Supplementary materials

Investigation of dose-response relationships for effects of white light exposure on correlates of alertness and executive control during regular daytime working hours

Running title: Effects of light intensity on daytime alertness and executive control

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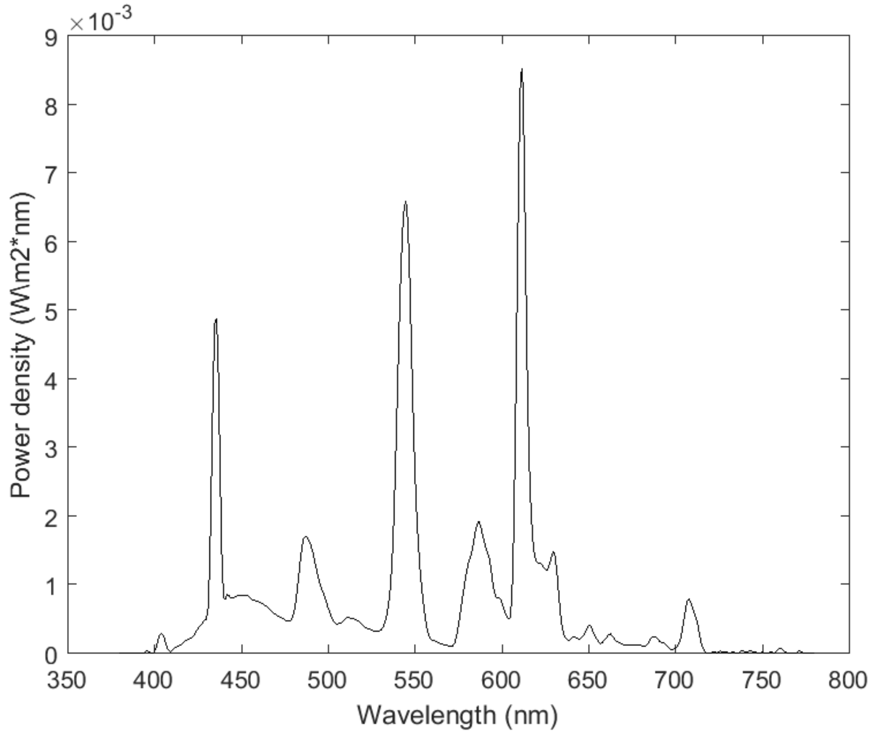

Figure S1.1 Spectral power distribution, measured in the 100 lux (4000K) condition (at the eye).

Table S1.1 Target and measured illuminance levels and spectrally weighted α-opic lux levels at the eye for each light condition

Condition	Target illuminance level (in lux)	Measured illuminance level (in lux)	Melanopsin (in α-opic lux)	S-Cone (in α-opic lux)	M-Cone (in α-opic lux)	L-Cone (in α-opic lux)	Rods (in α-opic lux)
1	20	20.7	13.6	15.5	18.5	20.2	15.6
2	32	32.8	21.4	24.6	29.3	31.9	24.6
3	41	43.3	28.2	32.2	38.7	42.1	32.4
4	51	52.8	34.3	39.2	47.2	51.4	39.5
5	65	66.5	43.3	49.0	59.4	64.7	49.8
6	82	82.4	53.4	59.8	73.6	80.0	61.6
7	104	103.4	71.2	71.9	93.1	100.7	80.7
8	132	134	92.2	93.4	120.6	130.5	104.6
9	168	166.2	114.6	116.5	149.6	162.0	129.8
10	189	187.5	129.1	132	168.8	182.8	146.3
11	239	241.2	166.1	170.0	217.1	235.1	188.3
12	302	305.5	210.3	215.0	274.9	297.7	238.4
13	383	384.4	264.8	269.4	346.1	374.6	300.2
14	485	483.7	333.1	337.1	435.5	471.2	377.8
15	614	616.9	424.4	428.4	555.4	600.9	481.6
16	778	780.1	535.3	529.4	702.5	759.0	608.8
17	985	983.2	672.2	651.6	885.4	955.8	766.2
18	1247	1249.5	849.9	799.9	1125.4	1212.8	972.3
19	1579	1575.4	1060.8	977.7	1417.4	1526.3	1220.3
20	2000	2002.2	1329.8	1218.5	1798.4	1935.5	1540.2

Note. Values for α-opic lux are computed based on the irradiance toolbox by Lucas et al. (2014).

Statistical analyses

Preparatory analyses. Preparatory analyses were first performed to investigate 1) potential deviations of participant's sleep-wake timing during the pre-exposure day(s) from his or her self-reported preferred sleep-wake timing and habitual sleep-wake pattern on work/lecture days, and 2) differences in sleep timing prior to the spring vs. winter sessions and prior to the morning vs. afternoon laboratory sessions. Potential differences in the mid-sleep during the pre-exposure day(s) and participants' chronotype (assessed with mid-sleep on days off) and their habitual mid-sleep on work and/or lecture days as reported in the MCTQ were tested by means of Linear Mixed Model (LMM) analyses. These analyses were employed to test whether 1) potential differences in sleep timing were significantly different from zero, and 2) whether they were moderated by Season and/or Time of day. As dependent variables, we used difference scores where the habitual mid-sleep on days off or work/lecture days was subtracted from the mid-sleep during the pre-exposure day(s). Next, the (average) mid-sleep during the pre-sampling day(s) was used as dependent variable to test whether participants' mid-sleep prior to the experimental sessions significantly differed for the spring vs. winter sample and for the morning vs. afternoon sessions. For this series of preparatory analyses, mid-sleep computed based on self-reported sleep onset and sleep offset during the pre-exposure day(s) was used as marker. In addition to sleep timing, potential differences in sleep duration, sleep latency, and duration of sleep inertia during the pre-sampling day(s) between the two seasons and morning vs. afternoon sessions were investigated by means of LMM analyses. All these preparatory LMM analyses were performed for the various sleep markers during the last day and the last three days prior to the experimental sessions, separately.

In addition to these preparatory analyses for sleep timing, sleep duration, sleep latency and sleep inertia, we explored potential differences in confounding variables related to participants' behavior prior to the experimental sessions (i.e., caffeine consumption, food intake, and travelling time outdoors). Moreover, we tested potential baseline differences in the dependent measures between the two seasons and between the morning and afternoon laboratory sessions.

For this series of preparatory analyses, LMM analyses were performed on the complete dataset (i.e., data obtained in spring and winter including both the morning and afternoon sessions). In these LMMs, Participant ID was added as independent random intercept to indicate that the data measured during both experimental sessions within each participant were clustered. In addition, full factorial models were employed with the factors Season and Time of day added as independent fixed variables in these preparatory LMM analyses. Separate analyses were performed for each dependent variable. In contrast to the other analyses, caffeine consumption was analyzed with a logistic LMM analysis as this dependent variable was coded as a dichotomous variable with 0 corresponding to no caffeine consumption and 1 to at least one cup of caffeine. All preparatory analyses were performed using the lme4 and lmerTest package for mixed models in R 3.3.2.

Detailed description of effect testing and curve fitting. In order to determine the dose-response relationship between light intensity and markers of alertness and executive functioning, a curve fitting procedure was performed for each dependent variable. In addition, similar analyses were performed for the various indicators of mood and appraisals. For each variable, two functions were investigated: a linear relationship and a four-parameter logistic model. In these analyses, the log-transformed light intensity was used as independent variable.

First, LMM analyses were performed to fit a linear relationship between light intensity and markers of alertness and executive functioning, and test the effects of the Timing of the light exposure (morning vs. afternoon), Season (spring vs. winter) and Block on the various markers. To this end, a LMM with Light intensity (log transformed), Time of day, Season, and Block as fixed factors was run for each of the dependent variables. In these models, the 2-way and 3-way interaction effects between Time of day, Season, and Block were included. In case a significant effect of Light intensity emerged or visual inspection of the data revealed clear time-of-day, seasonal or time-in-session dependent differences in responsiveness, we also explored potential moderations in this linear relationship by Time of day, Season, and Block. For each of the dependent variables, we used difference scores where the baseline value was subtracted from the raw value measured during the experimental light exposure phase. Participant ID and Session (first vs. second visit to the laboratory) nested within Participant ID were included as independent random intercepts to cluster the repeated measurement data from the four blocks within an experimental session for each a participant. These LMM analyses were performed using the lme4 package in R 3.3.2. The lmerTest and r2glmm packages were used to determine corresponding p-values and (partial) R-squared, respectively.

In addition to these multilevel analyses, we fitted a four-parameter logistic model which was similar to the model constructed for nighttime by Cajochen et al. (2000) and used in the analysis by Hommes and Gimenez (2015): $f(x) = d + (a-d)/(1+(x/b)^c)$. The parameters of the four-parameter logistic models (a, b, c, and d) represent the value of the intercept (i.e., value at 0 lg lux), Hill's slope (i.e., steepness of curve at the intensity (in log lux) at which 50% of the maximum response occurs), inflection point (i.e., intensity (in log lux) at which 50% of the maximum response is achieved), and the asymptotic maximum response, respectively. In these analyses, the average difference scores over all four measurement blocks during the light exposure phase within one experimental session were used as dependent variables. For each dependent variable, two separate four-parameter logistic models were fitted, one for the morning and one for the afternoon data due to dependency in the data and the fact that we wanted to investigate potential time-of-day-dependent differences in responsiveness. The fits were estimated by means of a non-linear least squares estimation using Levenberg-Marquardt method. The parameters and 95% confidence intervals of the four parameters for these models were inspected to check whether these were different from zero and whether parameters a and b had no overlapping intervals. Moreover, R-squared was used as an indicator for the goodness of fit of the models. This curve fitting was performed in Matlab R2015b.

Results

Sleep timing during pre-sampling days. Results of the LMM analyses with the average difference in mid-sleep over all three pre-exposure days revealed that both intercepts were significantly different from zero: Participants' mid-sleep during the three days prior to the experimental sessions was, on average, 39 min (*SE* = 9 min) earlier than their preferred mid-sleep ($t(1,83) = -4.53$; $p < .01$), but 40 min (*SE* = 8 min) later than participants' habitual work/lecture days ($t(1,85) = 5.28$, $p < .01$). Results revealed no significant main or interaction effects of Season and Time of day for these differences in mid-sleep (all $p > .05$). Similar analyses were performed for the difference between the mid-sleep on the last day prior to the experimental session and habitual mid-sleep on work/lecture days and days off. Results showed that the mid-sleep on the night prior to the experimental session occurred, on average, 57 minutes (*SE* = 9 min) earlier than participants' habitual mid-sleep on days off and 22 min (*SE* = 8 min) later than their reported habitual mid-sleep on work/lecture days. These differences were both significant different from zero (t(1,78) = -6.34, p < .01 and t(1,83) = 2.65, p < .01, respectively). Again no significant effects of Season, Time of day and Season*Time of day emerged (all p > .05).

Inspection of potential time-of-day-dependent and seasonal-dependent variations in participants' average mid-sleep during the three pre-sampling days and their mid-sleep during the last day prior to the experimental session revealed again no significant effects of Season, Time of day and Season*Time of day (all p > .05), suggesting no structural statically significant intra-individual and group-related differences in sleep timing. The intercept revealed that participants' mid-sleep occurred, on average, at 4:32 (SE = 9 min) during the three pre-exposure days, and at 4:12 (SE = 10 min) on the night prior to the laboratory sessions.

LMM analyses for sleep duration revealed a significant main effect of Time of day on the sleep duration during the night prior to the experimental session (F(1,59) = 4.10, p = .05, R^2 = .03), but not on the average sleep duration during the three pre-sampling days (F(1,57) = 1.14, p = .29). Participants slept longer on the night prior to the afternoon (EMM = 7.75, SE = .18) than the night prior to the morning sessions (EMM = 7.29, SE = .19). Season had no significant main or interaction effect on sleep duration during the pre-sampling day(s) (all p > .05). Season and Time of day had a significant main effect on the average sleep latency during the three pre-sampling days (F(1,61) = 10.95, p < .01, R^2 = .08, and F(1,57) = 6.47, p = .01, R^2 = .02, respectively), while the interaction effect was not significant (F<1, ns). The average sleep latency in minutes was longer during the three pre-sampling days in the winter sample (EMM_{Winter} = 43, SE = 4.18; EMM_{Spring} = 26, SE = 3.14) and prior to the morning sessions ($EMM_{Morning}$ = 38, SE = 3.02; $EMM_{Afternoon}$ = 31, SE = 2.90). Sleep latency during the night prior to the experimental sessions was only significantly different between the sample in the winter (EMM = 39, SE = 4.57) and in spring (EMM = 22, SE = 3.39; F(1,59) = 8.04, p < .01, R^2 = .07). Season and Time of day had no significant main or interaction effects on the average sleep inertia during the three pre-sampling days nor on sleep inertia in the morning prior to the experimental sessions (all p > .05).

Potential confounding variables. LMM analyses revealed no significant seasonal or time-of-day dependent differences in the self-reported amount of food intake prior to the experimental sessions (all F<1, ns). In contrast, there was a significant difference in caffeine consumption prior to the experimental session in the morning (EMM = .15, SE = .07) and afternoon (EMM = .39, SE = .11; Z = 3.07, $p < .01$, $R^2 = .10$). In addition, participants had spent less time (in minutes) outdoors prior to the experimental sessions in the morning (EMM = 23.61, SE = 2.10) than in the afternoon (EMM = 33.96; SE = 2.17; $F(1,61) = 14.59$, $p < .01$, $R^2 = .13$).

Baseline comparisons for the dependent measures. Table S2.1 provides the average baseline scores of the behavioral, self-reported, and physiological indicators for alertness and executive functioning in the morning and afternoon for the spring and winter sample. Baseline comparisons revealed that there was no significant difference in PVT speed at baseline between the spring and winter data collection phases, nor between the morning and afternoon sessions (both main effects and interaction effect: $F<1$, ns). In contrast, baseline comparisons for the tasks probing executive functioning revealed (near-) significant differences in baseline performance between seasons, indicating better performance on the Go-NoGo and 2-back task in the winter in terms of both speed and accuracy (see Table S2.2). There were no significant main or interaction effects of Time of day on baseline performance on these tasks, except for a significant Season*Time of day interaction effect on Go-NoGo accuracy ($F(1,60) = 5.33$, $p = .02$, $R^2 = .04$), suggesting that the difference in baseline Go-NoGo accuracy between the two seasons was larger in morning than in the afternoon sessions (see Table S2.2).

Baseline comparisons for self-reported sleepiness, vitality, tension, positive affect, and negative affect revealed no significant main or interaction effects of Time of day and Season (all $p > .05$). LMM analyses for the physiological indicators (HR and skin conductance level) showed also no significant baseline differences as function of Season and Time of day (all $p > .05$).

Table S2.1 Baseline scores of behavioral, subjective and physiological indicators for the morning and afternoon experimental sessions in spring and winter.

		Spring				Winter			
		Morning		Afternoon		Morning		Afternoon	
	Variable	*EMM*	*SE*	*EMM*	*SE*	*EMM*	*SE*	*EMM*	*SE*
Behavioral indicators	PVT	3.01	.06	3.04	.06	3.00	.08	2.97	.08
	Go-NoGo task - speed	3.63	.19	3.79	.19	4.16	.26	4.25	.25
	Go-NoGo task - accuracy	.27	.01	.29	.01	.50	.01	.48	.01
	2-Back task - speed	1.22	.02	1.20	.03	1.33	.03	1.31	.03
	2-Back task - accuracy	.80	.02	.79	.02	.85	.03	.87	.03
Subjective indicators	Sleepiness	5.58	.29	5.65	.30	5.68	.39	5.82	.39
	Vitality	2.92	.12	2.90	.12	2.94	.15	2.89	.15
Physiological indicators	HR	77.44	1.74	82.84	1.82	77.19	2.32	77.10	2.32
	SCL	5.59	.68	3.72	.70	5.74	.94	5.24	.86

Note. *EMM* stands for Estimated Marginal Means, *SE* stands for standard error.

Table S2.2. Statistics for baseline comparisons executive control: performance on Go-NoGo and 2-Back task

	Spring		Winter		Statistics			
	EMM	*SE*	*EMM*	*SE*	F	df	p	R^2
Go-NoGo task - speed	3.71	.17	4.20	.22	3.08	(1,58)	.08	.03
Go-NoGo task - accuracy	**.28**	**.01**	**.49**	**.01**	**326.48**	**(1,59)**	**<.01**	**.66**
2-Back task – speed	**1.21**	**.02**	**1.32**	**.03**	**8.42**	**(1,60)**	**.01**	**.09**
2-Back task - accuracy	**.79**	**.02**	**.86**	**.02**	**5.37**	**(1,60)**	**.02**	**.03**

Note. *EMM* stands for Estimated Marginal Means, *SE* stands for standard error. Significant differences are indicated in bold

Table S2.3. Parameter estimates with confidence intervals for the four-parameter logistic models of mood and appraisals, and goodness of fit based on data of the morning sessions

	Variable	A	b	c	d	R^2
Mood	Tension	.22 (.03, .41)	2.49 (-27.26, 32.24)	261 ($-1.04*10^6$, $1.04*10^6$)	-.08 (-.31, .15)	.07
	Positive affect	-.39 (-.64, -.14)	4.39 (-161, 170)	10.72 (-92.64, 114)	8.81 (-3300, 3317)	.03
	Negative affect	2.68 (-3646, 3651)	2.53 (-1469, 1474)	.29 (-408, 408)	-2.72 (-4056, 4051)	.04
Appraisals	Experienced pleasantness	1.32 (-.25, 2.89)	**1.47** **(1.01, 1.93)**	39.56 (-387, 466)	3.15 (2.85, 3.45)	.15
	Color of the lighting	**2.67** **(2.03, 3.30)**	1.77 (-8.10, 11.64)	212 ($-5.04*10^4$, $5.09*10^4$)	**3.65** **(3.37, 3.94)**	.15
	Disturbing	14.33 ($-4.30*10^7$, $4.30*10^7$)	1.26 ($-9.04*10^4$, $9.04*10^4$)	57.45 ($-3.05*10^6$, $3.05*10^6$)	2.35 (2.04, 2.65)	.07
	Brightness	.04 (-39.27, 39.36)	33.48 ($-1.06*10^4$, $1.06*10^4$)	1 (-29.03, 31.22)	58 ($-1.52*10^4$, $1.54*10^4$)	.38
	Activating	**1.95** **(1.52, 2.39)**	2.14 ($-1.72*10^4$, $1.72*10^4$)	418 ($-4.33*10^8$, $4.33*10^8$)	**3.24** **(2.88, 3.61)**	.30

Note: Parameters b and c are printed in **bold** if significantly different from 0; parameters a and d are printed in **bold** if their 95% confidence intervals do not overlap.

Table S2.4. Parameter estimates with confidence intervals for the four-parameter logistic models of mood and appraisals, and goodness of fit based on data of the afternoon sessions

	Variable	A	b	c	d	R^2
Mood	Tension	<.01 (-.18, .20)	2.70 ($-2.62*10^6$, $2.62*10^6$)	666 ($-1.20*10^{11}$, $1.20*10^{11}$)	-.33 (-.69, .02)	.06
	Positive affect	-1.04 ($-2.01*10^4$, $2.01*10^4$)	.73 ($-3.59*10^4$, $3.59*10^4$)	.20 (-4726, 4726)	.36 ($-1.31*10^4$, $1.31*10^4$)	<.01
	Negative affect	-.44 ($-1.82*10^4$, $1.82*10^4$)	.78 ($-8.10*10^4$, $8.10*10^4$)	-.15 (-7906, 7905)	.37 ($-2.45*10^4$, $2.45*10^4$)	<.01
	Experienced pleasantness	1.52 (-4.11, 7.16)	**1.43 (.47, 2.40)**	24.37 (-194, 242)	3.22 (2.90, 3.54)	.09
Appraisals	Color of the lighting	**2.30 (1.56, 3.04)**	**2.07 (1.75, 2.38)**	13.30 (-10.94, 37.54)	**3.89 (3.37, 4.41)**	.30
	Disturbing	2.20 (-1.89, 2.51)	2.84 (-5.91, 11.59)	367 ($-6.61*10^4$, $6.68*10^4$)	2.92 (2.24, 3.59)	.08
	Brightness	.88 (-3.75, 5.51)	**1.72 (0.60, 2.83)**	5 (-8.31, 18.98)	3.59 (2.36, 4.82)	.28
	Activating	**2.10 (1.68, 2.51)**	2.14 (-6.13, 10.40)	217 ($-1.12*10^5$, $1.12*10^5$)	**3.54 (3.21, 3.87)**	.36

Note: Parameters b and c are printed in **bold** if significantly different from 0; parameters a and d are printed in **bold** if their 95% confidence intervals do not overlap.