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Daytime light exposure and feelings of vitality: Results of a field study during regular weekdays

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ABSTRACT

In the current study, we investigated daily light exposure and its relation with vitality in everyday settings on an hour-to-hour basis. The method consisted of experience sampling combined with continuous light measurement and a sleep diary during three consecutive days. Data collection was distributed over a full year. Results revealed substantial inter- and intra-individual differences in hourly light exposure. The amount of light experienced was significantly related to vitality, indicating that persons who were exposed to more light experienced more vitality, over and above the variance explained by person characteristics, time of day, activity patterns and sleep duration during the previous night. This relationship was more pronounced in the morning, during the darker months of the year and when participants had experienced relatively low vitality during the previous hour. Overall, the results provide support for acute effects of light exposure on feelings of vitality during daytime, even in everyday life.

1. Introduction

Light not only enables us to see the world around us, but is also important for our physical and psychological functioning. Exposure to light can affect human experiences, performance and physiology via both image-forming and non-image forming processes (Berson, 2003; Boyce, 2003; Hanifin & Brainard, 2007; Warthen & Provencio, 2012). Via the visual system, light enables us to extract and process relevant visual information required for performing visual tasks, and influences how we visually experience the environment. In addition to activation of the visual system, photoreceptors in the human retina signal light information to brain areas involved in the regulation of behavior, mood and physiology (Hattar, Liao, Takoa, Berson, & Yau, 2002; Vandewalle, Maquet, & Dijk, 2009). This non-image forming pathway affects the timing of physiological and psychological processes throughout the 24-h light–dark cycle, as well as a person's state of alertness and mood, physiological arousal and cognitive processing.

To date, most studies investigating acute alerting effects of light on human behavior and physiology have been performed in the late evening or at night. Laboratory studies have shown that nocturnal exposure to higher illuminance levels or light in the blue spectrum can result in increased feelings of alertness, more physiological arousal and better cognitive performance at night (e.g., Cajochen, Zeitzer, Czeisler, & Dijk, 2000; Campbell & Dawson, 1990; Lockley et al., 2006; Myers & Badia, 1993; Zeitzer, Dijk, Kronauer, Brown, & Czeisler, 2000). Similar beneficial effects of bright light or morning dawn-simulating light exposure during daytime have been demonstrated for individuals who had first experienced substantial light and/or sleep deprivation (Gabel et al., 2013; Phipps-Nelson, Redman, Dijk, & Rajaratman, 2003; Rüger, Gordijn, Beersma, de Vries, & Daan, 2006; Vandewalle et al., 2006). Moreover, a recent laboratory study suggested that exposure to white light with a higher illuminance level also had beneficial effects on alertness and vitality during daytime, even in the absence of sleep and light deprivation (Smolders, De Kort, & Cluitmans, 2012).

The extent to which the activating effects of light shown in the laboratory can translate to benefits in everyday life is relatively unknown. Only few studies have explored these effects in the field. Moreover, the process is complex as vitality and alertness may fluctuate with numerous other variables (e.g., activities, food intake, social context) that cannot be controlled outside the laboratory. In addition, light exposure throughout the day is very

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dynamic and research has shown that the experienced amount of light is, among other factors, dependent on whether a person is indoors or outdoors, on time of day and season, working hours and type of job, age and chronotype, suggesting both intra- and inter-individual differences in daily light exposure (Goulet, Mongrain, Desrosiers, Paquet, & Dumont, 2007; Guillemette, Hébert, Paquet, & Dumont, 1998; Hébert, Dumont, & Paquet, 1998; Hubalek, Brink, & Schierz, 2010; Martin, Hébert, Ledoux, Gaudreault, & Laberge, 2012; Sadikes, Messin, Senger, & Kripke, 1986; Scheuermaier, Laffan, & Duffy, 2010; Staples, Archer, Arber, & Skene, 2009; Thorne, Jones, Peters, Archer, & Dijk, 2009). So an important challenge for lighting research today is to establish the alerting and vitalizing potential of light in everyday life, over and above the rich set of stimuli already experienced there.

A few studies have revealed beneficial effects of prolonged exposure to blue-enriched or bright light among office employees in the field. For instance, two field studies have shown that exposure to blue-enriched light in office environments for several weeks improved subjective alertness, sleep quality and self-reported performance compared to lighting with a lower correlated color temperature (Mills, Tomkins, & Schlangen, 2007; Viola, James, Schlangen, & Dijk, 2008). Partonen and Lönnqvist (2000) revealed improved vitality after four weeks of repeated exposure to very high illuminance levels (~2500 lx at the eye) during the darker winter months in Finland.

In addition to these effects of long-term exposure (order of weeks), several field studies have measured individuals' light exposure patterns and investigated its relationship with mood, social behavior, sleep quality and circadian phase of their rest–activity cycle on a day-to-day basis. Hubalek et al. (2010), for example, employed wearable light meters worn close to the eye in a naturalistic study (see Hubalek, Zöschg, & Schierz, 2006) and demonstrated that light exposure during the day can have a significant and positive effect on subjective sleep quality, but that it was not related to self-reported mood assessed at the end of day. Moreover, Figueiro and Rea (2010a; 2010b) showed that reduced exposure to light in the blue spectrum in the morning or exposure to light with a higher portion in the blue part of the spectrum in the evening may result in a delayed onset of sleep among adolescents in daily situations. A field study by Martinez-Nicolas, Ortiz-Tudela, Madrid, and Rol (2011) showed a relation between persons' light exposure, timing and quality of sleep and skin temperature, suggesting a link between the intensity and variability of a person's light exposure throughout the 24-h day and the amplitude and phase of his or her circadian rhythm. Moreover, Aan het Rot, Moskowitz, and Young (2008) showed that the duration of exposure to bright light during the morning, afternoon or evening was related to the amount of positive social interactions experienced among persons suffering from mildly seasonal affective disorder.

Yet, little is known about the relationship between persons' experienced light intensity levels and their momentary affective state throughout the day, i.e., acute effects. In the current field study, we explore the relation between daytime light exposure and feelings of vitality among healthy day-active persons on an hourly basis in everyday situations. Vitality refers to the positive feeling of having energy or resources available to the self (Ryan & Deci, 2008; Ryan & Frederick, 1997). Experiences of vitality are central to mental well-being, health and performance, and important for success in various realms of life including one's career, health, and quality of the social network (e.g., see Heatherton & Wagner, 2010). Vitality generally correlates closely with self-reported alertness and an item probing alertness is often included in vitality scales. Research has shown time-dependent and inter-individual variations in vitality as a function of, among others, persons' chronotype and general health (e.g., Ryan & Frederick, 1997; Thayer, 1989; Thayer, Takahashi, & Pauli, 1988). We therefore investigated the relationship of light exposure with vitality throughout the day correcting for inter- and intra-personal differences in experiences of vitality. More specifically, this study investigates whether light exposure would significantly predict vitality over and above the daily dynamics of vitality as a function of person characteristics, time of day, activity patterns and sleep duration during the previous night. Even though the relationship with vitality is the main focus of the current study, relationships between light exposure and feelings of tension, positive affect and negative affect were also investigated.

Based on earlier laboratory studies showing acute activating effects of light, we expected to see a positive relationship between the amount of light participants experienced and their level of vitality. In other words, we hypothesized that participants would feel more vital when they had experienced relatively more light. We had, however, no clear hypotheses concerning the relationship between light exposure with tension, positive and negative affect as – in contrast to potential activating effects - earlier findings on affective improvements under bright light have been inconsistent (e.g., Baron, Rea, & Daniels, 1992; Daurat et al., 1993; Hubalek et al., 2010; Kaida, Takahashi, & Otsuka, 2007; Partonen & Lönnqvist, 2000; Smolders et al., 2012). As earlier laboratory-based experiments have revealed time and mental status-dependent effects during daytime (e.g., Smolders et al., 2012; Vandewalle et al., 2006), we also investigate whether the relationship between light exposure and vitality is equally strong throughout the day, or whether instead it depends on time of day, or on previous vitality level. Moreover, we investigate potential seasonal variations and explore the role of light in the blue spectrum in the relationship between light and vitality.

2. Method

The method employed in this study was experience sampling, combined with continuous measurement of light exposure with a wearable device, a morning and evening diary and an online questionnaire.

2.1. Participants

Forty-two healthy persons participated in this field study, of which 10 participated twice, resulting in 52 sessions. Participants consisted mainly of office employees and students. Of these participants, 20 were male and 22 were female (mean age 25 years, $SD = 8.1$, range: 19–56). The participants all lived, worked, and/or went to university in the Eindhoven region (51° 44′ N, 5° 48′ E), the Netherlands. None of them had specific expertise in lighting. Up to two persons participated each week, rendering data on a wide range of light exposures, activities and settings. If a person participated twice, there were at least three months in between the two sessions. The study started in October 2010 and ran a full year until October 2011. Fourteen sessions took place during spring, 10 during summer, 12 during autumn and 16 during winter.

2.2. Measures

2.2.1. Light exposure

Light exposure at the eye was measured with a device, called Daysimeter (developed by RPI's Lighting Research Center, supplied by LumenTech Innovations), worn at eye level. The Daysimeter has two optical sensors to measure light exposure: one sensor corrected for the spectral sensitivity of the visual (photopic) system and one sensor that detects short wavelength light based on the spectral sensitivity of the circadian system determined by nocturnal melatonin suppression (the device and circadian sensitivity curve are further detailed in Bierman, Klein, & Rea, 2005). Light exposure was sampled at a frequency of 10 Hz. The Daysimeter provides average values for the light exposure every 30 s.

2.2.2. Experience sampling

An experience sampling method was employed to monitor persons' feelings on an hourly basis during their regular daily routine. We applied an interval-contingent sampling, i.e., self-reports at fixed times of day, to have multiple assessments of individuals' momentary state throughout the day and explore the relation between fixed (non-overlapping) light exposure periods prior to the questionnaire and person's affective states. We assessed participants' feelings of vitality, tension, positive and negative affect. Subjective vitality and tension were measured with a short scale consisting of six items adopted from the activation-deactivation checklist (Thayer, 1989). The vitality (energetic arousal) subscale consisted of four items ('energetic', 'lacking in energy' (reversed), 'alert' and 'sleepy' (reversed)) and was reliable with $\alpha = .84$. The subscale tension (tense arousal) was measured with two items ('tension' and 'calmness' (reversed)) and had a reliability coefficient of $\alpha = .58$. Positive affect ('happy') and negative affect ('sad') were each measured with a single item. The response scale of these eight items ranged from (1) 'definitely not' to (4) 'definitely'.

In addition to these affective state measures, the experience sampling questionnaire included context-related questions concerning the activity and location of the participant. Three items investigated the amount of 'physical effort', 'mental effort' and 'social interaction' the participant had engaged in during the 15 min prior to the questionnaire on a 5-point response scale ranging from (1) 'none' to (5) 'very much'. Questions about the location assessed whether the participant was indoors or outdoors, was in a more natural or more built environment, and was alone or together. These variables were each assessed with a single dichotomous item.

2.2.3. Diary

Participants also kept a sleep diary every morning and a general activities diary every evening. Sleep duration and subjective sleep quality of the night before were assessed with questions adopted from the Karolinska sleep diary (KSD; Åkerstedt, Hume, Minors, & Waterhouse, 1994) and the Pittsburgh sleep diary (PghSD; Monk et al., 1994). For instance, participants reported on time of going to sleep, time of awakening, experienced sleep quality and ease of falling asleep. Questions assessing estimates of the total time spent outdoors, engaged in physical activity, in mental activity, spent in company with others and on social interaction during the day were administered in the evening questionnaire. In addition, participants' affective states after awakening and before going to sleep were measured in the morning and evening diary respectively, with the same items as used in the experience sampling questionnaire.

2.2.4. Online questionnaire

The online questionnaire consisted of measures of person characteristics such as trait vitality, chronotype, general sleep quality and health, light sensitivity, neuroticism, age and gender. Trait subjective vitality was measured with the subjective trait level vitality scale with $\alpha = .90$ (Ryan & Frederick, 1997). Chronotype was assessed with the Dutch translation of the Munich Chronotype questionnaire (MCTQ; Roenneberg, Wirz-Justice, & Merrow, 2003) and computed according to the formula provided by Roenneberg et al. (2004). Subjective Light sensitivity was assessed with two items: 'How much trouble do your eyes give when you are exposed to bright light?' and 'How much do you suffer from headaches when you are exposed to bright light?' on a scale ranging from (1) 'not at all' to (5) 'very much'. General sleep quality was assessed with the Pittsburgh Sleep Quality Index (PSQI; Buysse, Reynolds, Monk, Berman, & Kupfer, 1989) consisting of 18 items concerning subjective sleep quality, sleep latency, sleep duration, sleep efficiency, sleep disturbances, sleeping medication and daytime dysfunction. Chronic fatigue was assessed with the Checklist Individual Strength (Beurkens et al., 2000) consisting of 20 items assessing subjective feelings of fatigue (8 items, $\alpha = .93$), concentration problems (5 items, $\alpha = .83$), motivational deficits (4 items, $\alpha = .86$) and low physical activity (3 items, $\alpha = .93$). General health was assessed with five items from the Dutch version of the SF-36 Health Survey (General health perception subscale, RAND-36; Van der Zee, Sanderman, Heyink, & de Haes, 1996). Neuroticism was assessed with a subscale of the Dutch translation of the Big Five questionnaire ($\alpha = .81$; Denissen, Geenen, Van Aken, Gosling, & Potter, 2008).

2.3. Procedure

One day prior to their participation, participants picked up the light measurement device, mobile phone and diary, and received instructions from the experimenter. Participants wore the measurement device and gave self-reports for three consecutive days between 8 am and 8 pm.[1] During these days, participants lived their lives as usual, apart from the fact that they were wearing a light measurement device, briefly filling out questionnaires every hour and completing the diary after awakening and before going to sleep. The questions of the experience sampling were administered on HTC mobile phones between 8 am and 8 pm (on 40 min past the hour). Participants were reminded of the questionnaire by a series of beeps: 15 beeps in the first 15 s and 5 beeps, with an interval of 1 s, at the start of every next minute. If the participant did not start the questionnaire within 5 min after the hourly signal, the start menu of the questionnaire disappeared and the next questionnaire appeared the next hour. On average, it took about one minute to complete the hourly questionnaire. Participants completed the online questionnaire at the end of the week. After the three days, participants handed in the devices and diary, were debriefed and thanked for their participation and received a compensation of 75 Euro.

2.4. Statistical analyses

First, the light measurement data were inspected and measurement periods during which the Daysimeter was not worn were coded as missing using Matlab R2010. Not wearing was determined based on the amount of activity measured with the Daysimeter (i.e., head movements). Only measurements during which the participants wore the device for at least 50% of the prediction interval (e.g., one hour) were used for the computations. After calculating the average light level per time span[2] these values were $\log_{10}$ transformed to meet the requirements for a normal distribution and values lower than 0 (i.e. < 1 lx) were coded as missing. In total, 1746 light measurements were used for the analyses (i.e., 92.3% of all measurement occasions between 8 am and 8 pm; $SD = 8.8$; range 63.9%–100% of the measurements occasions per session).

[1] Note that participants were instructed not to wear the light measurement device in situations which could damage the device, for instance, while doing sports or taking a shower.

[2] Note that the mean hourly light exposure during the first hour was based on the light measurements during the 40 min prior to the questionnaire (i.e., from 8:00 am to 8:40 am), since measurements only started at 8 am.

The response rate for the experience sampling was 88.2% ($SD = 8.23$; range 66.7%–100% per session). In total, complete data for both the light exposure and experience sampling questionnaire was collected for 1563 events.

Hierarchical linear model (HLM) analyses were performed to explore inter- and intra-individual variations in light exposure and affective state, and to investigate whether light exposure was a significant predictor for feelings of vitality and the other dimensions of mood. In these hierarchical models, Session and Day were entered as independent random variables to group the data for each session and measurement day, that is, to indicate that the same participant was measured multiple times a day during one session consisting of three consecutive days.[3] Measurement occasion was added as a repeated random variable for each day indicating that the measurements were nested within a Day, which in turn was nested within Participant. We modeled potential covariance between the measurement occasions during a measurement day using an autoregressive covariance structure matrix as this resulted overall in the best fit of the null model (i.e., an unconditional model with no predictors). This covariance structure assumes a higher correlation between two consecutive measurement occasions than between two occasions farther apart.

First, we modeled experienced light exposure to better understand how persons' light levels at the eye fluctuated in daily life. To assess the amount of inter- and intra-individual variance in participants' light exposure patterns throughout the day, HLMs were defined with hourly light exposure as dependent variable (separate analyses for photopic and circadian light levels). First, intra-class correlations (ICCs) of the unconditional models were investigated to determine the percentage of variance in light exposure attributable to the participant level and to the measurement (timeslot) level, i.e., the amount of variance between and within sessions, respectively.[4] Subsequently, time of day, time of day squared, season and person characteristics (in separate analyses to avoid multicollinearity) were added to the model, to explore whether these variables explained some of the variance in the hourly light exposure. Time of day and Time of day squared were added to model both a linear and parabolic function of light exposure throughout the day. The hourly photopic light exposure and circadian light exposure were highly correlated with each other ($r = .97$, $p < .01$). Therefore, as a general rule, results of subsequent tests exploring light exposure as predictor will be reported for illuminance level (photopic light exposure). Only if analyses with circadian light exposure differed from those with the photopic light as independent variable, will these results be reported. In addition to these two measures for the average experienced light intensity, we explored variations in the duration of exposure to bright light as a function of time of day, season and participants' level of chronic fatigue. To this end, the percentage of minutes of exposure to illuminance levels above 1000 lx at the eye was computed for each hour. As this variable was not normally distributed, non-parametric tests were performed to investigate whether the average duration of exposure to bright light per session differed between morning vs. afternoon exposure, between seasons and between participants experiencing relatively low vs. high chronic fatigue (based on median split).

[3] Subjects participating in two sessions were treated as two independent participants. Note that adding participant as additional (higher-level) random intercept did not change the results.

[4] A model with day as random intercept revealed an error showing that the Hessian matrix was not positive definite suggesting redundant covariance parameters. Therefore, we ran the model without day as random intercept.

Next, after this analysis of light exposure patterns, separate HLM analyses were performed to explore the relation between light exposure and vitality, tension, positive affect and negative affect. For each of these subjective state variables, we also first ran an unconditional model to explore the amount of variance that could be explained at each level by assessing ICCs. Subsequently, Time of day and Time of day squared were added as fixed factors, to investigate whether vitality and the other mood dimensions varied consistently with time of day. In the next step, Hourly light exposure was added to the model, to explore whether the amount of light experienced at eye level during the hour prior to filling in the questionnaire explained additional variance in vitality, tension, positive affect and negative affect. Subsequently, Social interaction and Physical effort were added as covariates, as we expected that these variables might influence individuals' affective state as well. In the final model, we also added sleep duration of the previous night and person characteristics as covariates. For all the hourly measurements (i.e., light exposure, social interaction and physical effort) as well as for prior sleep duration, the scores were centered on the overall mean of all sessions. To estimate standardized regression coefficients, all variables in the model were standardized by using *Z*-scores. Thus, the standardized regression coefficients reflect the parameter estimates for the *Z*-scores of the predictors.

Note that in the analyses, light exposure during the preceding hour was selected as predictor. This selection is in fact quite arbitrary, as we currently lack the knowledge to predict which time span, i.e., duration of exposure, is the best predictor for feelings of vitality. To get insight in whether the relation is dependent on exposure duration, the hierarchical analyses were subsequently performed with light exposure during different time spans (ranging from 2 h to 5 min) prior to the questionnaire. Moreover, we investigated time of day, time of year and antecedent vitality level as potential moderators of the relationship between hourly light exposure and subjective vitality. For these analyses, we used the same hierarchical model as reported above.

3. Results

3.1. Light exposure patterns

Fig. 1a shows a scatterplot of the hourly light exposure measurements over seasons. A hierarchical linear model (HLM) analysis revealed that 73.3% of the variance in hourly illuminance level occurred between measurement occasions and 26.7% of the variance occurred between persons, suggesting substantial inter-individual, but particularly intra-individual differences in illuminance levels. The correlation between two consecutive measurement occasions was $r = .56$ for hourly illuminance level ($p < .01$). Adding Time of day and Time of day squared rendered a significant time of day effect on hourly light exposure, showing a parabolic trend (both $p < .01$). Season also had a significant effect on the average hourly illuminance level [$F(3,51) = 14.94$; $p < .01$]. As would be expected, participants were exposed to higher illuminance levels in spring and summer ($EMM = 2.87$; $SE = .09$ and $EMM = 2.72$; $SE = .10$, respectively) than in the autumn and winter ($EMM = 2.30$; $SE = .10$ and $EMM = 2.17$; $SE = .08$, respectively). Person characteristics, such as Chronotype, Global sleep quality, Trait vitality, Light sensitivity, Neuroticism and Gender, were not significantly related to the hourly illuminance level (all $p > .10$), except for Age, showing that older participants were exposed to lower illuminance levels ($B = -.02$; $\beta = -.16$; $F(1,43) = 4.18$; $p = .05$). In addition, the relationship between Subjective chronic fatigue and experienced light exposure showed a non-significant trend for exposure to lower illuminance levels among participants who suffered more from chronic fatigue ($B = -.10$; $\beta = -.16$;

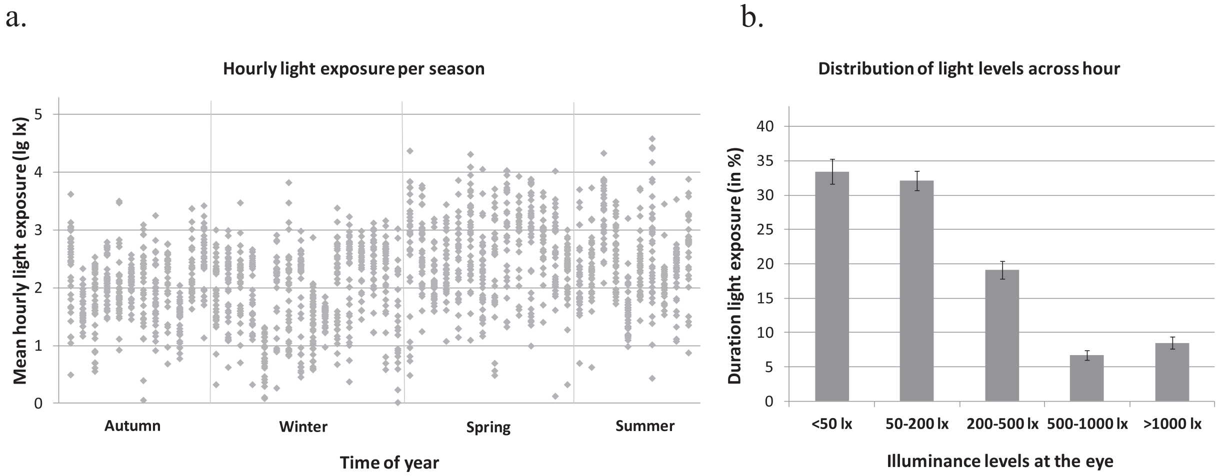

Fig. 1. (a) Variation in hourly light exposure over seasons and (b) duration of exposure to different illuminance levels as a percentage per hour. The whiskers represent the 95% confidence interval. These results show substantial inter- and intra-individual variations in light exposure. Moreover, participants were mainly exposed to illuminance levels below 500 lx.

$F(1,44) = 3.72$; $p = .06$). In contrast to these results for photopic light exposure, Age was not significantly related to hourly circadian light ($B = -.01$; $\beta = -.10$; $F(1,36) = 1.40$; $p = .25$). Subjective chronic fatigue was also not significantly related to circadian light exposure ($B = -.10$; $\beta = -.14$; $F(1,36) = 2.63$; $p = .11$), but instead Concentration problems were ($B = -.15$; $\beta = -.20$; $F(1,37) = 5.37$; $p = .03$), relating more chronic concentration problems to lower levels of light.

Fig. 1b shows the distribution of exposure to different illuminance levels. This figure indicates that participants were exposed to illuminance levels of 500 lx or higher at the eye for only around 15% of the time, far less frequently than they were exposed to lower levels (<500 lx). Exposure to bright light (>1000 lx at the eye) occurred, on average, only a few minutes per hour. A Kruskal–Wallis test revealed significant differences in the average percentage of bright light exposure per session between seasons [$\chi^2(3) = 25.45$; $p < .01$]. Posthoc comparisons using Mann–Whitney tests with Bonferroni correction showed that minutes of exposure to bright light in autumn and winter ($Mdn = 2.08$ and $Mdn = 2.44$ respectively) were significantly lower than in the spring and summer ($Mdn = 16.97$ and $Mdn = 7.04$ respectively). A Mann–Whitney test with time of day (morning vs. afternoon) as independent variable revealed that the average duration of exposure to bright light in the morning and afternoon per session was not significantly different ($Z = -1.22$; $p = .22$). Yet, participants who reported relatively low chronic fatigue were exposed to illuminance levels above 1000 lx at the eye for longer than participants experiencing relatively high chronic fatigue ($Mdn = 6.13$ and $Mdn = 3.31$ respectively; $Z = -2.09$; $p = .04$).

3.2. Relation between light exposure and vitality, tension, positive affect and negative affect

3.2.1. Vitality

The ICCs of the unconditional model for vitality indicated that 65.4% of the variance in feelings of vitality occurred between measurement occasions (level 1), 32.9% of the variance between persons (level 3) and only 1.7% of the variance between days (level 2). The correlation between two consecutive measurement occasions was $r = .52$ ($p < .01$). As the variance to be explained at the day level was not significant ($p = .58$), we removed the random intercept of day from the model. Adding Time of day and Time of day squared as predictors improved the model [$\chi^2(2) = 109.25$; $p < .01$]. Both effects were significant (both $p < .01$), suggesting that vitality varied with time of day according to a parabolic, instead of linear, function (see Fig. 2).

We then added Hourly illuminance level to the model. This improved the model further [$\chi^2(1) = 218.20$; $p < .01$], which indicates that the average amount of light a person experienced at eye level per hour explained additional variance in feelings of vitality. Hourly light exposure was positively related to vitality: Participants felt more energetic when they had experienced a higher amount of light during the previous hour ($B = .08$; $p < .01$).

Subsequently adding Social interaction and Physical effort improved the model further [$\chi^2(2) = 97.22$; $p < .01$], but did not change the results reported above. The relations between the amount of social interaction and physical effort, and feelings of vitality were significant (both $p < .01$): The more social interaction and more physical effort the participants had engaged in 15 minutes prior to completing the questionnaire, the higher their reported feelings of vitality ($B = .06$ and $B = .07$, respectively). Adding Prior sleep duration, Chronotype, Light sensitivity and Subjective chronic fatigue as covariates to the model further improved the model [$\chi^2(3) = 359.12$; $p < .01$], but did not change the earlier results. The results of the final model are presented in Table 1.

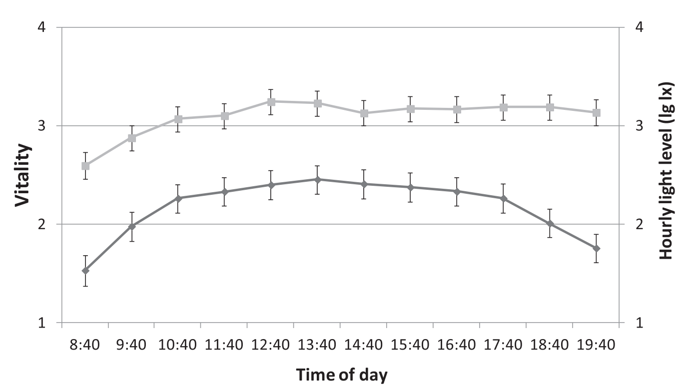

Fig. 2. Vitality (light grey) and hourly light exposure (dark grey) as function of time of day. The values are determined using HLM analyses with time of day as predictor, taking into account the hierarchical structure of the data. The whiskers represent the 95% confidence interval.

Table 1
Statistics of predictors for vitality.

	F	*Df*	*p*	*B*	Standardized *β*
Level 1 predictors					
Time of day	**39.51**	**(1,718)**	**<.01**	**.12 (.02)**	**.10**
Time of day squared	**31.13**	**(1,770)**	**<.01**	**−.01 (<.01)**	**−.16**
Hourly light exposure	**6.86**	**(1,1293)**	**<.01**	**.06 (.02)**	**.07**
Social interaction	**36.97**	**(1,1163)**	**<.01**	**.05 (.01)**	**.11**
Physical effort	**23.66**	**(1,1060)**	**<.01**	**.06 (.01)**	**.09**
Level 2 predictor					
Prior sleep duration	**20.00**	**(1,246)**	**<.01**	**.08 (.02)**	**.17**
Person characteristics					
Chronotype	.42	(1,43)	.52	−.05 (.08)	−.06
Light sensitivity	1.46	(1,42)	.23	.10 (.09)	.10
Chronic fatigue	**10.76**	**(1,43)**	**<.01**	**−.16 (.05)**	**−.31**

Note. Significant predictors are indicated in bold.

As shown in this table, Prior sleep duration was significantly and positively related to subjective vitality. In addition, Subjective chronic fatigue was significantly related to vitality with participants who experienced more chronic fatigue reporting lower feelings of vitality. Note that comparable results were found when the Hourly circadian light was added as predictor, instead of Hourly illuminance level, to the model: Participants reported higher vitality when they had experienced more light in the blue spectrum during the previous hour ($B = .08$; $\beta = .11$; $F(1,1125) = 11.87$; $p < .01$).

3.2.2. Tension, positive affect and negative affect

Results of unconditional models for tension, positive and negative affect showed that respectively 52.2%, 64.8% and 45.6% of the variance occurred between measurement occasions (level 1). In addition, 40.9% of the variance in feelings of tension, 30.5% of the variance in feelings of positive affect and 45.8% of the variance in negative affect occurred between persons (level 3) and respectively only 6.9%, 4.7% and 8.6% of the variance between days (level 2). The correlation between two consecutive measurement occasions was $r = .25$, $r = .27$ and $r = .16$ for feelings of tension, positive affect and negative affect, respectively (all $p < .01$).

Results of the HLM analyses with the hourly predictors, prior sleep duration and person characteristics added as covariates to the model revealed that hourly light exposure (either photopic or circadian light) was not significantly related to feelings of tension, positive or negative affect (all $p > .10$).

3.2.3. Summary

In line with our expectations, hourly light exposure was significantly related to feelings of vitality, even after time of day had already been entered as a predictor. The amount of social interaction and physical effort engaged in, prior sleep duration and subjective chronic fatigue explained further variance in vitality, while subjective light sensitivity and chronotype did not. Hourly light exposure did not correlate significantly with feelings of tension, positive affect and negative affect.

3.3. Exploring different time spans of exposure

To explore whether the relation between experienced light exposure and level of vitality varied depending on the length of the time span employed to compute the average light level, a series of HLM analyses were performed with different time spans, ranging from the last 2 h of light exposure prior to filling out the questionnaire to the last 5 min prior to the questionnaire. Table 2 reports on the results for the average light illuminance levels over these different time spans. The results indicate that the relation with photopic light exposure was significant for time spans ranging from five to 60 min prior to the questionnaire (all $p < .01$). A 2-h period of prior photopic light exposure showed only a non-significant trend ($p = .07$). Note that the average circadian light exposure during a 2-h period prior the questionnaire was a significant predictor for vitality ($B = .07$; $\beta = .08$; $F(1,786) = 5.24$; $p = .02$). Overall, these results suggest only subtle variations in predictive strength for the different time spans.

Table 2
Statistics of different time spans of photopic light exposure as predictors for vitality.

	F	*df*	*p*	*B*	Standardized *β*
Prior 2 h	3.11	(1,971)	.08	.05 (.03)	.06
Prior hour	**6.86**	**(1,1293)**	**<.01**	**.06 (.02)**	**.07**
Prior 30 min.	**9.92**	**(1,1247)**	**<.01**	**.06 (.02)**	**.08**
Prior 15 min.	**11.77**	**(1,1207)**	**<.01**	**.07 (.02)**	**.08**
Prior 10 min.	**12.18**	**(1,1192)**	**<.01**	**.07 (.02)**	**.08**
Prior 5 min.	**7.38**	**(1,1181)**	**<.01**	**.05 (.02)**	**.06**

Note. Significant predictors are indicated in bold.

3.4. Moderation of the relationship between light and vitality by time of day, season and prior vitality level

Fig. 3 shows scatter plots representing the relationship between hourly illuminance level and feelings of vitality for morning vs. afternoon exposure, autumn and winter vs. spring and summer and for participants reporting low vs. high levels of vitality during the previous hour. In the next sections, we test whether participants were more sensitive to variations in light exposure as a function of these potential moderating variables.

3.4.1. Moderation by time of day

To investigate whether time of day moderated the relation between light exposure and vitality, separate HLM analyses were performed for the morning and afternoon. In the morning, the relation between Hourly illuminance exposure and vitality was significant with $B = .10$ [$\beta = .13$; $F(1,598) = 9.51$; $p < .01$]. In contrast, the relation between Hourly illuminance level and feelings of vitality was not significant in the afternoon ($B = .02$; $\beta = .02$; $F(1,681) = .41$; $p = .52$). The results for Hourly circadian light as predictor, however, showed significant relationships with vitality both in the morning [$F(1,534) = 9.06$; $p < .01$] and afternoon [$F(1,585) = 3.88$; $p = .05$], although again the regression coefficient was higher in the morning ($B = .10$; $\beta = .14$) than in the afternoon ($B = .06$; $\beta = .08$).

3.4.2. Moderation by time of year

As results on light exposure revealed that intensity levels mainly differed between spring and summer vs. autumn and winter, we explored the relationship between hourly light exposure and vitality for these two periods of the year separately using HLM analyses with the same model as reported above. Results revealed that while the relationship between illuminance level and vitality was significant during the autumn and winter period ($B = .09$; $\beta = .10$; $F(1,705) = 5.17$; $p = .02$), there was only a non-significant trend during the spring and summer period ($B = .05$; $\beta = .07$; $F(1,551) = 3.24$; $p = .07$). In contrast, HLM analyses with circadian light as predictor revealed a significant relationship between light exposure and vitality during both the autumn and winter period ($B = .09$; $\beta = .11$; $F(1,690) = 6.20$; $p = .01$) and the spring and summer period ($B = .08$; $\beta = .12$; $F(1,433) = 5.83$; $p = .02$).

3.4.3. Moderation by pre-existing vitality level

To investigate whether subjective vitality would be more sensitive to light exposure under depleted than non-depleted conditions, the data was split based on the median into whether

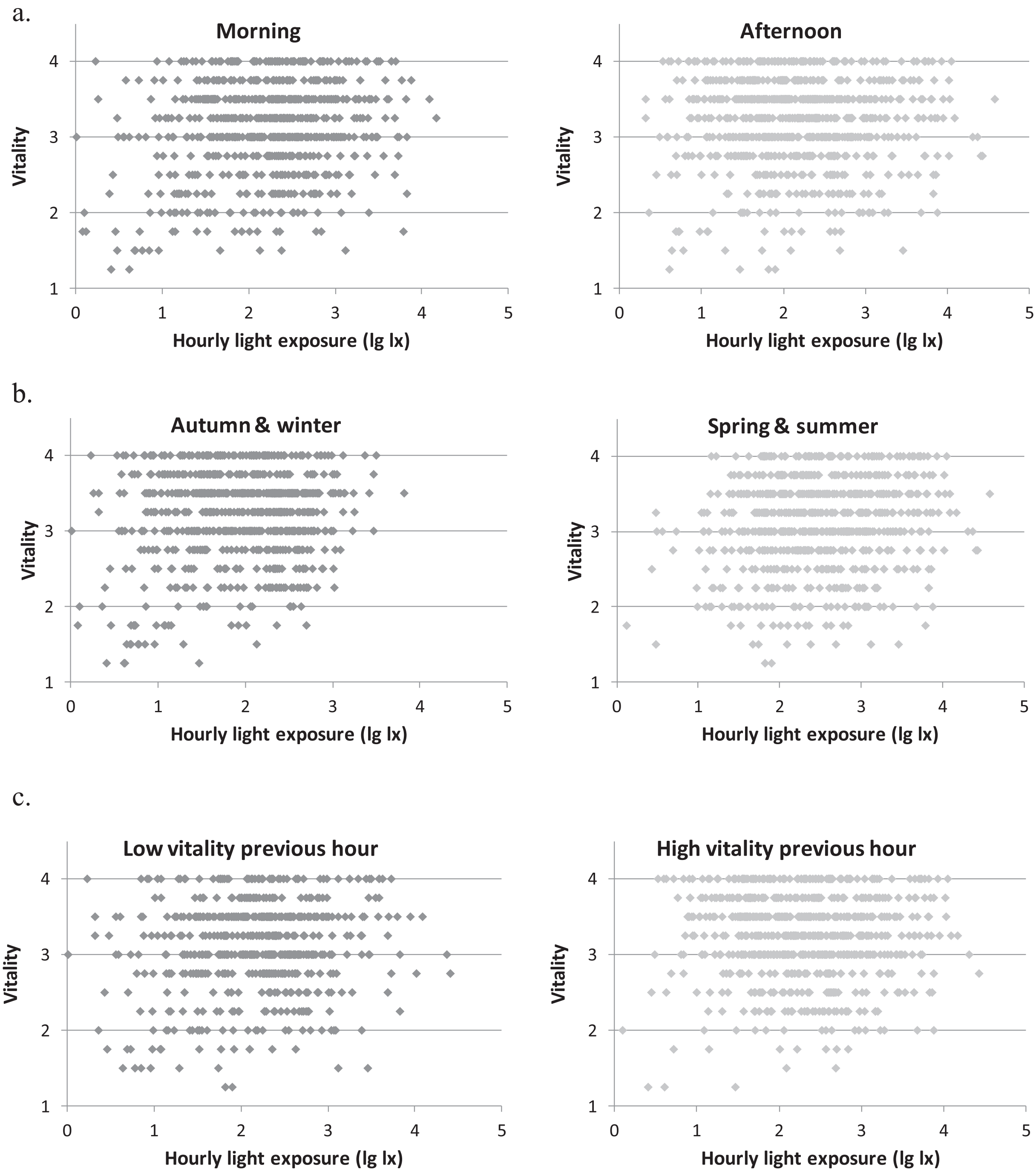

Fig. 3. Scatter plots representing the relationship for subjective vitality and hourly illuminance level based on the raw data (no hierarchy modeled) as function of (a) time of day (morning vs. afternoon), (b) period of year (autumn and winter vs. spring and summer) and (c) participants' prior mental state (low vs. high vitality). Results of the HLM analyses revealed that the relationship was most pronounced in the morning, autumn and winter and for participants experiencing relatively low vitality prior to completing the questionnaire.

participants experienced a low vs. high level of vitality during the hour preceding the prediction episode. For both mental states, HLM analyses were again performed with the same model as reported above. Results revealed a significant relationship between Hourly illuminance level and vitality when participants had reported relatively low feelings of vitality during the previous hour ($B = .08$; $\beta = .10$; $F(1,510) = 6.04$; $p < .01$). Hourly illuminance level was, however, no significant predictor of vitality when participants had reported relatively high feelings of vitality during the previous hour ($B = .03$; $\beta = .04$; $F(1,615) = 1.18$; $p = .28$). Again in contrast, Hourly circadian light significantly predicted vitality for both groups, although the relationship was stronger when participants experienced low prior vitality ($B = .09$; $\beta = .12$; $F(1,452) = 6.70$; $p = .01$) vs. high vitality during the previous hour ($B = .06$; $\beta = .08$; $F(1,538) = 4.07$; $p = .04$).

4. Discussion

The relevance of daytime light exposure patterns to the study of mental wellbeing becomes clear if we consider that, in line with our hypotheses, the amount of light at eye level significantly predicted feelings of vitality on an hour-by-hour basis. Analyses indicate that persons who were exposed to more light experienced higher feelings of vitality, over and above the variance explained by person characteristics, time of day, activity patterns and sleep duration during the previous night. In contrast, light exposure was not significantly related with feelings of tension, positive affect or negative affect. These findings are in line with those of a recent laboratory study reporting higher alertness and vitality under exposure to 1000 lx vs. 200 lx (at the eye), but no significant differences between the two light settings on the other dimensions of mood (Smolders et al., 2012). The current findings thus extend acute activating effects found in the laboratory to the potential of actual benefits in everyday life. In addition, our results complement the findings of the field study by Partonen and Lönnqvist (2000), which revealed improved vitality after four weeks of repeated exposure to very high illuminance levels during the darker winter months. Moreover, our results complement the findings by Hubalek et al. (2010) and Figueiro and Rea (2010a) suggesting that the amount of light exposure during the day not only affects individuals' sleep quality or sleep duration at night, but is also related to feelings of vitality throughout the day.

Light exposure showed substantial inter- and intra-individual variations in terms of illuminance level and circadian light exposure. Results showed a dynamic pattern as a function of time of day as well as systematic variations in experienced light exposure with season and individuals' self-reported level of chronic fatigue. Hourly light exposure followed, as expected, roughly a daylight curve with higher exposure levels in the early afternoon and lower levels in the early morning and evening. In line with earlier studies reporting generally low intensity levels (e.g., Aan het Rot et al., 2008; Espiritu et al., 1994; Guillemette et al., 1998; Hubalek et al., 2010), exposure to bright light (>1000 lx at the eye) was relatively rare and participants were exposed to illuminance levels below 500 lx at eye level for the majority of their day. Nevertheless, light intensity was related to variations in vitality, suggesting that relatively low light intensity levels or short durations of exposure to high illuminance levels can affect subjective vitality, even during daytime and in everyday situations.

The effect of hourly light exposure established in the current study may appear modest. However, one should bear in mind that numerous factors contribute to how vital and alert one feels: the type and intensity of activities performed earlier, food and beverage consumption, sleep quality, social context, and health to name but a few. If one considers the effect size in light of the other findings, the conclusion might be more nuanced. The effect of light exposure, in terms of size, on vitality appears to be in the same range as that of social and physical activities undertaken, time of day and even sleep duration of the night before.

Only the effect of chronic fatigue appears substantially bigger than that of the other predictors. Importantly though, the causality of this relationship is impossible to determine with the current data. Perhaps chronic fatigue leads persons to receive less light – maybe because of going outdoors less frequently, or staying in bed longer. But the opposite direction might also hold: those structurally receiving less light might feel more chronically fatigued. In this case we would be seriously underestimating the predictive strength of light exposure. A similar issue was reported by Martin et al. (2012). Their research indicated that students who were late chronotypes reported high levels of chronic fatigue and experienced less light during the day. As in the current study, the causality behind the link between fatigue and light exposure is unclear and deserves more research attention: It may be interesting to explore the potential for bright light therapy or healthy light applications for persons who are (temporarily) experiencing mental fatigue, or are under high mental pressure. This idea is supported by the finding from the current study that the relationship between light exposure and vitality was stronger when the antecedent vitality level was relatively low. It appears that particularly those in need of revitalization may benefit from exposure to more intense light.

4.1. Variations in relational strength with duration, time of day and season

Exploration of relationships of different time spans of light exposure prior to completing the hourly questionnaire suggested only subtle variations in strength depending on the length of the predictive time span. Although the average light exposure during 1 h prior to the questionnaire as well as shorter intervals significantly predicted vitality, the average illuminance level of the two preceding hours showed only a non-significant trend for a relation with subjective vitality. Overall, these results provide support for acute effects of exposure to higher light levels during daytime and in everyday life. In addition, they suggest that these effects may be quite transient and short-lived, in that shorter durations of exposure appear to predict state vitality better than longer (>1 h) measurement periods. This latter observation also brings our current findings in line with the findings from Hubalek et al. (2010), who found no predictive effect of daily light exposure for mood assessed at the end of the day. The exact dynamics of these effects do however require more research.

The relationship between hourly light exposure and vitality was most pronounced in the morning, suggesting that this relation is dependent on time of day. Note that participants were not exposed to more minutes of bright light (>1000 lx at the eye) in the morning than in the afternoon, so it cannot be bright light exposure per se that explains these effects. Yet, feelings of vitality were relatively lower in the early morning, which may explain the time-dependency of the relationship between light exposure and vitality in the present study. After all, the relationship between the amount of light experienced and feelings of vitality was most pronounced when participants had experienced relatively low vitality during the previous hour. These results suggest that exposure to more intense light may mainly have an effect when the mental state of a person can be improved.

The current study also showed that participants were more sensitive to variations in illuminance level during autumn and winter than during the spring and summer months. In line with the results by Guillemette et al. (1998) and Aan het Rot et al. (2008), subjects participating during the autumn and winter months experienced lower illuminance levels and were exposed to fewer minutes of bright light than subjects who participated during the spring and summer period. Although we did not measure participants' sensitivity to seasonal affective disorder, subjects participating in the autumn and winter did not report significantly more chronic fatigue or lower levels of vitality than did subjects during the spring and summer period (results not shown). This suggests that healthy day-active persons can – in addition to persons suffering from seasonal affective disorder – benefit more from higher illuminance levels during the darker months (i.e., autumn and winter).

4.2. Photopic vs. circadian light

We investigated the relation of both illuminance level and circadian light exposure with subjective vitality, to explore whether the relationship differs depending on the type of measure for the amount of light experienced. While illuminance level represents the amount of light corrected for the spectral sensitivity of the visual system, circadian light represents the amount of light corrected for the spectral sensitivity of the non-visual effects. This latter is determined by the suppression of melatonin at night, which is most sensitive to light in the blue spectrum (e.g., Brainard et al., 2001; Thapan, Arendt, & Skene, 2001), suggesting that the spectral sensitivity of the circadian system is blue-shifted compared to the visual system (Berson, Dunn, & Takao, 2002; Dacey et al., 2005; Hankins, Peirson, & Foster, 2008; Hattar et al., 2002; Provencio et al., 2000). Results for both indicators showed that exposure to relatively more photons at the eye were related to stronger feelings of vitality in daily life. Both measures showed large overlap, although a few results suggested somewhat stronger relationships between the experienced amount of light and vitality when measured in terms of circadian light. However, the differences in the current study are too subtle to draw conclusions concerning the optimal spectral composition of daytime light exposure to enhance mental wellbeing. Moreover, results of a very recent laboratory study provided indications that light in other parts of the visible spectrum may also induce alertness during daytime (Sahin & Figueiro, 2013). In fact, this study suggested alertness-enhancing effects of exposure to monochromatic red light (instead of blue light, both at 40 lx) in the afternoon. It is therefore not unlikely that the spectral sensitivity functions for light responses on persons' experiences and behavior differs from the function established for nocturnal melatonin suppression. More research is required to establish these spectral sensitivity curves for daytime light exposure.

4.3. Limitations

A potential limitation of the current study is that the study is correlational and therefore no causal relationships can be determined. Persons who feel vital may go outdoors more or otherwise also seek more light than depleted persons. However, the relationship between hourly light exposure and vitality was most pronounced for individuals who experienced relatively low vitality suggesting a reverse pattern: persons with a low vitality level appeared to benefit more from exposure to higher light levels. Moreover, the hierarchical and repeated design, and time-lagged structure of the data, that is, the predictor temporally precedes the dependent variable, do to some degree allow for causal inference (e.g., Bolton, Gray, & Litz, 2006; King et al., 2000; Weigel, 2010). Future research, however, should establish effects of daytime exposure to more intense light on mental wellbeing of healthy day-active persons as a function of their momentary state and affective trait level.

4.4. Conclusion

The relation between diurnal light exposure and feelings of vitality illustrates the relevance of light exposure throughout the day in everyday situations. Vitality is a psychological concept central to mental well-being, health and performance. Both short durations of exposure, e.g., 5–10 min, as well as 1 h of exposure showed to be relevant predictors for vitality throughout the day. The responsiveness to light was most pronounced in the morning, during the darker months of the year and when individuals experienced relatively low vitality during the previous hour. The current results support recent laboratory-based findings that light exposure can also have acute effects on experienced vitality during regular daytime hours. It also suggests that there might be potential for beneficial light treatments, beyond those currently employed for treating seasonal and non-seasonal depression or improving cognitive functioning and sleep quality among elderly persons (e.g., see Golden et al., 2005; Gordijn, 't Mannetje, & Meesters, 2012; Riemersma-Van der Lek et al. 2008; Terman et al., 1989), extending the application of light (natural or electric) to benefit the general population.

Disclosure statement

The authors report no conflicts of interest.

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