Effects of light transitions on measures of alertness, arousal and comfort

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ABSTRACT

Knowledge on the onset, persistence, and symmetry of effects of lighting transitions on humans is relevant when designing dynamic lighting scenarios and, additionally, can shed light on the dominance of underlying mechanisms. We examined temporal trajectories in measures of alertness, arousal and comfort after abrupt lighting transitions that were created using two strongly contrasting light conditions (warm, dim lighting vs. cool, bright lighting). In this controlled within-subjects experiment, thirtyeight healthy subjects participated in four separate sessions of 90 min. Subjective experiences (alertness, comfort and mood) and objective measures of vigilance (PVT performance), arousal (HR, HRV, SCL), and thermoregulation (skin temperature and DPG) were studied. The comparison of the temporal trajectories following the transition in light for the different variables indicates a complex interplay of underlying physiological and psychological processes driving these effects.

1. Introduction

Light enables us to perceive our environment, to see colors, shapes and contrasts, and it influences how we experience the world around us through the image forming (IF) pathway of light [10]. Furthermore, there is a so-called non-image forming (NIF) pathway through which light exerts circadian and acute effects [13]. These different physiological pathways give rise to fundamental differences in the response dynamics of appraisals, mental states and behaviors to transitions in a light scene. These concern, for instance, the onset of an effect, the persistence of an effect over time, or whether back-and-forth transitions generate symmetrical effects. These aspects are important to understand when designing dynamic lighting scenarios.

1.1. Visual perception and light appraisal

Onset, persistence and (a)symmetry have been thoroughly investigated for the effects of light-dark transitions on visual perception [10]. For instance, when moving from darkness into bright light, adaptation occurs within seconds. As soon as the eye is fully adapted, visual ability persists until the light changes again. The effect of light on visual ability is asymmetrical: when light is suddenly dimmed down, full recovery of visual ability may take more than 60 min, which clearly contrasts the fast adaptation in the opposite transition [10]. Contrarily, the response dynamics of many other variables, for instance visual appraisals and visual comfort, are still largely unknown, as they are often measured only once at the end of the experimental lighting condition (e.g., [26, 48]). Although we know that factors, such as, intensity, spectrum, uniformity and color rendering quality of light impact the subjective judgement of the momentary light condition [15], these processes are mediated and moderated by various psychobiological and psychological processes [55]. Only when these processes stabilize, a visual comfort verdict of a certain lighting condition can remain constant.

1.2. Mood

The processes underlying light effects on mood are understood even less than those on appraisals. Light has, via lighting appraisals, been suggested to affect mood [56]. Intensity-induced moderations in some dimensions of mood have been demonstrated both in the lab [19, 27, 30, 50] and in the field (e.g., [1, 37]). The same holds for effects of correlated color temperature (CCT; e.g., [6, 28, 32, 34, 49, 57]). Yet, the research on effects of illuminance and spectrum on mood lacks information about the response dynamics of these effects.

1.3. Temperature perception and thermoregulation

Illuminance and spectrum are also thought to influence temperature perception. The hue-heat hypothesis states that blueish light is associated with coolness and, therefore, an environment in blueish light is experienced cooler, although scientific evidence is mixed [14, 22].

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Bright light might also evoke associations with the sun, and therefore feel warmer [58]. Furthermore, changes in thermal comfort correlate with changes in visual comfort [54] and thus may follow a similar response dynamic as visual appraisals. Light intensity has also been suggested to lead to changes in thermal sensation and comfort via changes in skin temperatures [12, 53]. Last, effects of light on thermoregulation have been linked to feelings of sleepiness and alertness [29]. Studying the interaction between light and thermal responses is relatively new and there is a lot of work that remains to be done before knowledge on the thermal response dynamics can be implemented in dynamic lighting scenarios.

### 1.4. Alertness and arousal

Light is often suggested to induce alerting and arousing effects. Arousal is defined as physiological activation of the brain in relation to a person’s sleep-wake state, whereas the very closely related concept of (tonic) alertness also includes some cognitive processing and is considered synonymous with vigilance and sustained attention [36]. Although the existence of alerting and arousing effects of light is generally accepted, a close look into the literature shows rather inconsistent results (for reviews see [31, 52]). Moreover, only few studies specifically examined how long it takes before bright light leads to increased alertness or arousal and whether this effect persists over time. Although Rüger et al. [44] and Phipps-Nelson, Redman, Dijk, & Rajaratnam [38] investigated the persistence of the alerting effect of light using repeated measurements, detailed information about the onset and symmetry of this subjective alerting response is missing. Chang et al. [17] confirmed a persistent response of self-reported alertness to bright light exposure of different durations. Additionally, intermittent bright light pulses exerted immediate and persistent alerting effects [26]. Yet, other studies yielded mixed alertness-enhancing effects of light in terms of onset and persistence [23, 49, 50].

In parallel to subjective responses, alerting and arousing effects of light on human physiology have been studied [18, 24, 25, 39, 40, 44–46, 48, 50, 51]. Two studies, focusing on the temporal development of lighting effects on physiology, showed a decrease in electro-encephalographic activity (EEG) in response to light within a few minutes [39, 51]. Prayag et al. [39] showed a pupillary response within one minute, whereas cardiac activity and the DPG responded slightly later. The pupil and EEG responded persistently, but cardiac activity and the DPG continuously increased during the 50-min light exposure [39].

Although the existence of short-term effects of light on alertness and arousal has been shown in several studies (e.g., [23–25, 38, 39, 42, 47, 53]), the onset and persistence of these light effects often cannot be defined as analyses are regularly performed using the average of multiple measurements over time (e.g., [38]) or for one specific time interval (e.g., [53]). Few studies used high resolution measurements for more detailed insights in the onset and persistence of the effects (e.g., [23, 24, 50, 51]). Moreover, most studies investigated only increases in light levels (e.g., [39, 42, 47]). Boyce, Beckstead, Eklund, Strobel, and Rea [11] were one of the first and few to study the effects of both increases and decreases in light levels on performance and alertness during the night. The missing information on what happens when light levels decrease during daytime leads to a lack of knowledge concerning the symmetry of these daytime effects.

### 1.5. Rationale

We examined the onset, persistence and symmetry of subjective experiences and objective measures of vigilance, arousal and thermoregulation in response to light transitions with several purposes. First, by studying these effects for multiple variables simultaneously response patterns of the subjective and objective measures can be compared, through which evidence for underlying mechanisms may be unraveled.

**Fig. 1.** The four light conditions to which participants were exposed in separate sessions on different days. A) warm, dim light, no transition. B) warm, dim light, transition to cool, bright. C) cool, bright light, no transition. D) cool, bright light, transition to warm, dim.

Secondly, the findings help to optimize the resolution and timing of measurements in a study protocol. Last, pleasant and effective dynamic lighting scenarios can be further developed using this information. The following research question is posed: **How do subjective experiences and objective measures of vigilance, arousal and thermoregulation develop over time after an acute light transition?**

It is expected that the onset of effects of light through the IF pathway, such as visual comfort, occur relatively fast after a transition. Based on the knowledge of the visual system and its adaptive properties [10], these effects are expected to dissipate over time. Based on the modeling work by Veitch et al. [56] it is expected that the effect of light on mood is mediated by visual comfort and will thus follow a similar pattern. Effects on subjective alertness are expected to emerge within 15 min of bright light exposure [26, 48, 50] and persist towards the end of the light exposure [18, 48, 50]. Expectations for the cardiac and electrodermal activity (EDA) are that they will start to respond after 15 min of light exposure and then will continue to increase [39]. Thermoregulation is expected to respond slowly towards the end of 45-min light exposure [53] and, dependent on the pathway, thermal appraisals will follow either thermoregulation [14] or visual comfort [54].

**Table 1**

| Participant descriptors. | Overall (n=38) |
|--------------------------|---------------|
| **Body Mass Index**      | Mean (SD)     | 22.0 (± 2.5) |
|                         | Range         | 18 to 30     |
| **Midsleep (MSFsc)**     | Mean (SD)     | 4.9 (± 0.7)  |
|                         | Range         | 3.8 to 6.5   |
| **PSQI score**           | Mean (SD)     | 4.2 (± 1.5)  |
|                         | Range         | 1.0 to 9.0   |
| **General Health (SF-36)**| Mean (SD)     | 73 (± 13)    |
|                         | Range         | 40 to 100    |
| **Light Sensitivity (Eye Problems)** | Mean (SD) | 2.2 (± 0.9)  |
|                         | Range         | 1 to 5       |
| **Light Sensitivity (Headache)** | Mean (SD) | 1.4 (± 0.7)  |
|                         | Range         | 1 to 3       |
| **Light Sensitivity (Sunglasses)** | Mean (SD) | 2.2 (± 1.2)  |
|                         | Range         | 1 to 5       |
| **Thermal Sensitivity**  | Mean (SD)     | 3.2 (± 1.1)  |
|                         | Range         | 1 to 4       |
2. Method

2.1. Design

To study effects of an abrupt light transition, we worked with two strongly contrasting settings (warm, dim lighting vs. cool, bright lighting) of 45 min, resulting in four conditions (see Fig. 1). Participants experienced all four conditions in random order using partial counterbalancing. Phase I functioned as the baseline phase, Phase II as the experimental phase. We tested the effects of these light conditions separately for each of the baseline settings. Outcome parameters were subjective experiences (alertness, comfort and mood) and objective measures of vigilance (PVT performance), arousal (HR, HRV, and skin conductance level) and thermoregulation (skin temperature and DPG).

2.2. Participants

Healthy participants without visual or auditory impairment were recruited via the J.F. Schouten School for User-System Interaction Research database and screened through an eligibility questionnaire. The following exclusion criteria applied: extreme chronotype (Midsleep < 3.8 or > 6.6 based on Zavada, Gordijn, Beersma, Daan, & Roenneberg [59], as assessed by the Munich Chronotype Questionnaire; [41]), pregnancy, medication other than the contraceptive pill, hypertension or cardiovascular diseases, and intercontinental travelling < 3.8 or > 6.6 based on Zavada, Gordijn, Beersma, Daan, & Roenneberg [59], as assessed by the Munich Chronotype Questionnaire; [41]), pregnancy, medication other than the contraceptive pill, hypertension or cardiovascular diseases, and intercontinental travelling [41], pregnancy, medication other than the contraceptive pill, and pregnancy, medication other than the contraceptive pill.

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2.3. Setting and apparatus

The experiment was conducted in a climate chamber at the Eindhoven University of Technology. The dimensions of the room were 3.6 × 5.4 × 2.7 m³ (WxLxH). This room was split in two with a partition wall to create two work spaces in the room, as can be seen in Fig. 2a. The reflectance of the various surfaces in the room were measured using a Minolta Luminance Meter LS-100. The walls of the climate room were off-white with a reflectance of 80.9%, whereas the white wall separating the two working areas had a reflectance of 91.8%. The grey floor had a reflectance of 27.7%, and the desk was light grey with a reflectance of 49.0%. Indoor climate was kept at a constant level during all sessions (air velocity = 0.4 ± 0.3 m/s; relative humidity = 47.2 ± 3.0 %, air temperature = 20.4 ± 0.6°C and black bulb temperature = 20.0 ± 0.6°C).

A set of four ceiling-mounted luminaires (PowerBalance Tunable Whites; RC464B LED80S/TWH PSD W60L60) was installed above each desk. With these luminaires, the two light settings were created. These activated all photoreceptors differently (see Table 2), and should result in a radically different visual and non-visual experience. The warm, dim light setting (WD) had a CCT of 2708 K and 97 lux on the eye, measured using a Konica Minolta Spectrophotometer CL-500A. The cool, bright light setting (CB) had a CCT of 5854 K and 1021 lux on the eye. Fig. 2b shows the spectral power distribution of the light settings.

Table 2

| α-opic irradiances of the light settings. | Warm, dim light (lux) | Cool, bright light (lux) |
|----------------------------------------|-----------------------|-------------------------|
| S-cone-opic (I\(\lambda\,{\text{s-cone}}\)) | 26                    | 901                     |
| M-cone-opic (I\(\lambda\,{\text{m-cone}}\)) | 75                    | 982                     |
| L-cone-opic (I\(\lambda\,{\text{l-cone}}\)) | 99                    | 1010                    |
| Rhodopic (I\(\lambda\,{\text{r}}\)) | 46                    | 891                     |
| Melanopic (I\(\lambda\,{\text{\alpha}}\)) | 37                    | 855                     |

Preparations in the planning.

2.4. Procedure

The study was conducted between November 14th and December 21st, 2018. Subjects participated in four sessions of 90 min each, generally not on consecutive days to exclude session-to-session effects. Experimental sessions were scheduled during the entire working day, but sessions were always scheduled at the same time of day within participants. During the sessions, participants wore a cotton long-sleeved shirt, long jogging trousers, underwear, socks and shoes (estimated clothing value of .7 clo, including insulation of the chair).

Upon arrival, participants were welcomed and invited into the climate chamber. First, they completed a start questionnaire, after which they were given instructions. Subsequently, they practiced the Psychomotor Vigilance Task (PVT) for three min. Then, they read a book until the actual measurements started. After the adaptation period of 30 min, physiological arousal and thermoregulation were tracked continuously for the remaining 60 min of each session. Subjective and performance measures were taken every 15 min during this period. Participants took two to three minutes to complete the subjective measures and subsequently performed the 5-min PVT. As participants completed the questionnaires and task in seven to eight minutes, there was spare time between measurement blocks during which participants read a book. After the first 45 min, during which the

One participant had two sessions on subsequent days due to practical limitations in the planning.
baseline measurement was completed, the experimental phase started. In this phase, participants completed three repeated measurement blocks which were identical to the baseline measurement. Fig. 3 shows a schematic representation of this procedure for one session. For the three subsequent sessions, the procedure was identical, except for the debriefing at the end of the fourth session.

2.5. Measures

2.5.1. Measurements before each experimental session

Sleep timing, duration and quality before each experimental session were measured using the Consensus Sleep Diary [16]. In addition, questions on behavior, caffeine and food consumption before the session were administered (see Supplementary Materials). Furthermore, participants wore a light sensor (LightLog) on the day of the session. These measurements were merely used as a comfort measure: Participant's visual acceptance of the lighting (AcceptanceV) was evaluated using a binary scale: Acceptable/Unacceptable, for both perceived illuminance and color they evaluated sensation (SensationVC) with a seven-point scale ranging from Very Uncomfortable (-2) to Very Comfortable (3). The latter two correlated highly and had a Cronbach’s α of .85. Therefore, these were averaged into one visual comfort measure: ComfortV. Participants evaluated their mood on eight items using 5-point scales ranging from Definitely not (1) to Definitely (5). The following items were used: Calm, Tense, Sad, Happy, Lively, Drowsy, Sleepy and Awake. The latter four variables were combined into Vitality with a Cronbach’s α of .86. As Tense and Calm had a Cronbach’s α of .55 and Sad and Happy of .46, these were kept as separate variables for the analyses. The variablesTense and Sad were recoded into binary variables (recode key: 1 = 0 and 2-5 = 1) and Calm into three categories (recode key: 1-3 = 1, 4 = 2 and 5 = 3) to account for skewed distributions. The Karolinska Sleepiness Scale (KSS) was used to measure the subjective sleepiness/alertness of participants on a 9-point Likert scale [2]. Responses were given on a scale that ranged from Extremely alert (1) to Extremely sleepy (9). Lastly, participants evaluated the effort they had exerted to complete the PVT on a visual analogue scale ranging from None (0) to Very Much (20). On a similar scale, participants evaluated the effort they made on reading in the spare time between measurement blocks. The entire questionnaire can be found in the Supplementary Materials.

2.5.2.2. Performance task. In the 5-min auditory version of the PVT [20], participants responded as fast as possible to short auditory stimuli of 400 Hz by pressing the space bar of the keyboard. The inter-stimulus interval at each trial was randomly drawn from a uniform distribution between 6 and 25 s. The mean reaction speed was used as an indicator of vigilance.

2.5.2.3. Physiological measurements. Electrocardiography and EDA were used to collect physiological indicators of arousal. Both were measured using TMSi software. For HR and HRV, participants attached three electrodes; one on the left clavicula, one on the soft tissue below the right clavicula and one on the soft tissue right below the ribs on the left side of the body. Electrodes for EDA were attached to the first phalanx of the middle finger and the ring finger of the non-dominant hand. Outlier and artefact detection was done using institutional software [7–9]. The root mean square of successive differences (RMSSD) was used as marker for HRV. The mean skin conductance level (SCL) in micro Siemens during the 5-min PVT was used as a tonic measure of EDA. For the analyses, we used the mean HR, RMSSD and SCL over the period during the 5-min PVT, which started two to three minutes into each measurement block.

Skin temperatures were measured using iButton (DS1925) data-loggers with a sample interval of 300 s, which were attached using Fixomull Stretch tape. Mean skin temperature (TmeanSkin) was calculated as an average of 14 ISO-defined body sites [35]. The scapula, para-vertebral, upper chest, and abdomen skin temperature were averaged as the proximal skin temperature (Tproximal). The distal skin temperature (Tdistal) was calculated using an average of the finger tip, instep, hand, and forehead skin temperature. To avoid a disproportional distribution, fingertip and hand temperatures were averaged before. Extra buttons were placed at the underarm and the middle finger to assess peripheral vasoconstriction [43]. Mean skin temperature and the DPG (Tdistal – Tproximal) during the 5-min PVT were computed.

2.6. Statistical analyses

Normality distributions and outliers were checked to clean the data. For binary variables, no statistical analyses were done, but only percentages were calculated and visually inspected. The results of these inspections for Tense and Sad can be found in the Supplementary Materials.

Using linear mixed modeling with Participant as random intercept, we tested potential differences in the control variables assessed at session level between the experimental conditions and time of day. As these did not exist, no control variables were added in the models. Subsequently, the relationships between the control variables at block level and the dependent variables were examined visually, using correlation plots to determine plausible covariates to include. Differences between outcome variables at baseline were tested using linear mixed modeling with measurements nested within Participant, of which the results can be found in the Supplementary Materials. As baseline differences existed for some outcome variables, baseline scores were...
added as a covariate in the model.

The main analyses examined the effect of a transition for the two sessions that started in WD light separate from those starting in CB light. In these mixed model analyses, Participant (P) and Session (S; nested within Participant) were added as random intercepts within the model. The models for each of the different dependent variables further included measurement block (1/2/3), transition (yes/no), the interaction ‘Transition*Block’ and time of day (morning/afternoon) as fixed predictor variables. The baseline score and reading effort were included as covariates. Reading effort was added as an indicator of participants’ effort spent in between assessments. The model was specified as follows:***

Based on the models, contrast analyses were performed to test differences between the two conditions per block to examine the onset of the effect. Main effects were tested using contrast analyses in which the average score in the constant (no transition) condition was compared with the average score in the transition condition. For all main analyses, an α of .01 was used as cut-off for statistical significance.

Last, exploratory analyses were done to test whether the antecedent light setting played a role in the acute effects of light. Using contrast analyses, the measurements in the conditions for which the lighting condition in Phase II was the same - but the antecedent setting was different – were compared with each other per measurement block. For these analyses, a cut-off value (α) of .05 was used.

RStudio 1.1.463 was used for all preparatory and statistical analyses. For the preparatory steps, the psych and plyr packages were used. The following packages were used for the statistical analysis: emmeans, Hmisc, lme4 and lmerTest. All visualizations were made using ggplot2.

3. Results

Onset and persistence of responses for all dependent variables were tested. The symmetry of the responses is visualized by presenting the sessions starting in WD light and the sessions starting in CB light side by side. In this section, the results of the contrast analyses are described. In Table 3, the test statistics of the main effect of the transition can be found, whereas Figs. 4-9 show the contrasts per measurement block. A complete overview of the contrasts per measurement block and the full model statistics can be found in the Supplementary Materials.

3.1. Onset, persistence and symmetry

3.1.1. Visual appraisals

Participants’ sensation of both illuminance and color changed, according to expectations, immediately after the transition from WD to CB lighting (Fig. 4). This transition resulted in a brighter and cooler perception of the light. Participants’ evaluations remained constant throughout the remainder of the session. Similarly, the transition from CB to WD immediately led to a less bright and warmer perception of the light. Again, this effect persisted throughout the light condition. Visual acceptance of the light setting was generally high in the constant WD condition (Acceptance_V, Block1 = 97%, Acceptance_V, Block2 = 92% and Acceptance_V, Block3 = 92%), whereas right after the transition condition to CB light, only 68% of the participants rated the lighting acceptable. Fifteen minutes later, in the same lighting, acceptance votes increased to 87%, and remained at a similar level for the remainder of the session. In the constant CB condition, fewer participants accepted the light compared to the constant WD condition (Acceptance_V, Block1 = 95%, Acceptance_V, Block2 = 92% and Acceptance_V, Block3 = 89%). The transition condition from CB to WD lighting also showed a drop in acceptance with the lowest acceptance rate after the transition (79%), albeit not as low as right after the transition from WD to CB light. Participants’ acceptance vote increased to 87% and 89% after fifteen and thirty minutes, respectively.

Table 3

| Dependent Variable | WD to CB vs. Constant WD | CB to WD vs. Constant CB |
|--------------------|--------------------------|--------------------------|
| SensationVI        | 2.2                      | 2.2                      |
| SensationVC        | -2.2                     | 2.4                      |
| ComfortV           | -1.7                     | 2.4                      |
| Calm               | 1.1                      | 2.4                      |
| Happy              | 0.0                      | 2.4                      |
| Vitality           | 1.0                      | 2.4                      |
| Alertness (KSS)    | -0.7                     | 2.4                      |
| Mean RT            | 1.8                      | 2.4                      |
| Mean SCL           | 0.0                      | 2.4                      |
| Mean HR            | 0.3                      | 2.4                      |
| Mean HRV           | 1.0                      | 2.4                      |
| Average Tskin      | 0.0                      | 2.4                      |
| DPG                | -0.2                     | 2.4                      |

Note: Δ represents the estimated difference between the two conditions.

Fig. 4. Trajectory of visual appraisal parameters with WD light (left) and CB light (right) during baseline for: a) Sensation of Light Intensity, b) Sensation of Color Temperature, c) Visual Acceptance (in % - no stat. testing), and d) Visual Comfort. Error bars are standard errors (SE). Comparisons between the two conditions were done for each Measurement Block: ** indicates p<0.01, * p<0.05.
minutes respectively. Participants’ visual comfort\textsuperscript{2} showed a significant decrease right after the transition from WD to CB lighting. Despite the absence of significant differences in the other measurement blocks, comfort with the light was, on average, lower after the transition to CB lighting compared to the constant WD condition. For the reverse transition, participants’ visual comfort levels did not significantly differ between conditions.

3.1.2. Thermal appraisals

Neither transition in lighting significantly affected Sensation\textsubscript{T} compared to the constant conditions. The thermal environment was generally accepted in all four conditions, and this percentage decreased slightly over time in both constant and transition conditions (Fig. 5). Comfort\textsubscript{T} did not differ significantly in the transition conditions compared to the constant conditions.

3.1.3. Mood

Participants reported fewer calm feelings right after the transition from WD to CB light, compared to the constant WD light condition (Fig. 6). Participants’ calmness increased again within fifteen minutes in the CB light and stabilized at a similar level as in the constant WD condition. No statistically significant overall effect (i.e., across blocks) of the transition from WD to CB was found. Despite an upward trend from baseline to Block 1, the transition from CB to WD lighting did not yield significant contrasts, nor was an overall effect of the transition found. Feelings of happiness did not significantly differ between the lighting conditions.

3.1.4. Subjective vitality and alertness

Right after the transition from WD to CB lighting, participants felt more vital and less sleepy (or more alert) compared to the constant condition. This effect diminished within fifteen minutes and disappeared within thirty minutes into the new light setting (see Fig. 7). On average, participants did feel significantly more vital and alert after the transition to CB lighting compared to the constant WD condition. No significant effects emerged as a result of the transition from CB to WD lighting.

3.1.5. Vigilance and arousal

The mean PVT reaction time was not significantly affected by either light transition, as can be seen in Fig. 8. Furthermore, SCL did not respond to the transition from WD to CB lighting, but in the reverse condition from CB to WD participants’ SCL was significantly lower compared to the constant CB condition in the last measurement block (see Fig. 8). The overall effect of this transition was not significant. Mean HR was not influenced by the transition in lighting, neither was mean HRV.

3.1.6. Thermophysiology

Thermophysiological responses are depicted in Fig. 9. Participants’ mean skin temperature or DPG were not significantly affected by the lighting transitions.

3.2. Effects of antecedent setting

To explore the effects of the antecedent light setting, we performed complementary analyses, comparing the outcome measurements in the same light settings in Phase II after differing settings in Phase I. As we have no baseline measurement prior to Phase I for these comparisons, the results are reported as exploratory analyses and should be interpreted with care. The test statistics can be found in the Supplementary materials.

\textsuperscript{2} Visual comfort regarding the illuminance and CCT were also analyzed separately and showed similar trends.
3.2.1. Visual appraisals

Participants’ sensations of illuminance and color significantly differed across all three measurement blocks for both light settings in Phase II as a result of the antecedent setting (Fig. 10). After exposure to CB lighting, participants experienced the WD lighting as significantly less bright and warmer than they did in the constant WD condition. Moreover, the participants evaluated the lighting brighter and cooler in all measurement blocks when they first had been exposed to WD lighting compared to the continuous exposure to CB light. Although acceptance of the light was very high in the constant WD light, acceptance of the WD light was lower \( V, \text{Block} 1 = 79\% \) right after the antecedent exposure to CB light. After 15 min, acceptance of the WD light increased again \( V, \text{Block} 2 = 87\%, \text{Block} 3 = 89\% \). In CB light, this effect was even stronger. Participants’ comfort with the light in the WD condition was significantly lower right after the transition from CB light and this difference disappeared in Block 3. Similarly, participants’ comfort with the light in the constant CB condition was significantly lower in Blocks 1 and 2, but not in Block 3 when the antecedent lighting was WD.

3.2.2. Thermal appraisals

The thermal sensation in the WD condition was significantly warmer right after initial exposure to CB lighting compared to the constant WD condition (Fig. 11). In the next measurement block, this difference disappeared. The thermal sensation in the CB condition was cooler in the second measurement block only when the antecedent lighting was WD compared to the continuous CB light setting. Thermal comfort and acceptance were not influenced by the antecedent light setting.

3.2.3. Mood

Participants’ reports of calm feelings in WD lighting were significantly higher in the last measurement block when the antecedent setting had been CB lighting (see Fig. 12). Feelings of happiness were not significantly affected by the antecedent light setting.

3.2.4. Subjective alertness and vitality

No significant effects of the antecedent light setting were visible for people’s subjective experience of alertness. In the WD lighting, feelings of vitality were not affected by the antecedent light setting (Fig. 13). In contrast, participants did indicate a higher level of vitality in the CB light setting right after the WD antecedent setting compared to constant CB lighting.

3.2.5. Vigilance and arousal

PVT performance and the physiological variables (HR, HRV, SCL) did not show significant effects of the antecedent light setting in either condition, as can be seen in Fig. 14.

3.2.6. Thermoregulation

Fig. 15 shows that average skin temperature in neither condition was affected by antecedent light setting. In contrast, the DPG was lower in the WD lighting in the second and third measurement block when participants had been exposed to CB light before. In the CB condition, no statistically significant effects of antecedent light exposure emerged.

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**Fig. 7.** Trajectories of subjective alertness parameters with WD light during baseline (left) and CB light (right) during baseline for: a) Alertness (KSS) and b) Vitality. Error bars are SE. Comparisons between the two conditions were done for each Measurement Block: ** indicates \( p < 0.01 \), * \( p < 0.05 \).

**Fig. 8.** Trajectories of vigilance and arousal parameters with WD light (left) and CB light (right) during baseline for: a) Reaction Time on PVT, b) Skin Conductance, c) Heart Rate, and d) Heart Rate Variability. Error bars are SE. Comparisons between the two conditions were done for each Measurement Block: ** indicates \( p < 0.01 \), * \( p < 0.05 \).
4. Discussion

In this study, we aimed to examine the temporal trajectories of how people respond to light transitions. Studying these trajectories for multiple variables simultaneously may allow us to unravel underlying mechanisms by comparing response patterns. Additionally, the findings can be used in determining the required measurement resolution and timing in measurement protocols. Last, knowledge on these response dynamics is required to design dynamic lighting scenarios that can be applied in, for instance, office environments.

4.1. Onset, persistence and symmetry

The most prevalent responses within 45 min after a light transition emerged amongst the subjective indicators. Visual appraisals, feelings of calmness, alertness and vitality responded immediately to the transition. It appears that subjective experiences are induced immediately, if at all; those subjective experiences that showed no immediate response (thermal responses, happiness) also did not emerge later. The SCL did show a modest gradual increase in constant CB light compared to the transition from CB to WD light, which might indicate the late onset of a NIF-driven activating mechanism. However, none of the other physiological indicators (HR, HRV, ST, DPG) responded to the abrupt light transition, nor did PVT performance. These results contradict the results in the study by Prayag et al. [39] in which very rapid and often transient effects of light were visible on both cognitive performance and physiological arousal. This difference may be explained by the method of analysis, as we analyzed the physiological responses during the PVT to control for the potential effect of task type. The PVT mostly started two to three minutes after the start of the measurement block, which implies that the physiological response immediately after the transition was not quantified. Furthermore, the study by Prayag et al. [39] was conducted in the evening after dark adaptation. Moreover, the fast response dynamics in their study occurred independent of the different lighting conditions (blue-enriched vs. red-enriched light). This indicates that, although physiological responses to light can be exerted quickly during periods of melatonin production when contrasting very dim light (Ev < 5 lux) with light pulses (Ev = 120-140 lux), this does not necessarily occur with variations in light levels between 100 and 1000 lux during daytime. This indication is in line with the study by Rüger et al. [44] in which effects of bright light (5000 lux) compared to very dim light (Ev < 10 lux) were found on physiological variables during the night but not during the day.

Notably, effects on visual sensation were persistent throughout the 45 min of the experimental setting, whereas visual acceptance and comfort showed transient responses. These results can be explained by an adaptation process which – despite the persistence in the sensation of the light setting – causes the acceptance and comfort votes to change. Apparently, visual responses can have different response trajectories, just as Prayag et al. [39] showed for non-visual responses. This implies that neither the speed of the onset, nor the transience or persistence of a response can be taken as an indicator for the underlying pathway at play. Remarkably, subjective calmness showed a transient response pattern similar to the visual acceptance and comfort, whereas effects on subjective alertness and vitality persisted throughout the remainder of the light setting. These latter results are in line with Smolders et al. [50] and Smolders and De Kort [48] who also reported persistent bright light...
effects on alertness and vitality. Although the light setting seemed to have a continuous effect on the subjective alertness and vitality, it remains unclear whether this should be attributed to the IF or NIF pathway.

Although the sensation of the changing light settings showed a symmetry in responses, the acceptance and comfort votes of the light settings were asymmetrical and suggested that the CB light was evaluated more negative than the WD light, particularly if the CB light followed WD light. The fact that the amplitude of these response depended on the direction of the transition was quite unexpected, especially since the responses in terms of sensation did appear to be symmetrical. We have no explanation for these findings, and recommend to replicate and investigate this more deeply in future studies. Similar to the asymmetry in the response patterns of acceptance and comfort votes, the participants felt less calm, less sleepy and more vital when the light transitioned from WD toward CB lighting, but not after the transition from CB to WD lighting. This alerting response pattern was in line with the study by Sithravel et al. [47], in which only the conditions with increasing illuminance significantly facilitated participants’ level of alertness, whereas the constant and decreasing light conditions had no statistically significant effects.

4.2. Effects of antecedent setting

The exploratory analyses seemed to show that the antecedent setting also moderated participants’ responses. The different antecedent settings immediately led to different visual appraisals of the experimental light setting, as well as moderations in thermal sensation and vitality. Calm feelings and the DPG were also affected by the antecedent light setting, but only later in the session. The antecedent light setting did not affect happiness, thermal comfort and the objective measurements of vigilance and arousal.

The visual sensation of the light setting and the DPG were the only outcome variables that persistently responded to the different antecedent light settings, as well as moderations in thermal sensation and vitality. Calm feelings and the DPG were also affected by the antecedent light setting, but only later in the session. The antecedent light setting did not affect happiness, thermal comfort and the objective measurements of vigilance and arousal.

Fig. 11. Trajectory of thermal appraisal parameters with measurements in WD light (left) and CB light (right) for: a) Thermal Sensation, b) Thermal Acceptance (in % - no stat. testing), and c) Thermal Comfort. Error bars are SE. Comparisons between the two conditions were done for each Measurement Block: ** indicates $p < 0.01$, * $p < 0.05$.

Fig. 12. Trajectory of mood parameters with measurements in WD light (left) and CB light (right) for: a) Calm, and b) Happy. Error bars are SE. Comparisons between the two conditions were done for each Measurement Block: ** indicates $p < 0.01$, * $p < 0.05$.

Fig. 13. Trajectories of subjective alertness parameters with measurements in WD light (left) and CB light (right) for: a) Alertness and b) Vitality. Error bars are SE. Comparisons between the two conditions were done for each Measurement Block: ** indicates $p < 0.01$, * $p < 0.05$. 

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The visual sensation of the light setting and the DPG were the only outcome variables that persistently responded to the different antecedent light settings, i.e., where the effect of antecedent setting remained visible throughout the subsequent light setting. An increase in the DPG (i.e., bigger temperature difference between distal and proximal temperature) has been related to a decrease in sleepiness [29], which might be explained by a continued activating effect of the prior
CB light. However, as this effect was not visible in the constant CB condition and for none of the other physiological indicators of arousal, we hesitate to draw any firm conclusions and recommend further investigation.

The only symmetrical response occurred in the visual sensation of the light settings. When the antecedent setting was different from the experimental setting, participants’ visual experience persistently and symmetrically polarized towards the extremes of the scale. This polarization could possibly be explained by a bias through anchoring of the response range [21]. For the exploratory analysis, the conditions that were compared differed in their light setting during the measurement in Phase I. According to the theory of Fotios and Houser [21], participants have likely developed the internal criteria for a response scale during this measurement. Based on these criteria, they would make their subsequent responses within that session. Therefore, participants’ interpretation of the response scale may have depended on the setting in Phase I, resulting in these polarized responses. In contrast to this bias, our perceptual system. Judgments on the brightness and color of the momentary light setting are based on - and influenced by - previously experienced light settings [10]. Thus, a light setting might be experienced differently, dependent on the antecedent setting.

4.3. Theoretical reflections

When comparing the temporal trajectories of the outcome measures, we saw many different patterns, which suggests that multiple physiological and psychological mechanisms may be at play. The IF pathway may be important for the rapid onset of visual appraisals and the initial alerting, vitalizing and calming effects. However, we cannot be sure as Prayag et al. [39] also found very rapid responses on physiological measures and attributed these to NIF pathways, even though they did not always emerge exclusively for blue-enriched light. Some of the immediate responses in the current study were persistent throughout exposure to the experimental light settings, whereas others dissipated over time. The latter suggests that gradual adaptation starts after stimulus onset affecting visual acceptance, visual comfort and calm feelings, but not sensation, alertness, and vitality. Generally, adaptation processes are linked to the IF pathway, but adaptation may also emerge in NIF processes. Yet, adaptation in the NIF pathway is generally assumed to be much slower, and not typically seen in, for instance, experiments studying melatonin suppression over the course of multiple hours [33, 60]. Therefore, the persistent responses of subjective alertness and vitality and the late onset response of SCL are more suggestive of a contribution of the NIF pathway through which effects slowly build up, although this cannot be concluded firmly given the current intervention, which addressed both IF and NIF pathways. The asymmetrical responses that mainly showed effects of the transition to CB light suggest acute alerting and activating effects of light transitions to brighter and more blue light, despite lower visual comfort.

Interestingly, subjective and objective responses in this study did not always show similar patterns nor a direct relationship whereas this was expected at some points. This emphasizes the importance of taking both subjective and objective measurements. Moreover, these transient and persistent trajectories have direct implications for determining the optimal time interval between light transition and measurement when evaluating visual appraisals, mood and correlates of alertness and
4.4. Practical implications

Overall, abrupt transitions in lighting had various consequences; sometimes desirable and sometimes undesirable. When people need a mental boost or a calming experience while working, light transitions may be employed to provide this at low cost. For instance, abrupt changes may be used to (temporarily) induce vitality, alertness or calmness. To this end, based on the current findings, one should consider not only the target setting to jump to, but also the antecedent setting that people start from, as the direction of the transition is important and may render different outcomes. Additionally, our results suggest that abrupt changes in light may be used to alter the perception of the thermal environment. Insights such as these may be employed when designing a dynamic lighting schedule for office environments. Even though such subjective experiences do not always translate into performance enhancements, they are relevant in and of themselves because of their contribution to people’s perception of quality of life [3].

4.5. Limitations

Some limitations deserve to be mentioned. CCT and illuminance were manipulated simultaneously to maximize both the difference in visual experience and melanopic activation. However, because of this combined manipulation, effects cannot be attributed to either illuminance or CCT. Future studies should dissect these by separately manipulating illuminance and CCT. Secondly, based on prior research (e.g., [4, 25, 44, 49, 50]), it is expected that an individuals’ responsiveness to light depends on the time of day. In this study, participants were asked to come to the lab at the same time of day for each session to control for these effects within participants. Whether time of day moderated the effect of light on the dependent variables between participants could not be tested due to group sizes. Therefore, we recommend another study with a larger sample size to examine whether these effects depend on the time of day.

4.6. Future research

An interesting topic for future research would be variation of the transition speed. In this study abrupt transitions were used, which led to both significant positive and negative results. It is worth studying whether these negative results are due to, for instance, visual comfort disappears when using more gradual transitions and whether the positive results on subjective alertness remain visible. Furthermore, to be able to generalize the results, the research should be replicated with participants from different cultural backgrounds. Finally, as this laboratory study lasted only 90 min, the results should be validated in longer experiments and in field settings before they can be implemented in the built environment.

5. Conclusions

Response trajectories after transitions in lighting are different for subjective experiences and objective measures of vigilance, arousal, and thermoregulation. Most variables that responded to the light manipulation represented subjective experiences and responded immediately after the transition in lighting. From the performance and the physiological indicators, only SCL and DPG were affected by the different types of light exposure. This study furthermore shows no direct relationship between subjective and objective responses, confirming that subjective responses are valuable sources of information and that a multi-measure approach is preferred when studying effects of light. Comparing the temporal trajectories of the subjective experiences and objective indicators shows a complex pattern concerning the onset, persistence and symmetry of the responses. Presumably, there are various underlying pathways that can explain these effects, but more fundamental research is needed to unravel those. Irrespective thereof, findings do consistently suggest that acute effects of day-time light exposure exist. Abrupt transitions in lighting may be used in the built environment to alter subjective experiences. If and where effects of light transitions towards cool, bright light emerged, they generally were alerting and activating, yet not necessarily comfortable.

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Supplementary materials

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