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Exploring inter-individual variations in light exposure patterns and sensitivity to acute vitalizing effects of light in everyday life

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Introduction

Studies on non-image forming effects of light have shown that the acute effects of light on affective, cognitive and physiological functioning vary with light intensity (e.g., Cajochen, 2007). Whereas most of these studies were performed during the biological night, several laboratory studies have provided evidence that exposure to bright light during the biological day can also induce acute alerting and vitalizing effects (Phipps-Nelson, Redman, Dijk & Rajaratnam, 2003; Rüger et al., 2006; Smolders, de Kort & Cluitmans, 2012; Smolders & de Kort, 2014; Vandewalle et al., 2006). Extending these results acquired under controlled laboratory conditions to everyday life, a recent field study confirmed a significant relationship between light intensity and subjective vitality during daytime (Smolders, de Kort & van den Berg, 2013). Participants reported higher vitality when they had been exposed to more light during the previous hour. Subjective vitality refers to the positive feeling of having energy or resources available to the self, and is important for well-being, health, performance and success in life (Ryan & Frederick, 1997).

Recent research also showed that the effects of light intensity on alertness and vitality during daytime may depend on the timing of the light exposure and a person's momentary state (e.g., sleepy vs. alert). More specifically, exposure to higher levels of light induced stronger feelings of alertness and vitality in the morning and when individuals felt sleepy and less vital (Smolders et al., 2013; Smolders & de Kort, 2014). However, little is known about inter-individual

differences in the sensitivity to these acute effects during daytime.

Controlled laboratory studies (Chellappa et al., 2012; Vandewalle et al., 2011) have provided evidence that individuals' sensitivity to light may not only depend on local time (i.e., clock time), but also on a person's internal time (chronotype; Roenneberg, Wirz-Justice & Mellow, 2003). Whether chronotype as well as persons' level of general fatigue also affect their sensitivity to light during daytime in real life is as yet unknown. Such insights, however, would be vital for the development of intelligent person-centered lighting scenarios.

In the current study, we explored inter-individual variations in light exposure and sensitivity to acute vitalizing effects of light in real life as a function of chronotype, social jetlag and general fatigue. Chronotype refers to an individual's preference in the timing of sleep and wake and quantifies an individual's phase of entrainment (Roenneberg et al., 2003); social jetlag refers to the amount of misalignment between biological and social time (Wittmann, Dinich, Mellow & Roenneberg, 2006).

We will report on additional analyses on the data collected in Smolders et al. (2013), exploring time-dependent variations in light exposure and subjective vitality patterns during the day in early vs. late chronotypes, individuals with a relatively high vs. low social jetlag and individuals who experience relatively high vs. low levels of general fatigue. In addition, we investigated differences in the strength of the relationship between the amount of light experienced and subjective vitality during daytime in everyday life as a function of chronotype, social jetlag and general fatigue.

Method

We applied an experience sampling protocol, combined with a continuous measurement of light exposure, a morning diary and an online questionnaire (see Smolders et al. (2013) for more details).

Participants. Forty-two healthy individuals participated in this field study, of which 10 participated twice, resulting in 52 sessions. For the present analysis, data of 38 participants (48 sessions) were analyzed due to missing data on chronotype, social jetlag and general fatigue of four participants. Of these participants, 20 were male and 18 were female (mean age 26 years \pm SD = 8.1, range: 19-56).

Procedure. Participants wore the light measurement device and reported on their level of vitality during three consecutive days from 8 am to 8 pm during their daily routine. The questions of the experience sampling were administered on an hourly basis with a questionnaire provided by an app on a mobile phone. An interval-contingent sampling was applied to have multiple assessments of individuals' momentary affective state throughout the day and explore the relation between fixed (non-overlapping) light exposure periods prior to completion of the questionnaires and person's affective states. Participants completed the online questionnaire at the end of the week.

Measures. The amount of light at eye level was continuously logged with a head-worn device (Daysimeter, developed by RPI's Lighting Research Center, supplied by LumenTech Innovations, USA).

Subjective vitality was assessed with four items adopted from the energetic arousal subscale of the Activation-deactivation checklist ($\alpha = .84$; Thayer, 1989).

Chronotype and social jetlag were assessed with the Munich Chronotype Questionnaire (Roenneberg et al., 2003). General experienced feelings of fatigue were assessed with a subscale of the Checklist Individual strength (Beurkens et al., 2000) consisting of 8 items ($\alpha = .93$). These scales were included in the online questionnaire.

Statistical analyses. Average light intensity at eye level (in lx; log transformed)

was computed for each 1-hour interval prior to each momentary assessment. If the light measurement device was worn for less than 50% of the time, the data for that hour was coded as missing. Hierarchical linear model (HLM) analyses were performed with Session and Day as independent random variables and Measurement hour as repeated random variable for each day (using an autoregressive covariance structure) to indicate that the measurements were nested within a day, which in turn was nested within a session. To explore potential moderations in light exposure and subjective vitality patterns with time of day (clock time) by chronotype, social jetlag and level of fatigue, the data was split based on the median for chronotype ($Mdn = 4.78$; range: 3.14-6.38), social jetlag ($Mdn = 1.25$; range: 0.00-2.63) or level of general subjective fatigue ($Mdn = 2.56$; range: 1.38-5.50).

First, systematic variations in light exposure were modeled as a function of clock time: HLM analyses were performed with Time of day and Time of day squared as fixed factors and hourly light level as dependent variable for participants with an early or late chronotypes, a relatively high or low social jetlag and a high or low level of general subjective fatigue respectively.

To explore differences in dynamic patterns of vitality throughout the day, similar HLM analyses were performed with subjective vitality as dependent variable separately for early vs. late chronotypes, participants with a high vs. low social jetlag and with a high vs. low general fatigue, respectively. In addition, Hourly light exposure was added as fixed factor to the model to explore differences between the respective groups in the strength of the relationship between hourly light exposure and subjective vitality, after controlling for systematic variations in feelings of vitality as a function of clock time.

Results

On average, late chronotypes were exposed to lower light levels and reported lower vitality in the morning than early chronotypes (Figure 1a). Participants with a higher social jetlag received more light at

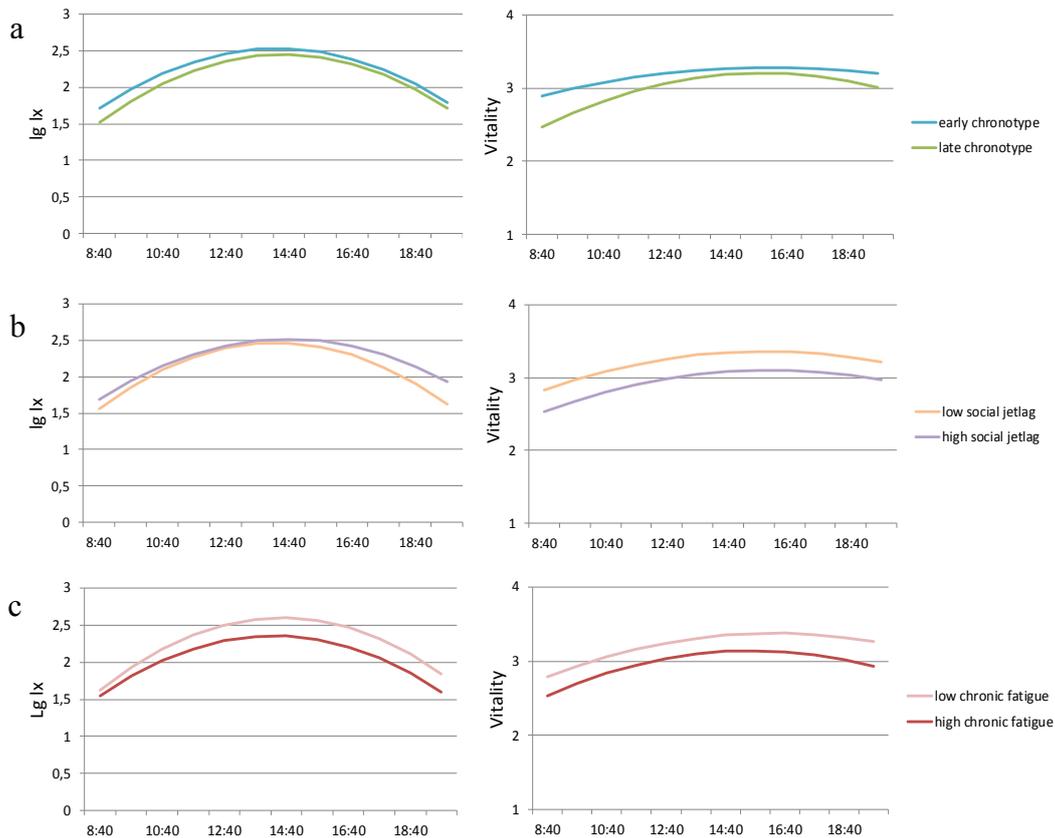


Fig. 1: Average light exposure and subjective vitality patterns throughout the day among (a) early vs. late chronotypes, (b) persons with a relatively small vs. large social jetlag and (c) persons with a relatively low vs. high general level of subjective fatigue.

eye in the late afternoon and early evening than those with a lower social jetlag, but they reported lower vitality throughout the day (Figure 1b). Participants with high ratings of fatigue were exposed to lower light levels and reported lower vitality throughout the day (Figure 1c).

HLM analyses to test whether variations in the average amount of light experienced per hour were related to feelings of vitality for each group revealed inter-individual differences in the relational strength as a function of chronotype and social jetlag. The relationship between the average amount of light experienced during the hour prior to completing the questionnaires and vitality was significant among late chronotypes ($\beta = .14$; $p < .01$), but not among early types ($\beta = .03$; $p = .36$). Similarly, light intensity was a significant predictor for subjective vitality among participants with a high social jetlag ($\beta = .13$; $p < .01$), but not with a low social jetlag ($\beta = .05$; $p = .14$). General level of subjective fatigue did not moderate the relationship between light exposure and

vitality. Yet, this relationship was significant for participants with either a low ($\beta = .11$; $p < .01$) or a relatively high level of general fatigue ($\beta = .09$; $p = .03$). Note that both circadian phenotype measures were related ($r = .67$, $p < .01$), while general fatigue only showed a subtle correlation with chronotype and social jetlag ($r = .28$ and $r = -.10$, respectively).

Discussion

The current results show that individuals' light exposure during the day and acutely vitalizing effects of white light in everyday life depend on chronotype. These findings complement earlier results by Martin et al. (2012), which demonstrated inter-individual differences in light exposure patterns throughout the day as a function of individuals' chronotype. Moreover, they corroborate results on inter-individual differences in responsiveness to acute effects of blue or blue-enriched light exposure on alertness as a function of individual's clock gene polymorphisms (Chellappa et al, 2012;

Vandewalle et al., 2011). In the current study, late chronotypes felt more energetic when they were exposed to more light during the previous hour, while light intensity was not significantly related to subjective vitality in early chronotypes.

It should be noted that the current results cannot be translated to individuals' sensitivity to acute activating effects of light in the late evening, as we did not measure participants' light exposure and feelings of vitality at these time points (i.e., after 8 pm). In fact, results by Chellappa et al. (2012) suggested stronger acute effects of light with a high compared to low correlated color temperature on alertness in the late evening among early chronotypes.

In the current study, we also assessed inter-individual differences as a function of social jetlag and subjective fatigue. Participants with a higher social jetlag appeared to benefit most from exposure to higher light intensities during daytime hours. Yet, although individuals with relatively high levels of general fatigue were exposed to lower levels of light and reported lower vitality as compared to the less fatigued subjects, light intensity was a significant predictor for vitality in both groups.

In conclusion, we believe that our findings presented here will not only inspire further follow-up studies, but will also help to design biologically healthier lighting environments in the future.

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