Seasonal and time-of-day variations in acute non-image forming effects of illuminance level on performance, physiology, and subjective well-being


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ABSTRACT
This study investigated seasonal and time-of-day dependent moderations in the strength and direction of acute diurnal non-image forming (NIF) effects of illuminance level on performance, physiology, and subjective well-being. Even though there are indications for temporal variations in NIF-responsiveness to bright light, scientific insights into potential moderations by season are scarce. We employed a 2 (Light: 165 versus 1700 lx at the eye level, within) × 2 (Season: autumn/winter versus spring, between) × 2 (Time of day: morning versus afternoon, between) mixed-model design. During each of the two 90-min experimental sessions, participants (autumn/winter: N = 34; spring: N = 39) completed four measurement blocks (incl. one baseline block of 120 lx at the eye level) each consisting of a Psychomotor Vigilance Task (PVT) and a Backwards Digit-Span Task (BDST) including easy trials (4–6 digits) and difficult trials (7–8 digits). Heart rate (HR) and skin conductance level (SCL) were measured continuously. At the end of each lighting condition, subjective sleepiness, vitality, and mood were measured. The results revealed a clear indication for significant Light × Season interaction effects on both subjective sleepiness and vitality, which appeared only during the morning sessions. Participants felt significantly more vital and less sleepy in winter, but not in spring during bright light exposure in the morning. In line with these subjective parameters, participants also showed significantly better PVT performance in the morning in autumn/winter, but not in spring upon bright light exposure. Surprisingly, for difficult working memory performance, the opposite was found, namely worse performance during bright light exposure in winter, but better performance when exposed to bright light in spring. The effects of bright versus regular light exposure on physiology were quite subtle and largely nonsignificant. Overall, it can be concluded that acute illuminance-induced NIF effects on subjective alertness and vitality as well as objectively measured vigilance in the morning are significantly moderated by season. Possibly, these greater illuminance-induced benefits during the morning sessions in autumn/winter compared to spring occurred due to increased responsiveness to bright light exposure as a function of a relatively low prior light dose in autumn/winter.

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1. Introduction
Since the discovery of a novel class of light-sensitive photoreceptors in the inner layer of the retina, called intrinsically photosensitive retinal ganglion cells (ipRGCs) (Berson et al., 2002; Freedman et al., 1999; Provencio et al., 2000), an increasing amount of research has focused on the so-called non-image forming (NIF) pathway, where ipRGCs directly or indirectly project to various brain regions involved in sleep–wake regulation, alertness, arousal, and mood (Fuller et al., 2006; Saper et al., 2005; Vandewalle et al., 2009). Previous research on these NIF effects of light exposure revealed considerable evidence for acute changes in healthy individuals’ level of alertness, mood, and cognitive performance both during the night- and daytime (Cajochen, 2007; Chellappa et al., 2011). There is now ample evidence that daytime indoor bright light exposure can establish positive acute effects on alertness, vitality, mood, and performance in healthy day-active people (Huiberts et al., 2016; Kaida et al., 2007; Phipps-Nelson et al., 2003; Rüger et al., 2005; Smolders & De Kort, 2014; Smolders et al., 2012). These studies revealed bright light-induced improvements on alertness when healthy participants were experimentally sleep and/or light deprived before the
light exposure period (Phipps-Nelson et al., 2003; Rüger et al., 2005), but also when sleep and light history were not experimentally manipulated (Huiberts et al., 2016; Kaida et al., 2007; Smolders & De Kort, 2014; Smolders et al., 2012). It should be noted, however, that these positive acute NIF effects of bright light exposure are not consistently reported as studies have also shown null effects for a subset of the indicators (Huiberts et al., 2016; Rüger et al., 2005) and even some negative effects (Gabel et al., 2015; Huiberts et al., 2015; Smolders & De Kort, 2014) of bright versus dim light exposure on measures of alertness and performance.

A relatively understudied topic in the field of NIF effects is year-round variations in light-induced NIF-responsiveness. In the studies cited in the previous paragraph, the direction and magnitude of NIF effects of illuminance level on cognition, alertness, and mood varied, even if lighting conditions were quite similar between some of the studies. An interesting question is whether notable differences in NIF effects over seasons exist and whether these could – at least in part – explain some of these inconsistent findings. Interestingly, it has been found that rodents were more sensitive (i.e. showing greater circadian phase shifts) to 480 nm light of irradiances between 0.003 and 68.03 µW/cm² when their rhythm was entrained to a short versus a long photoperiod (Glickman et al., 2012). In humans, it has been found that significant acute light-induced melatonin suppression in the latter part of the night (between 5:00 and 6:00 AM) by regular room lighting (± 300 lx) was achieved in winter, but not in summer, which may be explained by possible increased responsiveness of the NIF pathway to light when the photoperiod is short instead of long (Owen & Arendt, 1992). Last, a correlational diurnal field study conducted by Smolders, de Kort et al. (2013) among healthy day-active persons indicated that acute positive effects of exposure to more intense light on subjective vitality were stronger during autumn/winter compared to spring/summer. Previous experimental studies on NIF effects of indoor light exposure during daytime have been conducted in various seasons, but direct comparisons between seasons regarding these effects in healthy people have – at least to our knowledge – not been empirically tested yet.

In line with the studies of Glickman et al. (2012), Owen and Arendt (1992) and Smolders et al. (2013), we hypothesized that indoor bright light exposure would induce weaker NIF effects in spring compared to autumn/winter. This hypothesis was based on two empirical underpinnings. First, research has shown that the magnitude and duration of acute alerting NIF effects of light exposure depend on prior light dose (Chang et al., 2013). Moreover, in vivo studies investigating isolated ipRGC’s from rodents found that ipRGC responses strongly depend on prior light dose, with decreased responsiveness to bright light during constant light exposure and increased responsiveness to light after dark adaptation (Do & Yau, 2013; Wong et al., 2005). In this line of reasoning, it is possible that acute NIF effects of indoor bright light exposure are reduced in spring/summer compared to autumn/winter, as prior natural light exposure usually is much brighter during this season at relatively high latitudes (Cole et al., 1995; Hébert et al., 1998; Smolders et al., 2013).

In addition to prior light dose, it is also known that, in general, people experience less vitality and a lower mood (although not at a clinical level as seen in seasonal affective disorder) when the light period is short in autumn/winter compared to long in spring/summer (Harmatz et al., 2000; Kasper et al., 1989; Murray et al., 2001). Because of this, it can be expected that more bright light-induced improvements in vitality and mood can be attained in autumn/winter compared to spring/summer. In fact, previous research has shown that participants may be more responsive to bright light-induced positive NIF effects when they feel more mentally fatigued (Smolders & De Kort, 2014) or less energetic (Smolders et al., 2013). In contrast to mood and vitality, cognitive performance seems to be quite stable across seasons (Meyer et al., 2016) or even better in winter on certain tasks (Brennen et al., 1999). It should be noted, however, that although performance may remain stable, the strength of brain activation responses during performance seems to vary across seasons (Meyer et al., 2016). Moreover, Meyer et al. (2016) found that the strength of
seasonality in cognitive brain responses may be dependent on the type of task that is performed (e.g. vigilance versus working memory tasks). Therefore, possible seasonality of acute NIF effects of illuminance level on cognitive performance may depend on the type of task that is performed.

The current study examined potential seasonal variations in NIF-responsiveness to diurnal bright light exposure in healthy day-active participants under naturalistic conditions. This was realized by replicating a study in autumn/winter, which had previously been performed in spring (reported in Huiberts et al., 2016). A secondary goal was to examine time-of-day dependent moderations in NIF-responsiveness in autumn/winter (morning versus afternoon), and compare these potential dependencies with the results obtained in the study conducted in spring. Hence, NIF effects of relatively bright (1700 lx at the eye level) versus regular office lighting (165 lx at the eye level) on both subjective (vitality, alertness, and mood) and objective indicators (task performance and physiology) were compared between seasons and between morning and afternoon. The study conducted in spring had shown some, but fairly modest effects of bright light exposure, which were also dependent on type of task and/or time of day (Huiberts et al., 2016). Significant improvements emerged during 1700 lx (versus 165 lx) exposure on difficult working memory performance, but not on psychomotor vigilance performance, nor easy working memory performance. Subjective indicators of vitality, alertness and mood also remained unaffected by the light manipulation. Physiological indicators – heart rate (HR) and skin conductance levels (SCL) – measured during cognitive tasks were higher under 1700 lx exposure compared to 165 lx exposure, but only significantly so for HR during PVT performance in the afternoon and for SCL during easy working memory performance.

For the current study, it was expected that subjective indicators of alertness, vitality and mood, as well as objectively measured sustained attention (Psychomotor Vigilance Task, PVT), would show stronger responses to bright (1700 lx) versus regular office lighting (165 lx) in autumn/winter as opposed to the null effects found in spring (Huiberts et al., 2016). Improvements in working memory were also expected to be more pronounced in autumn/winter than they had been in spring. Improvements in performance, mood, alertness, and vitality were expected to be stronger in the morning compared to the afternoon, since prior light dose is likely shorter and less intense in the morning. Moreover, previous studies also revealed more pronounced NIF effects in the morning compared to the afternoon (Smolders et al., 2012, 2013). Last, seasonal and time-of-day variations in the direction and magnitude of bright light-induced NIF effects on physiology were exploratory in nature since diurnal acute NIF effects on physiology are relatively underexplored and quite inconsistent (Huiberts et al., 2016; Rüger et al., 2005; Smolders & De Kort, 2014; Smolders et al., 2012).

2. Methods
2.1. Design
The current (autumn/winter) study replicated a study performed in spring, be it that the original study included three illuminance levels, whereas the current one only included the two outer levels (highest and lowest). Moreover, no blood pressure measurements were taken in the autumn/winter study. The study therefore employed a 2 (Light: 165 versus 1700 lx at the eye level, within) × 2 (Season: autumn/winter versus spring, between) × 2 (Time of day: morning versus afternoon, between) mixed-model design. Participants were randomly assigned to either the morning (9:00 to 10:30) or the afternoon (9:00 to 10:30) session, and to the order of the lighting conditions in a counterbalanced design. Dependent variables included performance (Psychomotor Vigilance Task (PVT) and Backwards Digit-Span Task (BDST)), physiology (heart rate (HR) and skin conductance level (SCL)), and subjective self-reports of sleepiness, vitality, and mood. Participants received a different BDST version (i.e. different number sequences) in each session. The order of BDST versions was counterbalanced across participants.

The autumn/winter study was conducted from 30 November 2015 to 23 February 2016. The spring study had run from 16 March 2015 to 5 June 2015 (Huiberts et al., 2016). The average photoperiod of the days in autumn/winter was...
9 hours and 17 minutes and average sunrise was at 8:29. In spring, the average photoperiod was 14 hours and 12 minutes and average sunrise was at 6:08.

2.2. Participants

Thirty-nine participants completed both the 165 lx and the 1700 lx condition in spring; thirty-three participants participated in the autumn/winter study (one subject only participated in the 165 lx condition). Participant characteristics can be viewed in Table 1.

Respondents were recruited via the university’s participant database. All participants had normal or corrected to normal vision (contact lenses or glasses) and no hearing or motoric impairments. They were not taking any medication other than birth control. Additional exclusion criteria were cardiovascular disease, time-zone travel or night shift work during the month preceding the study, or an extreme chronotype for the relevant age group (18–30 years age category). The chronotype score was established with the Munich Chronotype Questionnaire (MCTQ; Roenneberg et al., 2003). Participants falling outside the 25%–75% range of midpoint of sleep on free days (corrected for accumulated sleep pressure) were excluded from participation. In other words, all chronotype values ranged between 3.74 and 5.75 (Zavada et al., 2005), except for one participant. Accidentally, one person with a chronotype value below her age-related category range (3.37) participated in the autumn/winter study. Her data were included in the analyses as the chronotype value was no outlier in the autumn/winter sample and because we corrected for the chronotype in each analysis.

2.3. Setting

The study was performed in a simulated office environment at the Eindhoven University of Technology. For detailed specifications of the laboratory space see Huiberts et al. (2016). A 15.6-inch laptop was placed on the desk with a keyboard, in-ear headphones and a mouse. There was no daylight contribution during the experimental sessions.

Specifications of the ceiling luminaires used in both studies are reported in Huiberts et al. (2016). This section also describes the photon density, irradiance, and illuminance level horizontally at the table level, and depicts the spectral power distribution for each lighting condition. Alpha-opic illuminance values per photoreceptor for corneal spectral irradiance can be viewed in Table 2. These were computed using the toolbox developed by Lucas et al. (2014), assuming healthy human eyes (32 years old) and dilated pupils (7 mm).

2.4. Procedure

Before participating in the study, participants completed a set of questionnaires online probing possible confounding variables (i.e. chronotype,

<table>
<thead>
<tr>
<th>Table 1. General participant characteristics per season and time of day.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Spring</strong></td>
</tr>
<tr>
<td><strong>Morning</strong></td>
</tr>
<tr>
<td>Number of participants</td>
</tr>
<tr>
<td>Number of males</td>
</tr>
<tr>
<td>Number with 165 lx first</td>
</tr>
<tr>
<td>Mean age (SD)</td>
</tr>
<tr>
<td><strong>Chronotype</strong></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>General fatigue</td>
</tr>
<tr>
<td>General sleep quality</td>
</tr>
<tr>
<td>Light sensitivity</td>
</tr>
<tr>
<td>Trait vitality</td>
</tr>
</tbody>
</table>
global sleep quality, light sensitivity, general fatigue, and trait vitality). Participants came to the lab on two separate occasions at the same time of day (with at least two days in between sessions). In both studies, participants were instructed to keep their sleep onset and offset similar to their habitual sleep schedule (based on their sleep timing on workdays indicated in the MCTQ) two days before each session.

An overview of the procedure of one session is depicted in Figure 1. At the start of each laboratory session, participants were guided to their workstation (120 lx at the eye level) and were asked to apply the physiological sensors measuring the heart rate (HR) and skin conductance level (SCL) according to instructions. Subsequently, participants were informed about the procedure and completed a practice phase in which they completed questionnaires regarding state sleepiness, vitality, and mood, and briefly practiced the PVT and BDST trials. Subsequently, participants started with the four repeated measurement blocks as depicted in Figure 1. After the first measurement block (baseline), illuminance levels were switched from 120 lx to either 165 or 1700 lx at the eye level, depending on the experimental condition. Participants then completed three additional measurement blocks (52 minutes in total) during the light exposure and afterwards completed some closing questionnaires (see Sections 2.5.4. and 2.5.5).

In the autumn/winter study, participants also participated in an experience sampling (ESM) protocol probing subjective alertness, vitality, mood, and self-control capacity and wore a small light-logging device on their clothes prior to and after participating in the experiment. Since these data cannot be compared with the spring study, they are not reported here and the methodology is not detailed further in the current article.

Participants of the autumn/winter study received a 35-euro compensation after completing both experimental sessions and the ESM protocol. Participants of the spring study received a 45-euro compensation after completing all three experimental sessions (165 lx, 600 lx, and 1700 lx). Both studies were approved by the ethical board of the Human-Technology Interaction group in Eindhoven.

### 2.5. Measurements

#### 2.5.1. Task performance

Vigilance was measured by average reaction speed in a 10-min auditory PVT as developed by Dinges and Powell (1985). During the PVT, participants rested their dominant hand on the space bar and pushed the space bar as fast as possible upon hearing a short beep. Beeps (400 Hz) were presented at random intervals ranging between 6 and 25 s. Average reaction speed (s⁻¹; 1000/reaction time in milliseconds) was computed per measurement block, for all trials, for the 10% fastest trials, and for the 10% slowest trials.

The second task was an auditory Backwards Digit-Span Task (BDST). Participants heard sequences of digits presented at a rate of 800 ms per digit, and then reproduced the full sequence of digits in reversed order on a QWERTY keyboard. The length of sequences increased gradually from four digits to eight digits (four trials per length).

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**Table 2.** Spectrally-weighted α-opic lx levels at the eye level for each lighting condition based on calculations of Lucas et al. (2014).

<table>
<thead>
<tr>
<th>λ max</th>
<th>α-opic lx value (165 lx)</th>
<th>α-opic lx value (1700 lx)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Melanopsin</td>
<td>480.0</td>
<td>130</td>
</tr>
<tr>
<td>S-cone</td>
<td>419.0</td>
<td>135</td>
</tr>
<tr>
<td>M-cone</td>
<td>530.8</td>
<td>153</td>
</tr>
<tr>
<td>L-cone</td>
<td>558.4</td>
<td>158</td>
</tr>
<tr>
<td>Rods</td>
<td>496.3</td>
<td>142</td>
</tr>
</tbody>
</table>

**Figure 1.** Overview of the experimental design. Note. SI stands for Subjective Indicators.
Maximum response time was 2 s plus 2.3 s for every digit in the sequence. We computed the percentage of correctly reported full digit-spans per measurement block for easy trials (lengths four to six) and for difficult trials (lengths seven and eight) separately.

2.5.2. Physiological indicators
Physiological arousal was assessed by the heart rate (HR) and skin conductance level (SCL). Both were recorded using the TMSi software with a sampling frequency of 1024 Hz. Three Kendall H124SG ECG electrodes were applied for HR measurement using the lead-II placement: the first one (ground) on top of the collar bone near the left shoulder, the second one under the collar bone near the right shoulder and a third one underneath the left ribs. Average HR values (beats per minute (bpm)) were calculated from the RR intervals in the raw electrocardiography (ECG) data. Separate scores were computed per task (PVT, easy BDST, difficult BDST) and per measurement block using Matlab R2013a. One experimental session from the autumn/winter study was excluded from the analyses as HR recordings failed during the light exposure session (165 lx at the eye level). Two experimental sessions (165 lx and 1700 lx at the eye level) from the spring study were excluded from analyses due to failed HR recordings.

Two electrodes on the distal phalanges of the left middle and ring finger recorded SCL (in μSiemens). Again we computed average SCL values separately for the PVT, easy BDST, difficult BDST trials and per measurement block using Matlab R2013a. SCL data of both sessions of two participants and one 1700 lx session in the autumn/winter study were excluded from the analyses due to failed recordings. In the spring study, SCL data of both sessions of two participants were excluded due to failed recordings.

2.5.3. Subjective sleepiness, vitality, and mood
Participants’ subjective sleepiness was examined with the Karolinska Sleepiness Scale (KSS, Åkerstedt and Gillberg (1990)), a 9-point scale running from 1 (extremely alert) to 9 (extremely sleepy–fighting sleep). Subjective vitality was assessed with four items (energetic, alert, sleepy (reversed), lacking energy (reversed); $\alpha_{\text{winter}} = 0.86; \alpha_{\text{spring}} = 0.88$) adopted from the activation-deactivation checklist (Thayer, 1967). Mood had three components: tension was assessed with two items (tense and calm (reversed); $\alpha_{\text{winter}} = 0.57; \alpha_{\text{spring}} = 0.64$) adopted from the activation-deactivation checklist (Thayer, 1967); a single item probed positive affect (‘happy’) and one probed negative affect (‘sad’). All items had 5-point rating scales from 1 (definitely not) to 5 (definitely).

2.5.4. Evaluation of the lighting condition
Participants evaluated the lighting in the room at the end of each session using items adopted from Flynn et al. (1973). Three items probed the experienced pleasantness of the lighting (‘unpleasant–pleasant’, ‘uncomfortable–comfortable’, ‘disturbing–not disturbing’; $\alpha_{\text{winter}} = 0.73; \alpha_{\text{spring}} = 0.85$). Three single items measured experiences concerning the color of the lighting (‘warm–cold’), brightness (‘dim–bright’) and whether the lighting was activating (‘relaxing–stimulating’), all on 5-point rating scales.

2.5.5. Possible confounding variables
Several potential confounding variables were assessed before the start of the experiment. These included the Munich Chronotype Questionnaire (Roenneberg et al. (2003)); the Pittsburg Sleep Quality Index, using a calculated scale ranging from 0 to 21 (Buysse et al., 1989); the Checklist Individual Strength using a 7-point rating scale (Vercoulen et al., 1999), with $\alpha_{\text{winter}} = 0.92$ and $\alpha_{\text{spring}} = 0.89$; Trait Subjective Vitality using a 7-point rating scale (Ryan and Frederick, 1997), with $\alpha_{\text{winter}} = 0.81$ and $\alpha_{\text{spring}} = 0.91$; and a 3-item subjective light sensitivity scale ($\alpha_{\text{winter}} = 0.73$ and $\alpha_{\text{spring}} = 0.61$) adopted from Smolders et al. (2012) using 5-point rating scales. After the last measurement block participants completed a short questionnaire measuring sleep onset and offset, sleep quality of the preceding night (scale from 0–100), time spent outside, travelling time outside, caffeine and food consumption during the hour before the start of the experiment and total consumption of caffeinated drinks since awakening.
2.6. Statistical analyses

Preparatory Linear Mixed Model (LMM) analyses with Participant added as independent random intercept and BDST version as fixed factor were conducted to investigate baseline differences in performance on BDST easy versus difficult trials to examine whether the two BDST tasks indeed significantly differed in the difficulty level. Subsequent preparatory LMM analyses examined possible significant differences in baseline scores and confounding variables at the session level, as well as possible significant differences in trait confounders (i.e. chronotype, general sleep quality, general fatigue, light sensitivity and trait vitality) between seasons and timing of the session (i.e. morning or afternoon).

LMM analyses were then conducted to investigate Light * Season interactions in the combined sample of participants who participated in spring or autumn/winter. The hierarchical model for performance and physiological indicators consisted of the levels ‘Participant’, ‘Experimental session’ and ‘Block’. The participant identifier variable was included as random intercept in the analyses and Block was assigned as repeated variable nested within Experimental session, nested within participants. The model was run for each dependent variable separately. LMM analyses without a repeated measurement structure for Block were carried out to test the effect of Light * Season on sleepiness, vitality, mood, and light appraisals as these measures were only administered at the end of the light manipulation. Post hoc tests comparing lighting conditions per seasons were performed in case significant Light * Season interactions were found. In case no Light * Season interactions were found, main effects of Light were examined and reported for the combined sample. For these post hoc tests, Estimated Marginal Means (EMM’s) and Standard Errors (SE’s) were reported.

Secondary LMM analyses were conducted investigating Light * Time of day and Light * Block interactions in the autumn/winter sample only, as this was also done in the study conducted in spring (Huiberts et al., 2016). This was done in order to examine whether effects were more pronounced in the morning or in the afternoon, and whether they occurred immediately after the light manipulation or more toward the end of the 1h light exposure. In case a significant interaction effect of Light * Time of day or Light * Block was found, post hoc tests with Bonferroni correction were used to investigate differences between lighting conditions during respectively morning versus afternoon and each measurement block. In view of a concise results section, only statistically significant main and interaction effects of Light were reported. All LMM analyses included (if applicable) main effects of Block and Time of day as fixed factors to control for time-on-task and time-of-day effects. Moreover, all analyses were corrected for baseline values of the corresponding outcome measure and the same individual characteristics (see Section 2.5.5.) as in the study conducted in spring (i.e. chronotype, light sensitivity and general fatigue). These control variables were chosen because they were not inter-correlated (all p’s ≥ 0.08), to avoid potential multicollinearity, while other potential control variables were significantly correlated with these or other variables in the model (e.g. Time of day).

Effect sizes (pseudo $R^2$-values ($R^2_{pseudo}$)) were calculated for models containing statistically significant or near-significant ($p < 0.10$) main or interaction effects of Light. $R^2_{pseudo}$ indicates the proportion (percentage) of reduction in variance of residuals from the null-model to the final (full) model at level two (Raudenbush & Bryk, 2002). Note that the full models also contain baseline measurements, covariates and (if applicable) Season, Time of day, and Block as predictors for the outcome measures. Therefore, the total reduction in residual variance includes the variance explained by all of these variables compared to the null-model.

3. Results

3.1. Preparatory analyses

3.1.1. Manipulation check for easy versus difficult BDST performance

In order to investigate whether long BDST trials (length seven and eight) were indeed more difficult than short trials (length four until six) in the combined sample, a LMM analysis was conducted
including Task type as predictor. This analysis revealed a significant main effect of Task type on BDST performance ($F(1,186) = 353.27, p < 0.001$), indicating that participants performed significantly better (in terms of percentage correct) on the easy trials ($EMM = 80.77\%; SE = 2.19\%) compared to the difficult trials ($EMM = 37.60\%; SE = 2.37\%)$.

### 3.1.2. Comparison of background variables: General characteristics and characteristics measured at the session level

Table 1 shows the average values for chronotype, general fatigue, general sleep quality, light sensitivity, and trait vitality per season and per time of day. LMM analyses showed no significant main effects of Season and no significant Season * Time of day interactions for these variables. Table 3 shows the values for several self-reported variables measured at the session level (hours spent in bed, sleep quality, sleep inertia, travel time to the laboratory and total time spent outside before the session). Only one significant two-way interaction of Light * Season was found for sleep quality ($F(1,72) = 5.55, p = 0.02$). However, post hoc tests did not reveal any significant differences between sessions per season (both $p$’s > 0.06).

### 3.1.3. Baseline differences in outcome variables

A few significant differences between the sample tested in autumn/winter versus the sample tested in spring at baseline were found (see Table 4). Participants performed significantly better on BDST easy trials in spring compared to autumn/winter and were significantly more sleepy and less vital at baseline in spring compared to autumn/winter. In addition, participants had a significantly higher HR during the PVT and the BDST difficult trials and had significantly higher SCL during all tasks in autumn/winter compared to spring (see Table 4 for post hoc EMM’s and SE’s). Table 5

### Table 3. Values of possible confounding variables: characteristics measured at the session level.

<table>
<thead>
<tr>
<th></th>
<th>Morning</th>
<th>Afternoon</th>
<th>Morning</th>
<th>Afternoon</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>165 lx</td>
<td>1700 lx</td>
<td>165 lx</td>
<td>1700 lx</td>
</tr>
<tr>
<td></td>
<td>EMM (SE)</td>
<td>EMM (SE)</td>
<td>EMM (SE)</td>
<td>EMM (SE)</td>
</tr>
<tr>
<td>Hours in bed (night before session)</td>
<td>8.20 (0.23)</td>
<td>8.11 (0.23)</td>
<td>8.12 (0.21)</td>
<td>7.60 (0.21)</td>
</tr>
<tr>
<td>Sleep inertia (min.)</td>
<td>21.80 (4.41)</td>
<td>22.24 (4.41)</td>
<td>20.57 (4.09)</td>
<td>24.00 (4.09)</td>
</tr>
<tr>
<td>Sleep quality previous night</td>
<td>63.97 (5.43)</td>
<td>62.36 (5.43)</td>
<td>67.44 (5.03)</td>
<td>57.96 (5.03)</td>
</tr>
<tr>
<td>Travel time to laboratory (outside; min.)</td>
<td>17.29 (2.52)</td>
<td>13.40 (2.52)</td>
<td>14.84 (2.34)</td>
<td>11.56 (2.34)</td>
</tr>
<tr>
<td>Total time outside before session (min.)</td>
<td>21.91 (7.50)</td>
<td>14.69 (7.50)</td>
<td>57.48 (6.95)</td>
<td>57.81 (6.95)</td>
</tr>
</tbody>
</table>

**Note.** EMM stands for Estimated Marginal Mean and SE stands for Standard Error.

### Table 4. Baseline scores of the outcome variables for the autumn/winter and the spring sample.

<table>
<thead>
<tr>
<th></th>
<th>Spring</th>
<th>Autumn/Winter</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>EMM (SE)</td>
<td>EMM (SE)</td>
</tr>
<tr>
<td>Overall speed on PVT</td>
<td>2.83 (0.06)</td>
<td>2.88 (0.06)</td>
</tr>
<tr>
<td>BDST easy trials</td>
<td>84.63% (2.04%)</td>
<td>76.92%* (2.23%)</td>
</tr>
<tr>
<td>BDST difficult trials</td>
<td>42.40% (3.90%)</td>
<td>35.53% (4.23%)</td>
</tr>
<tr>
<td>HR during PVT</td>
<td>74.10 (1.39)</td>
<td>78.20* (1.50)</td>
</tr>
<tr>
<td>HR during BDST easy trials</td>
<td>75.76 (1.41)</td>
<td>79.42 (1.53)</td>
</tr>
<tr>
<td>HR during BDST difficult trials</td>
<td>75.34 (1.42)</td>
<td>79.55* (1.54)</td>
</tr>
<tr>
<td>SCL during PVT</td>
<td>3.21 (0.34)</td>
<td>5.02** (0.37)</td>
</tr>
<tr>
<td>SCL during BDST easy trials</td>
<td>3.98 (0.38)</td>
<td>6.26*** (0.41)</td>
</tr>
<tr>
<td>SCL during BDST difficult trials</td>
<td>4.01 (0.35)</td>
<td>5.92** (0.38)</td>
</tr>
<tr>
<td>Sleepiness</td>
<td>5.43 (0.25)</td>
<td>4.56* (0.28)</td>
</tr>
<tr>
<td>Vitality</td>
<td>2.96 (0.10)</td>
<td>3.27* (0.11)</td>
</tr>
<tr>
<td>Tension</td>
<td>2.26 (0.11)</td>
<td>2.20 (0.12)</td>
</tr>
<tr>
<td>Happy</td>
<td>2.82 (0.10)</td>
<td>2.72 (0.11)</td>
</tr>
<tr>
<td>Sad</td>
<td>1.58 (0.09)</td>
<td>1.44 (0.10)</td>
</tr>
</tbody>
</table>

**Note.** EMM stands for Estimated Marginal Mean and SE stands for Standard Error. Significant differences are indicated in bold. * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$. 

The values for several self-reported variables measured at the session level (hours spent in bed, sleep quality, sleep inertia, travel time to the laboratory and total time spent outside before the session). Only one significant two-way interaction of Light * Season was found for sleep quality ($F(1,72) = 5.55, p = 0.02$). However, post hoc tests did not reveal any significant differences between sessions per season (both $p$’s > 0.06).
shows baseline scores for each of the outcome variables for the autumn/winter and the spring sample, in the morning and afternoon, for both lighting conditions. Significant Season * Time of day * Light interactions at baseline were only found for SCL during PVT and BDST performance (see Table 5 for post hoc EMM’s and SE’s).

### Table 5. Baseline scores for the autumn/winter and the spring sample, in the morning and afternoon, for both lighting conditions.

<table>
<thead>
<tr>
<th>Outcome</th>
<th>Morning</th>
<th>Afternoon</th>
<th>Morning</th>
<th>Afternoon</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>165 lx</td>
<td>1700 lx</td>
<td>165 lx</td>
<td>1700 lx</td>
</tr>
<tr>
<td></td>
<td>EMM (SE)</td>
<td>EMM (SE)</td>
<td>EMM (SE)</td>
<td>EMM (SE)</td>
</tr>
<tr>
<td>Overall speed on PVT</td>
<td>2.82 (0.09)</td>
<td>2.85 (0.09)</td>
<td>2.88 (0.08)</td>
<td>2.78 (0.08)</td>
</tr>
<tr>
<td>BDST easy trials (% correct)</td>
<td>84.60 (3.78)</td>
<td>85.06 (3.78)</td>
<td>84.22 (3.50)</td>
<td>84.62 (3.50)</td>
</tr>
<tr>
<td>BDST difficult trials (% correct)</td>
<td>40.84 (6.60)</td>
<td>41.64 (6.75)</td>
<td>44.76 (6.11)</td>
<td>42.37 (6.11)</td>
</tr>
<tr>
<td>HR during PVT</td>
<td>76.35 (2.26)</td>
<td>75.74 (2.31)</td>
<td>71.57 (2.13)</td>
<td>72.74 (2.09)</td>
</tr>
<tr>
<td>HR during BDST easy trials</td>
<td>77.86 (2.78)</td>
<td>76.19 (2.32)</td>
<td>73.82 (2.14)</td>
<td>75.17 (2.11)</td>
</tr>
<tr>
<td>HR during BDST difficult trials</td>
<td>76.79 (2.32)</td>
<td>76.44 (2.36)</td>
<td>73.22 (2.18)</td>
<td>74.89 (2.14)</td>
</tr>
<tr>
<td>SCL during PVT</td>
<td>3.82 (0.58)</td>
<td>3.19 (0.58)</td>
<td>2.70 (0.53)</td>
<td>3.19 (0.53)</td>
</tr>
<tr>
<td>SCL during BDST easy trials</td>
<td>4.80 (0.73)</td>
<td>3.98 (0.73)</td>
<td>3.21 (0.69)</td>
<td>3.93 (0.67)</td>
</tr>
<tr>
<td>SCL during BDST difficult trials</td>
<td>4.74 (0.61)</td>
<td>4.00 (0.61)</td>
<td>3.25 (0.57)</td>
<td>4.07 (0.56)</td>
</tr>
<tr>
<td>Sleepiness</td>
<td>5.16 (0.44)</td>
<td>5.21 (0.44)</td>
<td>5.48 (0.41)</td>
<td>5.86 (0.41)</td>
</tr>
<tr>
<td>Vitality</td>
<td>3.07 (0.17)</td>
<td>3.07 (0.17)</td>
<td>2.89 (0.16)</td>
<td>2.81 (0.16)</td>
</tr>
<tr>
<td>Tension</td>
<td>2.20 (0.19)</td>
<td>2.39 (0.19)</td>
<td>2.14 (0.18)</td>
<td>2.31 (0.18)</td>
</tr>
<tr>
<td>Happy</td>
<td>2.95 (0.17)</td>
<td>2.78 (0.17)</td>
<td>2.81 (0.15)</td>
<td>2.76 (0.15)</td>
</tr>
<tr>
<td>Sad</td>
<td>1.55 (0.15)</td>
<td>1.66 (0.15)</td>
<td>1.48 (0.14)</td>
<td>1.62 (0.14)</td>
</tr>
<tr>
<td>HR during BDST easy trials</td>
<td>6.14 (0.63)</td>
<td>6.84 (0.67)</td>
<td>6.14 (0.63)</td>
<td>6.49* (0.64)</td>
</tr>
<tr>
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</tr>
<tr>
<td>Happy</td>
<td>2.95 (0.17)</td>
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<td>1.48 (0.14)</td>
<td>1.62 (0.14)</td>
</tr>
</tbody>
</table>

Note. EMM stands for Estimated Marginal Mean and SE stands for Standard Error. Significant differences between lighting conditions at baseline are indicated in bold. *p < 0.05.

### 3.2. Main, season-, and time-of-day-moderated effects of light on performance

#### 3.2.1. PVT performance

Average speed during the PVT revealed no significant main effect of Light, nor a significant Light * Season interaction. However, subsequent LMM analyses on the autumn/winter data did render a significant Light * Time of day * Light interaction (F(1,26) = 5.66, p = 0.03; $R^{2}_{pseudo} = 10.81\%$), which had not emerged in spring (F(1,46) < 1, ns.). Post hoc tests indicated that participants responded significantly faster in the morning when exposed to 1700 lx (EMM = 2.81; SE = 0.04) compared to 165 lx (EMM = 2.69; SE = 0.04; p = 0.02), but not in the afternoon (see Figure 2). Indeed, a LMM in the combined dataset only including morning sessions also rendered a significant Light * Season interaction on average speed (F(1,31) = 6.24, $p = 0.02$; $R^{2}_{pseudo} = 9.77\%$). This improvement was largely due to an increase in speed on the 10% slowest trials, as demonstrated by a similar Light * Time of day interaction for this indicator (F(1,34) = 9.66, p = 0.004; $R^{2}_{pseudo} = 21.14\%$). Speed on the 10% slowest trials was significantly higher in the morning when participants were exposed to 1700 lx (EMM = 2.31; SE = 0.05) compared to 165 lx (EMM = 2.14; SE = 0.05; p = 0.005), while again there was no significant difference between lighting conditions in the afternoon.

#### 3.2.2. BDST performance

LMM analyses revealed no significant Light * Season interaction or main effect of Light on easy BDST performance (see Figure 2).

In contrast, for difficult BDST performance a significant Light * Season interaction was found (F(1,106) = 17.61, p < 0.001; $R^{2}_{pseudo} = 9.38\%$). Post hoc tests revealed that participants performed significantly better on the difficult BDST trials in spring when they were exposed to 1700 lx (EMM = 49.75%; SE = 2.51%; p < 0.01). In autumn/winter, however, participants performed significantly worse when they were exposed to 1700 lx (EMM = 34.20%;
SE = 2.77%) compared to 165 lx (EMM = 42.50%; 
SE = 2.73%; p < 0.01). LMM analyses conducted for 
the autumn/winter sample revealed a significant 
Light * Time of day interaction (F(1,44) = 5.72, 
p = 0.02; R²pseudo = 20.69%). Post hoc tests showed 
that participants performed significantly worse on 
difficult trials when exposed to 1700 lx 
(EMM = 30.94%; SE = 3.78%) compared to 165 lx 
(EMM = 46.81%; SE = 3.56%; p < 0.001) in the 
afternoon, but not in the morning (see Figure 2).

### 3.3. Main, season-, and time-of-day-moderated effects of Light on physiological arousal

#### 3.3.1. Effects of light on HR

LMM analyses on HR only revealed a near-significant 
effect of Light on HR during PVT performance (F 
(1,73) = 3.22, p = 0.08). Irrespective of season, participants had somewhat, but not significantly, higher HR under 1700 lx exposure compared to 165 lx. This difference only was significant in spring during PVT performance in the afternoon (see Figure 3). For
autumn/winter data only, LMM analyses found a near-significant interaction effect of Light * Time of day on HR during difficult BDST trials ($F_{(1,37)} = 3.53, p = 0.07; R^2_{\text{pseudo}} = 61.62\%$) indicating that participants had somewhat higher HR during 1700 lx exposure than during 165 lx exposure in the afternoon but not in the morning. See Figure 3 for all EMM’s SE’s per season and time of day.

### 3.3.2. Effects of light on SCL

During the PVT performance, a significant Light * Season interaction on SCL emerged ($F_{(1,63)} = 6.94, p = 0.01; R^2_{\text{pseudo}} = 57.10\%$). Post hoc tests revealed that participants had significantly higher SCL during the PVT in autumn/winter when they were exposed to 165 lx ($EMM = 5.98; SE = 0.22; p = 0.03$) compared to 1700 lx ($EMM = 5.36; SE = 0.23; p = 0.03$).
In spring, however, participants had higher SCL during the PVT when they were exposed to 1700 lx ($EMM = 3.92; \ SE = 0.20$) compared to 165 lx ($EMM = 3.58; \ SE = 0.20$) but not significantly so ($p = 0.17$).

LMM analyses also revealed a significant Light $\times$ Season interaction on average SCL during BDST easy trials ($F_{BDST\text{easy}}(1,67) = 4.70, \ p = 0.03; \ R^2_{\text{pseudo}} = 64.32\%$) but not significantly so during difficult trials ($F_{BDST\text{diff}}(1,79) = 3.23, \ p = 0.08; \ R^2_{\text{pseudo}} = 65.05\%$). Similar as during the PVT, post hoc tests revealed that participants had somewhat higher SCL during easy BDST performance in autumn/winter when they were exposed to 165 lx compared to 1700 lx but not significantly so ($p = 0.16$). In spring, participants had higher SCL during the easy BDST when they were exposed to 1700 lx compared to 165 lx) but also not significantly so ($p = 0.11^*$). See Figure 4 for all $EMM$’s $SE$’s per season and time of day.

**Figure 4.** Effects of illuminance level on SCL during PVT and BDST performance in the morning and afternoon sessions, in spring versus autumn/winter. Average SCL values ($\mu$Siemens) during the light exposure are displayed as $EMM$’s and error bars as $SE$’s resulting from the LMM post hoc analysis. These values are corrected for corresponding baseline values. $^*p < 0.1$. 
3.4. Main, season-, and time-of-day-moderated effects of light on subjective indicators

3.4.1. Sleepiness, vitality and mood

LMM analyses on sleepiness and vitality ratings revealed a significant Light * Season interaction for both measures (resp. \( F(1,72) = 6.85, p = 0.01; \) \( R^2_{\text{pseudo}} = 21.35\% \) and \( F(1,71) = 4.12, p = 0.05; \) \( R^2_{\text{pseudo}} = 20.25\% \)). Post hoc tests revealed that participants felt significantly less sleepy (\( \text{EMM} = 4.33; \) \( \text{SE} = 0.29 \)) and more vital (\( \text{EMM} = 3.23; \) \( \text{SE} = 0.12 \)) under 1700 lx exposure compared to 165 lx exposure (resp. \( \text{EMM} = 5.26; \) \( \text{SE} = 0.29 \) and \( \text{EMM} = 2.91; \) \( \text{SE} = 0.12 \)) in autumn/winter, while no such differences were found in spring (see Figure 5). For autumn/winter data alone, LMM analysis on sleepiness revealed a significant Light * Time of day interaction (\( F(1,33) = 9.29, p < 0.01; \) \( R^2_{\text{pseudo}} = 45.81\% \)). Post hoc tests showed that participants felt significantly less sleepy during 1700 lx exposure (\( \text{EMM} = 3.86; \) \( \text{SE} = 0.39 \)) than during 165 lx exposure (\( \text{EMM} = 5.81; \) \( \text{SE} = 0.39; p < 0.001 \)) in the morning, but not in the afternoon (see Figure 5). In line with this, a significant Light * Time of day interaction was found for vitality ratings in autumn/winter (\( F(1,32) = 6.87, p = 0.01; \) \( R^2_{\text{pseudo}} = 50.98 \)). Post hoc ratings revealed that participants felt significantly more vital during 1700 lx exposure (\( \text{EMM} = 3.43; \) \( \text{SE} = 0.15 \)) than during 165 lx exposure (\( \text{EMM} = 2.78; \) \( \text{SE} = 0.15; p = 0.001 \)) in the morning, but not in the afternoon (see Figure 5). Light * Time of day interactions for subjective

Figure 5. Effects of illuminance level on feelings of sleepiness and vitality during the morning and afternoon sessions in spring versus autumn/winter. Average sleepiness and vitality values during the light exposure are displayed as EMM’s and error bars as SE’s resulting from the LMM post hoc analyses. These values are corrected for corresponding baseline values. \( \dagger p < 0.1; \) \( * p < 0.05; \) \( *** p < 0.001. \) Note. When sleepiness values in spring were compared between 165 lx versus 1700 lx, instead of 165 lx versus 600 lx versus 1700 lx, a significant effect of Light on sleepiness appeared in the afternoon, which showed increased sleepiness after 1h of 1700 lx exposure compared to 165 lx. This difference did not reach statistical significance during the spring study reported in Huiberts et al. (2016) when three light conditions were compared and Bonferroni adjusted for multiple comparisons.
sleepiness and vitality in spring did not reach statistical significance (resp. \( F(1,38) = 2.99, p = 0.09 \); and \( F(1,39) = 3.83, p = 0.06 \); see Figure 5). No significant main effects of Light or Light * Season interactions were found for mood.

### 3.4.2. Light appraisals

With respect to pleasantness of the lighting, a main effect of Light was found in the combined sample \( (F(1,143) = 7.37, p < 0.01; R^2_{\text{pseudo}} = 16.78\%) \), indicating that the 1700 lx condition was experienced as significantly less pleasant \((EMM = 2.98; SE = 0.09)\) than the 165 lx condition \((EMM = 3.34; SE = 0.09)\). However, it should be noted that although there was no Light * Season interaction \( (F(1,143) < 1, ns.) \), main effects of Light on pleasantness of the lighting only reached statistical significance in the spring sample \( (F(2,78) = 9.31, p < 0.001; R^2_{\text{pseudo}} = 20.48\%) \), but not in the autumn/winter sample \( (F(1,65) = 1.39, ns.) \).

As expected, a significant main effect of Light on brightness evaluation was found for the combined dataset \( (F(1,72) = 118.53, p < 0.001; R^2_{\text{pseudo}} = 54.17\%) \). Participants rated the 1700 lx condition as significantly brighter \((EMM = 4.59; SE = 0.07)\) compared to the 165 lx condition \((EMM = 3.35; SE = 0.09)\). Moreover, a significant main effect of Light was found for appraisals related to whether the lighting was experienced as activating \( (F(1,71) = 27.83, p < 0.001; R^2_{\text{pseudo}} = 28.17\%) \). Participants rated the 1700 lx condition as significantly more activating \((EMM = 3.80; SE = 0.09)\) than the 165 lx condition \((EMM = 3.18; SE = 0.09)\).

### 4. Discussion

The current study investigated seasonal and time-of-day variations in diurnal NIF effects of indoor illuminance level on cognitive performance, physiology and subjective indicators of alertness, vitality, and mood. This was realized by replicating an experiment in autumn/winter that was previously performed in spring (Huiberts et al., 2016). By combining these data, moderation by season of the NIF effects was examined. It was hypothesized that NIF effects of bright (1700 lx at the eye) versus regular (165 lx at the eye) indoor lighting would be more pronounced in autumn/winter since, in general, people report feeling less vital in autumn/winter compared to spring (Harmatz et al., 2000; Kasper et al., 1989; Murray et al., 2001) and thus have more room for improvement. Moreover, because the prior light dose is likely to be lower in autumn/winter compared to spring (see e.g. Smolders et al., 2013), individuals may experience increased bright light-induced NIF effects due to greater responsiveness of the ipRGCs and the subsequent NIF pathway. (Chang et al., 2013).

Findings revealed that seasonal variations in responsiveness to illuminance level indeed occurred for several indicators, generally demonstrating beneficial NIF effects primarily during the darker months of the year. More specifically, seasonal variations in NIF effects were quite pronounced for subjective feelings of vitality and alertness. In autumn/winter, subjective alertness and vitality significantly improved under morning bright light, while in spring no such improvements were found. Notably, two previous studies with a similar experimental design (Smolders & De Kort, 2014; Smolders et al., 2012) did reveal NIF induced improvements on sleepiness and vitality in spring/summer, albeit less pronounced than in the autumn/winter period of the current study. Both these studies did have higher statistical power – allowing them to detect smaller effects – as their design employed repeated measurements for these indicators.

For mood, however, no effects of bright light exposure were found in either autumn/winter or spring. For tension, this is consistent with most earlier studies (Huiberts et al., 2015; Smolders et al., 2012). Positive and negative affect had shown more inconsistent results earlier. Two studies – conducted in spring – had found no significant effects of illuminance level on mood (Huiberts et al., 2015; Smolders et al., 2012), whereas two other studies did, even within 30 minutes of bright light exposure (Kaida et al., 2007; Smolders & De Kort, 2014). These latter two studies were respectively conducted in late summer/early autumn and early spring and yet nonetheless showed acute indoor bright light-induced improvements in mood. It should be noted, however, that Kaida et al. (2007) employed natural...
instead of artificial bright light and explored effects during lunch time; Smolders and De Kort (2014) manipulated mental state (fatigued versus relaxed) before the light exposure period. These differences complicate direct comparisons with the current study. Nevertheless, taken together these findings suggest that season does not consistently moderate bright light-induced changes in mood.

With respect to seasonal variations in acute NIF effects on performance, results on the vigilance task were in line with those of subjective alertness and vitality. That is, participants who were exposed to bright light in autumn/winter in the morning sessions showed significant improvements on reaction speed during the PVT. In spring, in contrast, no such improvements were found.

Regarding working memory, illuminance level did not impact performance on easy tasks in either season. In contrast, difficult working memory performance was differentially affected by illuminance level in spring versus autumn/winter. Quite unexpectedly, participants performed significantly better on difficult trials in spring during bright versus regular light, while they performed significantly worse when exposed to bright light in autumn/winter. Further inspection of the autumn/winter data revealed that participants only performed significantly worse on the difficult trials in the afternoon during 1700 lx exposure. A previous study also revealed detrimental effects of bright light exposure in the afternoon (1000 lx at the eye level versus 200 lx at the eye level) on the same working memory task (Huiberts et al., 2015). Interestingly however, this study was conducted in spring. Apparently, indoor bright light may under certain circumstances interfere with executive functioning and impede performance in the afternoon, but NIF effects on working memory are not very consistent (e.g. Gabel et al., 2015; Huiberts et al., 2015) and seasonal differences alone cannot explain these inconsistencies.

In addition to the self-report and performance measures, we also studied HR and SCL during tasks. Overall, illuminance level did not show a significant impact on HR and there was no significant moderation of season in NIF effects of light on HR assessed during the PVT or BDST. Overall, participants had a somewhat higher HR during bright light exposure compared to regular light exposure, but this difference did not reach statistical significance. Some previous studies likewise revealed nonsignificant effects of illuminance level on HR during daytime (Leproul et al., 2001; Rüger et al., 2006). In contrast, one previous study did reveal significant increases in HR during a PVT under 1000 lx versus 200 lx (at the eye) in summer, both during the morning and afternoon (Smolders et al., 2012). It should be noted, however, that a different PVT format was used in this latter study, with shorter inter-stimulus intervals. There are some indications that the type of task performed during HR recording may influence illuminance-induced effects on HR (Huiberts et al., 2016). Moreover, a previous 24h constant routine study revealed that increases in HR when exposed to bright light (800 lx at the eye) compared to darkness are strongest during the middle of the night and in the early morning and nonsignificant during daytime (Scheer, van Doornen et al., 1999). Overall, these findings suggest that if there are any effects of illuminance level on HR during daytime, they are expected to be relatively modest.

In contrast to HR, SCL did show a significant interaction between illuminance level and season when measured during PVT and easy BDST trials, but not during difficult BDST trials. Also here, NIF effects were quite subtle, as post hoc tests only showed a significant difference in SCL in winter during PVT performance, with higher SCL during regular compared to bright light exposure. The opposite pattern – higher SCL during 1700 lx compared to 165 lx exposure, albeit not significantly so, emerged in spring. Previous studies had also revealed significantly higher SCL under bright (1000 lx at the eye level) versus regular light exposure (200 lx at the eye level) while performing a PVT in spring and summer (Smolders & De Kort, 2014; Smolders et al., 2012). Although we controlled for baseline differences in our analyses, it should be noted that baseline seasonal differences in SCL were detected. Possibly, average SCL was higher in winter compared to spring due to large outside versus inside temperature differences which may have led to increased sweating in winter when moving from relatively cold (outdoor) to warm (indoor) temperatures.
Future research is necessary to investigate whether and why illuminance level may influence SCL during cognitive tasks in a different way in autumn/winter compared to summer/spring.

In addition to the NIF effects, appraisals regarding the lighting were also investigated. As expected, in both seasons 1700 lx was rated as significantly brighter compared to 165 lx. In addition, the bright light condition was rated as significantly more activating than the regular lighting condition in both seasons. Color was not rated as significantly different between conditions, which makes sense as color temperature was kept constant. Interestingly, participants rated the bright light condition compared to the regular light condition as significantly less pleasant in spring, but not in autumn/winter. Other similar spring/summer studies also revealed that participants rated the bright compared to regular light conditions as significantly less pleasant (Smolders & De Kort, 2014; Smolders et al., 2012). Apparently, indoor bright light exposure is more tolerated in autumn/winter compared to spring. Since the lighting was rated as similarly pleasant in the morning and afternoon in autumn/winter, it is unlikely that improved alertness and vitality can explain these seasonal differences. After all, these only improved during the morning sessions. Moreover, previous studies conducted in spring and summer also found significantly lower pleasantness ratings of bright (1000 lx at the eye) versus regular (200 lx at the eye) light while subjective alertness and vitality significantly improved (Smolders & De Kort, 2014; Smolders et al., 2012).

With respect to alertness – measured objectively (vigilance) and subjectively (vitality, alertness) – the current findings revealed a moderation by season during the morning hours. Two possible hypotheses were formulated that may explain why season may moderate NIF effects of indoor illuminance level. First, we suggested that people may be more responsive to bright light-induced NIF effects during darker months because of lower base rates in autumn/winter compared to spring/summer (Harmatz et al., 2000; Kasper et al., 1989; Murray et al., 2001). However, this first hypothesis did not apply in the current study, as participants in autumn/winter felt significantly more vital and alert at baseline than those who participated in spring. Alternatively, we hypothesized that people would be more responsive to light-induced NIF changes due to a lower prior light dose (Chang et al., 2013; Do & Yau, 2013; Wong et al., 2005), which is likely in autumn/winter compared to spring/summer (Smolders et al., 2013), particularly in the morning. Based on the current findings, this does appear to be the more likely underlying mechanism. The fact that no differences in alertness – whether measured objectively or subjectively – were found in the afternoon, may be because prior light dose before the afternoon sessions was already relatively high (above saturation), even in autumn/winter. The results on physiology and working memory performance were more mixed and no consistent moderating role of season was found for these indicators. Likely, other factors play a more important role in determining the magnitude and direction of illuminance-induced NIF effects on working memory and physiology.

Although the two studies (spring versus autumn/winter) reported in this article had a very similar design, it should be noted that the study conducted in spring (Huiberts et al., 2016) included a third physiological measure: blood pressure. This meant that baseline blood pressure was measured before the start of each session by using an automatic blood pressure device and that participants wore a blood volume pulse ear clip during the spring sessions. Moreover, the spring study employed a third, intermediate light level (600 lx at the eye level). With respect to the latter difference, we consider it unlikely that this extra lighting condition would have impacted the results as in both studies the order of the lighting condition was counterbalanced and all sessions were conducted on separate days. Last, in the autumn/winter study an ESM protocol was added before and after the laboratory session and participants wore a light sensor during the day of their visit to the lab. Although the laboratory set-up of both the autumn/winter and spring study already was quite transparent with respect to the general study goals, as participants are not blind to the light manipulation, the ESM protocol and wearing the light sensor in autumn/winter might have additionally sensitized participants to the general study goals.

With respect to the study design, we have to acknowledge that we employed a between-subjects
design, whereas a counterbalanced crossover design, testing the same participants in spring and autumn/winter and counterbalancing the order of season, would have been more ideal. Given the high risk of drop-out we decided to opt for the first and employ a between-subjects design in the current study. Considering the positive indications in this first exploration, we do recommend testing seasonal variations in NIF effects within subjects in the future.

Overall, we can conclude that season does seem to play a moderating role in acute NIF effects of illuminance level in case of subjective indicators of alertness and vitality as well as objectively measured vigilance during the morning hours. That is, effects of indoor bright light exposure were beneficial for these indicators during the morning in autumn/winter (even if participants already feel quite vital and alert), while in spring no such beneficial effects of bright light exposure were found. It is possible that increased NIF-responsiveness to indoor bright light exposure in autumn/winter due to lower outdoor lighting levels can explain these differences between seasons (see for example, Chang et al., 2013; Do & Yau, 2013; Wong et al., 2005). However, this hypothesis should be empirically tested in future research. Findings on the role of season in illuminance-induced changes in physiology and working memory performance were found to be less consistent and future research is necessary to determine whether season plays a consistent moderating role here.

NIF effects of illuminance level on most of the indicators investigated in this study (i.e. subjective vitality and sleepiness, vigilance and difficult working memory performance) revealed time of day moderation, especially in winter. Practical implications for the current findings may be that personalized indoor lighting has to be tuned based on time of year and time of day in order to maximize beneficial NIF effects of light. Future research on temporal variations in responsiveness to bright light-induced NIF effects is necessary to gain more insight in determining the direction and magnitude of illuminance-induced changes in subjective, physiological and performance indicators.

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Declaraton of Interest

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References


