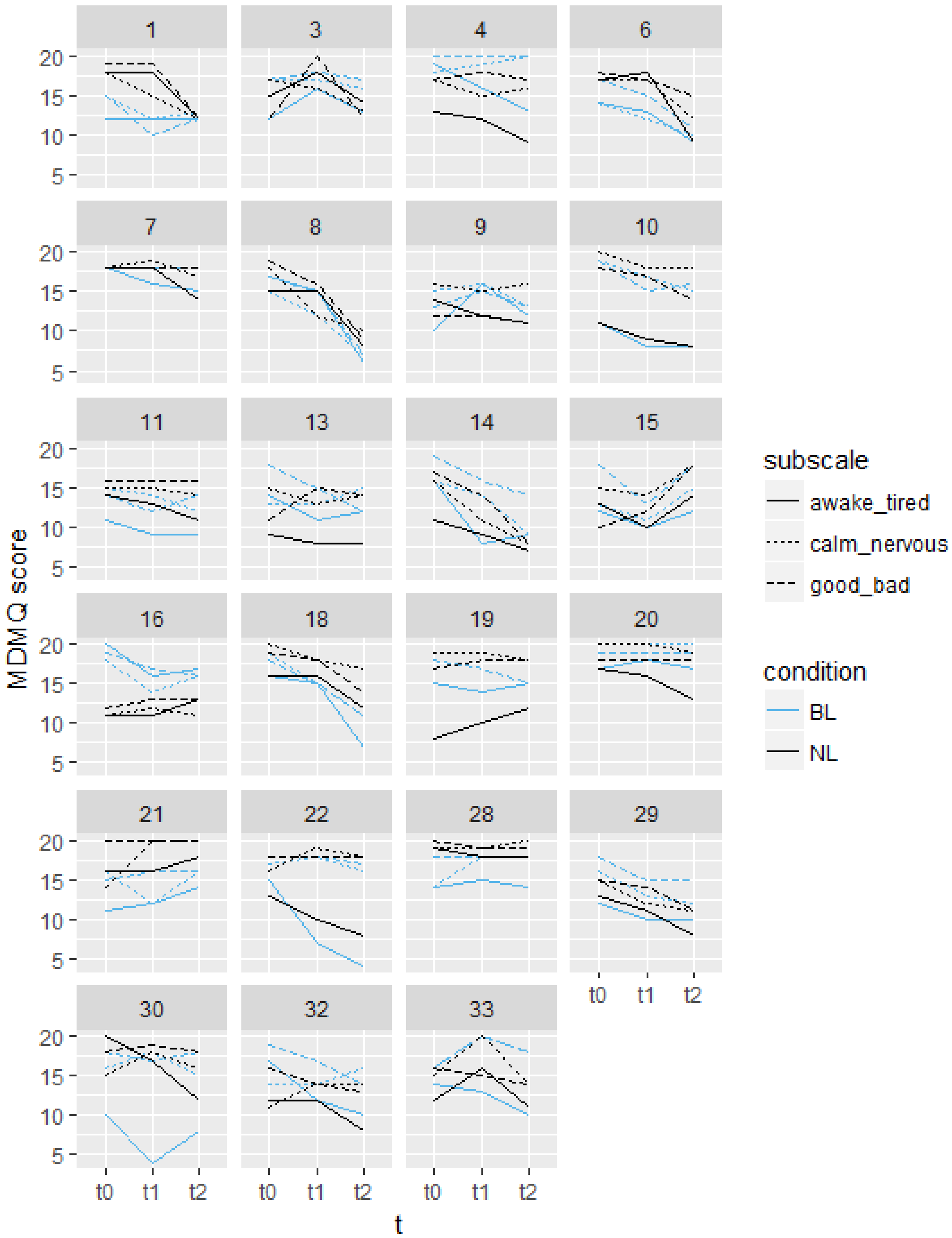

Figure 27: MDMQ score trajectories on subject level by condition and subscale

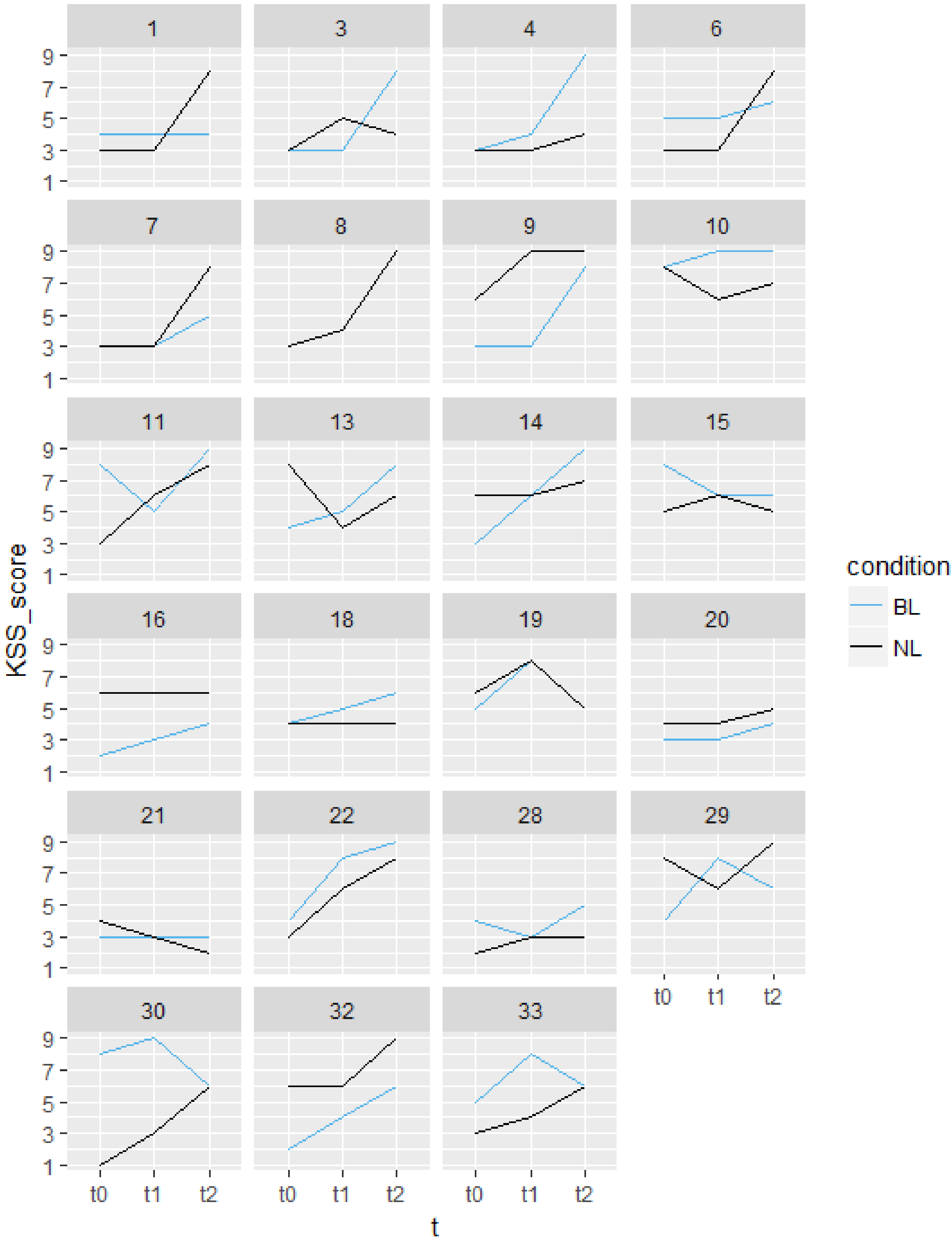

Figure 28: KSS score trajectories on subject level by condition

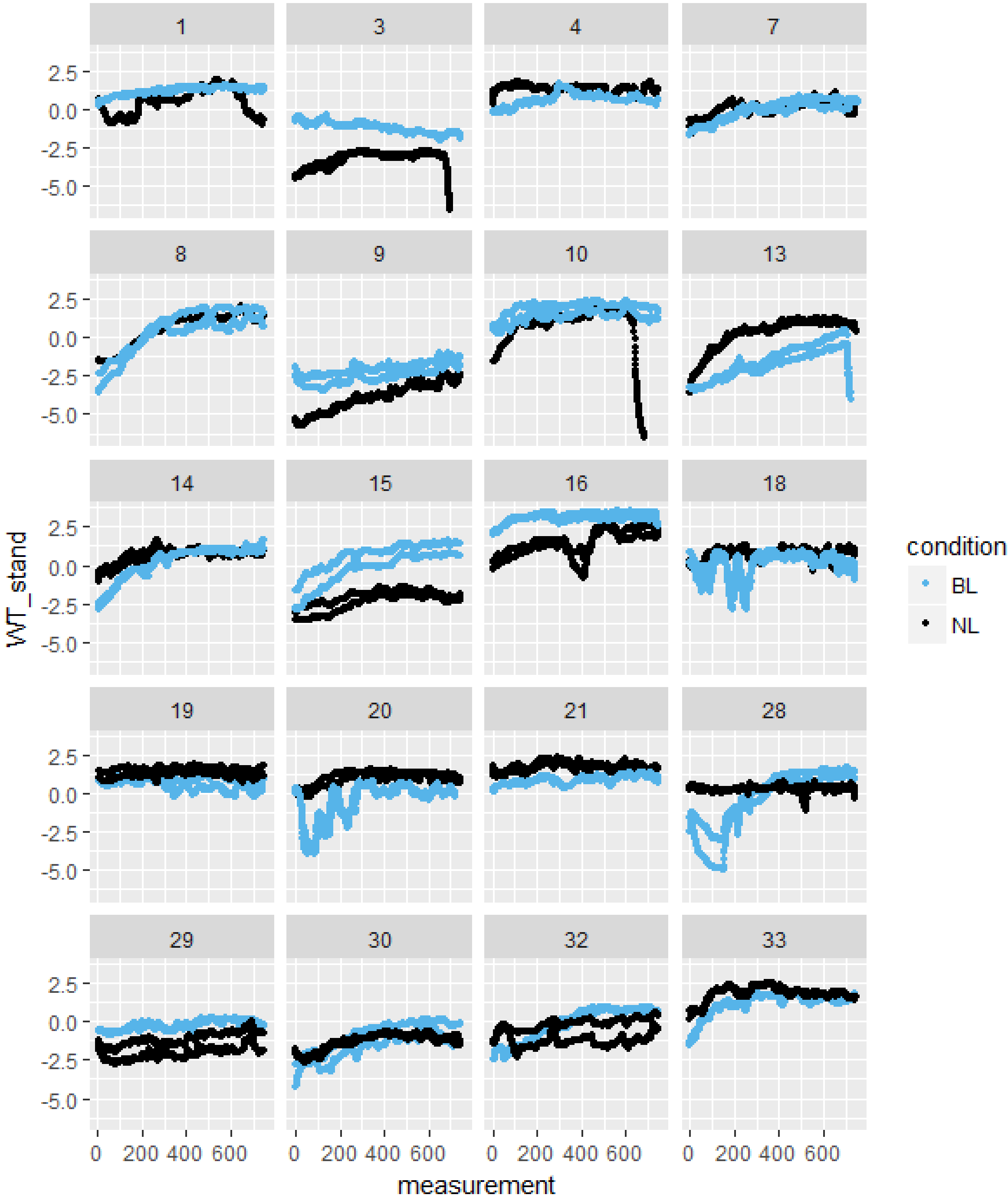

Figure 29: WT trajectories on subject level (standardized) by condition

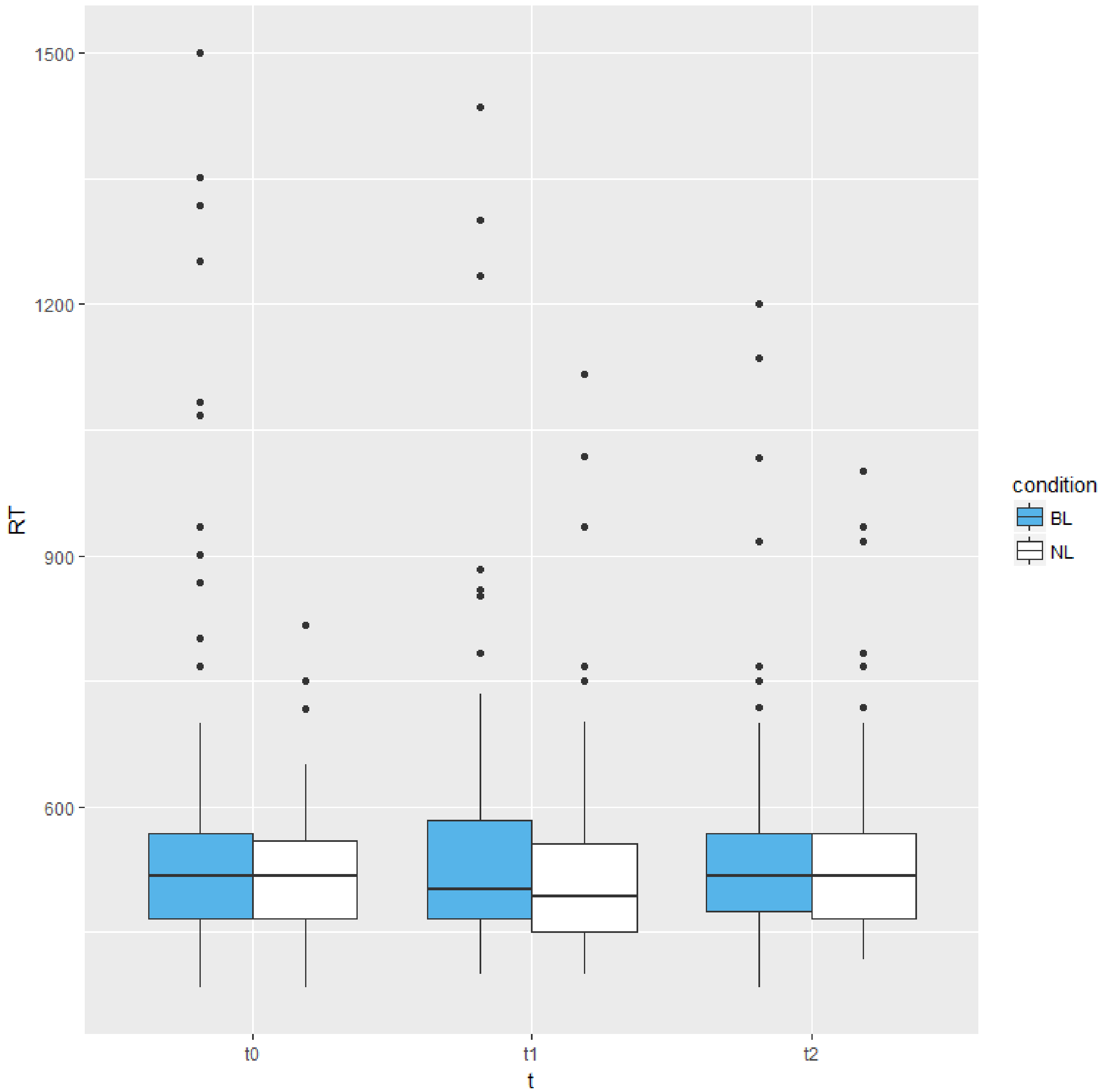

Figure 30: Boxplot indicating median RT by measurement point and condition

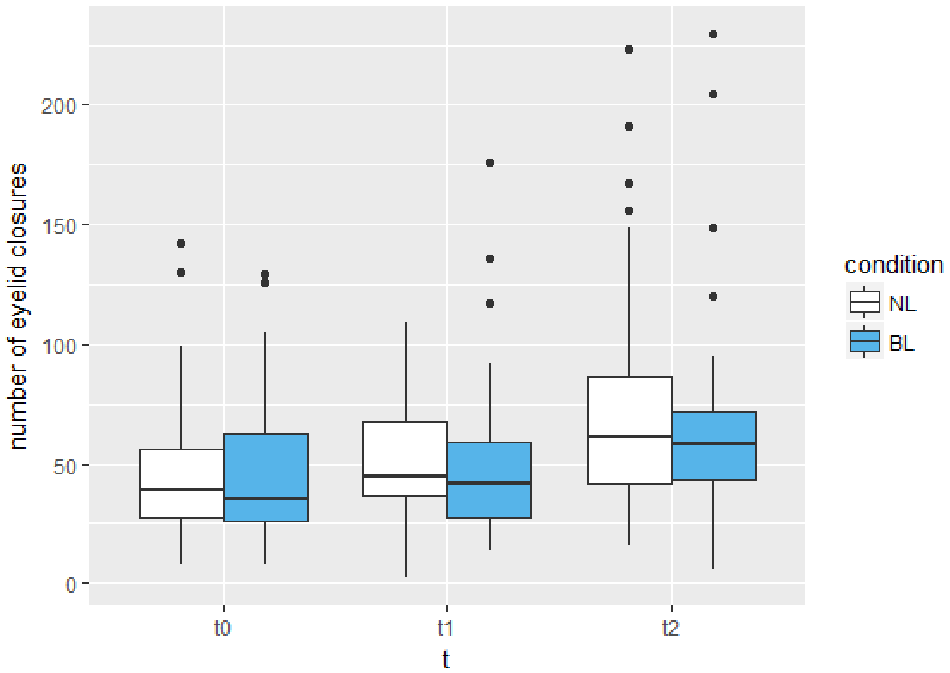

Figure 31: Boxplot indicating median number of eye lid closures by measurement point and condition

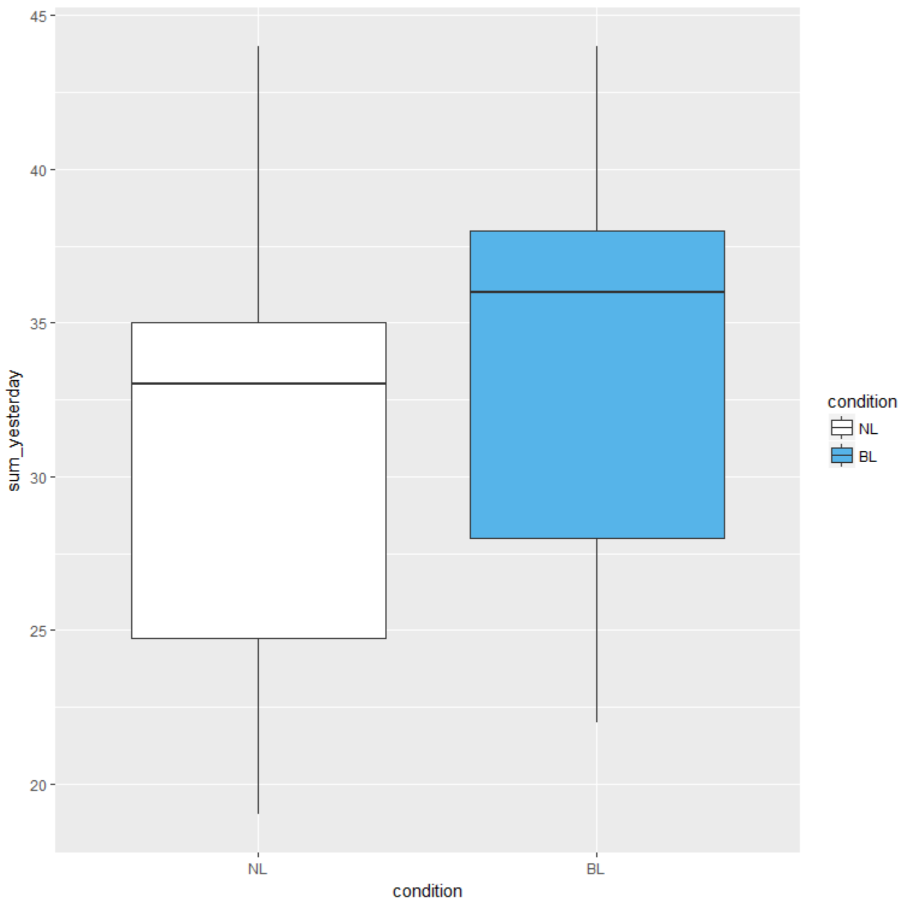

Figure 32: Boxplot indicating median number score for the sustained light effect by condition

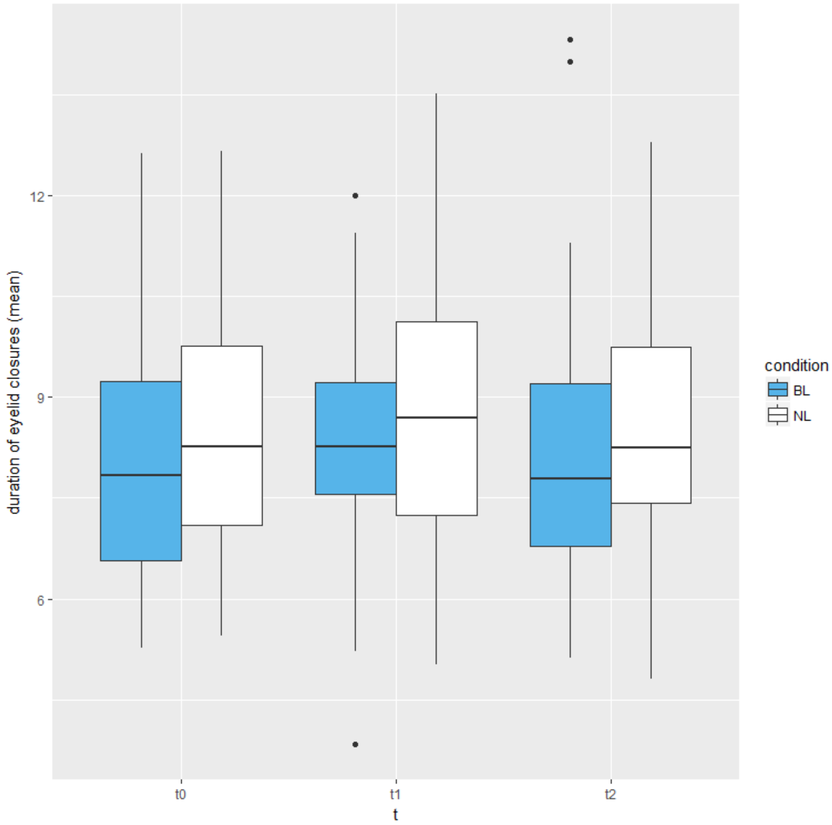

Figure 33: Boxplot indicating median mean duration of eye lid closures by measurement point and condition

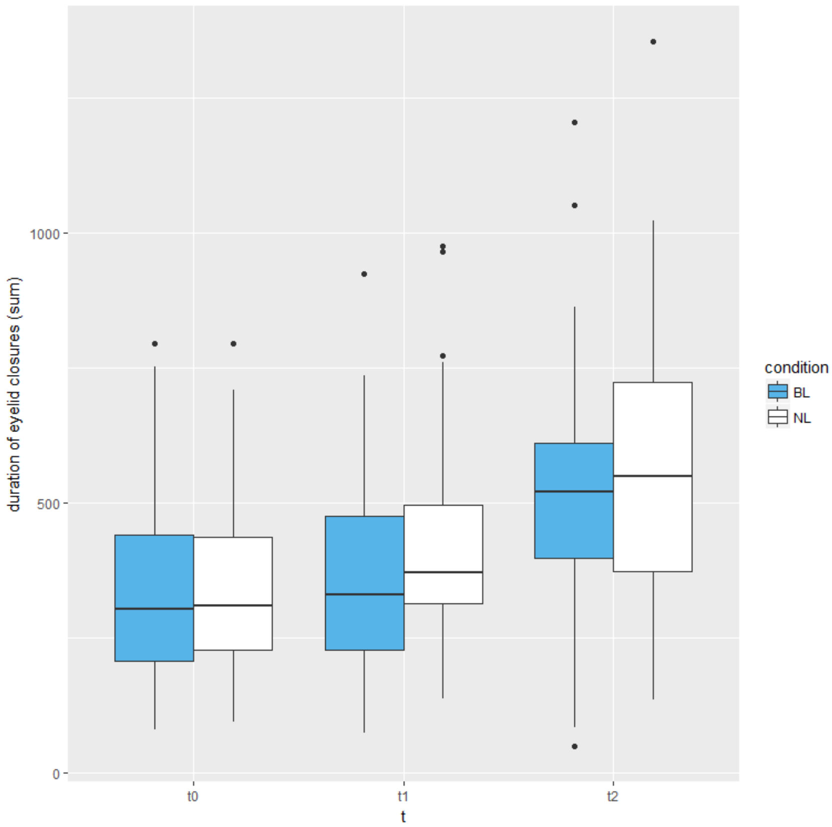

Figure 34: Boxplot indicating median summed duration of eye lid closures by measurement point and condition

Appendix G: Regression results tables

MDMQ

Table 15: Fixed effects results for mood, posterior distributions summarized as mode (location) and 95% certainty

Beta	Parameter	Location	CI.025	CI.975
β_0	(Intercept)	15.62	11.22	19.91
β_C	conditionBL	.44	-.81	1.67
$\beta_{t[1]}$	t1	-.22	-.91	.49
$\beta_{t[2]}$	t2	-2.05	-3.14	-.91
$\beta_{t\|C[1]}$	conditionBL:t1	-1.16	-2.14	-.17
$\beta_{t\|C[2]}$	conditionBL:t2	-.45	-1.36	.50

Table 16: Subject-level variation (*SD*) of mood, posterior distributions summarized as mode (location) and 95% certainty

Sigma	Parameter	Location	CI.025	CI.975
σ_S	subject	.00	.00	.95
$\sigma_{S\|C}$	condition:subject	1.68	1.27	2.21
$\sigma_{S\|t[0]}$	1.subject	.00	.00	.70
$\sigma_{S\|t[1]}$	2.subject	.00	.00	1.28
$\sigma_{S\|t[2]}$	3.subject	2.07	1.51	3.13
σ_{Su}	subscale	1.59	.00	9.19
$\sigma_{Su\|C}$	condition:subscale	.00	.00	3.35
$\sigma_{\epsilon[0]}$	1.units	2.03	1.78	2.33
$\sigma_{\epsilon[1]}$	2.units	2.18	1.90	2.50
$\sigma_{\epsilon[2]}$	3.units	1.95	1.73	2.27

KSS

Table 17: Fixed effects results for KSS ratings, posterior distributions summarized as mode (location) and 95% certainty

Beta	Parameter	Location	CI.025	CI.975
β_0	(Intercept)	4.34	3.56	5.11
β_C	conditionBL	-.01	-1.09	1.09
$\beta_{t[1]}$	t1	.46	-.32	1.25
$\beta_{t[2]}$	t2	2.00	1.06	2.95
$\beta_{t\|C[1]}$	conditionBL:t1	.52	-.62	1.61
$\beta_{t\|C[2]}$	conditionBL:t2	.16	-1.16	1.50

Table 18: Subject-level variation (*SD*) of KSS ratings, posterior distributions summarized as mode (location) and 95% certainty

Sigma	Parameter	Location	CI.025	CI.975
σ_S	subject	.00	.00	.83
$\sigma_{S\|C}$	condition:subject	1.27	.80	1.76
$\sigma_{S\|t[0]}$	1.subject	.00	.00	.19
$\sigma_{S\|t[1]}$	2.subject	.00	.00	.42
$\sigma_{S\|t[2]}$	3.subject	.00	.00	1.08
$\sigma_{\epsilon[0]}$	1.units	1.35	1.00	1.86
$\sigma_{\epsilon[1]}$	2.units	1.32	.95	1.82
$\sigma_{\epsilon[2]}$	3.units	1.79	1.37	2.38

WT

Table 19: Fixed effects results for WT, posterior distributions summarized as mode (location) and 95% certainty

Beta	Parameter	Location	CI.025	CI.975
β_0	(Intercept)	30.67	29.92	31.41
β_C	conditionBL	-.12	-.96	.70
$\beta_{t[1]}$	t1	.85	.59	1.13
$\beta_{t[2]}$	t2	1.06	.68	1.44
$\beta_{t\|C[1]}$	conditionBL:t1	.12	-.17	.44
$\beta_{t\|C[2]}$	conditionBL:t2	.49	.01	.97

Table 20: Subject-level variation (*SD*) of WT, posterior distributions summarized as mode (location) and 95% certainty

Sigma	Parameter	Location	CI.025	CI.975
σ_S	subject	1.12	.00	1.41
$\sigma_{S\|C}$	condition:subject	1.02	.90	1.97
$\sigma_{S\|t[0]}$	1.subject	.04	.02	.70
$\sigma_{S\|t[1]}$	2.subject	.00	.00	.00
$\sigma_{S\|t[2]}$	3.subject	.00	.00	.00
σ_{Su}	sensor	.00	.00	.00
$\sigma_{Su\|C}$	condition:sensor	.00	.00	.03
$\sigma_{\epsilon[0]}$	1.units	.54	.41	.68
$\sigma_{\epsilon[1]}$	2.units	.33	.27	.42
$\sigma_{\epsilon[2]}$	3.units	.88	.75	1.07

Appendix H: Sustained light effect

Table 21: Mean and standard deviation per item and condition of the sustained light effect scale

Item	Condition	*M*	*SD*
wake	NL	3.45	1.18
	BL	3.45	1.01
vital	NL	3.23	1.15
	BL	3.27	0.98
unproductive+	NL	3.50	1.22
	BL	4.05	1.09

fit	NL	3.50	1.14
	BL	3.63	0.85
performance	NL	3.36	0.85
	BL	3.50	0.96
well	NL	3.68	0.95
	BL	3.95	0.72
tired+	NL	3.00	1.27
	BL	3.36	1.21
alert	NL	3.45	0.91
	BL	3.59	0.80
sleep	NL	3.77	0.81
	BL	4.18	0.73

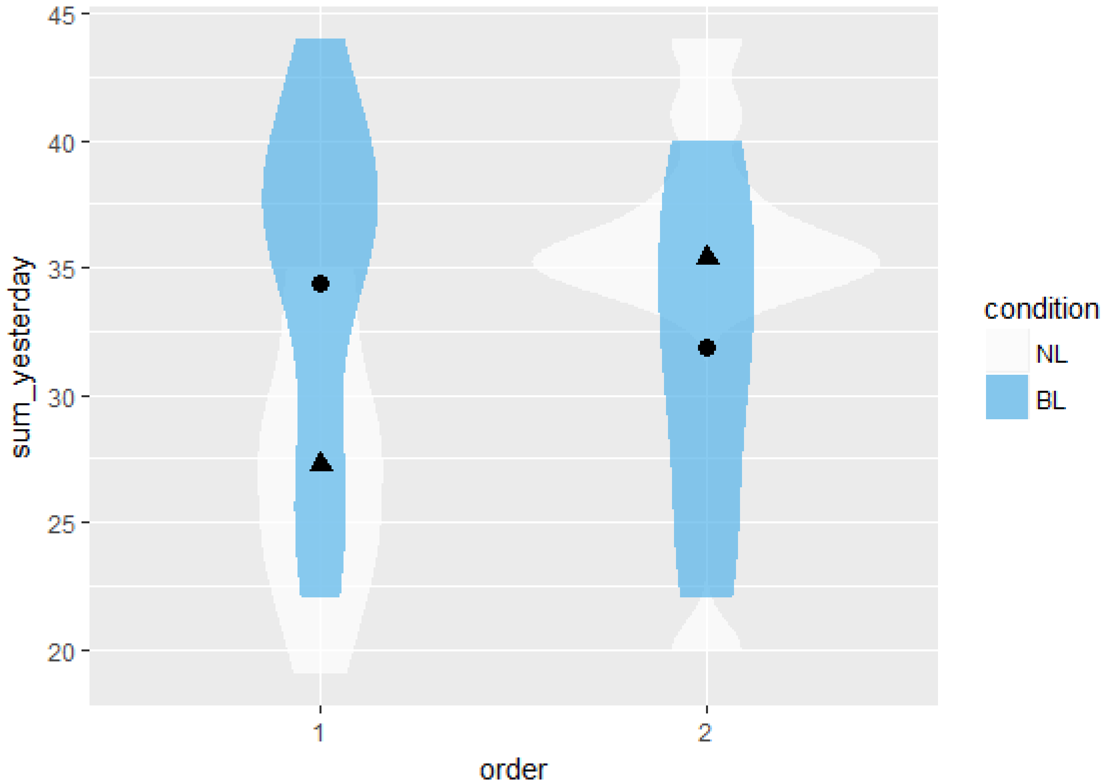

Figure 35: Distribution and mean of the sustained light effect scores by condition and order

Table 22: Fixed effects results for sustained light effect summarized as mode (location) and 95% confidence intervals

Parameter	Location	CI.025	CI.975
Intercept	27.25	23.85	30.65
conditionBL	7.15	2.11	12.19
Order2	8.15	2.11	13.19
conditionBL:order2	-10.72	-18.63	-2.80

Appendix I: Countermeasure to drowsy driving

There are already driver assistance systems for drowsiness detection; however, as accident statistics show, the driver drowsiness detection is not sufficient to avoid sleepiness caused crashes. One reason may be that some drivers cannot appropriately assess their own sleepiness and therefore do not trust in the sleepiness alerts provided by the driver assistance system (Filtness, et al., 2014). Another approach to counteract sleepiness on the wheel could help. One of the most frequent countermeasures to sleepiness is the consummation of stimulating substances such as caffeine containing beverages including energy drinks (14 – 17 % in professional drivers; Popp, 2005; Royal, 2003). The effectiveness of caffeine is proven in divers studies (e. g., Shekari Soleimanloo, 2016; Beaven & Ekström, 2013; Taillard, et al., 2012). Napping is a very effective strategy against sleepiness but may fail in the practical implementation. However, it is most reported (43 %) and effective activity professional drivers undertake in order to reduce sleepiness (Royal, 2003; Hammoud & Zhang, 2008). Further, regulating down the temperature within the vehicle, e. g. by opening a window, acustic stimuli such as music and physical and motoric activity, respectively, can be enumerated as common countermeasures (Popp, 2005; Royal, 2003; Gershon, Shinar, & Ronen, 2009; Davenne, Gauthier, Lericollais, Philip, & Taillard, 2011; Schwarz, et al., 2011). Less often reported are countermeasure like talking, changing drivers and eating (Royal, 2003). Strategies like rubbing the face or eyes, scratching, facial contortions, yawning, head movements and moving restlessly in the seat are probably not fully conscious and might be confounded with symptoms of sleepiness (Wiegand, McClafferty, McDonald, & Hanowski, 2009; Sun & Yu, 2014; Platho, Pietrek, & Kolrep, 2013). Conventional countermeasures possess either a minor effectiveness or are hardly realized in praxis (Popp, 2005; Farkas, Leib, Betz, & Rothe, 2015). Hence, less traditional efforts were developed: Popp (2005) found that olfactory stimulation with menthol can enhance alertness under certain circumstances.