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ABSTRACT

Mobile DNA and Sleep Quality

Previous studies have demonstrated a strong negative association between smartphone use and sleep quality. However, the majority of these studies quantified smartphone use with subjective self-reported metrics. In contrast, the current study contributes to the literature by objectively logging university students' smartphone use and investigating the association thereof with sleep quality. The extensive, nuanced smartphone usage information obtained from this logging also enables us to explore the validity of several mechanisms theorised to underlie the previously reported negative association between smartphone use and sleep quality. In contrast to earlier research, we do not find a significant association between sleep quality and the duration or frequency of students' daily smartphone use. However, students with the internalised habit of launching a greater number of applications per session ('gateway habits') experience worse sleep quality. This finding is consistent with literature showing that smartphone-related stress is more strongly associated with checking habits stemming from 'fear-ofmissing- out' than with overall screen time.

JEL Classification: I10, L86

Keywords: mobile DNA, smartphone use, smartphone use logging, fear-of-missing-out, gateway habits, sleep quality

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1. Introduction

Mobile phone ownership has risen sharply over the last decade. Only 35% of United States citizens owned a smartphone in 2011 compared to 81% eight years later (Pew Research Center, 2019). The ubiquity of smartphones is most evident among Americans aged 18–29. According to the Pew Research Center (2019), 96% of individuals in this demographic own a smartphone and 58% of them state that their smartphone is the primary device with which they access the Internet. Tertiary education (college and university) students comprise a large percentage of Americans in this age group. However, their smartphone usage patterns have been recently linked to negative socio-economic consequences such as lower exam scores (Amez & Baert, 2020; Amez et al., 2019; Felisoni & Godoi, 2018), worse mental health (Li et al., 2015), and reduced physical fitness (Lepp et al., 2013).

In addition to the effect of smartphone use on these socio-economic factors, recent studies have also explored whether heavy smartphone use affects students' sleep quality (Amez et al., 2020; Christensen et al., 2016). Indeed, this literature provides four different mechanisms supporting a negative effect of heavy smartphone use on sleep quality. First, there is a trade-off between sleep duration and the amount of time spent on a smartphone, commonly referred to as 'time displacement' (Cain & Gradisar, 2010; Foerster et al., 2019; Hysing et al., 2015). Stated otherwise, for every minute a student spends on her/his smartphone, (s)he loses one minute of sleep. Second, certain smartphone activities, such as playing video games, may lead to both psychological and physiological arousal, in turn interfering with sleep quality (Exelmans & Van den Bulck, 2017; Mauri et al., 2011). Third, students often feel the need to be continuously accessible and the desire not to miss out on anything happening online (i.e. ‘FOMO’, fear-of-missing-out; Thomée et al., 2010). This FOMO may lead to smartphone-related stress (van der Schuur et al., 2018) and the ensuing production of stress hormones such as cortisol (Sanford et al., 2014), which have been shown to interfere with sleep (Zeiders et al., 2011). Fourth, the production of the sleep-inducing hormone melatonin is inhibited by the bright (blue) light emitted by smartphone screens (Boniel-Nissim et al., 2015; Higuchi et al., 2005), potentially interfering with an individual’s ability to fall asleep (Orzech et al., 2016).

Studies probing the association between sleep quality and smartphone use among tertiary education students have operationalised the independent variable ‘smartphone use’ in a number of ways. First, a substantial proportion of these studies specifically focussed on smartphone use in the hours preceding bedtime. For example, by analysing survey data from 516 American undergraduate students, Li et al. (2015) found a significant negative association between night-time cell phone use and sleep quality. In contrast, other studies have focussed on how ‘problematic smartphone use’ (i.e. inordinate phone use and/or a smartphone addiction that presents with symptoms similar to those of substance use disorders; Elhai et al., 2019) was associated with sleeping problems. For instance, a recent meta-analysis revealed a significant negative association between problematic smartphone use and sleep quality in a general adult population (Yang et al., 2020). In addition, in a survey of more than 600 Korean university students, Min et al. (2017) reported that self-reported susceptibility to smartphone addiction was significantly associated with poor sleep quality. Similarly, Demirci et al. (2015) and Eyvazlou et al. (2016) reported a negative association between excessive smartphone use and sleep quality among university students in Turkey and Iran, respectively. Finally, to our knowledge, Amez et al. (2020) were the only authors to investigate the association between students' sleep quality and overall smartphone use (i.e. irrespective of the specific time of smartphone use or the addictive characteristics thereof). They found that increased smartphone use was associated with reduced odds of good sleep quality. Moreover, this negative association was stronger for female than for male students.

Although the currently available literature clearly supports a negative association between university students' smartphone use and their sleep quality, we believe that certain methodological limitations may compromise the validity of these findings. First, previous work primarily utilised cross-sectional research designs without exogenous variation in smartphone use, preventing us from drawing causal interpretations (Hale & Guan, 2015). Second, both smartphone use and sleep quality are typically measured through survey questions. These self-reported data may be susceptible to recall and/or social desirability biases, as well as underestimation bias due to an internalised unawareness of the intensity and nature of one's smartphone habits (Chen et al., 2016; Fossum et al., 2014; Liu et al., 2019). As such, earlier research has shown only a moderate correlation between self-reported smartphone use and actual logged data (Araujo et al., 2017; Boase & Ling, 2013). Notably, research on the negative consequences of students' smartphone use on another outcome, academic performance, has shown different results depending on whether smartphone use was self-reported or objectively tracked (Amez & Baert, 2020). In addition to these methodological limitations, few studies have focussed on the mechanisms underlying the observed negative association between students' smartphone use and their sleep quality (Amez et al., 2020).

The present study sought to fill the latter two gaps in the literature. First, rather than relying upon students' self-reported smartphone use, we tracked their actual smartphone use with an in-house mobile application, mobileDNA (Anrijs et al., 2018). mobileDNA yields objective information on when and how students use their smartphones. Specifically, we can capture when students use their smartphones, which applications they launch, and how much time they spend on their smartphones. Second, we also used these detailed data to explore the validity of the aforementioned mechanisms theorised to underlie the observed negative association between sleep quality and students' smartphone use. As such, we go beyond overall smartphone use as an independent variable, which allows us to get a more nuanced picture on its association with sleep quality.

The remainder of this manuscript is structured as follows. First, we explain the data collection procedure and discuss the characteristics of our study sample. Next, we report the results of our empirical analyses. Finally, we discuss our main findings, acknowledge the limitations of our study, and provide directions for future research.

2. Data

2.1. Participants and procedure

First-year students registered for one of five different study programmes (business and economics; engineering; pharmaceutical sciences; political and communication sciences; and psychological sciences) at Ghent University, Belgium, were recruited during the fall semester of 2018. All freshmen students enrolled in a primary course from each curriculum were approached directly by the principal investigator at the start of a lecture and asked whether they wished to participate. To obtain a homogeneous sample, non-freshmen students from other programmes who were taking the course as an elective course were excluded.

Students were required to complete three tasks to be included in our study sample. First, students were asked to immediately fill out a written questionnaire during the attended course. Second, students were invited to download mobileDNA and to keep the application active for the next two weeks.[1] Third, the written questionnaire contained a clause in which students consented to have their survey responses be linked to the information provided by mobileDNA. The researchers explained at the beginning of the survey that students were under no obligation to participate and could withdraw from the study at any time. Students were assured that their answers would remain confidential and anonymous.

Ultimately, 95 students met all three inclusion criteria. Fifty-two students (54.7%) were female and 43 (45.3%) were male. On average, participating students were 18.5 years old; this result is in line with expectations since Belgian students typically begin university at age 18. We also performed t-tests to examine whether the students in our sample differed substantially from their peers (n = 1,421) who attended the same classes but were not included in our final sample, with respect to (i) sleep quality, (ii) age, and (iii) gender. Compared to their peers, study participants experienced very similar sleep quality (p = 0.308) and were representative with respect to age (p = 0.370). Therefore, although female students were slightly underrepresented in our sample (p = 0.002), the students in our study

[1] Unfortunately, mobileDNA is only available for the Android operating system. Thus, students who owned a smartphone running another operating system were unable to participate. We return to the external validity of our sample below.

were fairly representative of the target population of the freshmen students attending classes within the five study programmes. We elaborate further on this issue in the Conclusion section.

2.2. Measures

To meet the need for objective quantification of smartphone use, as discussed in the Introduction section, students' smartphone use was tracked with mobileDNA. Overall smartphone use was measured in two ways. First, overall smartphone use was defined as the average amount of time students spent on their smartphones per day. As shown in Table 1, the participating students actively used their smartphones for an average of more than three hours (mean (M) = 3.049, standard deviation (SD) = 1.770), or approximately 183 minutes, per day. To obtain a second metric of overall smartphone use, we tracked the frequency of students' daily app-events, defined as the action of launching a mobile application. During the two-week study, on average, students launched an application approximately 103 times per day.

<Table 1 about here>

We also analysed more detailed characteristics of students' smartphone use to validate the mechanisms potentially underlying the aforementioned negative associations thereof with sleep quality discussed in the Introduction section.

First, the extent to which students experience FOMO and related physiological arousal may depend on the reasons for which they use their devices. Therefore, as suggested by Lissak (2018), we divided all applications used into nine different *application categories*: (i) social media, (ii) communication, (iii) tools, (iv), productivity, (v) video, (vi) music, (vii) news, (viii) entertainment, and (ix) games.[2] As presented in Table 1, students primarily used their smartphones to access social media, watch videos, and play games. This finding is in line with those of Allcott et al. (2020), who reported that American adults spend almost half of their smartphone time on the so-called FITSBY applications (Facebook, Instagram, Twitter, Snapchat, web browsers, and YouTube).

Second, two of the theoretical mechanisms discussed above suggest that especially smartphone use at night may be a particular detriment to good sleep quality. Specifically, the blue light emitted from smartphone screens suppresses the production of melatonin (Higuchi et al., 2005), whereas smartphone-related stress may induce cortisol production (Sanford et al., 2014). To test whether smartphone use at a particular *time of day* is more strongly associated with worse sleep quality, we calculated students' smartphone use according to specific time intervals: (i) during the day (i.e. between 6 am and 9 pm); (ii) in the evening (i.e. between 9 pm and 12 am); and (iii) at night (i.e. between 12 am and 6 am). Unsurprisingly, in absolute terms, students used their smartphones the most during the longest time interval (i.e. during the day). However, students' hourly smartphone use was slightly higher during the evening.

Third, the aforementioned time displacement mechanism predicts a linear relationship between sleep quality and overall duration of smartphone use.

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[2] Each application was assigned to a category based on an analysis of categories used in the Android Play Store. The most important applications (with respect to duration and frequency of use) were Instagram, Facebook, and Snapchat (social media); Facebook Messenger, Google Chrome, and WhatsApp (communication); Google, Clock, and Google Play (tools); Google Drive, Cold Turkey, and Forest (productivity); YouTube, Yelo, and Stievie (video); Spotify, Google Music, and Samsung Music (music); Twitter, Reddit, and VRT NWS (news); Netflix, 9GAG, and Google Play Games (entertainment); Clash of Clans, Subway Surfers, and Pokémon Go (games).

However, the observed negative impact of smartphone use on students' sleep quality may depend on the specific *distribution* of this smartphone use. For example, the influence of ten 3-minute sessions may differ from that of one uninterrupted 30-minute session. Moreover, students who check their smartphones very regularly for short periods of time may experience a higher level of FOMO (Thomée et al., 2010), whereas students who 'bundle' their smartphone use – and thereby multitask less – may experience less smartphone-related stress (Hysing et al., 2015). Therefore, we constructed two variables to capture how students distribute their smartphone use. That is, we counted (i) the number of daily periods, including night-time hours, in which students did not use their smartphones for at least one uninterrupted hour (M = 1.643, SD = 0.795) and (ii) logged the average number of different applications a student launched from the moment (s)he picked up the smartphone until the end of the smartphone session (M = 3.510, SD = 1.747).

Finally, students' sleep quality was measured with the subjective sleep quality component of the validated and widely used Pittsburgh Sleep Quality Index (PSQI; Buysse et al., 1989). Although this scale is subjective, previous research has shown that participants' self-reported sleep quality is consistent with objective sleep quality metrics (Akerstedt et al., 2016; Hoch et al., 1987). Specifically, in the written questionnaire, students were asked, 'During the past month, how would you rate your sleep quality overall?'; the four possible answer choices were: 'very bad' (score 0), 'fairly bad' (score 1), 'fairly good' (score 2), and 'very good' (score 3). The average sleep quality score in our sample was 1.968 (SD = 0.592), which approximates 'fairly good' sleep quality.

3. Results

We examine the association between multiple characteristics of students' objectively measured smartphone use and their reported sleep quality by means of linear regression analyses (ordinary least squares; OLS). Ordered logistic regression analyses yield very similar results and are available upon reasonable request.

First, we regress students' sleep quality on their (i) daily smartphone use measured in hours and (ii) their daily smartphone frequency measured in app-events. We keep gender and age constant – analyses controlling for additional variables such as perceived health and relationship status yield very similar results and are available upon reasonable request. The results presented in Table 2 show there are no statistically significant associations between sleep quality and overall smartphone use.[3] This finding is in contrast with those of previous studies reporting a significant negative association within different age groups. As mentioned above, a potential explanation for this discrepant result may relate to the fact that smartphone use is tracked objectively in the current study. Indeed, other research pertaining to the socio-economic consequences of smartphone use has shown that negative associations are weaker or non-existent when objective metrics are used (Amez & Baert, 2020). Moreover, this contradiction with previous findings suggests that focussing on overall smartphone use may not be sufficient to detect associations with sleep quality, as this variable does not provide information

[3] This lack of association does not seem to be the result of our limited sample size because the estimated coefficients (−0.014 and −0.001) are insignificant in economic terms too. Given the associated standard errors (0.035 and 0.001, respectively), rather small associations would have been distinguished from 0.

pertaining to when and how students use their smartphones.

<Table 2 about here>

In particular, as aforementioned, the association between smartphone use and sleep quality may depend upon the specific purpose for which individuals use their phones. That is, certain applications categories may induce a greater degree of psychological and physiological arousal than others, potentially resulting in worse sleep. Therefore, in Table 3, we estimate the association between sleep quality and students' daily use of individual smartphone application categories (model (1) to (9)), as well as all application categories together (10). Similarly, in Table 4, we estimate the association between students' sleep quality and the frequency with which they use each application category. In these regression models, except for model (10), overall smartphone use is kept constant, to prevent an application category variable from picking up the effect of another category.

With the exception of the 'tools' application category, we do not find any significant associations. This observation is surprising, particularly for applications in the 'social media' category, as Woods and Scott (2016) previously linked the use of these applications to poor sleep quality. We believe that the negative association found herein between sleep quality and students' use of 'tools' applications is a statistical artefact for two reasons. First, this application category only represents a negligible fraction of students' smartphone use. Second, there is no theoretical mechanism that may underlie this particularly strong association.

<Table 3 about here>

<Table 4 about here>

Next, to test the aforementioned mechanisms suggesting that smartphone use at night is particularly detrimental to students' sleep quality, we regress students' sleep quality on smartphone use according to the time of day, i.e. during the day, in the evening, and at night. In Table 5, models (1), (2), and (3) present estimates of the association between sleep quality and students' smartphone use during each of these three time periods. In model (4), the three independent variables are included jointly. Similarly, in models (5) through (8), we regress students' sleep quality on the daily frequency with which they use their smartphones during these three time periods. We do not find any significant associations between sleep quality and daytime or evening smartphone use. However, the results of models (3), (4), (7) and (8) demonstrate a statistically significant negative association between sleep quality and night-time smartphone use. These findings are consistent with those of Exelmans and Van den Bulck (2016) and Li et al. (2015), and are consistent with the theory that suppressed melatonin production prohibits good sleep (Higuchi et al., 2005). However, these estimates may also be indicative of reverse causality (discussed in more detail below).

<Table 5 about here>

Finally, Table 6 presents the estimation results of regressing the students' PSQI sleep quality component on the distribution of their smartphone use, keeping overall smartphone use constant. We do not find any significant association between students' sleep quality and the number of periods per day that they do not use their smartphones for at least one hour. In contrast, the average number of app-events per session is negatively associated with students' PSQI sleep quality scores. This association is robust to the inclusion of other independent variables and is significant both in statistical and economic terms. Specifically, students with an average number of app-events that is 1 SD higher have a self-reported sleep quality that is 0.233 SD lower.[4]

The latter finding does not corroborate our a priori expectation that students who ‘bundle’ the time spent on their smartphones – and thereby multitask less – may experience less smartphone-related stress. However, the consistent launching of multiple applications per session may indicate that students are experiencing FOMO, thereby supporting the idea that stress-hormones induced by smartphone-related stress lead to reduced sleep quality (Orzech et al., 2016). Alternatively, this particular behaviour may be indicative of so-called ‘gateway habits’, i.e. checking habits that may function as a gateway to the use of other smartphone functions and content (Oulasvirta et al., 2012). Ultimately, these habits may also be related to stress, and therefore to lower sleep quality.

<Table 6 about here>

4. Conclusion

In the current study, we contributed to the empirical literature investigating the association between smartphone use and sleep quality in two substantial ways. First, to our knowledge, this study is the first to objectively track smartphone use to investigate this association. Second, the extensive and detailed information gathered with an in-house developed tracking application allowed us to explore the empirical validity of potential theoretical mechanisms proposed to underlie

[4] $0.233 = (-0.079 \times 1.747)/(0.592)$. In this equation, −0.079 is the regression coefficient in column (3) of Table (6), 1.747 is the SD of average app-events per session (Table 1, Panel E), and 0.592 is the SD of the PSQI subjective sleep quality component (Table 1, Panel F).

associations between smartphone use and sleep quality.

In contrast to the available literature, we did not find a significant association between students' overall smartphone use and their sleep quality. This finding corroborates the results of previous studies of the impact of smartphone use on academic performance, which reported that associations are weaker when objectively logged data, rather than self-reported metrics, are used.

However, we did find a robust and significant negative association between students' sleep quality and the number of applications they launch per smartphone session. Checking a greater number of applications per session may be indicative of a higher level of FOMO, thereby leading to more smartphone-related stress. As such, this finding is consistent with the theory that hormones induced by smartphone-related stress lead to worse sleep quality.

Taken together, our findings show that (i) objectively logged smartphone usage data are necessary to accurately measure the (potential) consequences of smartphone use; and (ii) that a singular focus on overall smartphone use may be insufficient to estimate associations thereof with students' sleep quality.

Our study must be interpreted in view of its limitations and in the context of directions for future research. First, although our target population was very broad, consisting of freshmen students from multiple faculties and study programmes, our final sample size was rather limited. Similarly, Allcott et al. (2020) invited more than three million people to participate in their recent smartphone usage study; however, only slightly more than 5,000 individuals installed their mobile application. A potential explanation for this result is that the requirement to install an application may be perceived as intrusive. Nevertheless, future studies aiming to replicate our work should seek to base their findings on a larger sample than that used herein. A second limitation of our research design relates to the fact that mobileDNA is only available for smartphones that run the Android operating system, as Android smartphone users may differ substantially from those of other smartphone users. However, it was somewhat comforting in this respect that our sample turned out to be representative of the target population with respect to sleep quality and age.

Third, although our study enabled us to capture how and when students used their smartphones, we did not observe why they used their smartphones. In this respect, previous studies have shown that self-control (Exelmans, 2019) is a driver of intense, habitual smartphone use (Oulasvirta et al., 2012). Given our finding that the number of app-events per session was negatively linked with sleep quality, future studies should further investigate the role of gateway habits in the association between students' smartphone use and their sleep quality.

Fourth, our analyses are based on cross-sectional observational data, preventing us from drawing causal interpretations. This concern is especially relevant to a secondary result of our study, i.e. the observed association between night-time smartphone use and poor sleep quality. As Tavernier and Willoughby (2014) previously reported, smartphone use may be a result of poor sleep quality, rather than a cause. Specifically, students may use their smartphones as a distraction when they are unable to fall asleep. A potential methodological solution to this problem may be to adopt an instrumental variable approach, such as that used in Baert et al. (2020). However, exogenous predictors of the rich information on students' smartphone use as yielded by our tracking application may be challenging to identify.

Finally, but related to the former limitation, although tracking students' smartphone use yields extensive information, it does not consider the potential influence of other (mobile) devices (Hale & Guan, 2015). Specifically, students may use other technologies such as televisions, tablet computers, or laptops in addition to their smartphones. As such, the smartphone usage data logged by our application may capture the effects of media multitasking (van der Schuur et al., 2018). Future studies should attempt to control for the use of multiple devices, ideally by objectively tracking each one.

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Table 1. Summary Statistics

	Mean	Standard deviation
A. Control Variables		
Female (frequency)	0.547	-
Age (years)	18.505	1.138
B. Overall smartphone use		
Daily smartphone use (hours)	3.049	1.770
Daily smartphone frequency (app-events)	103.106	74.715
C. Smartphone use by application category		
Daily smartphone use (hours): social	1.004	0.783
Daily smartphone use (hours): communication	0.559	0.416
Daily smartphone use (hours): tools	0.052	0.061
Daily smartphone use (hours): productivity	0.097	0.166
Daily smartphone use (hours): video	0.572	0.616
Daily smartphone use (hours): music	0.056	0.077
Daily smartphone use (hours): news	0.094	0.179
Daily smartphone use (hours): entertainment	0.224	0.464
Daily smartphone use (hours): games	0.374	0.680
D. Smartphone use by time of day		
Daily smartphone use (hours): during the day	2.212	1.322
Daily smartphone use (hours): in the evening	0.627	0.431
Daily smartphone use (hours): at night	0.215	0.282
E. Smartphone use by distribution		
Number of periods per day of at least one hour without smartphone use	1.643	0.795
Average app-events per session	3.510	1.747
F. Sleep quality		
PSQI subjective sleep quality component	1.968	0.592
Number of observations	95	

Notes. See the Data section for a description of each variable. Standard deviations are not provided for binary variables. The following abbreviation is used: PSQI (Pittsburgh Sleep Quality Index).

Table 2. Estimated Associations between Sleep Quality and Overall Smartphone Use

	(1)	(2)
Estimation method	OLS	
Dependent variable	PSQI subjective sleep quality component	
Daily smartphone use	−0.014 (0.035)	-
Daily smartphone frequency	-	−0.001 (0.001)
Female	−0.177 (0.124)	−0.180 (0.124)
Age	0.059 (0.057)	0.061 (0.056)
Intercept	1.025 (1.047)	0.994 (1.028)
Number of observations	95	95

Notes. The presented values are coefficient estimates, with standard errors in parentheses. ***, **, and * indicate significance at the 1%, 5%, and 10% significance level, respectively. The following abbreviations are used: OLS (ordinary least squares) and PSQI (Pittsburgh Sleep Quality Index).

Table 3. Estimated Associations between Sleep Quality and Smartphone Use Duration by Application Category

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
Estimation method	OLS									
Dependent variable	PSQI subjective sleep quality component									
Daily smartphone use	−0.012 (0.041)	0.000 (0.037)	0.004 (0.034)	−0.015 (0.036)	0.011 (0.045)	−0.002 (0.036)	−0.014 (0.035)	−0.017 (0.036)	−0.029 (0.040)	
Daily smartphone use: social	−0.010 (0.091)	-	-	-	-	-	-	-	-	−0.008 (0.083)
Daily smartphone use: communication	-	−0.177 (0.158)	-	-	-	-	-	-	-	−0.078 (0.152)
Daily smartphone use: tools	-	-	−2.787*** (1.021)	-	-	-	-	-	-	−2.606** (1.071)
Daily smartphone use: productivity	-	-	-	0.052 (0.379)	-	-	-	-	-	0.395 (0.394)
Daily smartphone use: video	-	-	-	-	−0.117 (0.130)	-	-	-	-	−0.073 (0.108)
Daily smartphone use: music	-	-	-	-	-	−1.275 (0.810)	-	-	-	−1.218 (0.845)
Daily smartphone use: news	-	-	-	-	-	-	−0.113 (0.347)	-	-	−0.006 (0.356)
Daily smartphone use: entertainment	-	-	-	-	-	-	-	0.037 (0.137)	-	0.024 (0.133)
Daily smartphone use: games	-	-	-	-	-	-	-	-	0.080 (0.104)	0.066 (0.094)
Female	−0.176 (0.125)	−0.184 (0.124)	−0.238* (0.122)	−0.178 (0.125)	−0.192 (0.125)	−0.198 (0.123)	−0.182 (0.125)	−0.180 (0.125)	−0.169 (0.124)	−0.279** (0.128)
Age	0.059 (0.057)	0.056 (0.057)	0.086 (0.056)	0.059 (0.057)	0.057 (0.057)	0.059 (0.056)	0.059 (0.057)	0.059 (0.057)	0.058 (0.057)	0.085 (0.057)
Intercept	1.019 (1.054)	1.127 (1.050)	0.643 (1.021)	1.011 (1.057)	1.052 (1.049)	1.072 (1.039)	1.038 (1.053)	1.021 (1.053)	1.038 (1.050)	0.779 (1.053)
Number of observations	95	95	95	95	95	95	95	95	95	95

Notes. The presented values are coefficient estimates, with standard errors in parentheses. ***, **, and * indicate significance at the 1%, 5%, and 10% significance level, respectively. In model (10), we do not control for overall smartphone use to avoid multicollinearity. The following abbreviations are used: OLS (ordinary least squares) and PSQI (Pittsburgh Sleep Quality Index).

Table 4. Estimated Associations between Sleep Quality and Smartphone Use Frequency by Application Category

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
Estimation method	OLS									
Dependent variable	PSQI subjective sleep quality component									
Daily smartphone frequency	−0.002 (0.001)	−0.000 (0.002)	−0.000 (0.001)	−0.000 (0.001)	−0.000 (0.001)	0.000 (0.001)	−0.000 (0.001)	−0.001 (0.001)	−0.001 (0.001)	
Daily smartphone frequency: social	0.003 (0.003)	-	-	-	-	-	-	-	-	−0.000 (0.002)
Daily smartphone frequency: communication	-	−0.000 (0.004)	-	-	-	-	-	-	-	0.001 (0.003)
Daily smartphone frequency: tools	-	-	−0.017* (0.010)	-	-	-	-	-	-	−0.022** (0.010)
Daily smartphone frequency: productivity	-	-	-	−0.006 (0.004)	-	-	-	-	-	−0.004 (0.004)
Daily smartphone frequency: video	-	-	-	-	−0.013 (0.016)	-	-	-	-	−0.013 (0.017)
Daily smartphone frequency: music	-	-	-	-	-	−0.015 (0.010)	-	-	-	−0.008 (0.011)
Daily smartphone frequency: news	-	-	-	-	-	-	−0.006 (0.010)	-	-	−0.006 (0.012)
Daily smartphone frequency: entertainment	-	-	-	-	-	-	-	0.026 (0.017)	-	0.022 (0.020)
Daily smartphone frequency: games	-	-	-	-	-	-	-	-	0.010 (0.007)	0.008 (0.008)
Female	−0.188 (0.124)	−0.179 (0.124)	−0.217* (0.124)	−0.186 (0.123)	−0.206 (0.128)	−0.203 (0.124)	−0.183 (0.124)	−0.180 (0.123)	−0.178 (0.123)	−0.273** (0.128)
Age	0.061 (0.056)	0.060 (0.057)	0.067 (0.056)	0.077 (0.057)	0.057 (0.057)	0.060 (0.056)	0.062 (0.057)	0.066 (0.056)	0.069 (0.056)	0.089 (0.057)
Intercept	0.993 (1.030)	0.999 (1.039)	0.952 (1.017)	0.716 (1.038)	1.133 (1.044)	1.031 (1.022)	0.975 (1.033)	0.852 (1.026)	0.841 (1.027)	0.636 (1.051)
Number of observations	95	95	95	95	95	95	95	95	95	95

Notes. The presented values are coefficient estimates, with standard errors in parentheses. ***, **, and * indicate significance at the 1%, 5%, and 10% significance level, respectively. In model (10), we do not control for overall smartphone use to avoid multicollinearity. The following abbreviations are used: OLS (ordinary least squares) and PSQI (Pittsburgh Sleep Quality Index).

Table 5. Estimated Associations between Sleep Quality and Smartphone Use by Time of Day

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Estimation method	OLS							
Dependent variable	PSQI subjective sleep quality component							
Smartphone use: during the day	−0.019 (0.047)	-	-	−0.020 (0.071)	-	-	-	-
Smartphone use: in the evening	-	0.062 (0.144)	-	0.287 (0.207)	-	-	-	-
Smartphone use: at night	-	-	−0.403* (0.124)	−0.577** (0.276)	-	-	-	-
Smartphone frequency: during the day	-	-	-	-	−0.001 (0.001)	-	-	−0.002 (0.002)
Smartphone frequency: in the evening	-	-	-	-	-	−0.000 (0.004)	-	0.011 (0.007)
Smartphone frequency: at night	-	-	-	-	-	-	−0.020* (0.010)	−0.026** (0.012)
Female	−0.176 (0.124)	−0.174 (0.123)	−0.245* (0.128)	−0.295** (0.131)	−0.179 (0.123)	−0.171 (0.124)	−0.242* (0.128)	−0.270** (0.128)
Age	0.059 (0.057)	0.065 (0.057)	0.070 (0.056)	0.091 (0.057)	0.061 (0.056)	0.061 (0.056)	0.070 (0.056)	0.079 (0.056)
Intercept	1.021 (1.046)	0.829 (1.058)	0.892 (1.010)	0.441 (1.057)	0.992 (1.027)	0.943 (1.033)	0.907 (1.011)	0.702 (1.018)
Number of observations	95	95	95	95	95	95	95	95

Notes. The presented values are coefficient estimates, with standard errors in parentheses. ***, **, and * indicate significance at the 1%, 5%, and 10% significance level, respectively. The following abbreviations are used: OLS (ordinary least squares) and PSQI (Pittsburgh Sleep Quality Index).

Table 6. Estimated Associations between Sleep Quality and Smartphone Use by Distribution

	(1)	(2)	(3)	(4)	(5)	(6)
Estimation method	OLS					
Dependent variable	PSQI subjective sleep quality component					
Daily smartphone use	−0.020 (0.042)	−0.007 (0.034)	−0.010 (0.042)	-	-	-
Daily smartphone frequency	-	-	-	−0.001 (0.001)	−0.000 (0.001)	−0.001 (0.001)
Number of periods per day of at least one hour without smartphone use	−0.025 (0.093)	-	−0.011 (0.091)	−0.034 (0.090)	-	−0.022 (0.089)
Average number of app-events per session	-	−0.080** (0.035)	−0.079** (0.035)	-	−0.079** (0.035)	−0.078** (0.035)
Female	−0.176 (0.124)	−0.220* (0.122)	−0.220* (0.123)	−0.179 (0.124)	−0.223* (0.122)	−0.222* (0.123)
Age	0.057 (0.057)	0.063 (0.055)	0.063 (0.056)	0.060 (0.057)	0.064 (0.055)	0.064 (0.055)
Intercept	1.109 (1.098)	1.223 (1.027)	1.260 (1.075)	1.075 (1.056)	1.214 (1.010)	1.266 (1.037)
Number of observations	95	95	95	95	95	95

Notes. The presented values are coefficient estimates, with standard errors in parentheses. ***, **, and * indicate significance at the 1%, 5%, and 10% significance level, respectively. The following abbreviations are used: OLS (ordinary least squares) and PSQI (Pittsburgh Sleep Quality Index).