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Adolescents' Digital Nightlife: The Comparative Effects of Day- and Nighttime Smartphone Use on Sleep Quality

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Abstract

The smartphone occupies a substantial part of adolescents' daily life, from the moment they wake up to, for some, well beyond their bedtime. The current study compared the impact of adolescents' daytime, pre-bedtime, and post-bedtime smartphone use on their sleep quality. In addition, it explored the differential effects of lean-back and lean-forward smartphone apps. We collected data from 155 adolescents across 21 days using smartphone tracking (745,706 app activities) in combination with experience sampling (1,950 sleep quality assessments). We found no significant effects of daytime and pre-bedtime smartphone use on sleep quality, but a negative association of post-bedtime smartphone use with sleep quality ($\beta = -.09$). The association between smartphone use and sleep quality varied across app categories: Time spent on lean-forward apps around bedtime, such as social media apps right before ($\beta = -.08$) and game apps after bedtime ($\beta = -.23$), was associated with lower sleep quality. The use of lean-back apps (i.e., video players) was not associated with sleep quality, neither before nor after bedtime.

Keywords

nighttime, gaming, social media, sleep quality, ESM

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Sleep is essential for a healthy and balanced lifestyle. The basis for healthy sleep patterns is formed during adolescence (Dregan & Armstrong, 2010). However, proper sleep is not self-evident for many adolescents (Gradisar et al., 2011). For instance, studies have shown that about half to two-thirds of adolescents experience poor sleep quality, characterized by difficulty falling asleep, restless sleep, or frequent awakenings (Akçay & Akçay, 2018; Amra et al., 2017; Gradisar et al., 2013). Poor sleep quality may have important consequences for adolescents' mental health: It may lead to depression (Alonzo et al., 2021; Gradisar et al., 2022; Orchard et al., 2020), anxiety (Alonzo et al., 2021; Orchard et al., 2020), and increases in negative mood states (Triantafillou et al., 2019).

A key factor that could impair adolescents' sleep quality is their smartphone usage. This topic has been studied and debated extensively over the past decade. At least five meta-analytical reviews have delved into this topic (Chu et al., 2023; Han et al., 2024; Yang et al., 2020), of which two focused on adolescents in particular (Carter et al., 2016; Sohn et al., 2019). In addition, seven reviews have synthesized the existing evidence regarding the effects of adolescents' smartphone use on sleep quality (Brautsch et al., 2023; Cain & Gradisar, 2010; Hale et al., 2019; Hale & Guan, 2015; LeBourgeois et al., 2017; Mac Cárthaigh et al., 2020; Silva et al., 2022). Drawing upon dozens of empirical studies (e.g., Burnell et al., 2022; Cabré-Riera et al., 2019; Caumo et al., 2020), these reviews and meta-analyses indicate that increased smartphone use, especially at night, may impair adolescents' sleep quality. Yet, these reviews and meta-analyses also highlight at least two important gaps in the literature.

A first gap in the literature is that it is not well understood whether the impact of smartphone use on sleep quality varies depending on the time of day that the smartphone is used. About half of the existing studies investigated the effects of nighttime smartphone use (e.g., Amra et al., 2017; Galland et al., 2020; Munezawa et al., 2011), while the other half focused on overall or problematic smartphone use irrespective of the time of use (e.g., Huang et al., 2020; X. Li et al., 2021; Liu et al., 2017). As a consequence, there is a lack of research that specifically addresses the effect of *daytime smartphone use* on sleep quality (Brautsch et al., 2023). In addition, it remains unclear whether two different forms of nighttime smartphone use, that is, smartphone use shortly before bedtime (*pre-bedtime use*) and after bedtime (*post-bedtime use*), have comparable effects on adolescents' sleep quality. Although pre- and post-bedtime use may inherently differ in their effects on sleep quality (see Exelmans & Van Den Bulck, 2017), this distinction has often been overlooked in previous research (e.g., Kühnel et al., 2021; So et al., 2021; Tkaczyk et al., 2023). Therefore, the current study differentiates between daytime, pre-bedtime, and post-bedtime usage in investigating the effects of adolescents' smartphone use on their sleep quality.

A second gap in the literature that has been brought forward by the review articles and meta-analyses is the lack of objective measures of smartphone use, such as smartphone tracking (Carter et al., 2016; Hale & Guan, 2015; LeBourgeois et al., 2017; Mac Cárthaigh et al., 2020; Yang et al., 2020). Most existing studies among adolescents to date have relied on self-report measures of smartphone use (for notable exceptions, see, e.g., Tkaczyk et al., 2023). Self-report measures of smartphone use easily lead to

biased time estimates (Ellis et al., 2019; Parry et al., 2021), which may particularly apply to time estimates around bedtime. Therefore, the current study uses an objective measure of smartphone use—continuous smartphone app tracking—to investigate its effects on sleep quality.

The Current Study

To address these two voids in the literature, the current preregistered study (https://osf.io/kxw2h) aims to investigate the day-to-day within-person effects of adolescents' daytime, pre-bedtime, and post-bedtime smartphone use on their sleep quality. In addition, on an exploratory basis, we examine how the use of three popular smartphone app categories—social media, game, and video player apps—may differentially impact adolescents' sleep quality within the three timeframes. To that end, we adopt an intensive longitudinal design in which we combine a 3-week experience sampling method (ESM) study with continuous smartphone tracking during that period.

Following Phillips et al. (2020), we describe sleep quality as the overall evaluation of one's sleep during the previous night. This operationalization includes both objective and subjective sleep factors (Buysse et al., 1989), which are typically significantly interrelated ($r \approx .30$; for example, Du et al., 2021), and has been identified as the gold standard in sleep research (Cappelleri et al., 2009; Krystal & Edinger, 2008). Specifically, this sleep quality assessment has proved to be better able to predict relevant outcomes (e.g., school performance, health, and well-being) than only objective measures of its underlying dimensions, such as sleep duration, onset latency, and efficiency (Dewald et al., 2010; Krystal & Edinger, 2008; Pilcher et al., 1997). Sleep quality was measured every morning for 21 consecutive days during the ESM study via the experience sampling app *Ethica* (renamed *Avicenna Research* in 2023), which adolescents installed on their smartphones.

Following previous research, we define pre-bedtime smartphone use as the time spent on the smartphone during the hour before bedtime (e.g., Christensen et al., 2016; Galland et al., 2020; Gradisar et al., 2013), post-bedtime use as the time spent on the smartphone while being in bed, that is, from bedtime until wake-up time (Brunborg et al., 2011; Dewi et al., 2021; Scott & Woods, 2018), and daytime use as the time spent on the smartphone from wake-up time until 1 hr before bedtime (Lee et al., 2021). To measure adolescents' smartphone use, their foreground app use was continuously tracked for 21 consecutive days via the *Ethica App Usage Stream* app, which was installed on their smartphones.

Most earlier studies, including the meta-analyses and reviews that integrated these studies, have focused on the between-person associations of smartphone use with sleep quality—with a few exceptions (see Burnell et al., 2022; Sumter et al., 2024; Tkaczyk et al., 2023). Establishing between-person associations of smartphone use with sleep quality is important, for example, if one wants to identify whether more intensive smartphone users experience lower sleep quality than less intensive users. However, between-person results are suboptimal to demonstrate media effects. Specifically, media effects involve within-person processes, reflecting a change in the

outcome as a result of media use, which may differ across individuals (Hamaker, 2012; Potter, 2011; Valkenburg & Peter, 2013). Our intensive longitudinal design offers the ability to distinguish within- from between-person associations while maintaining high ecological validity and low recall bias (Scollon et al., 2003). These advantages are pivotal for (dis)confirming and refining existing media effects theories, including those tapping into the effects of smartphone use on sleep quality.

Pre-Bedtime Smartphone Use and Sleep Quality

For many adolescents, smartphone use around bedtime has become part of their daily routine (Gradisar et al., 2013; Johansson et al., 2016; Toh et al., 2019). Adolescents engage at least three times per week in the following smartphone activities in the hour before bedtime: social media (88%), web browsing (78%), and texting (77%; Galland et al., 2020). While smartphone use right before bedtime is common among adolescents, it may prevent adolescents from getting proper sleep. This could be explained by the pre-sleep arousal hypothesis (Cain & Gradisar, 2010), which suggests that increased cognitive arousal from smartphone content leaves adolescents restless while trying to get to sleep. Cognitive arousal may arise when adolescents use apps that evoke stress (Scott et al., 2019; Wolfers & Utz, 2022), rumination (Y. Li et al., 2019; Thomsen et al., 2003; You et al., 2020), or excitement (Wang & Scherr, 2022; Weaver et al., 2010). Research has shown that such psychophysiological stimulations may, in turn, negatively affect adolescents' quality of sleep (Tang & Harvey, 2004; Tkaczyk et al., 2023). Likewise, an experimental study found that young adults who performed an arousal-inducing task right before sleep had more difficulties falling asleep and had increased mental activity during crucial sleep phases, compared to the control group (Wuyts et al., 2012). Therefore, we hypothesize:

> H1: Adolescents experience lower sleep quality during nights when they spend more time on their smartphone in the hour before bedtime (i.e., pre-bedtime use).

Post-Bedtime Smartphone Use and Sleep Quality

In addition to smartphone use right before bedtime, research has shown that 64% of adolescents keep their smartphone with them in bed or close to their bed at night (Karsay et al., 2023). Likely due to a lack of self-regulation (Kroese et al., 2016; J. Li et al., 2015), adolescents may feel tempted to check for social media updates once more, play yet another online game, or finish that final episode of their favorite series in bed right before sleeping. However, such post-bedtime smartphone use may yield adverse effects on sleep (Lemola et al., 2015). Similar to pre-bedtime use, using the smartphone in bed may negatively impact sleep quality due to increased arousal (Kheirinejad et al., 2023). In addition, the sleep displacement hypothesis postulates that the time spent on the smartphone may directly displace sleep duration (e.g., Cain & Gradisar, 2010). For instance, adolescents' smartphone use after getting into bed may result in longer shuteye latencies, that is, extending the period between bedtime

and closing the eyes (Exelmans & Van Den Bulck, 2017), leaving less time for sleep. As sleep duration is an important aspect of one's overall evaluation of sleep (Phillips et al., 2020), it is likely that adolescents' prolonged smartphone use directly after bedtime negatively affects their sleep quality.

Although less common, smartphone use may also occur in between sleeping. Research has shown that adolescents may receive messages at any time during the night (Van Den Bulck, 2007), experience smartphone-induced sleep interruptions several times a week (Gradisar et al., 2013), and spend, on average, half an hour on their phones in between sleeping (Lee et al., 2021). Burnell et al. (2022) explained that nocturnal awakenings may result from adolescents experiencing difficulties to disconnect from the online conversations that they started earlier that night. Consequently, such awakenings due to smartphone use may negatively impact overall sleep quality (Adams & Kisler, 2013), as a result of shorter (Rod et al., 2018) and more fragmented sleep periods (Snyder & Chang, 2019). Taken together, post-bedtime smartphone use may affect sleep quality because of increased pre-sleep arousal, sleep displacement, or nocturnal awakenings. Therefore, we hypothesize:

H2: Adolescents experience lower sleep quality during nights when they spend more time on their smartphone after bedtime (i.e., post-bedtime use).

Daytime Smartphone Use and Sleep Quality

As daytime smartphone use comprises the largest portion of adolescents' daily smartphone use, it is arguable that this may also affect adolescents' sleep quality. For many adolescents, smartphone use starts right after they wake up and is intertwined with all kinds of activities throughout the day (Serra et al., 2021; Toh et al., 2019). Several hypotheses may explain the relationship between daytime smartphone use and sleep quality. The cognitive overload hypothesis argues that individuals' ability to process information effectively is impaired when cognitive demands of incoming information exceed individuals' available cognitive resources (Yoo & Do, 2022). Given the vast amounts of information coming from incoming notifications, endless timelines, and social demands, ubiquitous smartphone use may likely result into cognitive overload. Such overload may negatively impact sleep quality among users, due to higher levels of technostress (Yao & Wang, 2022). Other hypotheses postulate that smartphone apps may increase social demands during the day (e.g., availability expectations, fear of missing out), and digital stress (Freytag et al., 2021; Hefner & Vorderer, 2016; Steele et al., 2020), which may, in turn, lead to poor sleep quality (Thomée et al., 2011; Yao & Wang, 2022).

Empirical evidence on the effect of daytime smartphone use on sleep quality among adolescents is scarce (see Brautsch et al., 2023 for a review). To our knowledge, only one study has investigated the association of daytime smartphone use with adolescents' sleep quality and found no evidence for such an association (Caumo et al., 2020). Another study focused on the effect of daytime smartphone use on adolescents' sleep *duration* and found that an increase in daytime smartphone use was associated

with a decrease in total sleep time that night (Lee et al., 2021). Although sleep duration differs from sleep quality, it is widely considered an important dimension of sleep quality (Buysse et al., 1989). Hence, the association of increased daytime smartphone use with decreased sleep duration might be an indication that adolescents' daytime smartphone use affects their sleep quality.

Beyond the limited number of studies focusing on the effects of daytime smartphone use on adolescents' sleep quality and duration, a substantial body of research has explored the impact of general smartphone use, regardless of time of day, on adolescents' sleep quality (for reviews, see Hale & Guan, 2015; Mac Cárthaigh et al., 2020; Sohn et al., 2019). Most of these studies have shown that daily smartphone use is negatively related to sleep quality (e.g., Murdock et al., 2017). Since a significant portion of daily smartphone usage occurs during the daytime, the negative effects on sleep quality are likely caused by daytime use. Still, these studies cannot distinguish whether the effect of daily smartphone use on sleep quality is due to either daytime smartphone use or pre- and post-bedtime smartphone use. Therefore, as called upon by other scholars (Brautsch et al., 2023), we will investigate whether adolescents' daytime smartphone use may affect their sleep quality. We pose the following research question:

RQ1: Do adolescents experience lower sleep quality during nights when they spend more time on their smartphone during the preceding day (i.e., daytime use)?

Differential Effects of Lean-Back and Lean-Forward Smartphone Apps

Aside from the time spent with smartphones, the type of apps that adolescents use may impact their sleep quality (Sumter et al., 2024). Scholars have argued that the effects of lean-forward apps may differ from those of lean-back apps (e.g., Jansz, 2005). Lean-forward apps (e.g., social media or video games) demand both physical (e.g., navigation on a screen) and cognitive (e.g., decision-making) interaction and engagement from a user. In contrast, lean-back apps (e.g., video players) require a receptive user mode, whereby users absorb content without needing to interact with it. Several communication theories propose that lean-forward media may amplify media effects. For example, Sundar et al.'s (2015) Theory of Interactive Media Effects (TIME) proposes that lean-forward apps may stimulate behavioral change, which may be explained by enhanced user engagement (Sundar et al., 2015), arousal (Cain & Gradisar, 2010), or stress (Wolfers & Utz, 2022).

Researchers have argued that lean-forward apps may be more detrimental to sleep than lean-backward apps (e.g., Hale & Guan, 2015; Lee et al., 2021; McManus et al., 2021). The "input control" of playing a game or responding to a social media message seems to result in a higher level of arousal and cognitive processing compared to merely viewing a video (e.g., on Twitch; Juvrud et al., 2022). Social media and video game apps are particularly designed to keep users engaged and aroused via alerts, likes, messages, or competition elements. As a consequence, adolescents who play

games right before falling asleep have more difficulty initiating their sleeping process (Dworak et al., 2007; Kheirinejad et al., 2023; Weaver et al., 2010). Likewise, adolescents who use more social media at night experience lower sleep quality (Harbard et al., 2016; Scott & Woods, 2018). However, despite growing evidence that lean-forward apps may have more sizeable effects on sleep quality than lean-back apps, to our knowledge, no study has compared the effects of the two types of apps on adolescents' sleep quality. Therefore, the final aim of this study is to answer the following question:

> RQ2: Does adolescents' use of lean-forward apps (i.e., social media and game apps) and lean-back apps (i.e., video player apps) differentially impact their sleep quality?

Method

This preregistered study (https://osf.io/kxw2h/) is part of a larger project that investigates the psychosocial effects of social media use among adolescents. The project adopted a measurement burst design including two 3-week ESM studies, which both consisted of six ESM surveys per day. The current study uses data from the second ESM study, which was fielded in June 2020, shortly after suspension of the national measure to close all schools due to the COVID-19 pandemic. It only uses the 21 morning ESM surveys because these surveys contained the questions about sleep quality, bedtime, and wake-up time. In addition to the ESM data, continuous smartphone app tracking data was obtained throughout the 3-week ESM study.

Participants

Participants in this study were recruited at a large secondary school in the south of Netherlands. In total, 312 adolescents participated in the second ESM burst. App tracking data could only be extracted from Android smartphones, and therefore, 152 participants (49%) with different smartphone operating systems could not participate in this study. Of the 160 participants whose app data could be tracked, five participants were excluded from the analyses because they missed all morning surveys. Hence, the final sample consisted of 155 adolescents. The participants had a mean age of 14.5 years (SD = 0.7; range = 13–16), with 48% identifying as girl, 52% as boy, and 1% identifying otherwise. Participants were enrolled in three different educational tracks: 39% were enrolled in lower prevocational secondary education, 34% in intermediate general secondary education, and 27% in academic preparatory education. The group of excluded participants (i.e., non-Android users) consisted of more girls (67%) than the group of participants included in the final sample, but they did not differ in age and educational background. Our sample was a good representation of adolescents in the specific region of the Netherlands in terms of educational level and ethnic background (Statistics Netherlands, 2020). More information about the sample can be found on the Open Science Framework (OSF; https://osf.io/2yjqp).

Procedure

The procedure of this study was approved by the Ethics Review Board of the University of Amsterdam. In November 2019, participants were enrolled in the larger project after being informed about the project, providing informed assent, and having obtained their parent's informed consent. Shortly before the onset of the data collection, participants installed the *Ethica* app and *Ethica App Usage Stream* app on their smartphone which were required for receiving and completing the ESM surveys and for the smartphone tracking, respectively.

ESM Surveys. Participants received an ESM survey every morning throughout the data collection period ($T = 21$) via the *Ethica* app. On weekdays, the morning surveys were prompted at random time points between 7:00 and 7:30 and could be completed within 60 min after receiving them. On Saturday and Sunday, the morning surveys were prompted somewhat later—between 10:30 and 11:00—to account for adolescents sleeping in and could be completed within 30 min to avoid overlap with the subsequent ESM survey from the larger project. Reminders were automatically sent after 10 min in case the survey had not been completed yet. The surveys consisted of 24 items including measures of bedtime, wake-up time, sleep quality, and various psychosocial measures not included in this study. It took about 2 min to complete the survey. In total, participants completed 1,950 out of 3,255 surveys (i.e., 21×155 participants), resulting in 60% compliance and an average of 12.6 completed morning surveys ($SD = 5.5$) per participant. Participants received 30 euro cents for every completed survey.

Smartphone Tracking. During the 3-week ESM data collection period, participants' smartphone activities were continuously tracked via an app named *Ethica App Usage Stream*. This tracking app recorded the onset times and the durations of all foreground app activities, that is, app activities that were visible to the user. App activities that ran in the background were not recorded. In addition, app activity durations of 0 s (not rounded) were removed from the data since they could not be perceived by the user. Our tracking data collection procedure resulted in 745,947 recorded app activities.

Measures

Smartphone Use. Smartphone use was obtained via continuous app use tracking and was divided into three timeframes: daytime, pre-bedtime, and post-bedtime smartphone use. The timeframes were determined based on participants' bedtimes and wake-up times, which were assessed in the ESM surveys by asking participants "At what time did you go to bed last night?" and "At what time did you wake up this morning?", respectively. Participants responded to both questions by indicating the times in hours (i.e., 00–23) and minutes (i.e., 00–59). Responses to the bedtime and wake-up time items that were considered untrustworthy (4.7%; e.g., equal bedtimes and wake-up times) were filtered out and responses in which the 24-hr clock was mistakenly confused with the 12-hr clock (15.1%; e.g., bedtimes of 09:30 instead of

21:30) were adjusted. Furthermore, missing wake-up times from the day before (i.e., 34%; mainly due to missed surveys) were needed to demarcate the daytime timeframe and were therefore imputed from the data. Imputations were based on the participant's average wake-up time minus one standard deviation to avoid misclassification of daytime smartphone activities that occurred just before the average wake-up time. These personal averages and standard deviations were established separately for weekdays and weekend days.

Smartphone use was then calculated for every day, for each timeframe: *Daytime use* represented the total time spent on the smartphone from wake-up time until 1 hr before bedtime (Lee et al., 2021), *pre-bedtime use* was the time spent on the smartphone from 1 hr before bedtime until bedtime (e.g., Christensen et al., 2016; Galland et al., 2020; Gradisar et al., 2013), and *post-bedtime use* was the time spent on the smartphone from bedtime until wake-up time (Brunborg et al., 2011; Dewi et al., 2021; Scott & Woods, 2018).

Lean-Forward and Lean-Back App Use. To investigate the effects of app type on sleep quality, the app activities were assigned to the category *social media* or *game* apps, representing lean-forward app activities, or to the category *video player* apps, representing lean-back app activities. The social media app category included Instagram, WhatsApp, Snapchat, TikTok, Twitter, Facebook, Facebook Messenger, Reddit, and Discord. The game app category encompasses all apps labeled with genres related to gaming by the Google Play Store (e.g., Adventure, Role Playing, Simulation). Examples of popular game apps were Brawl Stars, Clash of Clans, Clash Royale, Hay Day, Pokémon Go, Roblox, and Subway Surfers. The video player category included YouTube, Netflix, Twitch, Disney+, Videoland, Ziggo GO, V Live, Huawei Video, Pokémon TV, MTV Play, Amazon Prime Video, and NPO. App activities that did not belong to one of the three categories of interest were not considered. We calculated social media, game, and video player app use as the total time spent on that app category per day, for each timeframe (daytime, pre-bedtime, and post-bedtime).

Sleep Quality. Sleep quality was measured using the sleep quality item of the Pittsburgh Sleep Diary scale (Monk et al., 1994), a derivative of the widely adopted Pittsburgh Sleep Quality Index (PSQI; Buysse et al., 1989) that is adjusted for repeated daily measurement. Every morning, participants were asked "How did you sleep last night?" in the ESM survey. Participants responded on a 7-point scale ranging from 1 (*not good at all*) to 7 (*very good*) with 4 (*somewhat good*) as the midpoint. This item has been widely used in previous studies (Chen et al., 2022; Y. Li et al., 2023; Lydon et al., 2016; Murdock et al., 2017; Zhang & Wu, 2020) and shows good psychometric properties (Cappelleri et al., 2009).

Statistical Analyses

All analyses were performed in line with our preregistration (https://osf.io/kxw2h/), except for the removal of outliers in the smartphone tracking data. Specifically, a small

portion of the tracked app activities lasted exceptionally long, for instance, over 12 hr for a single app activity, which may either indicate a technical error in the tracking or prolonged unattended use. Such unattended use may occur in so-called "idle games," where in-game resources can be collected (e.g., often coins or crops) without continuous interaction of the user. Based on a reviewer recommendation, we deviated from our preregistration and excluded all app activities exceeding the 99.9th percentile of all app durations in the game and video player categories, as these represented the longest app interactions. In practice, this means that we removed app activities lasting more than 4.8 hr (i.e., 241 app activities; 0.03%), resulting in 745,706 app activities that were used in our main analyses. The results of the analyses including these outliers, as originally preregistered, can be found in Table A1 in Appendix 1.

To investigate our hypotheses and research questions, we used Dynamic Structural Equation Modeling (DSEM) in Mplus version 8.8 (Muthén & Muthén, 2017). As a first step, we tested the assumption of stationarity for sleep quality throughout the data collection period (McNeish & Hamaker, 2020). The assumption was confirmed as the day of the study explained only 2.3% of the variance in sleep quality. Hence, there was no need to detrend the data (McNeish & Hamaker, 2020).

We then ran three two-level autoregressive lag-1 models, with observations (level 1; within-person level) nested within individuals (level 2; between-person level) and with sleep quality as the outcome variable. At the within-person level, we included daytime smartphone use (Model 1; RQ1), pre-bedtime smartphone use (Model 2; H1), and post-bedtime smartphone use as predictors (Model 3; H2), while controlling for the autoregressive effect of sleep quality (i.e., the lagged sleep quality score). The predictors and lagged sleep quality scores were specified as time-varying covariates and centered using latent person-mean centering. At the between-person level, each model included the latent mean levels of the predictor and sleep quality, the correlation between these two, and the between-person variance around the within-person effect (i.e., random effect).

The model parameters were estimated using Bayesian Markov Chain Monte Carlo (MCMC) simulations, which allowed for $N=1$ within-person standardization and latent centering (McNeish & Hamaker, 2020). The standardized parameter estimates were interpreted upon model convergence with 5,000 iterations. In addition, the number of iterations was doubled to 10,000 to check for a potential premature stoppage error (Schultzberg & Muthén, 2018).

We evaluated the within-person effects (RQ1-RQ2, H1-H2) based on both the significance of the effect (i.e., Bayesian p-values) as well as the effect size. We considered $\beta=|.05|$ as the Smallest Effect Size of Interest (SESOI; Lakens et al., 2018) as suggested by previous work (Meier & Reinecke, 2021), and $\beta=|.07|$ and $\beta=|.12|$ as medium and large effects, respectively (Orth et al., 2024).

Data Availability

The materials used in the current study, including the R syntaxes, the Mplus syntaxes (https://osf.io/tpj98/), and the preregistration of the current study (https://osf.io/

kxw2h/), can be found on OSF. The anonymized dataset underlying this article is publicly available on Figshare (see Siebers et al., 2024).

Results

Descriptive Statistics

Participants spent on average 6 hr 8 min on their smartphone per day (*SD* = 2 hr 58 min). As presented in Figure 1, the distribution of adolescents' average daily smartphone use ranged from 1.2 to 14.9 hr per day. The figure shows that one in four adolescents spent on average 1.2 to 4.7 hr on their smartphones per day, and the other fourths spent 4.7 to 5.9 hr, 5.9 to 7.5 hr, and 7.5 to 14.9 hr per day. Figure 2 displays the distribution of adolescents' average time spent on the smartphone during each of the three timeframes: during the daytime (Figure 2a), in the hour before bedtime (Figure 2b), and after bedtime (Figure 2c). The figure shows that daytime and pre-bedtime smartphone use are relatively normally distributed across respondents. It also shows that post-bedtime use is right-skewed, indicating that most respondents spent little time on their smartphones after bedtime, with only a few spending a lot. The timeframes are based on the bedtimes and wake-up times that were determined per adolescent per day. During weekdays, participants went to bed at 22:45 (*SD* = 1 hr 9 min) and woke up at 7:24 (*SD* = 36 min), on average. During weekend days, average bedtime (*M* = 0:15, *SD* = 1 hr 30 min) and wake-up time (*M* = 9:13, *SD* = 1 hr 29 min) were shifted by approximately 1.5 hr.

Table 1 shows the mean levels, standard deviations, and intra-class correlations of daytime, pre-bedtime, and post-bedtime smartphone use and sleep quality. Roughly 86% of daily smartphone use occurred during the daytime (*M* = 5 hr 26 min, *SD* = 2 hr 37 min), 6% in the hour before bedtime (*M* = 23 min, *SD* = 19 min), and about 8% after bedtime (*M* = 29 min, *SD* = 49 min). Participants reported good sleep quality, on average (*M* = 5.53, *SD* = 1.31, range = 1–7). The intraclass correlations (ICCs) of daytime smartphone use (0.49) and sleep quality (0.47) indicate that their within- and between-person variances are about equal. The ICCs of pre- (0.30) and post-bedtime smartphone use (0.30) indicate that most of their variance can be attributed to day-to-day fluctuations within individuals, and less to differences between individuals.

Table 1 also presents the within- and between-person correlations between all four variables. It shows that daytime, pre-bedtime, and post-bedtime smartphone use correlated positively at the between-person level. At the within-person level, pre-bedtime use correlated positively with daytime and post-bedtime use, while daytime and post-bedtime smartphone use correlated negatively. Sleep quality only correlated negatively with post-bedtime smartphone use at the within-person level, implying that adolescents slept worse during nights when they had spent more time on their smartphone after bedtime compared to other nights. No other within- or between-person correlations were found between sleep quality and daytime, pre-bedtime, or post-bedtime smartphone use.

The three most frequently used app categories among participants in our sample were social media, game, and video player apps. Table 2 shows an overview of the

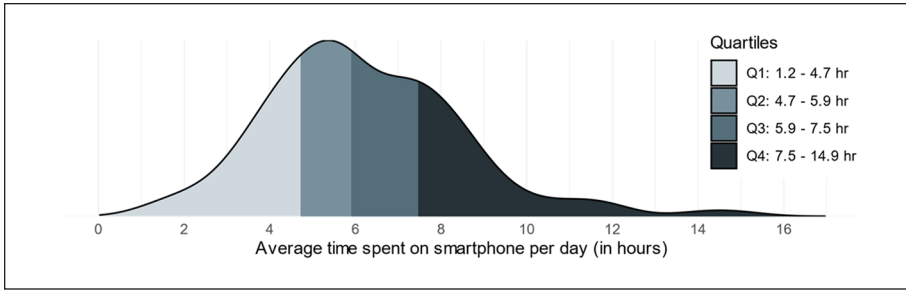

Figure 1. Density distribution of participants' average daily smartphone use.

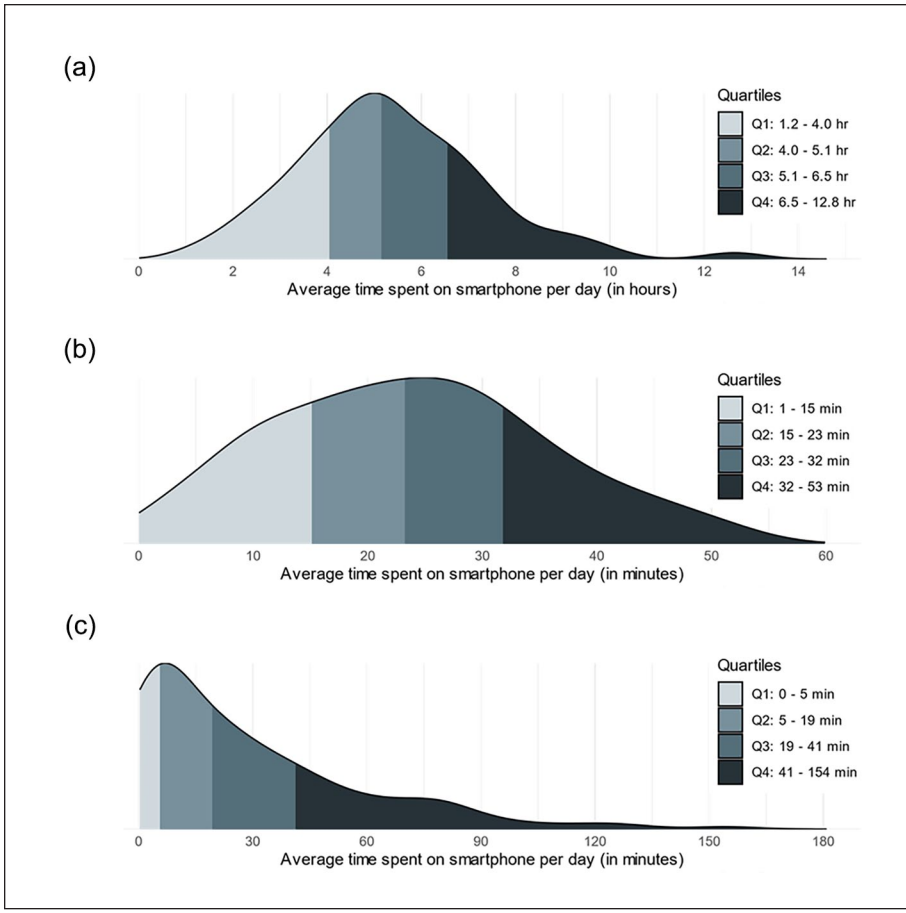

Figure 2. Density distribution of participants' average daytime, pre-bedtime, and post-bedtime smartphone use: (a) daytime use, (b) pre-bedtime use, and (c) post-bedtime use

Table 1. Descriptives and Correlations for All Study Variables.

	Descriptives					Correlations[a]			
Study variable	*M*	*SD*	Var(W)	Var(B)	ICC	1.	2.	3.	4.
1. Daytime use	5 hr 26 min	2 hr 37 min	3.59	3.40	0.49	—	.09***	−.05*	−.02
2. Pre-bedtime use	23 min	19 min	0.07	0.03	0.30	.57***	—	.07**	−.02
3. Post-bedtime use	29 min	49 min	0.47	0.20	0.30	.26***	.34***	—	−.06*
4. Sleep quality	5.53	1.31	0.92	0.82	0.47	−.02	.11	−.11	—

Note. Var(W) = within-person variance; Var(B) = between-person variance; ICC = intraclass correlation coefficient.
[a]Within-person correlations are depicted above the diagonal and between-person correlations below the diagonal.
*$p < .05$. **$p < .01$. ***$p < .001$.

Table 2. The Average Time Spent on Social Media, Game, and Video Player apps, for Daytime, Pre-Bedtime, and Post-Bedtime Use.

	Daytime use		Pre-bedtime use		Post-bedtime use	
App category	*M*	*SD*	*M*	*SD*	*M*	*SD*
Social media	2 hr 26 min	2 hr 9 min	11 min	14 min	12 min	27 min
Game	1 hr 2 min	1 hr 26 min	3 min	9 min	4 min	20 min
Video player	2 hr 8 min	2 hr 2 min	11 min	17 min	14 min	35 min

average times (and standard deviations) that adolescents spent on each of the three app categories during the daytime, in the hour before bedtime, and after bedtime. All 155 participants used social media apps, of which the most popular ones were *WhatsApp*, *Instagram*, *Snapchat*, and *TikTok*. A total of 141 participants (91%) used game apps at least once throughout the data collection period. The most popular game apps were *Brawl Stars*, *Hay Day*, *Clash of Clans*, and *Clash Royale*. Finally, video player apps were used by all 155 participants, and *YouTube*, *Netflix*, *Twitch*, *Disney+*, and *Videoland* were the most popular in this category.

Within- and Between-Person Associations

Using DSEM analyses, we separated within-person effects from between-person associations to test our hypotheses and answer our research questions. Specifically, we examined the effects of smartphone use on sleep quality (to answer RQ1 and test H1 and H2) and the effects of lean-forward and lean-back smartphone apps on sleep quality (to answer RQ2).

Smartphone Use and Sleep Quality. As presented in Table 3, the results of our main analyses showed no significant within-person effects of daytime ($\beta = -.03$, $p = .122$; RQ1) or pre-bedtime smartphone use ($\beta = -.02$, $p = .162$; H1 rejected) on sleep quality. However, they did show a medium within-person association of post-bedtime smart-

Table 3. The Effects of Daytime, Pre-Bedtime, and Post-Bedtime Smartphone Use on Sleep Quality.

Effect	*b*	β	*p*	95% CI
Within-person				
Daytime → Sleep quality	−0.01	−.03	.122	[−0.073, 0.022]
Pre-bedtime → Sleep quality	−0.07	−.02	.162	[−0.067, 0.025]
Post-bedtime → Sleep quality	−0.14	−.09	.017	[−0.171, −0.006]
Between-person				
Daytime ↔ Sleep quality	−0.09	−.05	.291	[−0.236, 0.131]
Pre-bedtime ↔ Sleep quality	0.02	.11	.121	[−0.083, 0.302]
Post-bedtime ↔ Sleep quality	−0.05	−.12	.110	[−0.306, 0.071]

Note. *b*s are unstandardized effects. βs are standardized effects using StdYX. The data were analyzed using a Bayesian estimation procedure, and therefore included Bayesian one-tailed *p*-values and 95% credible intervals (McNeish & Hamaker, 2020).

phone use with sleep quality (β = -.09, $p = .017$; H2 supported), implying that adolescents experienced lower sleep quality during nights when they spent more time using their smartphone after bedtime, compared to other nights. We found no evidence for between-person associations of sleep quality with daytime (β = -.05, $p = .291$), pre-bedtime (β = .11, $p = .121$), and post-bedtime smartphone use (β = -.12, $p = .110$), as these associations did not reach statistical significance.

Lean-Forward and Lean-Back Smartphone Apps and Sleep Quality. In our exploratory DSEM analyses, we investigated the effects of social media and game app use (i.e., lean-forward) and video player app use (i.e., lean-back) on sleep quality within each of the three timeframes (RQ2). As Table 4 shows, we found a medium negative within-person effect of adolescents' pre-bedtime social media use on their sleep quality (β = −.09), implying that adolescents slept worse on nights when they had spent more time on social media apps in the hour before bedtime. Daytime and post-bedtime social media use did not affect adolescents' sleep quality.

Our DSEM results also showed a large negative within-person association of adolescents' time spent on game apps after bedtime with their sleep quality (β = -.16), implying that adolescents experienced lower sleep quality during nights when they spent more time on game apps after bedtime. In addition, we found a negative between-person association of game app use after bedtime with sleep quality (β = −.19), but this association was not statistically significant. No effects were found for daytime and pre-bedtime game app use.

Finally, the DSEM analyses showed no evidence that watching videos on the smartphone during the daytime, before bedtime, or after bedtime affected adolescents' sleep quality. However, our results did show a positive between-person association of pre-bedtime video player app use with sleep quality (β = .19), implying that adolescents who spent more time using video player apps in the hour before bedtime than their peers experienced higher sleep quality than their peers.

Table 4. The Effects of Social Media, Game, and Video Player Apps on Sleep Quality.

Effect	*b*	β	*p*	95% CI
Within-person				
Daytime social → Sleep quality	0.00	.00	.464	[−0.059, 0.062]
Daytime game → Sleep quality	−0.01	−.02	.359	[−0.134, 0.093]
Daytime video → Sleep quality	−0.03	−.06	.075	[−0.111, 0.014]
Pre-bedtime social → Sleep quality	−0.43	−.09	.001	[−0.144, −0.026]
Pre-bedtime game → Sleep quality	−0.58	−.09	.050	[−0.172, 0.015]
Pre-bedtime video → Sleep quality	0.17	.05	.070	[−0.017, 0.100]
Post-bedtime social → Sleep quality	−0.14	−.05	.113	[−0.153, 0.033]
Post-bedtime game → Sleep quality	−1.03	−.16	.024	[−0.329, −0.001]
Post-bedtime video → Sleep quality	−0.02	−.01	.451	[−0.119, 0.079]
Between-person				
Daytime social ↔ Sleep quality	−0.08	−.05	.303	[−0.225, 0.129]
Daytime game ↔ Sleep quality	0.02	.02	.418	[−0.211, 0.281]
Daytime video ↔ Sleep quality	0.09	.06	.261	[−0.125, 0.254]
Pre-bedtime social ↔ Sleep quality	−0.01	−.05	.311	[−0.241, 0.144]
Pre-bedtime game ↔ Sleep quality	0.01	.09	.264	[−0.190, 0.357]
Pre-bedtime video ↔ Sleep quality	0.03	.19	.037	[−0.015, 0.371][a]
Post-bedtime social ↔ Sleep quality	−0.01	−.06	.260	[−0.257, 0.132]
Post-bedtime game ↔ Sleep quality	−0.03	−.19	.061	[−0.445, 0.080]
Post-bedtime video ↔ Sleep quality	−0.02	−.05	.316	[−0.252, 0.156]

*Note. b*s are unstandardized effects. βs are standardized effects using StdYX. The data were analyzed using a Bayesian estimation procedure, and therefore included Bayesian *p*-values and 95% credible intervals (McNeish & Hamaker, 2020).

[a]The credible intervals may contain 0 because the Mplus output provides a Bayesian analog to a one-side *p*-value.

Discussion

This study investigated the day-to-day effects of adolescents' daytime, pre-bedtime, and post-bedtime smartphone use on their sleep quality. Relying on a data set of 745,706 tracked app activities and 1,950 assessments of sleep quality among 155 adolescents, our analyses showed no within-person effects of daytime and pre-bedtime smartphone use on sleep quality, and a negative within-person association of post-bedtime smartphone use with sleep quality ($\beta = -.09$). In other words, we found no evidence that adolescents' sleep quality was impaired when they spent more time on their smartphone during the preceding day (RQ1) or in the hour before bedtime (H1), but we did find evidence that their sleep quality was impaired when they had spent more time on their smartphone after they went to bed (H2).

An explanation for the null findings for daytime and pre-bedtime smartphone use could be that these effects may not be the same for every adolescent. Specifically, the Differential Susceptibility to Media Effects Model (DSMM; Valkenburg & Peter,

2013) argued, and existing research showed (Beyens et al., 2020), that media effects vary from adolescent to adolescent. The effects of daytime, pre-bedtime, and post-bedtime smartphone use on sleep quality may vary across adolescents due to individual differences in, for example, gender (McManus et al., 2021), chronotypes (Fossum et al., 2014), susceptibility to social media stress (Wolfers & Utz, 2022), or self-regulation abilities (Kroese et al., 2016; J. Li et al., 2015). However, our study had too few sleep quality observations (i.e., $M = 12.6$, maximum = 21), and therefore too little statistical power, to draw inferences at the person-specific level. Therefore, we encourage future research to adopt an idiographic (or $N = 1$) approach in investigating the within-person effects of day- and nighttime smartphone use on sleep quality by increasing the number of observations per person.

Several earlier studies have reported negative associations of post-bedtime smartphone use with sleep quality at the between-person level (Christensen et al., 2016; Lemola et al., 2015; Munezawa et al., 2011; Murdock et al., 2017), and some at the within-person level (e.g., Kühnel et al., 2021; Lee et al., 2021). But, to our knowledge, our study is the first to investigate the day-to-day within-person associations of post-bedtime smartphone use with sleep quality among adolescents in particular, using real-time smartphone data. Our findings underscore the potentially detrimental effects of this type of smartphone use. There are three potential pathways that may explain why adolescents' post-bedtime smartphone use is negatively associated with their sleep quality. First, smartphone use after bedtime may negatively impact sleep quality due to increased arousal at moments when adolescents try to sleep. Second, lengthy smartphone sessions after bedtime directly displace the time that adolescents need to obtain proper sleep, which, in turn, may impact their overall sleep evaluation of the past night. Third, smartphone notifications and beeps may interrupt adolescents' sleep by waking them (Fobian et al., 2016; Van Den Bulck, 2003), which could result in more fragmented and shallower sleep, leaving adolescents feeling less rested upon awakening and experiencing diminished sleep quality.

Although most earlier studies have conceptualized post-bedtime smartphone use as the predictor and sleep as the outcome, a reverse causal effect may also exist. It is well possible that adolescents awaken during the night and resort to their smartphones as a means of dealing with their sleeplessness, which may also result in a negative association between post-bedtime use and sleep quality (Bartel & Gradisar, 2017; Eggermont & Van Den Bulck, 2006). In the current study, we cannot preclude this potential alternative pathway because post-bedtime use and sleep quality were measured over the same timeframe in this study. Hence, future research should delve deeper into these pathways to ascertain which one most accurately explains the connection between post-bedtime smartphone use and sleep quality.

App-Specific Effects of Smartphone Use on Sleep Quality

To further scrutinize the effect of adolescents' smartphone use on sleep quality, we explored the role of different smartphone app categories. In line with previous

findings (Sumter et al., 2024), our exploratory analyses revealed that the effect of smartphone use on sleep quality was dependent on the type of app that adolescents used (RQ2). Specifically, using lean-forward apps around bedtime, such as social media apps in the hour before bedtime ($\beta = -.09$) and game apps after bedtime ($\beta = -.16$), was linked to adolescents' sleep quality. Yet, using lean-back apps (i.e., video player apps) before or after bedtime did not yield a similar adverse effect. The finding that the impact of smartphone use on sleep quality varies depending on the type of app that is used contradicts the displacement hypothesis. After all, if time displacement causes overall evaluations of impaired sleep quality, we would also expect to see an effect of video player apps since these apps also compete with sleep time.

The app-specificity of the effect of smartphone use on sleep quality can be explained by the pre-sleep arousal hypothesis. Research has shown that arousal before sleep negatively affects people's subjective evaluation of their sleep (Tang & Harvey, 2004; Tkaczyk et al., 2023; Wuyts et al., 2012). Lean-forward apps, such as social media and games, are more likely to evoke such pre-sleep arousal than lean-back apps, such as video players, because of their (inter)active nature. Such interactivity has been suggested to negatively affect sleep quality (Gradisar et al., 2013). While using social media apps, adolescents may experience increased alertness toward social rewards from messages, likes, and comments, and toward social pressures to respond quickly to incoming notifications, making it difficult to fall asleep (Scott & Woods, 2018). Similarly, game apps may cause arousal due to increased alertness, which is often essential in the gaming context, causing more difficulties in falling asleep (Ivarsson et al., 2013; Weaver et al., 2010; Wolfe et al., 2014). In contrast, lean-back apps, such as video player apps tend to offer relaxation, entertainment, and replenishment, thereby facilitating a smoother transition to sleep (McNally & Harrington, 2017). Despite not having assessed pre-sleep arousal directly, the app-specificity of the effects on sleep quality suggests that pre-sleep arousal is most likely to explain the complex association between smartphone use around bedtime and impaired sleep.

In addition to the day-to-day within-person effects, our analyses also revealed between-person associations of nighttime app use with sleep quality. Specifically, we found that adolescents who spent more time watching videos on their smartphone in the hour before going to bed than their peers reported higher sleep quality than their peers. This may point at the adoption of bedtime routines in which adolescents watch videos before falling asleep. Indeed, qualitative research has shown that adolescents have such bedtime routines, for instance, to experience relaxation before falling asleep (Toh et al., 2019). Moreover, a recent study that combined daily diary surveys with smartphone tracking showed that young adults slept longer when they spent more time watching videos on their smartphones during the preceding evening (Sumter et al., 2024). Future research is encouraged to investigate to what extent and under which conditions incorporating smartphone use in bedtime routines could improve overall sleep quality.

Limitations and Suggestions for Future Research

The findings of the current study should be interpreted in light of two limitations. The first limitation is that the term "bedtime" may be perceived differently across adolescents. We asked adolescents each morning when they went to bed the previous night and used their responses to determine their daytime, pre-bedtime, and post-bedtime smartphone use. We cannot exclude the possibility that different adolescents perceive bedtime differently: Either as the time they start to get themselves ready for the night, enter their bedroom, get into bed, or fall asleep. These different perceptions could have affected our between-person results. However, our within-person results are not influenced by such differences in perception between adolescents, because they are based on the fluctuations of smartphone use and sleep quality around each adolescent's own average.

A second limitation of the current study is that we cannot be sure about the direction of the association between adolescents' smartphone use after bedtime and sleep quality. Given the overlap between the timeframe over which post-bedtime smartphone use and sleep quality were measured (i.e., from bedtime to wake-up time), we cannot conclude whether adolescents slept worse due to their smartphone use, or whether they turned to their smartphone as a way to cope with nocturnal awakenings or bad sleep. Nonetheless, the within-person association does reflect a change in sleep quality above and beyond the sleep quality of the previous day because we controlled for the autoregressive effect of sleep quality in the analyses.

Conclusion

Adolescents' smartphone use is seamlessly woven into their daily lives, extending well beyond daylight hours and granting them access to "digital nightlife." A large body of research has suggested that extensive smartphone use may affect adolescents' sleep quality, and some researchers suggested that this effect primarily operates through smartphone use around bedtime. However, the literature lacked empirical evidence for this assumption. This intensive longitudinal study found that while adolescents' daytime and pre-bedtime smartphone use do not yield adverse effects on their sleep quality, smartphone use after bedtime seems detrimental. We discovered that nighttime smartphone use has varying effects, based on the type of apps used. Specifically, using lean-back apps, like video players before or after bedtime, did not impact sleep quality. However, using lean-forward apps, such as social media before bedtime and gaming apps after bedtime, was linked to poorer sleep quality, supporting the pre-sleep arousal hypothesis. Findings at the between-person level revealed that adolescents who spent more time using video-player apps before bedtime had higher sleep quality than their peers, suggesting that lean-back activities may facilitate smoother transitions to sleep. Taken together, this study sheds new light on the widely explored effects of smartphone use on sleep quality by showing that the effect is both time- and app-specific.

Appendix 1

Table A1. The Effects of Daytime, Pre-Bedtime, and Post-Bedtime Smartphone use on Sleep Quality, Including Outliers (i.e., App Activities Longer Than 4.8 hr).

Effect	*b*	β	*p*	95% CI
Within-person				
Daytime → Sleep quality	0.00	−.01	.380	[−0.054, 0.049]
Pre-bedtime → Sleep quality	−0.06	−.02	.271	[−0.063, 0.033]
Post-bedtime → Sleep quality	−0.08	−.08	.059	[−0.182, 0.024]
Between-person				
Daytime ↔ Sleep quality	−0.22	−.12	.110	[−0.289, 0.071]
Pre-bedtime ↔ Sleep quality	0.01	.06	.266	[−0.129, 0.253]
Post-bedtime ↔ Sleep quality	−0.17	−.26	.007	[−0.445, −0.054]

Note. *b*s are unstandardized effects. βs are standardized effects using StdYX.

Declaration of Conflicting Interests

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Open Practice

The materials used in the current study, including the R syntaxes, the Mplus syntaxes (https://osf.io/tpj98/), and the preregistration of the current study (https://osf.io/kxw2h/), can be found on OSF. The anonymized dataset underlying this article is publicly available on Figshare (see Siebers et al., 2024).

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