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An Ambulatory Diary Study of Mobile Device Use, Sleep, and Positive Mood

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In the present ambulatory diary study, we focus on a highly topical and wide-spread behavior: late-night use of mobile devices (e.g., smartphones, tablets). Using a daily process approach and building on the two-process model of sleep regulation and the effort-recovery model, we propose that day-specific late-night use of mobile devices is related to day-specific diminished subsequent sleep and that diminished sleep, in turn, weakens the experience of positive mood the next day. Further, we propose that affective consequences of sleep are more pronounced for people who experience circadian misalignment. Circadian misalignment arises for people who sleep in misalignment with their biological preferences owing to obligations, such as their work schedules. Over the course of 8 consecutive days, we gathered 2 daily questionnaires and ambulatory assessments of sleep with wrist actigraphy from 51 employees (resulting in 312 days/units of matched data). Results confirm prevailing concerns about late-night use of mobile devices by showing that on days with longer late-night use of mobile devices, objectively measured subsequent sleep quality was reduced, which was, in turn, related to lower next-day positive mood. This unfavorable chain of events unfolded only for people who experienced circadian misalignment beyond a certain extent.

Keywords: sleep, mobile devices, social jetlag, ambulatory assessment, well-being

Using mobile devices, such as smartphones, tablets, and notebook computers, before going to bed is very common (Gradisar et al., 2013; Perlow, 2012). Unfortunately, this behavior may impair people's sleep because it exposes them to blue light emission (Chang, Aeschbach, Duffy, & Czeisler, 2015) and potentially confronts them with arousing and/or work-related content (Lanaj, Johnson, & Barnes, 2014). Consequently, late-night use of mobile devices may have detrimental trickle-down effects on people's experiences and behaviors on the next day because good sleep is crucial for people to engage and to successfully deal with demands the next day (Diestel, Rivkin, & Schmidt, 2015; Dinges et al., 1997; Kühnel, Zacher, de Bloom, & Bledow, 2017).

A growing body of cross-sectional evidence demonstrates that the use of mobile devices is negatively related to users' sleep (Christensen et al., 2016; Exelmans & Van den Bulck, 2016; Fossum, Nordnes, Storemark, Bjorvatn, & Pallesen, 2014). According to this evidence, people who in general more extensively use mobile devices before going to bed report more sleep disturbances, difficulties falling asleep, and more fatigue compared to people who in general less extensively use mobile devices before going to bed. However, results from these between-person, cross-sectional studies have fallen short because alternative explanations suggesting that the relationships found are solely owing to person-level third variables or recall bias cannot be fully ruled out (Bolger, Davis, & Rafaeli, 2003). The effect of events or specific behaviors on sleep and positive mood cannot be adequately studied with a between-person approach (Ilies, Dimotakis, & De Pater, 2010; Ilies, Schwind, & Heller, 2007). Thus, scholarly understanding of the impact of using mobile devices on sleep would largely benefit from a nuanced day-level perspective, which explicitly allows for analyzing within-person processes (Lanaj et al., 2014). The current ambulatory diary study addresses this issue by using a daily process approach, which enables us to investigate the phenomena of interest on the level on which they happen in real life (Bolger et al., 2003; Ilies, Aw, & Lim, 2016). That is, we investigate whether people sleep worse and shorter after evenings characterized by

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more extensive use of mobile devices before going to bed, compared to evenings characterized by less extensive use of mobile devices, and whether sleeping worse and shorter compromises the development of hedonic well-being in terms of high positive mood the next day. In our daily process approach, recall bias is minimized and people serve as their own controls, so that alternative explanations suggesting that relationships found are due to person-level third variables are unlikely. To further strengthen our daily process approach, we do not rely on self-reports of sleep but instead employ wrist actigraphy.

Moreover, we add an interindividual difference perspective to the investigation of daily processes. We propose that the day-specific chain of events particularly unfolds for people with high circadian misalignment. Circadian misalignment arises for people who sleep in misalignment with their biological preferences due to obligations, such as their work schedules (Roenneberg, Allebrandt, Merrow, & Vetter, 2012; Wittmann, Dinich, Merrow, & Roenneberg, 2006). Circadian misalignment is especially apparent in shift workers, but also affects the majority of day-time workers with standard work hours (Kühnel, Bledow, & Feuerhahn, 2016; Wittmann et al., 2006). It implies that people need to operate against their biological clock, what should make them especially dependent on the availability of resources restored during sleep to experience high positive mood the next day.

In doing so, the present study informs about trickle-down effects of a widespread behavior: late-night use of mobile devices. We combine two theoretical frameworks—the two-process model of sleep regulation (Borbély, 1982; Borbély, Daan, Wirz-Justice, & Deboer, 2016) and the effort-recovery model (Meijman & Mulder, 1998)—to develop a conceptual model that integrates largely unconnected streams of research on the implications of late-night use of mobile devices for sleep on one hand and on affective consequences of sleep on the other hand (Gish & Wagner, 2016). Focusing on late-night use of mobile devices as a factor that potentially contributes to impaired sleep and low positive mood is valuable because this widespread behavior can be acted upon to ensure good sleep, and to prevent low positive mood the next day. Gaining knowledge on how to promote positive mood is valuable because positive mood is a desirable state and engenders desirable life and organizational outcomes (Lyubomirsky, King, & Diener, 2005; Sonnentag, 2015). Moreover, we contribute to the growing research on sleep and circadian misalignment and their importance for employees' well-being. Circadian misalignment has been found to predict several indicators of an unhealthy lifestyle and impaired health (e.g., smoking and consumption of stimulants, depression, cardiovascular health; Levandovski et al., 2011; Roenneberg et al., 2012; Rutters et al., 2014; Wittmann et al., 2006) and has recently gained attention in the field of organizational behavior as well (Kühnel et al., 2016; Kühnel, Sonnentag, Bledow, & Melchers, 2018). By investigating whether daily processes unfold in an unfavorable manner for people who experience high circadian misalignment, our study may also provide important theoretical insights into how temporally stable dysfunctional sleep patterns shape the way how daily sleep influences affective processes within weeks or even longer time frames. Given that dysfunctional sleep patterns result in chronic impairments of well-being, our findings shed light on daily processes that might be involved in accumulation processes that eventually can result in unwanted long-term outcomes.

In the following sections, we will develop our research model (Figure 1). First, we will derive hypotheses on the consequences of day-specific late-night use of mobile devices for subsequent sleep. Then, we will turn to consequences of day-specific sleep for the next day's positive mood. Finally, we will develop hypotheses on the role of circadian misalignment for these day-specific processes.

Consequences of Late-Night Use of Mobile Devices for Sleep

Late-night use of mobile devices may impair subsequent sleep because of blue-light emission from the screens. The mobile devices taken into account in the present study (smartphones, tablets, and notebook computers) typically have displays with light-emitting diodes that shine into the eyes of the user from a close distance. On the basis of the prevalent conceptual model of sleep regulation, the two-process model (Borbély, 1982; Borbély et al., 2016), we predict that being exposed to light in the evening should make it more difficult to initiate and maintain sleep at night. Our prediction derives from the theoretical assertion that the timing and duration of sleep results from complex interactions between two processes: the sleep promoting process (Process S) and the circadian pacemaker (Process C). On one hand, the homeostatic Process S continuously accumulates during time awake, concomitant with an increase in sleepiness. On the other hand, Process C represents a wake-promoting drive that counteracts the accumulating homeostatic drive for sleep during wakefulness (Dijk, Duffy, & Czeisler, 1992). The interplay between these two processes results in an increase in alertness and performance at the beginning of the waking day and consolidated alertness and performance during the waking day. Alertness and performance decrease at the end of the waking day when the wake-promoting influence of Process C declines. Light is the most potent environmental signal that impacts when and how long the circadian pacemaker (Process C) exerts its wake-promoting drive (Eisenstein, 2013; Roenneberg, Kumar, & Merrow, 2007). Exposure to light at the end of the waking day prolongs the wake-promoting influence of Process C. Research has shown that being exposed to even small doses of light during the evening and early part of the night shifts the circadian pacemaker to a later point in time (Czeisler & Gooley, 2007; Khalsa, Jewett, Cajochen, & Czeisler, 2003) and suppresses the release of the sleep-facilitating hormone melatonin (Cajochen et al., 2011; Czeisler, 2013; Zeitzer, Dijk, Kronauer, Brown, & Czeisler, 2000), which would otherwise ensure the initiation and maintenance of sleep at night. Thus, late-night use of light-emitting mobile devices should impair the initiation and maintenance of sleep because the exposure to light prolongs the wake-promoting influence of Process C.

In addition to adverse effects of being exposed to blue-light emission, sleep may also be adversely affected by the media content people are confronted with when using mobile devices. Being confronted with arousing and/or work-related media content should make it more difficult to obtain high-quality sleep, which is defined as continuous sleep with no difficulties falling asleep (Åkerstedt, Hume, Minors, & Waterhouse, 1994). Work-related content may trigger thoughts about the elapsed or upcoming work day, and prevent employees from mentally switching off from work (Barber & Jenkins, 2014; Derks, van Mierlo, & Schmitz, 2014). Failure to mentally switch off from work in the evening

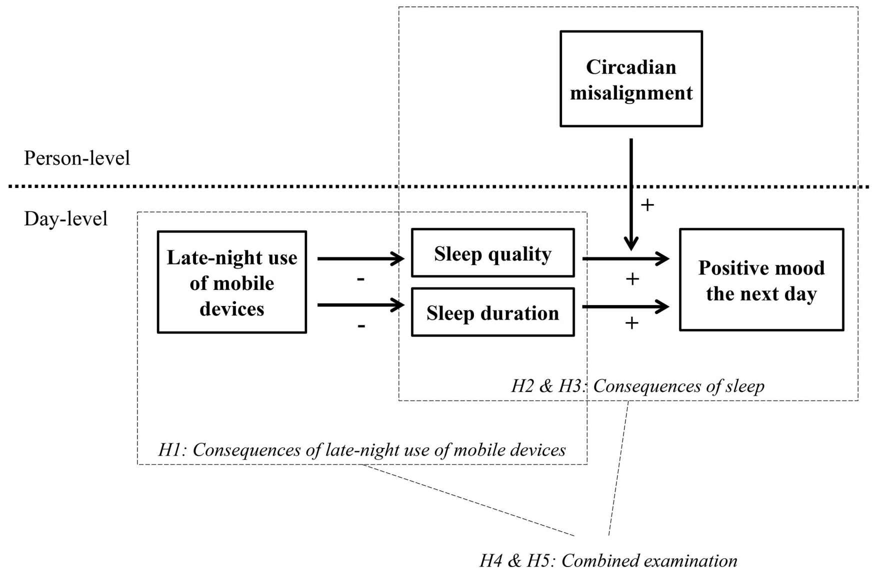

Figure 1. Conceptual daily process model linking late-night use of mobile devices with sleep and positive mood.

may prevent relaxation and cause continued activation and has been found to predict fragmented sleep (Hülsheger et al., 2014; Kecklund & Åkerstedt, 2004; Pereira, Meier, & Elfering, 2013; Sonnentag, Binnewies, & Mojza, 2008). Similarly, arousal stemming from nonwork-related media content may hamper falling asleep (Wuyts et al., 2012). Taken together, we hypothesize:

> *Hypothesis 1:* Day-specific late-night use of mobile devices is negatively related to (a) day-specific sleep quality and (b) day-specific sleep duration.

The Relevance of Day-Specific Sleep for the Next Day's Positive Mood

Besides predicting the timing and duration of sleep, the two-process model of sleep regulation (Borbély, 1982; Borbély et al., 2016) describes people's levels of well-being and cognitive functioning during the day as a function of—among other factors—sleep during the previous night. During sleep at night, the sleep debt (Process S) that was build up during the waking day declines. The decline of sleep debt ensures that people experience sound neurocognitive and affective functioning the next day (Durmer & Dinges, 2005; Franzen, Siegle, & Buysse, 2008). Restorative processes that take place during sleep can be explained with the help of the basic tenet of the effort-recovery model (Meijman & Mulder, 1998) that psychobiological systems can return to their baseline levels when they are no longer taxed. From the lens of the effort-recovery model, sleep can be understood as an important recovery activity that constitutes the recuperative process of the central nervous system (Åkerstedt, Nilsson, & Kecklund, 2009). Thus, sleep ensures that people's cognitive, energetic, and self-regulatory resources are restored in the morning the next day (Åkerstedt, Kecklund, & Gillberg, 2007; Barnes, Schaubroeck, Huth, & Ghumman, 2011; Baumeister, Muraven, & Tice, 2000). The availability of these resources should in turn enhance pleasurable experiences and foster the experience of hedonic well-being in terms of high positive mood during the day.

In adopting these theoretical ideas to our daily process approach, we propose that people experience more positive mood after nights characterized by good and sufficient sleep, compared to nights characterized by worse and shorter sleep. The availability of energetic and cognitive resources after good and sufficient sleep should enable people to capitalize on opportunities for goal attainment, which results in the experience of positive mood (Harris, Daniels, & Briner, 2003; Schmitt, Belschak, & Den Hartog, 2017; Zohar, Tzischinsky, Epstein, & Lavie, 2005). Moreover, when people have resources available, they more likely appraise events happening during the day in a positive manner, what should foster the experience of positive mood as well (Bower, Bylsma, Morris, & Rottenberg, 2010; Rothbard & Wilk, 2011). In line with our reasoning, previous within-person studies provided initial support for the prediction that *self-reports* of sleep duration or sleep quality are related to the experience of engagement and well-being the next day (Scott & Judge, 2006; Sonnentag et al., 2008; Totterdell, Reynolds, Parkinson, & Briner, 1994). The present study provides a more rigid test of these relationships by employing objectively assessed sleep parameters.

> *Hypothesis 2:* Day-specific (a) sleep quality and (b) sleep duration are positively related to positive mood during the next day.

Interindividual Differences in Affective Consequences of Day-Specific Sleep

Some people should be more affected by lower than usual day-specific sleep quality and shorter than usual day-specific sleep duration than other people. We propose that affective consequences of lower sleep quality and shorter sleep are stronger for people who experience circadian misalignment (Kühnel et al., 2016; Wittmann et al., 2006) because people who experience circadian misalignment should be more dependent on resources restored during sleep. Circadian misalignment refers to a misalignment between biological clocks and so-called *social clocks* and means that people do not sleep in accordance with their biologically preferred sleep times because of obligations stemming from their social environment (e.g., work and school start times). Circadian misalignment quantifies the extent of general discrepancies between an individual's biological clocks and social clocks (Wittmann et al., 2006). People differ with regard to the social obligations they have, as well as their biologically preferred sleep times. Individual differences in biologically preferred sleep times correspond with an individual's chronotype (Roenneberg, Wirz-Justice, & Merrow, 2003). The continuum of chronotypes in the population ranges from morning people (early *larks*), who prefer to go to bed earlier in the evenings and get up earlier in the mornings, to evening people (late *owls*), who prefer to go to bed later in the evenings and to get up later in the mornings (also referred to as morningness–eveningness; Horne & Østberg, 1976).

A person's biological preference for specific sleep-wake times can come into conflict with work schedules and other social obligations, which regularly occur within longer work periods. This conflict is most apparent among employees who work night shifts—a period of time in which most people would prefer to sleep (Åkerstedt, 2003; Kühnel, Sonnentag, et al., 2018). However, work schedules that regularly start early in the morning are likely to interfere with the biological sleep preferences of a large portion of employees because moderate to late chronotypes represent the majority of the population (Wittmann et al., 2006). On work days, these employees have to adjust their sleep–wake times to their work schedule. As a result, these employees are forced to sleep—at least partly—outside their biologically preferred window of sleep. Likewise, they are forced to be awake—at least partly—outside their biologically preferred window for being awake.

Operating *against one's biological clock* entails more regulatory effort in dealing with the circumstances, and thus requires a higher investment of energetic and self-regulatory resources every day (Roenneberg et al., 2012). Indeed, research has shown that late chronotypes, who more likely experience circadian misalignment, invest more effort in cognitive tasks compared to earlier chronotypes (Nowack & van der Meer, 2014). Because operating against one's biological clock may continuously put demands on people's self-regulation, and may force them to invest compensatory effort (Hockey, 1997), those people's daily need for energetic and self-regulatory resources should be high (Kühnel, Syrek, & Dreher, 2018). If the level of resources they can rely on in the morning is cut short due to shorter than usual sleep or sleep of worse quality than usual, they should experience greater difficulties in regulating mood and stabilizing well-being the next day compared to people who do not have to operate against their biological clock.

Accordingly, we argue that the restoration of resources during sleep and thus sleep of good quality and sufficient duration is particularly important for those people with high circadian misalignment because they have a high need for resources to cope with environmental circumstances in a way that enables the experience of positive mood. In conclusion, we hypothesize a tighter coupling of day-specific sleep quality and day-specific sleep duration with the experience of positive mood the next day the more circadian misalignment someone experiences:

> *Hypothesis 3 (circadian misalignment as cross-level moderator):* The positive relationship between (a) day-specific sleep quality / (b) day-specific sleep duration and positive mood during the next day (Hypothesis 2a/b) is moderated by circadian misalignment, such that the relationship is amplified as a function of increasing circadian misalignment.

Combined Examination: Linking Late-Night Use of Mobile Devices With Subsequent Sleep and the Next-Day Positive Mood

Earlier, we have argued that late-night use of mobile devices should be negatively related to subsequent day-specific sleep (Hypothesis 1) because people are exposed to blue-light emission and confronted with arousing media content when using mobile devices. Good sleep quality and sufficient sleep duration, in turn, should be crucial for the experience of positive mood the next day (Hypothesis 2) because sleep ensures the restoration of resources needed to experience positive mood the next day. From the perspective of theories on regulatory mechanisms of sleep (Lanaj et al., 2014), late-night use of mobile devices should thus have trickle down effects on positive mood the next day via worse day-specific sleep quality and lower day-specific sleep duration (Figure 1). On a conceptual level, late-night use of mobile devices should exert negative indirect effects on positive mood the next day via day-specific sleep quality and day-specific sleep duration:

> *Hypothesis 4 (indirect effects):* There are indirect effects linking late-night use of mobile devices to lower positive mood during the next day via (a) lower sleep quality and (b) shorter sleep duration.

Furthermore, we have argued that day-specific processes differentially unfold depending on the extent of circadian misalignment someone experiences. More specifically, the links between day-specific sleep characteristics and positive mood the next day should be stronger for people who experience high circadian misalignment (Hypothesis 3). In conceptual terms, the indirect effects of late-night use of mobile devices on positive mood via day-specific sleep characteristics should be strengthened by circadian misalignment. More specifically, the paths linking sleep quality with positive mood and sleep duration with positive mood should be stronger for people who experience more circadian misalignment compared to people who experience less circadian misalignment. Because these paths should be stronger for people who experience circadian misalignment, the resulting indirect effects should be stronger for these people. Taken together, we derive the prediction of conditional indirect effects (Figure 1):

> *Hypothesis 5 (conditional indirect effects):* The indirect effects linking day-specific late-night use of mobile devices to low positive mood during the next day via (a) lower day-specific sleep quality / (b) lower day-specific sleep quality are moderated by circadian misalignment, such that the indirect effects become stronger as circadian misalignment increases.

Method

Sample and Procedure

Employees from companies in diverse industries participated in this study. Participants worked in the job clusters engineering, mechanics, and technology (43%), business and trade (18%), education and social affairs (12%), finance and insurance (10%), and other (17%). The participants were recruited through a convenience sampling approach whereby two students approached their network. Only nonshift workers and employees without diagnosed sleep disorders were allowed to participate. To motivate employees to take part in the study, we offered individual feedback on the sleep data assessed in the study. Employees who gave their consent to participate were equipped with a wristwatch-sized accelerometer that records movement during wakefulness and sleep (wGT3X-BT device by ActiGraph LLC, Florida, US) and a booklet containing several paper-and-pencil questionnaires. Participants wore the accelerometer on the wrist of the nondominant hand and filled in the paper-and-pencil booklet for eight consecutive days. We did not impose any restrictions on participants' sleep schedule. At the beginning of the study, participants filled in a general questionnaire assessing sociodemographic variables and data to calculate general circadian misalignment. On each study day, participants were asked to answer two daily questionnaires, the first one in the morning, to assess late-night use of mobile devices on the preceding evening, and the second one at the end of the work day or at the same time of day on work-free days, to assess positive mood. We instructed participants not to catch up on a questionnaire that they missed filling in, but to leave this section blank. Moreover, we took measures to control whether participants filled in the surveys at the instructed points in time: We asked for the current date, the current day of the week, and the current time at the beginning of all daily surveys, and we checked the congruity of information.

Of the 53 participants who agreed to take part in the study, two participants had to be excluded from the analyses due to incomplete survey data on the variables of interest. Thus, the final sample comprised 51 employees who provided complete survey data that could be successfully matched with sleep data on 312 days (624 occasions; 6.12 days average cluster size). In all, 35% of the sample were women, mean age was 34 years ($SD = 10$), and about 18% had at least one child living with them. On average, participants had 11 years of professional experience ($SD = 11$) and worked 39 hr/week ($SD = 8$). The majority of the sample consisted of full-time employees (84%), yet eight participants worked part time. About 62% of the sample held a bachelor's, master's, or higher academic degree.

Measures: General Questionnaire

Circadian misalignment was assessed with the Munich ChronoType Questionnaire (Roenneberg et al., 2003). This questionnaire determines circadian misalignment based on typical sleep behavior. The questionnaire consists of simple questions about people's typical sleep timing on work days and on work-free days by asking them to indicate their typical sleep onset and typical sleep offset (separately for work days and for work-free days). On work-free days, people can sleep in accordance with their biological preference for sleep–wake times. Thus, the midpoint of sleep on work-free days is an indicator of individuals' biological preference for sleep–wake times.[1] The midpoint of sleep on work-free days shows high test–retest reliability ($r = .88$, Kühnle, 2006) and correlates strongly with the gold standard biochemical marker to assess individuals' biological preference for sleep–wake times, that is, dim light melatonin onset ($r = .89$, Martin & Eastman, 2002). The separate assessment of typical sleep onset and typical sleep offset for work days and for work-free days allowed us to calculate the midpoint between sleep onset and offset for work days and for work-free days, respectively. Circadian misalignment is defined and computed as the absolute difference between the midpoint of sleep on work-free days and the midpoint of sleep on work days (Wittmann et al., 2006). Higher values represent more circadian misalignment, that is, a greater discrepancy between typical sleep patterns on work-free days and work days. For example, a person whose sleep onset and sleep offset on work-free days are at 12 midnight and at 9 a.m., respectively, has a midpoint of sleep on work-free days at 4:30 a.m. When this person's sleep onset and sleep offset on work days are at 12 midnight and at 7 a.m., respectively, the midpoint of sleep on work days is 3:30 a.m. The resulting difference between midpoint of sleep on work-free days (4:30 a.m.) and on work days (3:30 a.m.) is one hour. Thus, this person experiences a circadian misalignment of 1 (hr).

Measures: Day-Specific Measures

Late-night use of mobile devices. To assess late-night use of smartphones, tablets, and/or notebook computers, we adapted the item from Lanaj et al. (2014) that assesses late-night use of smartphones, so that it now reads: "How many minutes did you use your smartphone, tablet, and/or notebook computer after 9 pm last night?" Participants answered this question after getting up in the morning. On average, participants reported 40 min of late-night use of mobile devices each day ($SD = 33$).

Sleep characteristics. Sleep characteristics were assessed by means of wrist-band accelerometers (ActiGraph® wGT3X-BT devices) that record movement during wakefulness and sleep. The ActiLife® software (Version 6.13.3) algorithm (Cole-Kripke) was used to score the data (Cole, Kripke, Gruen, Mullaney, & Gillin, 1992), and all data from each participant were checked individually. Sleep efficiency and total sleep time served as objective indicators for sleep quality and sleep duration, respectively. Among the physiological indicators of sleep that can be obtained with wrist-band accelerometers, sleep efficiency is most closely related to subjective sleep quality ($r = .78$; Åkerstedt et al., 1994). It was therefore used as an indicator of sleep quality in the present study. Sleep efficiency is defined as the percentage of actual sleep time as a function of time in bed. A sleep efficiency of 85% or higher is considered to be good, a sleep efficiency lower than 85%

[1] Biologically preferred sleep–wake times (chronotype) cannot be calculated with the Munich ChronoType Questionnaire for individuals who do not report their *unrestricted* sleep times on work-free days (Roenneberg et al., 2003). Exclusion criteria are when respondents use an alarm to wake up on work-free days, or when their naturally occurring sleep on work-free days is prematurely terminated because of small children or pets requiring attention. Consequently, people who cannot self-determine their sleep times on work-free days (e.g., people with small children) could not take part and were not included in the present study.

is considered to be poor (Buysse, Reynolds, Monk, Berman, & Kupfer, 1989). Total sleep time is the actual amount of time spent asleep (in minutes), that is, total time in bed excluding sleep latency and excluding periods of wakefulness at night (wake after sleep onset).

Positive mood. Participants' positive mood was assessed with the items alert, excited, active, strong, and interested from the Positive and Negative Affect Schedule scales (Watson, Clark, & Tellegen, 1988). Items had to be answered on a 5-point scale ranging from 1 (*strongly disagree*) to 5 (*strongly agree*). Cronbach's α ranged between .73 and .80 across the days.

Results

Descriptive Statistics

Table 1 shows means, standard deviations, intraclass correlations (ICCs), and intercorrelations between variables. All day-specific variables showed substantial day-to-day variation (within-person variance, 1-ICC). More specifically, 62% of the variance in late-night use of mobile devices, 73% of the variance in sleep quality, 70% of the variance in sleep duration, and 82% of the variance in positive mood resided at the within-person level.

Analytic Strategy

We used the Hierarchical Linear Modeling 7.01 software package (Raudenbush, Bryk, Cheong, Congdon, & du Toit, 2011) to conduct multilevel analyses. To ensure unbiased estimations (Enders & Tofighi, 2007), we centered day-level predictor variables around the respective person mean (person/group-mean centering) and the person-level predictor variable circadian misalignment around the grand mean (grand-mean centering). To test Hypotheses 1 to 3, we specified and compared nested hierarchical linear models to predict day-specific sleep quality, day-specific sleep duration (Table 2), and day-specific positive mood (Table 3). To test Hypotheses 4 and 5, we computed indirect within-person effects and conditional indirect within-person effects (Preacher, Zhang, & Zyphur, 2011; Preacher, Zyphur, & Zhang, 2010) with M*plus* 7.11 (Muthén & Muthén, 1998–2007).

Test of Hypotheses

Hypotheses 1a and 1b stated negative consequences of late-night use of mobile devices for sleep quality and sleep duration. Model 1 for sleep quality and Model 1 for sleep duration in Table 2 show that late-night use of mobile devices was significantly related to sleep quality (estimate $= -0.019$, $SE = 0.007$, $t = -2.50$, $p < .05$), but not significantly related to sleep duration (estimate $= -0.185$, $SE = 0.122$, $t = -1.51$, $p = .131$). Model 1 for sleep quality fit the data better than the Null model ($\Delta -2 \times$ Log likelihood $= 6.192$, $df = 1$, $p < .05$). Thus, in support of Hypothesis 1a, employees' objective sleep quality was worse on nights when they reported more, compared to less, extensive use of mobile devices before going to bed. By contrast, Hypothesis 1b—stating a negative relationship between late-night use of mobile devices and sleep duration—was not supported.

Hypotheses 2a and 2b stated relationships between day-specific sleep characteristics and the next day's positive mood. Model 1 in Table 3 shows that sleep quality was significantly related to positive mood (estimate $= 0.022$, $SE = 0.009$, $t = 2.32$, $p < .05$), but that sleep duration was not significantly related to positive mood (estimate $= 0.000$, $SE = 0.001$, $t = 0.46$, $p = .646$). Model 1 fit the data better than the Null model ($\Delta -2 \times$ Log likelihood $= 6.127$, $df = 2$, $p < .05$). Thus, in support of Hypothesis 2a, employees' positive mood was higher on days following nights characterized by better compared to worse sleep. By contrast, Hypothesis 2b—stating a positive relationship between sleep duration and positive mood—was not supported.

Hypotheses 3a and 3b stated that the relationships between day-specific sleep characteristics and positive mood are moderated by circadian misalignment, such that the positive relationship between sleep quality and positive mood and between sleep duration and positive mood is stronger as circadian misalignment increases. To test Hypothesis 3, we first added the person-level predictor variable circadian misalignment (main effect) and random slopes of sleep quality and of sleep duration predicting positive mood in Model 2.[2] In Model 3a, we added circadian misalignment as a predictor of the random slope of sleep quality (cross-level interaction). Circadian misalignment was a significant cross-level moderator of the relationship between sleep quality and positive mood (estimate $= 0.034$, $SE = 0.014$, $t = 2.36$, $p < .05$), and Model 3a fit the data better than Model 2 (Δ–$2 \times$ Log likelihood $= 5.14$, $df = 1$, $p < .05$). Circadian misalignment explained more than 50% of the variance in the slope of sleep quality predicting positive mood. The interaction effect between circadian misalignment and sleep quality is depicted in Figure 2. Please note that only *slopes* of regression lines should be interpreted. The difference in intercepts between the regression lines, which estimates the circadian misalignment main effect, had a 95% confidence interval (CI) that included 0.

We performed simple slope tests with the computational tool by Preacher, Curran, and Bauer (2006). For employees who experienced less circadian misalignment (-1 *SD*), the slope between sleep quality and positive mood was not significant (simple slope $= 0.000$, $SE = 0.013$, $t = 0.013$, $p = .989$). For employees who experienced average (*M*) or high circadian misalignment ($+1$ *SD*), the slopes between sleep quality and positive mood were positive and significant (simple slope $= 0.020$, $SE = 0.001$, $t = 2.00$, $p < .05$, and simple slope $= 0.039$, $SE = 0.012$, $t = 3.26$, $p < .01$, respectively). Inspection of the region of significance of the slope between sleep quality and positive mood showed that the slope was significant for values of the moderator circadian misalignment greater than 0.81 hr, that is, for people with a circadian misalignment of 49 min or more. Taken together, positive mood the next day depended on day-specific sleep quality for employees who experienced a circadian misalignment of 49 min or more. Thus, our data provide support for Hypothesis 3a.

[2] We followed best practice recommendations of Aguinis, Gottfredson, and Culpepper (2013) and built a random intercept and random slope model to test whether the slopes of sleep quality and sleep duration predicting positive mood were random. The random slopes of sleep quality and sleep duration were not significant ($p < .50$). However, Aguinis et al. (2013) argued that in many situations, there may be an incorrect conclusion that the slope variance is not significantly different from zero because of the insufficient statistical power of this test. Thus, we followed their recommendations (see p. 1502) and proceeded with the cross-level interaction tests (Bliese, Maltarich, & Hendricks, 2018).

Table 1
Means, Standard Deviations, and Correlations of Variables

Variable	*M*	*SD*	ICC[a]	1	2	3	4	5	6
1. Day-specific late-night use of mobile devices	39.54	33.13	.38		−.15*	−.10	.10		
2. Day-specific sleep quality (sleep efficiency)	89.42	3.31	.27	.25		.18**	.16*		
3. Day-specific sleep duration (TST, in minutes)	408.91	53.30	.30	.18	.39*		.05		
4. Positive mood the next day	2.81	0.43	.18	.36	.25	.31			
5. Circadian misalignment	0.83	0.56	—	−.13	−.06	−.07	.18		
6. Age	33.62	9.55	—	−.58***	−.12	−.08	−.09	−.09	
7. Gender[b]	0.35	0.48	—	−.12	.07	.13	−.09	−.16	.01

Note. Within-correlations ($N = 312$) are depicted above the diagonal, between-correlations are depicted below the diagonal ($N = 51$). Correlations and their significances are estimated with Mplus. TST = total sleep time; ICC = intraclass correlation.
[a] ICC = ratio of the between-person variance to the total variance, 1-ICC = ratio of the within-person variance to the total variance. [b] Gender: 0 = *male*, 1 = *female*.
* $p < .05$. ** $p < .01$. *** $p < .001$.

To test Hypothesis 3b, in Model 3b, we added circadian misalignment as a predictor of the random slope of sleep duration (cross-level interaction). Circadian misalignment was not a significant cross-level moderator of the relationship between sleep duration and positive mood (estimate = −0.001, *SE* = 0.001, $t = -1.25$, $p = .386$), and Model 3b did not fit the data better than Model 2 (Δ−2 × Log likelihood = 0.73, *df* = 1, $p > .500$). Thus, Hypothesis 3b was not supported.

In Model 3c, we simultaneously tested circadian misalignment as a predictor of the random slope of sleep quality and of the random slope of sleep duration. Model 3c fit the data better than Model 2 (Δ−2 × Log likelihood = 7.80, *df* = 2, $p < .05$). Results for Hypotheses 3a and 3b did not change.

Hypotheses 4a and 4b proposed indirect effects linking late-night use of mobile devices with impaired sleep and lower positive mood. We used the M*plus* syntax for the tests of indirect effects (1–1–1 multilevel SEM models) accompanying the publications of Preacher et al. (2010) and Preacher et al. (2011). Tests of indirect within-person effects revealed that neither the indirect effect linking late-night use of mobile devices with lower positive mood via impaired sleep quality (estimate = −0.001, *SE* = 0.000, $t = -1.94$, $p = .053$, 95% CI [−0.001, 0.000]) nor the indirect effect linking late-night use of mobile devices with lower positive mood via shorter sleep duration was significant (estimate = 0.000, *SE* = 0.000, $t = -0.85$, $p = .376$, 95% CI [0.000, 0.000]). A model taking both mediators into account simultaneously (1-[1,1]-1 multilevel SEM model) yielded equivalent results. Thus, results failed to support Hypotheses 4a and 4b.

Hypotheses 5a and 5b stated that the indirect effects linking late-night use of mobile devices with sleep quality and positive mood and with sleep duration and positive mood are moderated by circadian misalignment such that the negative indirect effects are stronger as circadian misalignment increases. To test Hypothesis 5a, we specified a conditional indirect effects model in which circadian misalignment is a cross-level moderator of the path linking sleep quality to positive mood. More specifically, in the indirect effect model, a random slope was modeled for the second path from sleep quality to positive mood, and circadian misalignment was modeled as a predictor of this random slope. The strength and significance of the indirect effect model for conditional values of the cross-level moderator circadian misalignment was investigated. Results showed that the indirect effect linking late-night use of mobile devices with lower positive mood via impaired sleep quality was significant for values of circadian misalignment of 0.97 hr and more, that is, for people experiencing a circadian misalignment of 58 min and more. For people experiencing a circadian misalignment of less than 58 min, late-night use of mobile devices was not significantly linked to lower positive mood via impaired sleep quality. Thus, Hypothesis 5a was supported.

Table 2
Results of Multilevel Analyses Predicting Day-Specific Sleep Quality and Day-Specific Sleep Duration

	Day-specific sleep quality (sleep efficiency)						Day-specific sleep duration (TST)					
	Null model			Model 1			Null model			Model 1		
Variable	Est	*SE*	*t*	Est	*SE*	*t*	Est	*SE*	*t*	Est	*SE*	*t*
Intercept	89.408	0.458	194.80***	89.408	0.458	194.7***	409.606	7.515	54.50***	409.600	7.514	54.50***
Level-1 predictor												
Day-specific late-night use of mobile devices				−0.019	0.007	−2.50*				−0.185	0.122	−1.51
Δ−2 × Log likelihood (*df*)		1,876.589 (3)			1,870.397 (4)			3,597.563 (3)			3,595.275 (4)	
Δ−2 × Log likelihood (*df*)					6.192 (1)*						2.288 (1)	
Level 1 Intercept variance (*SE*)		19.767 (1.729)			19.304 (1.688)			4,843.607 (423.793)			4,801.566 (420.117)	
Level 2 Intercept variance (*SE*)		7.401 (2.141)			7.478 (2.141)			2,059.134 (573.413)			2,065.525 (573.240)	

Note. Est = estimate. $N_{\text{Level 1}} = 312$. $N_{\text{Level 2}} = 51$.
* $p < .05$. *** $p < .001$.

Table 3
Results of Multilevel Analyses Predicting Positive Mood the Next Day

	Positive mood the next day																	
	Null model			Model 1			Model 2			Model 3a			Model 3b			Model 3c		
Variable	Est	*SE*	*t*	Est	*SE*	*t*	Est	*SE*	*t*	Est	*SE*	*t*	Est	*SE*	*t*	Est	*SE*	*t*
Intercept	2.802	0.059	47.12***	2.8028	0.059	47.12***	2.801	0.059	47.35***	2.801	0.058	47.49***	2.801	0.058	47.33***	2.8018	0.058	47.51***
Level-1 predictors																		
Day-specific SQ				0.022	0.009	2.32*	0.022	0.010	2.21*	0.019	0.009	1.96	0.021	0.010	2.12*	0.017	0.009	1.79
Day-specific TST				0.000	0.001	0.46	0.000	0.000	0.39	0.000	0.000	0.68	0.000	0.000	0.47	0.000	0.001	0.82
Level-2 predictor																		
Circadian misalignment							0.040	0.099	0.40	0.122	0.104	1.17	0.030	0.100	0.31	0.109	0.104	1.04
Cross-level interactions																		
Day-Specific SQ × Circadian Misalignment										0.036	0.014	2.45*				0.042	0.015	2.79**
Day-Specific TST × Circadian Misalignment													−0.001	0.001	−0.87	−0.001	0.001	−1.60
Δ−2 × Log likelihood (*df*)		693.219 (3)			687.092 (5)			682.209 (11)			676.755 (12)			681.469 (12)			674.407 (13)	
Δ−2 × Log likelihood (*df*)					6.127 (2)*			4.882 (6)			5.454 (1)*			0.739 (1)			7.801 (2)*	
L1 Intercept variance (*SE*)		0.471 (0.041)			0.460 (0.040)			0.448 (0.044)			0.441 (0.043)			0.446 (0.044)			0.438 (0.043)	
L2 Intercept variance (*SE*)		0.101 (0.036)			0.103 (0.036)			0.103 (0.035)			0.103 (0.035)			0.103 (0.035)			0.103 (0.035)	
L2 Slope variance SQ (*SE*)								0.001 (0.001)			0.000 (0.001)			0.001 (0.001)			0.000 (0.001)	
L2 Slope variance TST (SE)								0.000 (0.000)			0.000 (0.000)			0.000 (0.000)			0.000 (0.000)	

Note. SQ = sleep quality. TST = sleep duration (total sleep time). Est = Estimate; L1 = Level 1; L2 = Level 2. $N_{\text{Level 1}} = 312$. $N_{\text{Level 2}} = 51$.
$^{*} p < .05$. $^{**} p < .01$. $^{***} p < .001$.

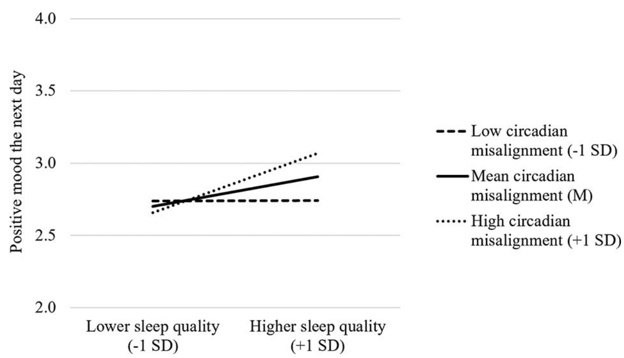

Figure 2. Cross-level interaction of circadian misalignment on the slope of sleep quality predicting positive mood (Hypothesis 3).

To test Hypothesis 5b, we specified a conditional indirect effects model equivalent to testing Hypothesis 5a, but with sleep duration instead of sleep quality as the mechanism. Results showed that the indirect effect linking late-night use of mobile devices with lower positive mood via lower sleep duration was not significant for any value of circadian misalignment that existed in our dataset (range of circadian misalignment = 0.04–2.38). Thus, Hypothesis 5b was not supported.

Additional Analyses

Data were collected on up to 8 consecutive days. Of the 312 days on which data collection took place, 238 were work days and 74 were nonwork days. Therefore, we conducted several additional analyses to investigate whether the kind of day influences the obtained relationships. Considering work day versus nonwork day as a control variable did not change the results. We also tested whether work day versus nonwork day was a moderator of the relationships of interest. Work day versus nonwork day did not moderate the relationship between late-night use of mobile devices and sleep quality (estimate = 0.000, $SE = 0.019$, $t = -0.04$, $p = .926$; Hypothesis 1a), nor the relationships between sleep quality and sleep duration, respectively, and positive mood (estimate = 0.025, $SE = 0.027$, $t = 0.93$, $p = .350$, and estimate = 0.000, $SE = 0.001$, $t = -0.68$, $p = .493$; Hypothesis 2a and 2b, respectively). However, work day versus nonwork day had a significant moderating influence on the relationship between late-night use of mobile devices and sleep duration (estimate = −0.639, $SE = 0.296$, $t = -2.15$, $p < .05$; Hypothesis 1b). The pattern of the interaction showed that the negative relationship between late-night use of mobile devices and sleep duration we had proposed in Hypothesis 1b was found on work days, but not on nonwork days.

Discussion

The aim of the present ambulatory diary study was to employ a daily process approach to investigate trickle down effects of late-night use of mobile devices on the experience of positive mood the next day via day-specific sleep characteristics. Moreover, we investigated whether affective consequences of lower sleep quality and shorter sleep duration are stronger for people who experience circadian misalignment. Results of our study confirmed prevailing concerns about late-night use of mobile devices: On days following longer late-night use of mobile devices compared to days following shorter use, participants' objectively measured sleep quality was worse. Day-specific sleep quality, in turn, predicted positive mood the next day, such that on days with better sleep quality, participants experienced more positive mood during the next day. Unfavorable trickle-down effects of late-night use of mobile devices on positive mood the next day were only found for people who experienced circadian misalignment beyond a certain extent, that is, 49 min or more. Thus, our results demonstrate that circadian misalignment is an individual factor that makes people with high circadian misalignment particularly dependent on day-specific sleep quality to regulate mood and stabilize well-being during the next day. The pattern of results for day-specific sleep *duration* differed remarkably, insofar as sleep duration was neither affected by late-night use of mobile devices, nor significantly related to the next day's positive mood, nor did circadian misalignment modulate the affective consequences of shorter sleep duration.

Theoretical Implications

Our results offer several implications for our theoretical understanding of how late-night use of mobile devices impairs sleep processes and shapes emotional experiences during the next day. On the one hand, in employing physiological measures of sleep, we were able to provide more nuanced and objective evidence for the deleterious effects of late-night use of mobile devices on sleep. The negative intraindividual relationships between late-night use of mobile devices and indicators of sleep are less contaminated by common method bias or individual attributional processes. Put differently, the strength of the estimated relations may be interpreted as *true*, or unbiased, effects, which are relevant, for instance, for meta-analytical estimations of effect sizes.

In light of the differential relationship patterns for sleep duration and sleep quality, our findings provide insight into the exact nature of sleep impairments as a result of late-night use of mobile devices and the effects of both sleep variables on emotional processes. In particular, whereas the participants of our study were not affected in their sleep duration on nonwork days, late-night use of mobile devices was consistently negatively related to sleep quality. In an attempt to explain these patterns, we believe that people can prolong their sleep on nonwork days so that sleep duration is not necessarily or considerably reduced by late-night use of mobile devices on nonwork days. On work days, however, people cannot prolong their sleep given their work schedules, so that sleep duration is affected by late-night use of mobile devices.

In contrast to day-specific sleep *quality*, day-specific sleep *duration* was unrelated to positive mood the next day. Our finding is in line with recent meta-analytical results that showed that sleep duration is consistently less strongly related to affective outcomes, as compared to sleep quality (Litwiller, Snyder, Taylor, & Steele, 2017). Whereas the meta-analysis by Litwiller et al. (2017) focused on negative mood (sleep duration: $\rho = -.09$; sleep quality: $\rho = -.37$), we provide similar results for positive mood.

From a theoretical perspective, sleep duration may not reflect underlying regulatory mechanisms or homeostatic dynamics of sleep, which determine processes of resource recovery during sleep (Tononi & Cirelli, 2006). That is, although someone may be able to sleep sufficiently, restfulness of sleep may not be sufficient for effective mood regulation the next day. In conclusion, given that sleep duration is not a strong precursor of emotional processes, the present findings shed light on the different sleep processes that determine the effects of late-night use of mobile devices on positive mood in a different manner.

Finally, we also considered individual differences in circadian misalignment, which moderated the indirect effect of late-night use of mobile devices on positive mood via nightly sleep quality. We found that the indirect effect was contingent upon the degree of general misalignment between biologically preferred and socially restricted time windows for sleep. These findings provide support for our theoretical proposition that living against one's biological clock may require a higher investment of resources every day because people who experienced stronger circadian alignment were more dependent on day-specific high-quality sleep—that ensures the sufficient availability of regulatory resources in the morning—to experience positive mood. The present results are also in line with previous research, which demonstrated that people who experience circadian misalignment have more difficulties putting their intentions into actions after nights characterized by low sleep quality, compared to nights with high sleep quality (Kühnel et al., 2016). Given that positive mood plays a crucial role in the initiation of action (Bledow, Schmitt, Frese, & Kühnel, 2011; Kazén, Kaschel, & Kuhl, 2008), our research provides additional support for the notion that sleep quality fosters emotional processes that ensure effective motivational and volitional processes of goal-directed behavioral regulation.

Strengths, Limitations, and Avenues for Future Research

Of course, the present study is not without limitations, which should be thoroughly discussed. The first limitation is that our design does not allow for us to establish a causal relationship between late-night use of mobile devices and subsequent sleep characteristics. In our study, we observed the co-occurrence of late-night use of mobile devices and subsequent sleep characteristics. We cannot fully rule out the alternative explanation that people may experience difficulties falling asleep on some days—due to reasons *unrelated* to the use of mobile devices—and that they started using their mobile devices because they were experiencing difficulties falling asleep. Reasons for the experience of difficulties falling asleep could be, for example, heavy caffeine consumption in the evening and/or exercising shortly before going to bed. These behaviors that may compromise subsequent sleep constitute inadequate sleep hygiene (Mastin, Bryson, & Corwyn, 2006). Future research may thus capture day-specific sleep hygiene behaviors to rule out this alternative explanation and to assess the relative impact of sleep hygiene behaviors on subsequent sleep, in comparison to late-night use of mobile devices. A complementary approach would be to conduct intervention studies in which late-night use of mobile devices is experimentally manipulated (e.g., prohibited on one evening and compulsory on the next). However, this approach would raise the question of whether prohibiting versus enforcing a certain behavior is similar to, and has the same implications as, naturally occurring behavior.

Another limitation is that we relied on self-report data for late-night use of mobile devices. It would be preferable to have objective data on the late-night use of devices, such as screen time (that is, the number of minutes the screen is on). Although this could be realized with a smartphone application measuring the screen time of the smartphone (Christensen et al., 2016), it might be cumbersome to install on all mobile devices, and it may pose further challenges regarding the protection of privacy. In addition, we employed a rather undifferentiated assessment of late-night use of mobile devices. Across several types of devices (smartphones, tablets, or notebook computers) and across the various media content that people are confronted with, late-night use of mobile devices seems to threaten employees' sleep quality. However, the use of certain devices might be less harmful than others. The screens of some devices may emit less blue light and/or people may tend to use certain devices to consume specific media content that is less threatening to subsequent sleep. Moreover, employees may use their mobile devices for work-related purposes in a way that enables subsequent psychological detachment from work-related issues, which, in turn, may foster subsequent sleep (Scullin, Krueger, Ballard, Pruett, & Bliwise, 2018; Syrek, Weigelt, Peifer, & Antoni, 2017). Taken together, it would be a promising avenue for future research to use more differentiated and objective measures of mobile devices and media content.

Another limitation is that we only focused on positive mood as an outcome of the interplay of circadian misalignment, sleep, and late-night use of mobile devices. Although positive mood is conceptualized as the core of hedonic well-being (Sonnentag, 2015) and highly relevant for a wide range of behaviors, such as proactive behavior and creativity—and also for volitional control (Bledow, Rosing, & Frese, 2013; Fay & Sonnentag, 2012; Fredrickson, 2001)—future research might jointly examine these phenomena and might extend the current line of research to behavioral outcomes of positive mood in the work and nonwork domain.

In contrast to the previously acknowledged limitations, a strength of our daily process approach is that we realized repeated measures of the independent and the dependent variables that were separated in time (late-night use of mobile devices was assessed in the morning and positive mood was assessed at the end of the work day). Furthermore, we obtained ambulatory data on sleep quality and sleep duration. That is, by analyzing the effects of late-night use of mobile devices on positive mood via physiologically operationalized sleep variables, we were able to identify patterns of relationships which were not contaminated by common method variance and thus validly reflect underlying psychological mechanisms (Podsakoff, MacKenzie, & Podsakoff, 2012).

Practical Implications

To foster good sleep quality, the results of our study suggest that late-night use of mobile devices should be limited. This could be achieved by shutting off mobile devices at a certain point in time in the evening. However, given that we know that the recommendation to shut off all mobile devices in the evening is easier said than done, individuals might use blue-light filter applications when they cannot refrain from using their devices. Blue-light filter applications determine when the sun is scheduled to set (or to self-chosen, prescheduled times), and then adjust the screen color to a warmer hue that minimizes blue-light emission. However, blue-light filter applications alone might not be sufficient because they do not prevent people from being confronted with arousing content.

Companies may support their employees in refraining from late-night use of mobile devices—at least for work-related purposes. For example, they may introduce polices to prevent their employees from being *always available* by discouraging sending company emails late at night. For example, a health care consultancy in Philadelphia established a policy that discourages employees from sending emails between 10 p.m. and 7 a.m. during the week, and all day on weekends: "If employees choose to work during off-hours, the policy discourages them from putting their habits onto others by sending emails during this time; they simply save the messages as drafts to be manually sent later, or they program their email client to automatically send the messages during work hours" (Thomas, 2015). Moreover, supervisors may clearly communicate (and serve as role models) that they do not expect employees to be available and to read and answer emails late at night. For example, a big German telecommunications provider has a "Black Berry policy" in place, calling on bosses to respect their subordinates' leisure time and to accept that mobile phones will be turned off.

To minimize potential negative consequences of lower sleep quality for positive mood, circadian misalignment should be reduced. This can be achieved by modifications of the light environment, such as decreased exposure to artificial light in the evening (Wright et al., 2013). Moreover, work times should be aligned with employees' biologically preferred sleep–wake times. For example, Vetter, Fischer, Matera, and Roenneberg (2015) implemented an intervention study in a real-life industrial setting that adjusted work shifts to individuals' biologically preferred sleep–wake times and found that workers' sleep improved (Czeisler, Moore-Ede, & Coleman, 1982). For nonshift work employees, companies may offer flexible work schedule arrangements in the form of idiosyncratic deals (i.e., *i-deals*) that may be beneficial for both the employee and the employer (Hornung, Rousseau, & Glaser, 2008). I-deals allow for working arrangements (e.g., later work start times) that are tailored to an employee's biological preferences. Likewise, companies may offer flextime with as little as possible core work time to allow employees to better align work time with their biological preferences.

Conclusion

This present ambulatory diary study sheds light on a highly topical, wide-spread behavior: late-night use of mobile devices. Our results confirm prevailing concerns about late-night use of mobile devices, suggesting that late-night use of mobile devices is related to lower subsequent sleep quality that is, in turn, related to lower next-day positive mood. Our findings also suggest that this negative chain of events unfolds for people who are forced to sleep in misalignment with their biological preferences, that is, people who experience circadian misalignment. Thus, our study underscores the importance of people's behavior before going to bed for subsequent sleep and positive mood the next day, and we hope that it stimulates more research on these important topics.

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