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Exposure to Bright Light Biases Effort-Based Decisions

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Secreted in the evening and the night, melatonin suppresses activity of the mesolimbic dopamine pathway, a brain pathway involved in reward processing. However, exposure to bright light diminishes—or even prevents—melatonin secretion. Thus, we hypothesized that reward processing, in the evening, is more pronounced in bright light (vs. dim light). Healthy human participants carried out three tasks that tapped into various aspects of reward processing (effort expenditure for rewards task [EEfRT]; two-armed bandit task [2ABT]; balloon analogue risk task [BART). Brightness was manipulated within-subjects (bright vs. dim light), in separate evening sessions. During the EEfRT, participants used reward-value information more strongly when they were exposed to bright light (vs. dim light). This finding supported our hypothesis. However, exposure to bright light did not significantly affect task behavior on the 2ABT and the BART. While future research is necessary (e.g., to zoom in on working mechanisms), these findings have potential implications for the design of physical work environments.

Keywords: effort-based decision making, reinforcement learning, risk taking, bright light, motivation

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Because of societal change and technological progress, it is becoming more and more common for people to do work during the evening and the night, rather than only during the day (Madden, Jones, & Pew Research Center, 2008; Purcell, Rainie, & Pew Research Center, 2014). Against the background of this transition, it is potentially worthwhile to study human decision-making processes as they occur in the evening and the night. In this research, we examine how different lighting conditions (bright light vs. dim light), in the evening, impact people's reward- and effort-related decisions. As explained in greater detail below, our main line of reasoning draws from research on melatonin—dopamine interactions and from research on the role of the mesolimbic dopamine pathway in reward processing. Building on this prior work, we hypothesize that reward processing in the evening is more pronounced in bright light (vs. dim light).

In humans, melatonin secretion, which occurs from the pineal gland, is controlled by the suprachiasmatic nucleus (SCN), an endogenous circadian oscillator (Bass, 2012; Cajochen, Kräuchi, & Wirz-Justice, 2003). Melatonin's main function is to maintain the body's circadian rhythm; for example, by helping to initiate and maintain sleep (Bass, 2012; Cajochen et al., 2003; Shochat, Luboshitzky, & Lavie, 1997). Under normal circumstances, the SCN triggers melatonin secretion starting in the evening (Bass, 2012; Reppert, Perlow, Tamarkin, & Klein, 1979). Importantly, however, melatonin secretion can be inhibited by exposure to light. That is, the SCN receives input from light-sensitive cells in the retina (specifically, from nonimage forming intrinsically photosensitive retinal ganglion cells; Lucas et al., 2014). As a result of such input, even brief periods of exposure to bright light (e.g., 20 min), particularly short-wavelength light (e.g., 475 nm; Brainard et al., 2008; Thapan, Arendt, & Skene, 2001), are sufficient to suppress melatonin secretion. So, it is commonly assumed that melatonin release during the evening is suppressed (or even prevented) by exposure to bright light.

Over the last decades, evidence has accumulated for the idea that melatonin inhibits functioning of the mesolimbic dopamine pathway, a collection of neurons projecting from the ventral tegmental area to the striatum. Early support for this idea comes from in vivo studies in rats, which showed diminished activity in striatal neurons after melatonin administration (Castillo-Romero, Vives-Montero, Reiter, & Acuña-Castroviejo, 1993; Escames, Acuña Castroviejo, & Vives, 1996). These findings are complemented by in vitro studies, which showed diminished dopamine release from slices of cells (e.g., from the rat hypothalamus) after melatonin infusion (Zisapel, 2001; Zisapel, Egozi, & Laudon, 1982; Zisapel & Laudon, 1982). Also, in rats, several reward-related behaviors (which depend on the mesolimbic dopamine pathway) have been shown to be suppressed by melatonin (Takahashi, Vengeliene, & Spanagel, 2017; Vengeliene, Noori, & Spanagel, 2015). In humans, melatonin likely serves a similar inhibitory function. At least, melatonin M1 receptors have been found to be expressed in the striatum, in a similar way as in mice (Uz et al., 2005). Also, in humans, dopamine release follows both a circadian (Korshunov,

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Blakemore, & Trombley, 2017) and a seasonal pattern (Eisenberg et al., 2010), suggesting a connection to melatonin. Thus, prior research is consistent with the idea that melatonin inhibits functioning of the mesolimbic dopamine pathway across species.

The mesolimbic dopamine pathway, in turn, supports various aspects of adaptive reward processing. In particular, activity in the striatum represents the value of outcomes that can be earned (Delgado, 2007; Knutson, Adams, Fong, & Hommer, 2001; Knutson, Taylor, Kaufman, Peterson, & Glover, 2005). As such, the mesolimbic dopamine pathway is involved in *effort-based decisions*, that is, decisions about whether a reward is worth expending effort (Pardo, López-Cruz, San Miguel, Salamone, & Correa, 2015; Pas, Custers, Bijleveld, & Vink, 2014; Phillips, Walton, & Jhou, 2007; Salamone, 1988; Salamone, Correa, Farrar, Nunes, & Pardo, 2009). Also, it is involved in *reinforcement learning,* that is, learning what actions, or choices, reliably predict rewards (Hollerman & Schultz, 1998; Pessiglione, Seymour, Flandin, Dolan, & Frith, 2006; Treadway et al., 2012; Vink, Pas, Bijleveld, Custers, & Gladwin, 2013). Furthermore, the mesolimbic dopamine pathway is involved in *decision making under risk*, that is, making choices between options with different reward probability/value combinations (Kuhnen & Knutson, 2005; St Onge & Floresco, 2009).

To recap, prior work shows that (a) bright light inhibits melatonin release in the evening, (b) melatonin suppresses functioning of the mesolimbic dopamine pathway, and (c) the mesolimbic dopamine pathway is involved in reward processing. On the basis of these lines of research, we expect that reward processing in the evening is more pronounced in bright light (vs. dim light).

Here we present an experiment to test the latter hypothesis. Participants visited the laboratory twice, both times in the evening (9:00 p.m. to 11:00 p.m.). Both times, they carried out three standard tasks to observe effort-based decision making, reinforcement learning, and decision-making under risk. During one of the sessions, they were exposed to bright light; during the other session, they were exposed to dim light.

To examine effort-based decision making, we used the effort expenditure for rewards task (EEfRT; Treadway, Buckholtz, Schwartzman, Lambert, & Zald, 2009). In the EEfRT, participants repeatedly choose to exert effort to earn varying amounts of money, at varying probabilities. We expect that participants use information about reward value (absolute value and expected value) more strongly when they are exposed to bright light (vs. dim light). To examine reinforcement learning, we used a two-armed bandit task (2ABT; Chowdhury et al., 2013). In the 2ABT, participants repeatedly choose between two options, each of which led to reward with a varying probability. We expect that participants have a higher learning rate when they are exposed to bright light (vs. dim light). To examine decision making under risk, we used the balloon analogue risk task (BART; Lejuez et al., 2002; Lejuez, Aklin, Zvolensky, & Pedulla, 2003). In the BART, participants repeatedly choose between safe options (yielding little money) and risky options (potentially yielding more money). We expect participants to be more inclined to choose risky options when they are exposed to bright light (vs. dim light).

Method

Data Availability

All materials, data and code can be downloaded from our project page at the Open Science Framework (see https://osf.io/nqdhf/).

Participants and Design

Thirty-six students (M_{age} = 24.0, SD = 7.2; 26 female, 13 male) were recruited to participate in the experiment that had a within-subjects design (brightness: bright vs. dim). Participants visited the laboratory twice, with at least 4 days in between. During one of their visits, participants carried out the three tasks in bright light. During their other visit, they carried out the same three tasks in dim light. The order of the brightness treatments was counterbalanced across subjects. A priori exclusion criteria were as follows: use of photosensitizing medication, pregnancy, abnormal sensitivity to light, having a sleep disorder. All participants gave written informed consent. Participants received either course credits or a gift voucher, worth €15 (≈$19), for their participation. In addition, they could earn extra gift vouchers during the task (for details, see the following text).

Procedure

When participants arrived at the laboratory, they were seated in a cubicle that contained a desk and a computer. Lighting in this cubicle was adapted according to the manipulation, as detailed below. All sessions took place between 9:00 p.m. to 10:00 p.m. or 10:00 p.m. to 11:00 p.m. All sessions were planned in March, before the start of daylight saving time. As a result, all sessions started at least one hour after sundown.

Participants first filled out a brief questionnaire to measure their current mood state (this took ±1 min). Specifically, they self-rated the extent to which they felt alertness, sadness, tension, effort, happiness, fatigue, calmness, sleepiness, and anxiety, on a scale ranging from *not at all* (1) to *very much* (7). In addition, they filled out the Karolinska Sleepiness Scale, a verbally anchored rating scale, ranging from *extremely alert* (1) to *fighting sleep* (9), (Åkerstedt & Gillberg, 1990).

To adapt to the bright light (or the dim light, depending on condition), participants then listened to a neutral music fragment for 10 min. Next, participants performed the three tasks: the EEfRT (±2-min instructions +20-min task performance), the 2ABT (±1-min instructions + ±19-min task performance), and the BART (±1-min instructions + ±6-min task performance). These tasks are described in detail in the following text. In all sessions, tasks were presented in this fixed order. All computer tasks were scripted such that they had a black background, to minimize the amount of light emitted by the monitor.

When participants finished the three tasks, they again filled out the same questionnaire as before (±1 min), so that we could explore whether their mood state had changed during the session. Finally, they were debriefed (they learned the hypothesis after the second session), paid, and thanked for their participation.

Light Manipulation

In the bright light condition, fluorescent office lighting was switched on. In addition, the room was lit with a 30W LED

floodlight, which lit the white wall behind the computer monitor. Measured near the eye, illuminance was 360–400 lux (depending on sitting posture). Peak wavelength was 470–585 nm (depending on gaze direction and current screen content). In the dim light condition, office lighting in the cubicle was switched off. In addition, the cubicle window was covered with cardboard. Near the eye, illuminance was 0–1 lux.

We assume that our specific bright light versus dim light manipulation (i.e., 360 to 400 lux, between 9:00 p.m. and 11:00 p.m., throughout the 1-hr session) will impact melatonin secretion. In our view, this is a safe assumption, given the following previous findings. First, several studies showed that short light pulses are sufficient to impact melatonin secretion (e.g., 12 min, Chang et al., 2012; ≤2 min, Rahman et al., 2017). Second, several studies showed that single pulses of bright light are sufficient to suppress melatonin (Figueiro & Overington, 2015; West et al., 2011). Third, several studies showed that subtle light manipulations (e.g., ≤200 lux illuminance difference between conditions) are sufficient to suppress melatonin secretion. These studies, for example, compared light-emitting e-readers against books (Chang, Aeschbach, Duffy, & Czeisler, 2015), or normal room light against dim light (Gooley et al., 2011). Fourth, several studies showed that light pulses administered in the evening (between 9:00 p.m. and 11:00 p.m.) can suppress melatonin secretion (Cajochen et al., 2011; Santhi et al., 2012). So, the key ingredients our light manipulation have previously been shown to be effective.

We further note that all studies cited in the previous paragraph found effects of bright light on melatonin concentrations in either blood plasma or saliva. However, there is no compelling reason to assume that melatonin needs to be in blood (or saliva, for that matter) in order to reach the mesolimbic dopamine system. In fact, to reach neurons involved in reward processing (e.g., in the striatum), melatonin does not need to travel much: the pineal gland directly releases melatonin into the cerebrospinal fluid of the third ventricle, from where it disperses into the brain (Reiter, Tan, Kim, & Cruz, 2014). Indeed, animal studies suggest that melatonin concentrations in the cerebrospinal fluid are much higher, and much more sensitive to circadian processes, than melatonin concentrations in blood (Hedlund, Lischko, Rollag, & Niswender, 1977; Skinner & Malpaux, 1999). Thus, we reasoned, as bright light manipulations (much like ours) suppress melatonin concentrations in blood and saliva, it is highly plausible that the same manipulations reach brain structures that are part of the mesolimbic dopamine pathway. However, since we did not include melatonin measurements in our design, we cannot test this assumption empirically (see the Discussion, Limitations and Alternative Explanations section).

Tasks

Effort expenditure for rewards task (EEfRT). The EEfRT can be used to assess the extent to which people's decisions to exert effort are affected by reward value, reward probability, and their combination (i.e., expected value). The task was closely based on the task described by Treadway et al. (2009), with the main difference that our version was presented against a black background. For a schematic overview of a typical trial of this task, see Figure 1A. Participants worked on the EEfRT for 20 min in total; on average, they completed 52 trials during this time.

In the EEfRT, participants repeatedly chose between two activities that differ in their difficulty and their potential payoff. Specifically, on each trial of the task, participants chose between an easy task and a difficult task. When they chose the easy task, they had to tap a key on the keyboard 30 times in 7 s, with the index finger of their dominant hand. When they chose the difficult task, they had to tap a key on the keyboard 100 times in 30 s, with the pink of their nondominant hand. Right-handed participants had to use the Q key for the easy task and the P key for the difficult task. For left-handed participants, this was the other way around.

Before making their choice to do either the easy or the difficult task, participants were informed of the potential payoff of both options. The easy task's potential payoff was always €1 (≈$1.20). The difficult task's potential payoff was drawn from a uniform distribution, with range = [€1.20, €3.75] and M = €2.48. To win money, participants needed to successfully complete the task of their choice (easy or difficult) within the set time limit. However, even if they completed the task in time, participants were not guaranteed to always win the money. That is, some trials were so-called win trials, whereas other trials were "no win" trials. Before making their choice, participants learned the probability of the present trial being a win trial. This probability was either 12%, 50%, or 88%. Participants were informed that, at the end of the task, two trials would be randomly drawn from all win trials. Participants received additional gift vouchers representing the value of these two win trials. As such, in each session, participants could earn an additional €7.50 (≈$9.30) in gift vouchers during the EEfRT, depending on their choices and on chance.

In summary, on each trial participants learned (a) the amount of money that they could potentially win by choosing the difficult task and (b) the probability of that trial being a trial on which money could be won in the first place. After getting this information, participants decided whether or not to do the difficult task. These decisions served as the main dependent variable.

Two-armed bandit task (2ABT). The two-armed bandit task can be used to assess how strongly people use reward feedback to make decisions. In short, in this task, people repeatedly chose between either of two pictures. Their choice led to reward feedback or not. This reward feedback was probabilistic, with the probabilities changing during the session, which consisted of 200 trials. Using a reinforcement learning algorithm, we estimated people's learning rate α, which was the main dependent variable. We modeled our task after Chowdhury et al. (2013). For a schematic overview of a typical trial of this task, see Figure 1B.

More specifically, the task went as follows: Each trial began with a choice screen that contained two fractal images (the same images were presented on each trial). On each trial, participants had to select either of the two, based on their own free choice. They did so by pressing either of the *P* and *Q* keys of the keyboard. When they made their choice, the selected fractal image was framed with a red rectangle. The choice screen was always on screen for 3,000 ms. After their choice, participants received feedback. This feedback was either win feedback (a green euro sign) or no-win feedback (a red cross), depicted in the center of the screen for 1,000 ms. Participants were told that the participant who attained the most win feedback would receive a gift voucher, worth €50 (≈$62), in addition to their regular payment. The probabilities of attaining win feedback after choosing each stimulus were independent of each other, and varied on a trial-by-trial basis according

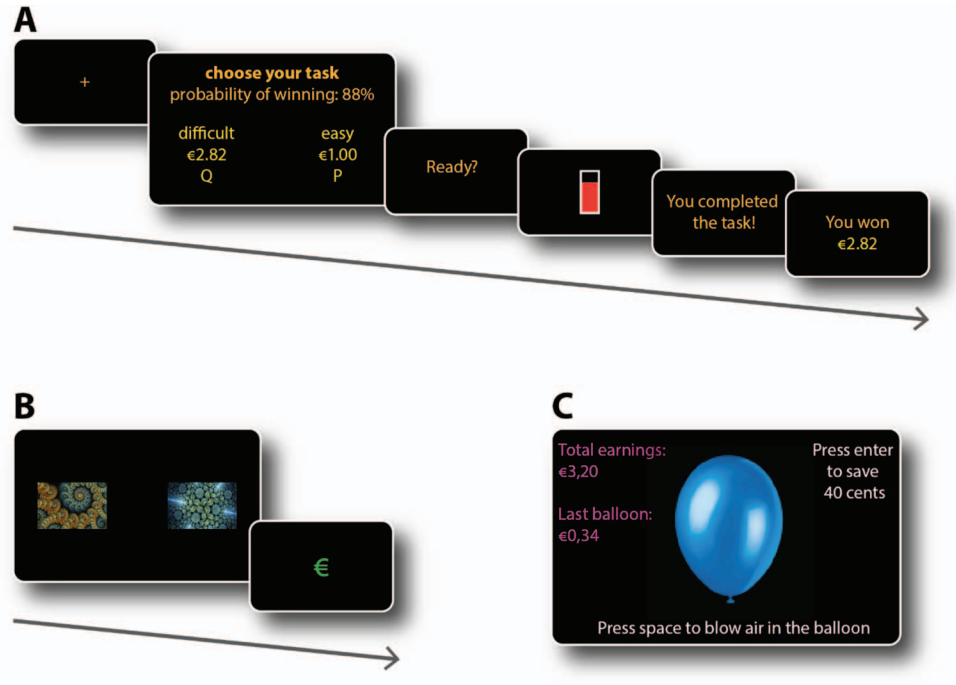

Figure 1. Schematic overview of task stimuli. Panel A: Overview of one typical trial of the effort expenditure for rewards task (EEfRT). Panel B: Overview of one typical trial of the two-armed bandit task (2ABT). Panel C: Overview of the main screen of the balloon analogue risk task (BART). See the online article for the color version of this figure.

to a Gaussian random walk (see Figure S1 in the online supplemental material). On both testing days, different pairs of fractal images were used, as well as different random walks. The order of the random walks was counterbalanced across subjects; this was done orthogonally to the order of the light treatment.

To compute participants' learning rate α from their choice behavior, we fitted a basic reinforcement learning model on the data, using an algorithm developed by Ahn, Haines, and Zhang (2017). In addition to α, this algorithm computes an inverse temperature parameter τ, which reflects participants' general tendency to shift back and forth between choice options. We had no specific predictions about how light exposure would affect τ.

To make parameter estimates based on participants' choices, the Ahn et al. (2017) algorithm uses hierarchical Bayesian modeling. This entails that individual- and group-level parameters were estimated simultaneously, in a mutually constraining fashion, using a Markov Chain Monte Carlo (MCMC) sampling procedure (1,000 burn-in samples; 2,000 iterations; and two chains; the chains converged to stationary distributions). We used a Rescorla-Wagner updating equation to compute predicted values (e.g., Chowdhury et al., 2013), by updating the predicted value of the chosen option with the prediction error:

$$V_{Lt} = V_{Lt-1} + \alpha(r_{t-1} - V_{Lt-1}) \quad (1)$$

or

$$V_{Rt} = V_{Rt-1} + \alpha(r_{t-1} - V_{Rt-1}), \quad (2)$$

where V_L and V_R are the predicted values for the left and the right option, respectively; α is the learning rate; and r is the reward that was received.

To translate learned values for V_L and V_R into choices, we used a softmax function:

$$p(L) = \frac{\exp(\tau \cdot V_L)}{\exp(\tau \cdot V_L) + \exp(\tau \cdot V_R)}, \quad (3)$$

where p(L) is the probability of choosing the left stimulus, and τ is the inverse temperature.

BART. The BART can be used to assess people's tendency to take risks. As in our own prior work (Bijleveld & Veling, 2014; Veling & Bijleveld, 2015), this task was modeled after Lejuez et al. (Lejuez, Aklin, Jones, et al., 2003).

In the BART, participants were presented with a virtual balloon on the computer screen (see Figure 1C). Participants could pump air in this balloon by pressing the spacebar. When they did so, the size of the balloon increased. By inflating the balloon, participants could accumulate money: with each pump, they earned €0.05 (≈$0.06). However, pumping air in the balloon also increased the probability of popping it. Specifically, with the first blow of air, the probability of popping the balloon was 1/128; with the second, 1/127; with the third, 1/126; and so on until the 128th blow, with which the balloon was certain to explode (1/1). Importantly, when the balloon exploded, participants would lose all the money they had accumulated until then. Instead of pumping air in the balloon, participants could also choose to keep the money, and to start over with a new balloon. So, participants continuously chose between a risky option (accumulating more money at the risk of losing everything; pumping air in the balloon) and a safe option (keeping the money they accumulated; starting over with a new balloon).

Before starting the task, participants learned that they would get 30 balloons to earn money. Although they did not receive the money they accumulated, they were informed that the participant with the best score received a gift voucher, worth €50 (≈$62), in addition to their regular payment.

Following previous validation studies (Lejuez et al., 2002; White, Lejuez, & de Wit, 2008), the BART score was computed by averaging the number of times participants pumped per balloon, across all balloons that did not pop. In previous work, this score is usually referred to as the *adjusted BART score*. A higher score reflects a greater tendency to pump air in the balloons, that is, to choose the risky option. For more details about this task, please see Lejuez, Aklin, Jones, et al. (2003).

Results

Descriptive Statistics

Table 1 presents means and standard deviations for the main dependent measures, separately for the bright light and the dim light session. Also, Table 1 presents test–retest correlations.

We highlight two observations from Table 1 here. First, at least on first sight, Table 1 suggests that participants' behavior was not markedly different between the two sessions. For example, overall, participants did not tend to choose more difficult tasks in the EEfRT during either of the sessions (in both sessions, *Ms* ≈ 50% of decisions were for the difficult task); also, they did not have a markedly different BART score (in both sessions, *Ms* ≈ 36) and not a markedly different learning rate α (in both sessions, *Ms* ≈ .58). Thus, if we are to find any effects of brightness condition, this should be expected only on a more detailed level—for example, specifically on participants' responsivity to reward during the EEfRT, or on any of the measures only after controlling for the order of the sessions. Second, when administering the same task twice, even under different circumstances, one would expect to find at least a moderate correlation between the two measurements. While such correlations were present for the EEfRT and the BART, this correlation was less strong ($r = .33$) for the learning rate α from the 2ABT. This statistic may indicate that measurements from the 2ABT were less reliable than the other two tasks. Thus, findings from this task should be interpreted with caution. Further descriptive statistics are presented in Tables S1 and S2 in the online supplemental material.

Effort Expenditure for Rewards Task (EEfRT)

Following Treadway et al. (2009), we examined participants' choices, treated as a binary dependent variable, on a trial-by-trial basis. To analyze these choice data, we used a series of generalized linear mixed models (Pinheiro & Bates, 2000), to closely mimic the analytic strategy of this previous study. Results from our four models appear in Table 2 and are discussed in more detail below. In all models, we included the session number (1 or 2) as a covariate, to take into account session order. In addition, in all models, we controlled for sex and trial number (again, to closely mimic the previous study by Treadway et al., 2009). In all models, following established guidelines (Barr, Levy, Scheepers, & Tily, 2013), we included a per-participant adjustment to the intercept (i.e., a random intercept), to take into account variation in participants' general tendency to choose the difficult option in the model. In line with the same guidelines (Barr et al., 2013), we also included random slopes for all within-subjects predictors (e.g., trial number, reward probability), to take into account that the strength of the effect of these within-subjects predictors may vary across participants.

Model 1 tested for main effects of reward probability, reward value, expected value, and brightness condition. This analysis revealed a significant main effect of reward value (estimate = 1.01, $z = 4.9$, $p < .001$), indicating that participants were more likely to choose the hard task more when a higher absolute amount of money was at stake. In addition, there was a significant main effect of expected value (estimate = 3.65, $z = 7.9$, $p < .001$). This effect indicated that participants were more likely to choose the hard task, when a higher absolute amount co-occurred with a high probability of winning. There was no significant main effect of brightness (estimate = −0.06, $z = -0.2$, $p = .852$). So, participants did not choose notably more difficult trials in either bright or dim light conditions.

Table 1
Descriptive Statistics for the Main Indices of Task Behavior, Separately for Bright Versus Dim Sessions

Task	Bright *M* (*SD*)	Dim *M* (*SD*)	$r_{\text{Bright–Dim}}$
EEfRT			
Proportion of difficult choices: Overall	.49 (.19)	.51 (.26)	.50**
Proportion of difficult choices: Low probability trials	.19 (.23)	.23 (.29)	.18
Proportion of difficult choices: Medium probability trials	.54 (.26)	.55 (.31)	.44**
Proportion of difficult choices: High probability trials	.74 (.22)	.75 (.28)	.78**
2ABT			
Learning rate α	.57 (.32)	.59 (.31)	.33*
Inverse temperature τ	2.51 (1.46)	2.51 (1.66)	.45**
Proportion of win feedback	.57 (.07)	.57 (.06)	−.27
BART			
Adjusted BART score	35.4 (14.2)	36.6 (16.9)	.70**

Note. EEfRT = effort expenditure for rewards task; 2ABT = two-armed bandit task; BART = balloon analogue risk task.
* $p < .05$. ** $p < .01$.

Table 2
Results From the Effort Expenditure for Rewards Task

Model	Term	Estimate	*SE*	*z*	*p*
1	Sex = female	−.3	.7	−.4	.665
	Trial number	−1.3	.6	−2.3	.022
	Session number	.8	.3	2.4	.016
	Reward probability	−1.3	1.0	−1.4	.170
	Reward value	1.0	.2	4.9	<.001
	Expected value	3.7	.5	7.9	<.001
	Brightness = bright	−.1	.3	−.2	.852
2	Sex = female	−.3	.7	−.4	.683
	Trial number	−1.3	.6	−2.3	.024
	Session number	.9	.4	2.4	.016
	Reward probability	−1.3	1.1	−1.2	.213
	Reward value	1.0	.2	4.7	<.001
	Expected value	3.8	.5	7.9	<.001
	Brightness = bright	.1	.4	.3	.783
	Reward Probability × Brightness	−.4	.6	−.6	.536
3	Sex = female	−.5	.7	−.6	.516
	Trial number	−1.4	.6	−2.5	.014
	Session number	.8	.3	2.5	.012
	Reward probability	−1.3	1.0	−1.3	.190
	Reward value	.8	.2	3.5	<.001
	Expected value	3.7	.5	7.8	<.001
	Brightness = bright	−1.4	.5	−2.5	.011
	Reward Value × Brightness	.6	.2	3.0	.003
4	Sex = female	−.2	.8	−.2	.828
	Trial number	−1.3	.6	−2.3	.021
	Session number	.8	.3	2.3	.023
	Reward probability	−1.4	1.0	−1.4	.152
	Reward value	1.0	.2	4.8	<.001
	Expected value	3.7	.5	7.3	<.001
	Brightness = bright	−.1	.4	−.1	.902
	Expected Value × Brightness	−.1	.3	−.3	.790

Note. This table presents results from the four generalized linear mixed model analyses we used to examine participants behavior during the Effort Expenditure for Rewards Task. Dependent variable: Choice (to do the difficult task).

Model 2 tested the interaction between reward probability and brightness. This interaction was not significant (estimate = −0.35, $z = -0.6$, $p = .536$). Thus, we found no evidence for the idea that exposure to bright light changes the extent to which people take into account reward probability.

Model 3 tested the interaction between reward value and brightness. This interaction was significant (estimate = 0.55, $z = 3.0$, $p = .003$). In line with our hypothesis, this effect indicated that the effect of absolute reward value was stronger when participants were exposed to bright light (vs. dim light). We explored this interaction in greater detail, as reported in Figure 2. Importantly, inspection of Figure 2 suggested that most participants—with only few exceptions—relied more strongly on reward value when they were exposed to bright light (vs. dim light).

To explore the robustness of this Reward Value × Brightness interaction, we explored whether this interaction depended on the inclusion of the other fixed effects in the model. First, we reran Model 3, but now without including sex, trial number, and session number as predictors. The Reward Value × Brightness interaction was still present (estimate = 0.48, $z = 2.5$, $p = .014$). Second, we ran a model with reward value, brightness, and the Reward Value × Brightness interaction as the only predictors. Also here, the Reward Value × Brightness interaction was still present (estimate = 0.28, $z = 2.12$, $p = .037$). These exploratory analyses suggest that the presence of the Reward Value × Brightness interaction is not an artifact of the particular combination of predictors that were included in the model.

Model 4 tested the interaction between expected value and brightness. This interaction was not significan (estimate = −0.07, $z = -0.3$, $p = .790$). Thus, there was no evidence for the idea that brightness changes the extent to which people take into account the expected value of their choice.

2ABT

As described in Method section, we derived participants' learning rate α from their choice behavior, separately for each session. We analyzed learning rate α using a linear mixed model, again using sex and session number as covariates. Also, we controlled for which of the two variants of the task was used in that session (i.e., which "walk"; see Method section). Like before, we included a per-participant adjustment to the intercept (i.e., a random intercept) in the model, to take into account variation in baseline learning rates. Results are presented in Table 3. Against our expectations, brightness did not significantly predict learning rate α (estimate = −0.02, $t[33.1] = -0.3$, $p = .772$). So, we found no support for the prediction that brightness impacts learning rate.

We next explored whether brightness affected the other dependent variables derived from the two-armed bandit task, that is, inverse temperature τ and the proportion of win feedback participants managed to get. We had no specific hypothesis. We used the same analytic approach as for learning rate α, and results are presented in detail in Table S3 in the online supplemental material. In summary, findings revealed no evidence that brightness affected τ (estimate = 0.00, $t[33.0] = 0.0$, $p = .998$), nor evidence that brightness affected participants' capability to attain win feedback (estimate = −0.60, $t[32.8] = 0.3$, $p = .773$).

BART

We analyzed participants' adjusted BART score with a linear mixed model, again using sex and session number as covariates. Like before, we included a per-participant adjustment to the intercept (i.e., a random intercept) in the model, to take into account variation in people's general tendency to take risk. Results are presented in Table 4. Against our hypothesis, brightness did not predict participants' BART score (estimate = −.39, $t[34.0] = -0.2$, $p = .815$). Thus, we found no evidence for the idea that brightness affects decision making under risk. Neither in support nor in contrast to our expectations, we did find that participants had a higher BART score during the second session ($M = 39.8$, $SD = 14.0$), as compared with the first ($M = 32.2$, $SD = 16.2$; estimate = 7.55, $t[34.0] = 4.6$, $p < .001$). We report analyses of session order effects in greater detail in the online supplemental material). These analyses do not challenge any of our conclusions.

Mood Questionnaires

Finally, we explored participants' responses on the mood questionnaire that we administered at the beginning and at the end of

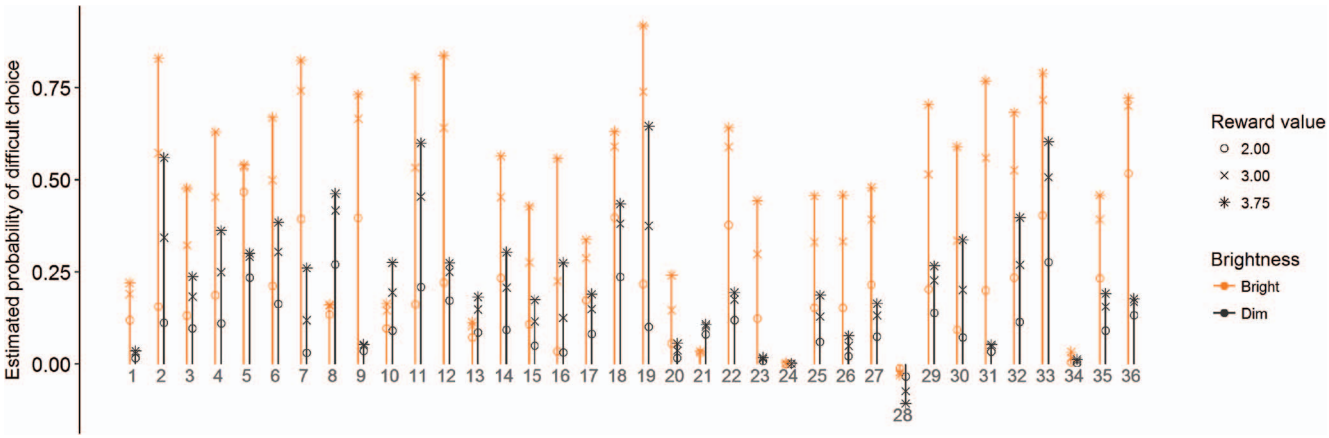

Figure 2. We used Model 3 to generate estimated probabilities of choosing the difficult option, separately for the brightness conditions (bright vs. dim), separately for three levels of reward (€2.00 [≈$2.50] vs. €3.00 [≈$3.70] vs. €3.75 [≈$4.60], which was the maximum value that appeared in the task), and separately for each participant. All estimates are relative to €1.00 (≈$1.20)—for example, an estimate of .25 means that the estimated probability (for that reward value, for that participant, for that brightness condition) of choosing the hard task is 25% higher compared with a reward value of €1.00 (≈$1.20). The plot illustrates two findings. First, nearly all estimates increase with value, indicating that nearly all participants were more likely to choose the hard task when this could yield them more money. Second, and more important, for nearly all participants (exceptions: 8, 10, 13, 21), estimates are higher in the bright condition versus the dim condition, indicating that nearly all participants responded more strongly to reward value when exposed to bright light. See the online article for the color version of this figure.

each session. Descriptive statistics are presented in Table 5. Descriptive statistics suggested that participants self-rated their state, on average, as moderately alert, calm, and happy (*M*s ≈ 5 on a 7-point scale), and neither very sad, tense, nor anxious (*M*s ≈ 3). Similarly, on average, participants' scores on the Karolinska Sleepiness Scale (*M*s ≈ 4 on a 9-point scale) corresponded to the label *rather alert*.

Like before, we used general linear mixed models to explore whether brightness affected how people self-rated their mood state, controlling for session number. First, we explored mood scores at the start of sessions. These were not significantly different in the bright light versus dim light (*t*s < 1.8, *p*s > .076). Next, we explored whether brightness affected the difference scores (i.e., end—start), to examine whether brightness changed people's participants' mood, again controlling for session number. This test was significant only for sadness (estimate = −.75, $t[67] = -2.9$, $p = .004$), which decreased during bright light sessions ($M = -0.36$), but increased during dim light sessions ($M = .37$).

The latter finding raises the possibility that bright light (vs. dim light) affected effort-based decision making through sadness. That is, it seems possible that that dim light increased sadness, which in turn diminished people's responsivity to reward value during the EEfRT. If this possibility would be true, we reasoned, changes in sadness should be associated with people's responsivity to reward value during the EEfRT. To test this idea, we reran the model in which we found the effect of brightness (i.e., Model 3, see Table 2), now replacing brightness with (change in) sadness as a predictor. There was no significant main effect of change in sadness (estimate = 0.29, $z = 0.7$, $p = .502$), suggesting that change in sadness was not associated with a general tendency to (not) choose the difficult option in the EEfRT. Crucially, there was also no significant Reward Value × Sadness interaction, (estimate = −0.18, $z = -1.2$, $p = .242$). Thus, we found no evidence that sadness was associated with a diminished responsivity to reward value. Results from this analysis are presented in full in Table S4 in the online supplemental material. We return to the role of sadness in the Discussion section.

Discussion

In our experiment, in line with our hypothesis, we found that exposure to bright light affected effort-based decisions. Specifically, in the EEfRT (Treadway et al., 2009), people used the value

Table 3
Results From the Two-Armed Bandit Task

Term	Estimate	*SE*	*df*	*t*	*p*
Sex = female	.1	.1	34.1	.9	.386
Walk	−.1	.1	34.8	−1.6	.116
Session	.0	.1	33.1	.0	.966
Brightness = bright	.0	.1	33.1	−.3	.772

Note. Dependent variable: Learning rate α.

Table 4
Results From the Balloon Analogue Risk Task

Term	Estimate	*SE*	*df*	*t*	*p*
Sex = female	−3.4	5.0	34.0	−.7	.503
Session	7.5	1.6	34.0	4.6	<.001
Brightness = bright	−.4	1.6	34.0	−.2	.815

Note. Dependent variable: Adjusted BART score.

Table 5
Means of Self-Rated Feeling States (Rated on a 1 to 7 Scale) and the Karolinska Sleepiness Scale (Rated on a 1 to 9 Scale)

Feeling state	Bright–T_0	Bright–T_1	Dim–T_0	Dim–T_1
Alert	5.2 (0.8)	5.5 (1.1)	5.4 (0.9)	5.5 (1.1)
Sad	2.3 (1.3)	1.9 (1.0)	2.1 (1.2)	2.4 (1.3)
Tense	2.6 (1.5)	3.3 (1.7)	2.6 (1.3)	3.3 (1.8)
Effort	2.6 (1.3)	2.6 (1.2)	2.6 (1.2)	3.1 (1.4)
Happy	4.6 (1.1)	4.5 (1.1)	4.9 (1.3)	4.7 (1.3)
Tired	3.3 (1.3)	3.0 (1.5)	3.3 (1.3)	3.5 (1.8)
Calm	4.8 (1.5)	4.0 (1.7)	4.7 (1.5)	3.9 (1.7)
Sleepy	2.9 (1.2)	2.8 (1.5)	2.7 (1.1)	3.2 (1.8)
Anxious	1.9 (1.3)	1.9 (1.2)	1.7 (1.0)	2.1 (1.4)
Karolinska Sleepiness	4.1 (1.5)	3.7 (1.5)	3.8 (1.3)	3.9 (1.8)

Note. Means are presented separately for the start (T_0) versus the end (T_1) of the sessions and separately for bright light versus dim light sessions. Values in parentheses are standard deviations.

of potential rewards in their decisions to expend effort—but more strongly so when they were exposed to bright light (vs. dim light). This finding is consistent with the idea that exposure to bright light (in the evening) suppresses melatonin secretion, which in turn affects functioning of the mesolimbic dopamine pathway. However, not in line with our hypothesis, we found no effects of exposure to bright light on reinforcement learning (examined with the 2ABT; Chowdhury et al., 2013) and on risky decision making (examined with the BART; Lejuez et al., 2002).

Although they partially support our hypothesis, our findings raise an important question: why did bright light (vs. dim light) only affect effort-based decision making, but not reinforcement learning and risky decision making? We now provide four post hoc explanations.

First, although all three behavioral phenomena are known to depend on the mesolimbic dopamine pathway, their exact neural underpinnings are different. In particular, all three behavioral phenomena depend on somewhat distinct targets of dopamine neurons. Very generally, effort-based decision making depends on the ventral striatum (Assadi, Yücel, & Pantelis, 2009; Croxson, Walton, O'Reilly, Behrens, & Rushworth, 2009; Salamone & Correa, 2012; Treadway et al., 2012), perhaps particularly on the left side (Treadway et al., 2012), the anterior cingulate cortex (ACC; Assadi et al., 2009; Croxson et al., 2009), and the ventromedial prefrontal cortex (vmPFC; Treadway et al., 2012). Reinforcement learning depends on the ventral and dorsal striatum; Balleine, Delgado, & Hikosaka, 2007; Schönberg, Daw, Joel, & O'Doherty, 2007; Vink et al., 2013), the orbitofrontal cortex (OFC; Schoenbaum, Chiba, & Gallagher, 1998), and the amygdala; Schoenbaum et al., 1998). Risky decision making, at least during the BART, depends on the ventral and dorsal striatum (Rao, Korczykowski, Pluta, Hoang, & Detre, 2008), ACC (Rao et al., 2008; Schonberg et al., 2012), anterior insula (Rao et al., 2008; Schonberg et al., 2012), and several parts of the PFC (Rao et al., 2008; Schonberg et al., 2012). Assuming that melatonin receptors are distributed unevenly across all these structures, which is plausible (Uz et al., 2005), it makes sense that some, but not all, reward-related behaviors are especially affected by bright light versus dim light. Very speculatively, the present research raises the possibility that the influence of melatonin may be particularly strong in the (left) ventral striatum, the ACC, and/or the vmPFC.

Second, related to the previous, models of dopamine function usually make distinctions between different psychological processes (e.g., wanting, liking, and learning; e.g., Berridge, Robinson, & Aldridge, 2009) or between different aspects of dopamine transmission (e.g., transmission via D1 vs. D2 receptors, e.g., Durstewitz & Seamans, 2008; in the striatum vs. the prefrontal cortex, e.g., Cools & D'Esposito, 2011; via phasic vs. tonic activity, e.g., Niv, Daw, Joel, & Dayan, 2007). With regard to the present study, the distinction between phasic and tonic dopamine activity may help to interpret the pattern of findings. Specifically, dopamine neurons show spiking bursts in activity (i.e., phasic activity), while they also show a steady stream of background activity that is independent of current task stimuli (i.e., tonic activity). Phasic activity signals unexpected outcomes (i.e., prediction errors); this type of activity plays a key role in learning from experience (Schultz, Dayan, & Montague, 1997). Tonic activity, by contrast, may reflect a more general motivational state of the organism; this type of activity is thought to play a role in enabling and energizing behavior (Niv et al., 2007; but see Hamid et al., 2016). Interestingly, one could reasonably argue that the EEfRT mainly taps into functions of tonic dopamine activity, whereas the 2ABT and the BART mainly tap into functions of phasic dopamine activity. So, very speculatively, the pattern of findings we observed could stem from the fact that bright light—via melatonin—mainly affects tonic, not phasic, dopaminergic transmission.

Third, it is possible that bright light impacts reinforcement learning and risky decision making only in some people, making it difficult to find effects on the group level. In support of this idea, it is worthwhile to consider a prior study on risky decision making (Macoveanu et al., 2016). In this study, which was conducted during the winter season, healthy participants were exposed to light every morning for 3 weeks. Brightness of the light varied between subjects. Before and after the 3-week light treatment, participants carried out a gambling task, which was conceptually similar to the BART. Consistent with the present study, findings indicated no effect of brightness on change in risk taking on the group level. However, among the subset of participants who were genetically predisposed to high serotonin transmission (specifically, participants homozygous for the long allele of 5-HTTLPR), brighter light exposure predicted increases in risk taking. Although there are several important differences between this previous study (Macoveanu et al., 2016) and the present study (e.g., morning vs. evening light exposure; repeated vs. single-dose light exposure; motivated by serotonin vs. melatonin/dopamine literature), this previous study does highlight the importance of individual differences in understanding the effects of light on reward-related behavior.

Fourth, the order of the tasks in our test battery was not counterbalanced; the EEfRT was the first task in all sessions. It could be the case that the effect of light exposure became weaker throughout the session—and thus, that the tasks later in the session were unaffected by exposure to bright light due to stimulus adaptation or response saturation. Though speculative, this possibility is consistent with research that shows that suppression of melatonin secretion is strongest during the beginning of a light pulse (Beersma et al., 2009; Smith, Schoen, & Czeisler, 2004).

Limitations and Alternative Explanations

The most important limitation of our design was that we did not measure or manipulate melatonin levels, which we suggested to be part of the working mechanism of the hypothesized effect. Thus, at this point, we should clearly be very cautious in assuming that the observed effect is due to melatonin-dopamine interactions. Future research is needed to examine the assumed working mechanism in detail. In our view, such research could take either of two approaches. First, future research could employ a similar design as the present study, while adding measurements of melatonin (e.g., in blood plasma). Such a design would allow for a direct test of the role of melatonin suppression, by bright light, in affecting effort-based decisions. Second, future research could test the effect of bright light at multiple time points during the day. After all, when melatonin levels are already low (e.g., in the afternoon), bright light should have no effect on effort-based decisions. Regardless of the approach that is chosen, future research should take into account individual differences in sleep habits (e.g., by measuring bedtimes or, even better, by assessing dim light melatonin onset). If the assumed working mechanism exists, these should moderate the effect of light on effort-based decisions.

Especially given the absence of melatonin data, it is important to consider alternative explanations for the effect that we observed. Notably, one could argue that dim light increases *anxiety*, causing people to attend to threats rather than rewards (Mogg, Bradley, De Bono, & Painter, 1997), in turn affecting effort-based decisions. Similarly, one could argue that dim light boosts feelings of fatigue, diminishing people's interest in task-related rewards (Inzlicht & Schmeichel, 2012). Yet, exposure to dim light was neither associated with changes in anxiety, nor with changes in fatigue—thus, results do not clearly support anxiety- or fatigue-related explanations.

It is important to note, however, that feelings of sadness decreased in bright light, but increased in dim light. So, one could speculate that dim light increases sadness, which would in turn diminish people's sensitivity to rewards. Interestingly, this explanation is consistent with research on people with depression, who often have feeling of sadness and are less sensitive to rewards (Treadway et al., 2009). However, exploratory analyses did not support this alternative explanation. Also, from this perspective, it is still difficult to account for the null findings with respect to the 2ABT and the BART.

Another limitation of this study was that we did not use a preregistered analysis plan. Using such a preregistered plan would have enabled us to more clearly distinguish between true effects and false positives (Munafò et al., 2017).

Conclusion

We found that bright light (vs. dim light) biases effort-based decision making. While further research is needed, it is interesting to consider this finding against the background of recent and ongoing changes in working conditions. Generally, labor is getting less and less tied to specific locations (e.g., the office) and timeslots (e.g., nine to five), whereas the use of light-emitting devices (e.g., smartphones and notebooks) is getting more and more common (Madden et al., 2008; Purcell et al., 2014). We suggest that circadian models may provide an interesting starting point to examine the behavioral consequences of spending time in these modern working environments.

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