Received: 10 July 2020 | Revised: 4 September 2020 | Accepted: 16 September 2020

DOI: 10.1111/jsr.13213

REGULAR RESEARCH PAPER

Journal of Sleep Research ESRS

Temporal association between objectively measured smartphone usage, sleep quality and physical activity among Chinese adolescents and young adults

Paul H. Lee[1] | Andy C. Y. Tse[2] | Cynthia S. T. Wu[1] | Yim Wah Mak[1] | Uichin Lee[3]

[1]School of Nursing, Hong Kong Polytechnic University, Kowloon, Hong Kong

[2]Department of Health and Physical Education, Education University of Hong Kong, New Territories, Hong Kong

[3]Department of Knowledge Service Engineering, Korea Advanced Institute of Science and Technology, Daejeon, Korea

Correspondence
Paul H. Lee, School of Nursing, GH527, Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong.
Email: paul.h.lee@polyu.edu.hk

Funding information
This study was funded by the General Research Fund Early Career Scheme (Ref: PolyU 251056/16M) from the University Grants Committee of the Hong Kong Special Administrative Region, China.

Abstract

We studied the association between objectively measured smartphone usage and objectively measured sleep quality and physical activity for seven consecutive days among Hong Kong adolescents and young adults aged 11–25 years ($n = 357$, 67% female). We installed an app that tracked the subjects' smartphone usage and had them wear an ActiGraph GT3X accelerometer on their wrist to measure their sleep quality and physical activity level. Smartphone usage data were successfully obtained from 187 participants (52.4%). The participants on average spent 2 h 46 min per day on their smartphone. Multilevel regression showed that 1 min of daytime smartphone usage was associated with 0.07 min decrease in total sleeping time that night ($p = .043$, 95% confidence interval [CI]: −0.14, −0.003). Broken down for different usage purposes, 1 min of daytime social network usage and games and comics was associated with a 0.28 ($p = .02$, 95% CI: −0.52, −0.04) min and 0.18 min ($p = .01$, 95% CI: −0.32, −0.04) decrease in total sleeping time that night, respectively. One minute of daytime smartphone usage was associated with an increase of 4.55 steps in the number of steps ($p = .001$, 95% CI: 1.77, 7.34) on the next day. To conclude, time spent on a smartphone in the daytime was associated with total sleeping time that night and number of steps the next day, but was not associated with sleep efficiency, wake after sleep onset and moderate-to-vigorous-intensity activity (MVPA) among Hong Kong adolescents and young adults.

KEYWORDS

exercise, gaming, screen, smart device, smartphone monitoring, youth

1 | INTRODUCTION

The use of smartphones has been increasing rapidly in recent years. The number of smartphone users worldwide was 1.5 billion in 2014 and this figure is expected to be doubled in 2020 (Statistista, 2015). Smartphones have become substitutes for mp3 music players, video players and handheld game consoles, as they allow easy access to all of these functions at any time and any place at the user's convenience (Kwon et al., 2013). Smartphones also allow the taking of instant photos and videos and sharing them through the internet. Moreover, smartphones allow users to download attractive and powerful applications for education, entertainment and stock transactions. Smartphones are becoming so important that 29% of their owners "can't imagine living without" them (Pew Research Center, 2015).

Smartphone ownership and usage are a global phenomenon, with Hong Kong being one of the cities with the highest penetration rates around the world (ranked eighth out of 47 countries or places in 2013) (Mashable, 2013). Local studies have revealed that almost all adults, more than 50% of primary school students and more than 90% of secondary school students possess at least one smartphone (HKSARG Department of Health, 2015). Another study conducted by the Hong Kong Polytechnic University showed that 30% of school students used smart devices (including smartphones and tablets) for 1 to 4 h per day (Shek & Yu, 2013).

Although appropriately using smartphones can improve our quality of life, excessive usage can possibly lead to adverse health outcomes. The excessive usage of smartphones was associated with sedentary lifestyles (Lepp et al., 2013), poor sleeping habits (Punamaki et al., 2007) and increased waking-time tiredness (Punamaki et al., 2007). A recent large-scale cross-sectional study among adolescents in Norway showed that both the daytime and bedtime use of electronic devices was associated with sleep problems (Hysing et al., 2015), confirming the theoretical pathway that the lighted screen of a smartphone suppresses melatonin and affects sleep. Furthermore, increased time spent in bedtime smartphone usage will shorten the user's total sleeping time, and the resulting tiredness may reduce time spent in physical activity the next day.

Note that all of the aforementioned studies suffered a common major limitation, namely the cross-sectional nature and the possibility of reverse causation (that is, sleep quality causing smartphone usage) could not be eliminated, the use of self-report of the level of smartphone usage, in which the reporting was subjected to recall bias (Hysing et al., 2015), unknown validity and reliability (Hysing et al., 2015), and an inability to track the frequently changing smartphone usage (Benson et al., 2013).

Objectively measured data on smartphone usage can be obtained by directly monitoring smartphone activities. Many smartphone monitoring applications have been written, most of which have been aimed at collecting information on data transfer and battery power consumption for further hardware development and improvement (Bohmer et al., 2011; Do et al., 2011; Falaki et al., 2010, 2011; Shye et al., 2010; Soikkeli et al., 2011). Very few studies have correlated objectively measured smartphone usage with other outcomes; to the best of our knowledge, there exists only one study correlating objectively measured smartphone usage with personality traits (Chittaranjan et al., 2013). To date, there have been no studies on the association between objectively measured smartphone usage and health outcomes. Here, we studied the temporal association between objectively measured smartphone usage in a day, the accelerometer-measured sleep quality that night, and the accelerometer-measured physical activity the next day, measured for seven consecutive days in Hong Kong Chinese adolescents and young adults. Furthermore, to complete the examination of the possible bidirectional association between smartphone usage and sleep quality, we also studied the temporal association between the accelerometer-measured sleep quality in a night and the objectively measured daytime smartphone usage on the next day.

2 | METHODS

2.1 | Participants

This study was conducted from March 2017 to May 2018. The participants were recruited from one secondary school (Tai Po Sam Yuk Secondary School, which corresponds to Years 7 to 12 in the US education system) and two universities (the Hong Kong Polytechnic University and Education University of Hong Kong) in Hong Kong. In the secondary school, invitation letters were sent to the parents of all students. In the two universities, invitation emails were sent to all undergraduate students. Only those aged 11–25 years, who were able to speak and read Chinese, and owned a smartphone with the Android operating system, were recruited to take part in this study. Phones with the Apple iOS operating system were excluded because Apple iOS app programmers are not allowed to collect smartphone usage data continuously. Written consent was obtained from all of the participants. For participants under the age of 18 years, parental written consent was also obtained. As a token of appreciation, a supermarket cash coupon worth HK $100 (approximately US $13) was given to the participants after the data were collected. This study was approved by the Human Subjects Ethics Sub-Committee of the Hong Kong Polytechnic University.

2.2 | Data collection

2.2.1 | Objectively measured smartphone usage

We installed a smartphone usage tracking app (created by our team) on the smartphone of all of the participants' smartphones for seven consecutive days. This app tracked the opening and closing of all apps in the smartphone. No private or personal data, such as the contents of instant messages and the web pages that were browsed, were collected. For those participants who possessed more than one smartphone, we installed the app in their most commonly used phone. We defined an app as being used when it was running in the graphical interface. It should be noted that the opening of one app would trigger the closure of the app currently being used, if any. The usage time was tracked in seconds. The names of the apps being used, their opening time and closing time were stored in the smartphone and uploaded to a remote server (Firebase) once an internet connection was available, and all uploaded data were removed from the smartphone.

2.2.2 | Sleep quality and physical activity level

During the 7-day monitoring period, all of the participants concurrently wore an ActiGraph GT3X accelerometer. This is a wrist-worn, water-proof accelerometer that has been validated for measuring sitting time (Ryde et al., 2012), physical activity

(Pfitzner et al., 2013) and sleeping time (Lee & Suen, 2017; Toon et al., 2016). The participants were instructed to wear the accelerometer on their non-dominant hand for 24 h a day over seven consecutive days. They were asked to record the removal time in a logbook, if any (for example, when the accelerometer might become damaged). Data were collected in 1-min epochs. To synchronize the accelerometer data with smartphone usage data, when initializing the accelerometers, Greenwich Mean Time + 8, obtained via the internet, was used.

2.3 | Data processing

2.3.1 | Sleep quality and physical activity level

Peak acceleration in the three axes was extracted from the raw acceleration. The resultant acceleration of the raw acceleration from the three axes was summarized by counts per minute (CPM). CPM of ≥4,514 of the vector magnitude was classified as moderate-to-vigorous-intensity activity (MVPA) (calibrated among Hong Kong young adults; Lee & Tse, 2019). Non-wearing time was defined as consecutive zero counts for 60 or more minutes. The amount of wearing time in a day was computed by subtracting the non-wearing time and sleeping time (determined by the accelerometer) from 24 h. A valid day must include at least 10 h of wearing time, excluding sleeping time. Steps were detected using the built-in algorithm of the ActiGraph that is based on the acceleration amplitude and frequency (John et al., 2018). Steps accumulated in time lengths of <10 s were removed by the ActiGraph. As we used a temporal analysis that treated a day as the unit of analysis and did not require the averaging of physical activity (PA) and sleep parameters of individual participants throughout the whole study period, participants who provided at least one valid day could be included in the analysis.

All of the minutes recorded from the accelerometers were classified as either sleep or awake using Sadeh's algorithm (Sadeh et al., 1994). According to Sadeh's algorithm, the sleep index of a minute is defined as $7.601 - (0.065 \times AVG) - (1.08 \times NATS) - (0.056 \times SD) - (0.703 \times LG)$, where AVG is the average CPM of the 11 min centred at the current minute, NATS is the number of minutes with CPM between 50 and 99 at the 11-min period, SD is the standard deviation of the current and five preceding minutes, and LG is the natural log of the CPM + 1 (to avoid log of 0) at the current minute. Recorded minutes with a sleep index of ≥−4 will be classified as sleep, and awake otherwise. Sleep onset was defined as the first 15 min of consecutive sleeping minutes, and awakening time was defined as the first 15 min of consecutive wake minutes. The total sleeping period was measured as beginning at sleep onset and ending at awakening. Total sleeping time was defined as the sleeping time within the total sleeping period. Sleep efficiency was defined as the total sleeping time divided by the total sleeping period. Wake after sleep onset (WASO) was defined as the waking time within the total sleeping period.

2.3.2 | Objectively measured smartphone usage

All recorded smartphone applications were categorized under social network (Facebook, Twitter, Instagram, Weibo, etc.), instant messaging (Whatsapp, Skype, Line, Wechat, etc.), web browsing (including browser and apps developed for browsing specific websites), games and comics (except games plug-ins and guides), multimedia (related to music, videos and image/photos, for example YouTube and MOOV), camera (including beauty-themed photos and video apps such as Meitu) and health (pedometer, GPS distance and speed tracker, etc.). The time spent on each session was computed as the difference between the closing time and opening time. Usage sessions of <1 s were discarded as such short times that they were likely to be an indication that the app had been accidentally pressed. All smartphone usage times were classified as either occurring in the daytime (defined as the time from waking up to 1 h before sleep, where the sleeping time was identified using the accelerometer data), at bedtime (defined as 1 h before sleep) or i a wakeful moment during sleep (or WASO).

2.4 | Statistical analysis

Descriptive statistics (mean, SD and frequency) were used to summarize the pattern of smartphone usage, sleep quality and physical activity level. Multilevel regression was used to examine the temporal association between daytime and bedtime smartphone usage and sleep quality that night and physical activity on the following day, adjusted for the data source (secondary school/university), sex and within-subject correlation. The within-subject correlation was assumed to have an autoregressive structure of order one (or AR(1)). The same model was also used to examine the temporal association between the sleep quality and the daytime smartphone usage on the following day. The intraclass correlation (ICC), autocorrelation and R^2 of all models were reported. The data from the first day that the smartphone usage tracking app was installed and the accelerometer was distributed were excluded due to the incompleteness of the data. All data were analysed both among the overall sample and stratified by school type (secondary school versus university). Histograms of the residuals and residual plots were used to examine the assumptions of multilevel regression, including normality, homoscedasticity and independence of observations. A p-value of <.05 was considered significant, and multiple comparisons were not controlled because of the high number of correlated null hypotheses in this study (Moran, 2003).

3 | RESULTS

A total of 393 students (156 from the secondary school and 237 from the two universities) agreed to participate, and 357 of them who provided at least one valid day of accelerometer data were included in the current analysis. Table 1 shows the characteristics

TABLE 1 Demographic characteristics and accelerometer-measured sleep quality and physical activity level of the participants (n = 357)

Variable	Secondary school students (number of participants = 125)	University students (number of participants = 232)	Overall (number of participants = 187)
	Frequency (%)	Frequency (%)	Frequency (%)
Sex			
Male	62 (50.4%)	55 (23.7%)	117 (33.0%)
Female	61 (49.6%)	177 (76.3%)	238 (67.0%)
	Mean (SD)	**Mean (SD)**	**Mean (SD)**
Age	18.4 (3.3)	18.4 (3.3)	18.4 (3.3)
Sleep quality	**Secondary school students (number of participants = 32, number of days = 176)**	**University students (number of participants = 155, number of days = 930)**	**Secondary school students (number of participants = 187, number of days = 1,106)**
Total sleeping time (h)	7.5 (1.8)	7.5 (1.8)	7.5 (1.8)
Sleep efficiency (%)	94.3 (4.5)	94.9 (4.1)	94.7 (4.2)
Wake after sleep onset (min)	25.2 (19.9)	22.6 (17.8)	23.4 (18.5)
Physical activity level	**Secondary school students (number of participants = 123, number of days = 459)**	**University students (number of participants = 229, number of days = 1,058)**	**Secondary school students (number of participants = 352, number of days = 1,517)**
Number of steps	10,315 (4,950)	10,003 (4,186)	10,095 (4,423)
Moderate-to-vigorous physical activity (min)	162.7 (102.6)	137.2 (73.2)	144.6 (83.6)

Note: Sleep and physical activity data were reported across measurement days. SD, standard deviation.

of the participants. Nearly two-thirds of them were university students. The secondary school sample was balanced regarding gender, but in the university sample less than one-fourth of them were male. The sleep quality and physical activity level of the two samples were comparable.

Of the 357 participants, smartphone usage data were successfully tracked for 187 (52.4%). The smartphone tracking app was written for Android 7.0 or above, and the tracking app did not work with some smartphones installed with earlier Android versions. The daytime and bedtime smartphone usage data are summarized in Table 2. The participants spent nearly 3 h per day on their smartphone. Secondary school students on average spent 40 more minutes per day on smartphones than university students. The most common types of usage among secondary school students and university students were games and comics apps (1 h 30 min per day) and instant messaging apps (1 h 13 min per day), respectively. Bedtime smartphone usage was recorded on 464 (42.0%) out of the 1,106 measured nights. On average, the participants spent 10 min per day on their smartphone during bedtime. Smartphone usage during WASO was recorded on 563 (50.9%) out of the 1,106 measured nights. On average the participants spent 29 min per day on their smartphone during WASO.

Table 3 shows the multilevel regression results of the association of smartphone usage on sleep quality. Results among the overall sample showed that 1 min of daytime smartphone usage was associated with 0.07 min decrease in total sleeping time that night (p = .043, 95% confidence interval [CI]: −0.14, −0.003). Broken down for different usage purposes, 1 min of daytime social network usage and games and comics was associated with a 0.28 min (p = .02, 95% CI: −0.52, −0.04) and 0.18 min (p = .01, 95% CI: −0.32, −0.04) decrease in total sleeping time that night, respectively. Daytime smartphone usage was not associated with sleep efficiency and WASO. One minute of bedtime social network usage was associated with 2.58 min increase in total sleeping time that night (p = .01, 95% CI: 0.60, 4.36). One minute of web browsing during WASO was associated with 2.29 min increase in total sleeping time (p = .047, 95% CI: 0.03, 4.55) and 0.46 min of WASO (p = .02, 95% CI: 0.08, 0.83) that night. Among secondary school students, 1 min of daytime smartphone usage was associated with 0.12 min decrease in total sleeping time that night (p = .042, 95% CI: −0.23, −0.007). Broken down for different usage purposes, only social network (β = −0.39, p = .03, 95% CI: −0.73, −0.04) was associated with total sleeping time. One minute of bedtime smartphone usage was associated with 0.32 min increase in wake after sleep onset that night (p = .04, 95% CI: 0.02, 0.62). One minute of smartphone usage during WASO was associated with sleep efficiency (β = 0.013%, p = .01, 95% CI: 0.003%, 0.023%) and WASO (β = −0.05, p = .04, 95% CI: −0.10, −0.005). Among university students, smartphone usage during the daytime, bedtime and sleep was insignificantly associated with sleep quality. Broken down for different usage purposes, daytime tools usage (β = 0.32, p = .02, 95% CI: 0.04, 0.60) and bedtime social network usage (β = 2.38, p = .02, 95% CI: 0.37, 4.39) were associated with total sleeping time, whereas instant messaging (β = 0.04, p = .048, 95% CI: 0.001, 0.07), web browsing (β = 0.47, p = .02, 95% CI: 0.09, 0.84) and camera usage (β = 25.79, p = .01, 95% CI: 6.22, 45.36) during WASO were associated with WASO.

Table 4 shows the multilevel regression results of the effects of smartphone usage on physical activity level. One minute of daytime smartphone usage was associated with a 7.15-step increase in the number of steps (p = .02, 95% CI: 1.02, 13.28) among secondary school students, a 3.52-step increase in the number of steps (p = .03, 95% CI: 0.37, 6.66) among university students, and 4.55-step increase in the number of steps (p = .001, 95% CI: 1.77, 7.34) in the overall sample on the next day. Social network, instant messaging, tools, multimedia usage and total smartphone usage (β = 0.06, p = .01, 95% CI: 0.01, 0.11) were positively associated with both the number of steps and the time spent on MVPA in the overall sample. Smartphone usage during bedtime and sleep were insignificantly associated with physical activity level, except for web browsing during WASO, which was associated with number of steps (β = 1,153.07, p = .04, 95% CI: 57.92, 2,248.22) among secondary school students.

Table 5 shows that, for both secondary school students and university students, better sleep quality was associated with a higher volume of physical activity level on the next day, except that a 1% increase in sleep efficiency was associated with a 112.44-step decrease (p = .02, 95% CI: 12.55, 212.33) among secondary school students. Table 6 shows that all associations between sleep quality and daytime smartphone usage were insignificant, except for a 1% increase in sleep efficiency, which was associated with a 9.42-s decrease in time spent on web browsing the next day (p = .02, 95% CI: −17.50, −1.33) among university students.

Histograms of the residuals and residual plots of all regressions are shown in Figures S1–S72. Overall, the residuals were normal (except for sleep efficiency, which was slightly skewed to the left), homoscedastic and independent of each other.

The ICC, autocorrelation and R^2 of all multilevel regression models can be found in Tables S1–S4. The overall sample showed small ICCs of 0.10–0.12 for total sleeping time and 0.14–0.15 for the number of steps, whereas the ICCs were of moderate size for the ICC of sleep efficiency (0.27–0.28), WASO (0.26–0.27) and MVPA (0.30–0.31). The autocorrelation showed that the sleeping variables were only slightly autocorrelated among both secondary school students and university students, whereas the physical activity variables had a small-to-moderate autocorrelation. The difference between ICC and R^2 of the models showed that the independent variables (data source, gender and smartphone usage) explained 7%–10% for total sleeping time and 9%–12% for sleep efficiency, WASO, number of steps and time spent on MVPA. In sum, the within-subject effect explained a larger proportion of variance than the between-subject effect for all sleep and PA variables.

4 | DISCUSSION

We conducted a study to examine the association between objectively measured smartphone usage, sleep quality and physical activity level among Hong Kong Chinese adolescents and young adults.

TABLE 2 Smartphone usage (min) of the participants (number of participants = 187, number of days = 1,106)

Smartphone usage	Secondary school students (number of participants = 32, number of days = 176)			University students (number of participants = 155, number of days = 930)			Overall (number of participants = 187, number of days = 1,106)		
	Daytime (mean (SD))	Bedtime (mean (SD))	During WASO (mean (SD))	Daytime (mean (SD))	Bedtime (mean (SD))	During WASO (mean (SD))	Daytime (mean (SD))	Bedtime (mean (SD))	During WASO (mean (SD))
Social network	23.1 (101.9)	1.1 (7.0)	2.2 (13.8)	24.2 (52.1)	2.0 (8.8)	4.4 (26.8)	24.0 (62.7)	1.9 (3.8)	4.0 (25.2)
Instant messaging	54.8 (96.5)	3.3 (12.2)	9.6 (43.9)	73.4 (112.6)	3.9 (12.3)	11.5 (73.8)	70.5 (110.3)	3.8 (12.3)	11.2 (69.9)
Tools	16.1 (45.1)	1.6 (10.9)	16.5 (106.7)	25.4 (58.1)	1.7 (9.8)	7.9 (65.5)	23.9 (56.3)	1.7 (10.0)	9.3 (73.6)
Web browsing	2.7 (13.8)	0.4 (2.4)	0.2 (1.3)	4.1 (17.5)	0.5 (3.3)	0.8 (6.1)	3.9 (17.0)	0.4 (3.2)	0.7 (5.6)
Games and comics	89.8 (199.1)	4.5 (13.0)	7.3 (28.3)	24.2 (78.1)	1.1 (6.7)	2.0 (23.2)	34.7 (109.5)	1.7 (8.1)	2.9 (24.1)
Multimedia	20.3 (60.7)	1.1 (7.0)	3.7 (46.3)	6.7 (32.0)	0.9 (6.5)	0.6 (7.6)	8.8 (38.3)	0.9 (6.6)	1.1 (19.7)
Health	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	0.4 (3.0)	0.0 (0.5)	0.0 (0.5)	0.3 (2.7)	0.0 (0.5)	0.0 (0.5)
Camera	0.6 (4.0)	0.0 (0.1)	0.0 (0.1)	0.2 (2.5)	0.0 (0.1)	0.0 (0.1)	0.3 (2.8)	0.0 (0.1)	0.0 (0.1)
Total	207.4 (309.1)	12.1 (26.4)	39.4 (136.6)	158.6 (199.4)	10.1 (21.3)	27.3 (107.6)	166.4 (221.0)	10.4 (22.2)	29.2 (112.7)

Note: Daytime was defined as the time from waking up to 1 h before sleep, and bedtime was defined as 1 h before sleep. Sleep onset was defined as the first 15 min of consecutive sleeping minutes.

Abbreviation: SD, standard deviation; WASO, wake after sleep onset.

TABLE 3 Multilevel regression results (reported as coefficient (95% confidence interval)) of smartphone usage (min) on sleep quality (number of participants = 187, number of days = 814)

	Secondary school students (number of participants = 32, number of days = 109)			University students (number of participants = 155, number of days = 705)			Overall (number of participants = 187, number of days = 814)		
	Total sleeping time (min)	Sleep efficiency (%)	Wake after sleep onset (min)	Total sleeping time (min)	Sleep efficiency (%)	Wake after sleep onset (min)	Total sleeping time (min)	Sleep efficiency (%)	Wake after sleep onset (%)
Daytime									
Social network	−0.39* (−0.73, −0.04); $\beta = -0.003$	−0.0088 (−0.0090, 0.0267); $\beta = 0.002$	−0.04 (−0.12, 0.04); $\beta = -0.002$	−0.19 (−0.51, 0.14); $\beta = -0.002$	−0.0034 (−0.0166, 0.0098); $\beta = -0.08$	0.004 (−0.06, 0.05); $\beta = -0.0001$	−0.28* (−0.52, −0.04); $\beta = -0.003$	−0.0013 (−0.0116, 0.0090); $\beta = -0.0003$	0.02 (−0.07, 0.12); $\beta = -0.0007$
Instant messaging	0.14 (−0.22, 0.49); $\beta = 0.001$	−0.0019 (−0.0175, 0.0138); $\beta = -0.0004$	0.04 (−0.04, 0.11); $\beta = 0.002$	−0.08 (−0.22, 0.06); $\beta = -0.001$	−0.0022 (−0.0080, 0.0036); $\beta = -0.05$	0.01 (−0.02, 0.03); $\beta = 0.0005$	−0.06 (−0.19, 0.07); $\beta = -0.0006$	−0.0030 (−0.0084, 0.0025); $\beta = -0.0007$	0.02 (−0.03, 0.06); $\beta = 0.001$
Tools	−0.46 (−1.15, 0.23); $\beta = -0.004$	−0.0006 (−0.0275, 0.0263); $\beta = -0.0001$	−0.04 (−0.17, 0.09); $\beta = -0.002$	0.32* (0.04, 0.60); $\beta = 0.003$	0.0031 (−0.0083, 0.0144); $\beta = 0.07$	0.01 (−0.03, 0.06); $\beta = 0.0008$	0.24 (−0.01, 0.49); $\beta = 0.002$	0.0013 (−0.0091, 0.0118); $\beta = 0.0003$	0.02 (−0.03, 0.06); $\beta = 0.0008$
Web browsing	−1.14 (−3.25, 0.96); $\beta = -0.01$	−0.0419 (−0.1238, 0.0401); $\beta = -0.001$	0.17 (−0.24, 0.57); $\beta = 0.009$	−0.69 (−1.74, 0.37); $\beta = 0.02$	0.0010 (−0.0434, 0.0454); $\beta = 0.02$	−0.05 (−0.24, 0.13); $\beta = 0.03$	−0.79 (−1.73, 0.15); $\beta = 0.02$	−0.0072 (−0.0468, 0.0325); $\beta = -0.002$	−0.01 (−0.18, 0.15); $\beta = -0.001$
Games and comics	−0.17 (−0.35, −0.004); $\beta = -0.002$	−0.0057 (−0.0134, 0.0020); $\beta = -0.001$	0.01 (−0.03, 0.05); $\beta = 0.008$	−0.17 (−0.37, 0.04); $\beta = -0.002$	−0.0036 (−0.0122, 0.0051); $\beta = -0.08$	0.06 (−0.03, 0.16); $\beta = 0.0008$	−0.18* (−0.32, −0.04); $\beta = -0.002$	−0.0054 (−0.0113, 0.0006); $\beta = -0.001$	0.01 (−0.01, 0.04); $\beta = 0.001$
Multimedia	−0.44 (−0.94, 0.06); $\beta = -0.004$	−0.0090 (−0.0286, 0.0105); $\beta = -0.002$	0.006 (−0.09, 0.10); $\beta = 0.0002$	0.003 (−0.46, 0.46); $\beta = -0.00002$	−0.0007 (−0.0192, 0.0177); $\beta = -0.02$	0.01 (−0.06, 0.09); $\beta = -0.0008$	−0.15 (−0.49, 0.19); $\beta = -0.001$	−0.0048 (−0.0186, 0.0090); $\beta = -0.001$	0.02 (−0.04, 0.07); $\beta = 0.001$
Health	N/A	N/A	N/A	0.38 (−4.38, 5.15); $\beta = 0.004$	0.0568 (−0.1332, 0.2469); $\beta = 1.32$	−0.19 (−0.97, 0.59); $\beta = -0.01$	0.50 (−4.16, 5.17); $\beta = 0.005$	0.0611 (−0.1258, 0.2480); $\beta = 0.01$	−0.20 (−0.98, 0.58); $\beta = -0.01$
Camera	3.20 (−4.96, 11.37); $\beta = 0.03$	−0.0129 (−0.3191, 0.2932); $\beta = -0.003$	0.02 (−1.43, 1.48); $\beta = 0.001$	0.02 (−5.54, 5.58); $\beta = 0.0002$	0.0568 (−0.1592, 0.2727); $\beta = 1.32$	−0.22 (−1.10, 0.66); $\beta = -0.01$	1.38 (−3.05, 5.80); $\beta = 0.01$	0.0020 (−0.1695, 0.1736); $\beta = 0.0005$	0.11 (−0.60, 0.83); $\beta = 1.72$

(Continues)

TABLE 3 (Continued)

	Secondary school students (number of participants = 32, number of days = 109)			University students (number of participants = 155, number of days = 705)			Overall (number of participants = 187, number of days = 814)		
	Total sleeping time (min)	Sleep efficiency (%)	Wake after sleep onset (min)	Total sleeping time (min)	Sleep efficiency (%)	Wake after sleep onset (min)	Total sleeping time (min)	Sleep efficiency (%)	Wake after sleep onset (%)
Total	−0.12* (−0.23, −0.007); $\beta = -0.001$	−0.0029 (−0.0077, 0.0019); $\beta = -0.007$	0.01 (−0.02, 0.03); $\beta = 0.003$	−0.04 (−0.13, 0.04); $\beta = -0.004$	−0.0012 (−0.0046, 0.0022); $\beta = -0.03$	0.01 (−0.01, 0.02); $\beta = 0.0003$	−0.07* (−0.14, −0.003); $\beta = -0.007$	−0.0024 (−0.0052, 0.0005); $\beta = -0.0006$	0.01 (−0.004, 0.02); $\beta = 0.0004$
Bedtime									
Social network	1.10 (−5.35, 7.55); $\beta = 0.01$	−0.1152 (−0.3542, 0.1239); $\beta = -0.03$	0.45 (−0.73, 1.64); $\beta = 0.02$	2.38* (0.37, 4.39); $\beta = 0.02$	−0.0022 (−0.0831, 0.0787); $\beta = -0.05$	0.15 (−0.18, 0.48); $\beta = 0.008$	2.58** (0.60, 4.36); $\beta = 0.02$	−0.0101 (−0.0861, 0.0659); $\beta = -0.002$	0.17 (−0.14, 0.49); $\beta = 0.009$
Instant messaging	1.77 (−1.38, 4.92); $\beta = 0.02$	−0.1231 (−0.2512, 0.0050); $\beta = -0.03$	0.64* (0.02, 1.25); $\beta = 0.03$	0.24 (−1.23, 1.70); $\beta = 0.002$	0.0456 (−0.0122, 0.1033); $\beta = 1.06$	−0.18 (−0.42, 0.06); $\beta = -0.01$	0.59 (−0.73, 1.92); $\beta = -0.006$	−0.0049 (−0.0134, 0.0035); $\beta = 0.006$	−0.06 (−0.28 0.15); $\beta = -0.004$
Tools	−4.34 (−10.25, 1.56); $\beta = -0.04$	0.1062 (−0.1155 0.3280); $\beta = 0.02$	−0.95 (−2.04, 0.14); $\beta = -0.05$	−0.86 (−3.25, 1.54); $\beta = -0.008$	−0.0460 (−0.1393 0.0473); $\beta = -1.07$	0.13 (−0.25, 0.51); $\beta = 0.007$	−1.07 (−3.24, 1.11); $\beta = -0.01$	−0.0260 (−0.1104 0.0585); $\beta = -0.006$	0.03 (−0.32, 0.38); $\beta = 0.002$
Web browsing	−3.06 (−9.35, 15.46); $\beta = 0.03$	0.2611 (−0.1877, 0.7080); $\beta = 0.06$	−0.94 (−3.18, 1.30); $\beta = -0.05$	−1.44 (−6.24, 3.36); $\beta = -0.01$	0.1174 (−0.0709, 0.3058); $\beta = 2.74$	−0.32 (−1.09, 0.45); $\beta = -0.02$	−0.73 (−5.12, 3.67); $\beta = -0.007$	0.1474 (−0.0246, 0.3195); $\beta = 0.03$	−0.43 (−1.15, 0.29); $\beta = -0.02$
Games and comics	0.42 (−2.17, 3.01); $\beta = 0.004$	−0.0802 (−0.1835, 0.0232); $\beta = -0.02$	0.45 (−0.06, 0.96); $\beta = 0.02$	1.75 (−0.44, 3.94); $\beta = 0.30$	0.0128 (−0.0735, 0.0991); $\beta = -0.003$	0.09 (−0.27, 0.44); $\beta = 0.005$	1.40 (−0.31, 3.11); $\beta = 0.01$	−0.0196 (−0.0879, 0.0486); $\beta = -0.005$	0.21 (−0.08, 0.49); $\beta = 0.01$
Multimedia	−4.00 (−10.78, 2.78); $\beta = -0.04$	−0.0100 (−0.2614, 0.2414); $\beta = -0.002$	−0.10 (−1.35, 1.16); $\beta = -0.005$	0.89 (−1.34, 3.11); $\beta = 0.008$	−0.0233 (−0.1099, 0.0633); $\beta = -0.54$	0.19 (−0.16, 0.54); $\beta = 0.01$	0.68 (−1.40, 2.77); $\beta = 0.006$	−0.0200 (−0.1012, 0.0611); $\beta = -0.005$	0.16 (−0.18, 0.50); $\beta = 0.009$
Health	N/A	N/A	N/A	17.22 (−8.78, 43.22); $\beta = 0.16$	0.5519 (−0.4686, 1.5720); $\beta = 12.86$	−1.98 (−6.17, 2.21); $\beta = -0.11$	17.47 (−8.06, 43.01); $\beta = 0.16$	0.5678 (−0.4335, 1.5691); $\beta = 0.13$	−2.03 (−6.22, 2.16); $\beta = -0.11$

(Continues)

TABLE 3 (Continued)

	Secondary school students (number of participants = 32, number of days = 109)			University students (number of participants = 155, number of days = 705)			Overall (number of participants = 187, number of days = 814)		
	Total sleeping time (min)	Sleep efficiency (%)	Wake after sleep onset (min)	Total sleeping time (min)	Sleep efficiency (%)	Wake after sleep onset (min)	Total sleeping time (min)	Sleep efficiency (%)	Wake after sleep onset (%)
Camera	−135.36 (−601.04, 330.32); $\beta = -1.27$	6.1200 (−11.1420, 23.3880); $\beta = 1.43$	−32.09 (−114.94, 50.76); $\beta = -1.73$	−116.63 (−251.81, 18.54); $\beta = -1.10$	3.6540 (−1.6020, 8.910); $\beta = -85.20$	−12.45 (−33.91, 9.01); $\beta = -0.67$	−128.41* (−255.77, −1.04); $\beta = -1.21$	4.1632 (−0.8016, 9.1281); $\beta = -0.97$	−15.17 (−35.78, 5.44); $\beta = -0.82$
Total	0.59 (−0.96, 2.13); $\beta = 0.006$	−0.0604 (−0.1219, 0.0010); $\beta = -0.01$	0.32* (0.02, 0.62); $\beta = 0.02$	0.68 (−0.18, 1.54); $\beta = 0.006$	0.0153 (−0.0188, 0.0494); $\beta = 0.36$	−0.01 (−0.15, 0.13); $\beta = -0.0004$	0.69 (−0.07, 1.45); $\beta = 0.006$	0.0033 (−0.0271, 0.0337); $\beta = 0.0008$	0.05 (−0.08, 0.17); $\beta = 0.002$
During WASO									
Social network	1.82 (−0.91, 4.55); $\beta = 0.02$	0.0433 (−0.0634, 0.1499); $\beta = 0.01$	−0.08 (−0.60, 0.45); $\beta = -0.004$	−0.02 (−0.63, 0.59); $\beta = -0.0002$	−0.0059 (−0.0297, 0.0179); $\beta = -0.14$	0.02 (−0.07, 0.12); $\beta = 0.001$	0.07 (−0.51, 0.65); $\beta = 0.0007$	−0.0048 (−0.0275, 0.0180); $\beta = -0.001$	0.02 (−0.07, 0.12); $\beta = 0.001$
Instant messaging	0.26 (−0.54, 1.07); $\beta = 0.002$	0.0119 (−0.0290, 0.0528); $\beta = 0.003$	−0.06 (−0.24, 0.13); $\beta = -0.003$	0.07 (−0.16, 0.29); $\beta = 0.0006$	−0.0069 (−0.0157, 0.0020); $\beta = -0.16$	0.04* (0.001, 0.07); $\beta = 0.002$	0.06 (−0.16, 0.27); $\beta = 0.0006$	−0.0049 (−0.0134, 0.0035); $\beta = -0.001$	0.03 (−0.01, 0.06); $\beta = 0.001$
Tools	0.60 (−0.01, 1.22); $\beta = 0.006$	−0.0018 (−0.0249 0.0213); $\beta = -0.0004$	0.06 (−0.05, 0.18); $\beta = 0.003$	0.04 (−0.30, 0.39); $\beta = 0.0004$	0.0062 (−0.0074 0.0197); $\beta = 0.14$	−0.02 (−0.08, 0.03); $\beta = -0.001$	0.13 (−0.15, 0.42); $\beta = 0.001$	0.0060 (−0.0051, 0.0171); $\beta = 0.001$	−0.02 (−0.06, 0.03); $\beta = -0.001$
Web browsing	12.67 (−10.03, 35.37); $\beta = 0.12$	−0.0062 (−1.2060, 1.1940); $\beta = -0.001$	0.53 (−4.47, 5.86); $\beta = 0.03$	2.13 (−0.19, 4.46); $\beta = 0.02$	−0.0740 (−0.1655, 0.0175); $\beta = -1.73$	0.47* (0.09, 0.84); $\beta = -0.003$	2.29* (0.03, 4.55); $\beta = 0.02$	−0.0725 (−0.1620, 0.0170); $\beta = -0.02$	0.46* (0.08, 0.83); $\beta = 0.02$
Games and comics	0.84 (−0.18, 1.86); $\beta = 0.008$	0.0095 (−0.0298, 0.0489); $\beta = 0.002$	0.02 (−0.17, 0.21); $\beta = 0.001$	0.25 (−0.34, 0.83); $\beta = 0.002$	−0.0125 (−0.0352, 0.0102); $\beta = -0.29$	0.06 (−0.03, 0.16); $\beta = 0.003$	0.35 (−0.16, 0.86); $\beta = 0.003$	−0.0086 (−0.0286, 0.0115); $\beta = -0.002$	0.05 (−0.03, 0.14); $\beta = 0.003$
Multimedia	0.13 (−0.89, 1.16); $\beta = 0.001$	0.0076 (−0.0350, 0.0501); $\beta = 0.002$	−0.03 (−0.23, 0.17); $\beta = -0.002$	1.74 (−0.06, 3.54); $\beta = 0.02$	−0.0291 (−0.0992, 0.0409); $\beta = -0.68$	0.28 (−0.01, 0.57); $\beta = 0.02$	−0.13 (−0.81, 0.54); $\beta = -0.001$	0.0027 (−0.0247, 0.0302); $\beta = 0.0006$	−0.01 (−0.12, 0.11); $\beta = -0.004$

(Continues)

TABLE 3 (Continued)

	Secondary school students (number of participants = 32, number of days = 109)			University students (number of participants = 155, number of days = 705)			Overall (number of participants = 187, number of days = 814)		
	Total sleeping time (min)	Sleep efficiency (%)	Wake after sleep onset (min)	Total sleeping time (min)	Sleep efficiency (%)	Wake after sleep onset (min)	Total sleeping time (min)	Sleep efficiency (%)	Wake after sleep onset (%)
Health	N/A	N/A	N/A	6.39 (−20.66, 33.45); $\beta = 0.06$	0.9240 (−0.1309, 1.9740); $\beta = 21.52$	−3.64 (−7.95, 0.68); $\beta = -0.20$	6.65 (−19.94, 33.24); $\beta = 0.06$	0.9387 (−0.0969, 1.9743); $\beta = 0.22$	−3.68 (−8.00, 0.65); $\beta = -0.20$
Camera	286.27 (−136.42, 708.96); $\beta = 2.69$	−13.5600 (−29.1660, 2.0460); $\beta = -3.16$	97.43* (23.21, 171.65); $\beta = 5.25$	157.39* (37.41, 277.37); $\beta = 1.48$	−3.4020 (−8.1900, 1.3920); $\beta = -79.27$	25.79* (6.22, 45.36); $\beta = 1.39$	171.80** (58.75, 284.85); $\beta = 1.61$	−4.2466 (−8.7582, 0.2651); $\beta = -0.99$	31.94** (13.21, 50.66); $\beta = 0.006$
Total	0.11 (−0.16, 0.37); $\beta = 0.001$	0.0130* (0.0028, 0.0232); $\beta = 0.003$	−0.05* (−0.10, −0.005); $\beta = -0.003$	0.02 (−0.13, 0.18); $\beta = 0.0002$	−0.0038 (−0.0098, 0.0023); $\beta = -0.08$	0.02 (−0.01, 0.04); $\beta = 0.001$	0.04 (−0.09, 0.18); $\beta = 0.004$	−0.0006 (−0.0059, 0.0047); $\beta = -0.0001$	0.005 (−0.02, 0.03); $\beta = 0.0002$

Abbreviations: N/A, not applicable; WASO, wake after sleep onset; β, standardized coefficient.

*/ **/ *** significant at 5%/ 1%/ 0.1% level.

We found that the explanatory power of total smartphone usage on sleep quality among secondary school students, university students and the overall sample was 3.14%–5.89%, 0.16%–0.34% and 0.02%–0.52%, respectively (Table S5). We concluded that the explanatory power of smartphone usage on sleep among university students was negligible (with similar explanatory power among US children; Przybylski, 2019), whereas smartphone usage was a significant contributor to sleep, in particular total sleeping time, among secondary school students. There were several advantages to using the objective measurement of smartphone usage. First, we could identify different purposes for which a smartphone was being used, and showed the effect of smartphone use on different aspects of life. For instance, we found that only the use of social network apps and games and comics apps was associated with total sleeping time. Second, together with sleeping parameters objectively measured with the accelerometer, we could define sleeping time and bedtime smartphone usage objectively, and exclude the possibility of reverse causation, that sleep quality has a negligible effect on smartphone usage the next day. Note that our data did not rule out (and could not identify) the complex, bidirectional nature of the relationship between sleep pattern and smartphone usage during sleep, whereby people with sleep problems would use their smartphone during bedtime as a way of spending their energy (Przybylski, 2019), and in turn the blue light emission from the smartphone will suppress melatonin secretion, which will further delay sleep onset (Figueiro & Overington, 2016). Third, although the validity of self-reported smartphone usage was questionable, the source of measurement error could be eliminated through objective measurement of smartphone usage.

In studies on the association between smartphone usage and sleep quality, most used a self-reported questionnaire to measure sleep quality and only three studies measured sleep quality with a wrist-worn accelerometer (Cabré-Riera et al., 2019; Fobian et al., 2016; Murdock et al., 2016). Surprisingly, all three studies found no association. On the one hand, the finding of a null association might be a true finding; on the other hand, it is possible that these studies committed a type II error because the sample sizes ranged from 55 to 110 only. Furthermore, in these studies, smartphone usage data were not collected in a daily manner and only the averaged accelerometer-measured sleep quality across the measurement period could be used, so that the within-subject variation was ignored. With a repeated measure of 814 nights, in a study involving 187 subjects that could examine both within-subject and between-subject variation, our study has the largest sample size and showed that both daytime and bedtime smartphone usage were associated with total sleeping time but not with sleep efficiency and WASO.

Several researchers attempted to differentiate between the physiological effects of daytime and bedtime smartphone usage. Compared to other devices with electronic screens, such as televisions and video game consoles, smartphones are more commonly used in bed as they are portable and are usually placed very close to the user (Twenge et al., 2019; Wood et al., 2013). To the best

TABLE 4 Multilevel regression results (reported as coefficient (95% confidence interval)) of smartphone usage (min) on physical activity level (number of participants = 187, number of days = 1,106)

	Secondary school students (number of participants = 32, number of days = 176)		University students (number of participants = 155, number of days = 930)		Overall (number of participants = 187, number of days = 1,106)	
	Number of steps	Moderate-to-vigorous physical activity (min)	Number of steps	Moderate-to-vigorous physical activity (min)	Number of steps	Moderate-to-vigorous physical activity (min)
Daytime						
Social network	10.49 (−11.04, 32.02); $\beta = 0.002$	0.12 (−0.27, 0.51); $\beta = 0.001$	13.52* (0.94, 26.11); $\beta = 0.003$	0.27* (0.06, 0.48); $\beta = 0.003$	10.70* (0.30, 21.10); $\beta = 0.002$	0.21* (0.03, 0.39); $\beta = 0.002$
Instant messaging	25.89* (5.96, 45.82); $\beta = 0.005$	0.37* (0.01, 0.72); $\beta = 0.004$	6.46* (1.03, 11.90); $\beta = 0.001$	0.09 (−0.01, 0.18); $\beta = 0.0002$	8.53** (3.13, 13.92); $\beta = 0.002$	0.11* (0.02, 0.20); $\beta = 0.001$
Tools	32.50 (−4.02, 69.01); $\beta = 0.007$	0.72* (0.08, 1.36); $\beta = -0.008$	1.27 (−6.94, 14.16); $\beta = 0.0003$	−0.02 (−0.21, 0.16); $\beta = -0.0003$	4.13 (−6.44, 14.70); $\beta = 0.001$	0.03 (−0.15, 0.21); $\beta = 0.0003$
Web browsing	77.94 (−32.26, 188.13); $\beta = 0.02$	0.94 (−0.98, 2.88); $\beta = 0.01$	22.77 (−19.82, 65.37); $\beta = 0.005$	0.29 (−0.46, 1.03); $\beta = 0.003$	32.85 (−8.17, 73.87); $\beta = 0.007$	0.31 (−0.39, 1.03); $\beta = 0.004$
Games and comics	5.35 (−4.76, 15.45); $\beta = 0.001$	−0.001 (−0.18, 0.18); $\beta = -0.000001$	0.77 (−7.55, 9.08); $\beta = 0.0002$	0.02 (−0.12, 0.16); $\beta = 0.002$	3.25 (−2.82, 9.32); $\beta = 0.001$	0.01 (−0.09, 0.12); $\beta = 0.0002$
Multimedia	25.69* (0.11, 51.26); $\beta = 0.005$	0.50* (0.05, 0.94); $\beta = 0.006$	7.27 (−10.87, 25.41); $\beta = 0.001$	0.14 (−0.16, 0.43); $\beta = 0.002$	14.41* (0.14, 28.68); $\beta = 0.003$	0.32** (0.08, 0.55); $\beta = 0.004$
Health	N/A	N/A	−9.45 (−198.77, 179.87); $\beta = -0.002$	−0.04 (−3.15, 3.06); $\beta = -0.001$	−2.01 (−199.72, 195.41); $\beta = -0.0004$	−0.07 (−3.35, 3.20); $\beta = -0.001$
Camera	−100.56 (−500.55, 299.42); $\beta = -0.02$	−1.96 (−8.93, 5.01); $\beta = -0.02$	17.52 (−200.06, 235.10); $\beta = 0.004$	0.17 (−3.34, 3.68); $\beta = 0.002$	−43.90 (−224.51, 136.71); $\beta = -0.009$	−31.40 (−116.22, 53.41); $\beta = -0.26$
Total	7.15* (1.02, 13.28); $\beta = 0.001$	0.09 (−0.02, 0.20); $\beta = 0.001$	3.52* (0.37, 6.66); $\beta = 0.001$	0.05 (−0.001, 0.11); $\beta = 0.001$	4.55* (1.77, 7.34); $\beta = 0.001$	0.06* (0.01, 0.11); $\beta = 0.001$
Bedtime						
Social network	−88.62 (−400.75, 223.50); $\beta = -0.02$	−1.28 (−6.74, 4.17); $\beta = -0.01$	−52.87 (−130.75, 25.01); $\beta = -0.01$	−0.48 (−1.75, 0.80); $\beta = -0.005$	−51.75 (−127.92, 24.43); $\beta = -0.01$	−0.46 (−1.72, 0.80); $\beta = -0.005$
Instant messaging	−66.99 (−233.06, 99.08); $\beta = -0.01$	−1.24 (−4.17, 1.68); $\beta = -0.01$	−25.11 (−82.23, 32.01); $\beta = -0.005$	0.34 (−0.59, 1.27); $\beta = 0.004$	−23.17 (−77.54, 31.21); $\beta = -0.005$	0.29 (−0.61, 1.19); $\beta = 0.003$
Tools	190.96 (−108.27, 490.19); $\beta = 0.04$	4.12 (−1.06, 9.31); $\beta = 0.05$	−57.54 (−152.49, 37.40); $\beta = -0.01$	−0.93 (−2.46, 0.60); $\beta = -0.001$	−34.38 (−124.87, 56.10); $\beta = -0.007$	−0.72 (−2.20, 0.76); $\beta = -0.01$
Web browsing	148.88 (−469.21, 766.97); $\beta = 0.03$	4.40 (−6.36, 15.15); $\beta = 0.05$	−29.05 (−217.86, 159.76); $\beta = -0.006$	0.07 (−3.01, 3.15); $\beta = 0.001$	−3.64 (−184.89, 177.61); $\beta = -0.0007$	0.94 (−2.05, 3.93); $\beta = 0.01$
Games and comics	−58.44 (−193.35, 76.46); $\beta = -0.01$	−0.26 (−2.60, 2.15); $\beta = -0.003$	−48.06 (−134.14, 38.01); $\beta = -0.01$	−1.11 (−2.52, 0.31); $\beta = -0.01$	−48.90 (−119.89, 22.10); $\beta = -0.01$	−0.66 (−1.85, 0.52); $\beta = -0.007$

(Continues)

TABLE 4 (Continued)

	Secondary school students (number of participants = 32, number of days = 176)		University students (number of participants = 155, number of days = 930)		Overall (number of participants = 187, number of days = 1,106)	
	Number of steps	Moderate-to-vigorous physical activity (min)	Number of steps	Moderate-to-vigorous physical activity (min)	Number of steps	Moderate-to-vigorous physical activity (min)
Multimedia	−3.92 (−336.54, 328.71); $\beta = -0.001$	2.03 (−3.74, 7.81); $\beta = 0.02$	10.16 (−76.11, 96.43); $\beta = 0.002$	0.17 (−1.22, 1.56); $\beta = 0.002$	5.39 (−78.81, 89.59); $\beta = 0.001$	0.22 (−1.17, 1.60); $\beta = 0.002$
Health	N/A	N/A	−665.89 (−1,683.57, 351.78); $\beta = -0.13$	−11.01 (−27.43, 5.40); $\beta = -0.12$	−694.69 (−1,749.65, 360.26); $\beta = -0.14$	−11.68 (−28.98, 5.62); $\beta = -0.13$
Camera	5,238.15 (−19,576.76, 30,053.05); $\beta = 1.04$	65.51 (−368.41, 499.43); $\beta = 0.73$	−3,562.48 (−8,812.56, 1,687.60); $\beta = -0.71$	−44.60 (−129.43, 40.23); $\beta = -0.50$	−2,553.19 (−7,715.52, 2,609.14); $\beta = -0.51$	−31.40 (−116.22, 53.41); $\beta = -0.35$
Total	−13.78 (−94.63, 67.07); $\beta = -0.003$	0.10 (−1.32, 1.52); $\beta = 0.001$	−26.24 (−59.56, 7.08); $\beta = -0.005$	−0.13 (−0.68, 0.41); $\beta = -0.002$	−24.52 (−55.58, 6.54); $\beta = -0.005$	−0.09 (−0.61, 0.42); $\beta = -0.001$
During WASO						
Social network	39.49 (−111.49, 190.47); $\beta = 0.008$	−0.01 (−2.66, 2.65); $\beta = -0.0001$	2.97 (−20.79, 26.72); $\beta = 0.001$	0.01 (−0.38, 0.39); $\beta = 0.0001$	4.85 (−18.89, 28.60); $\beta = 0.001$	0.02 (−0.37, 0.41); $\beta = 0.0003$
Instant messaging	29.84 (−12.52, 72.21); $\beta = 0.006$	0.65 (−0.10, 1.40); $\beta = 0.007$	6.27 (−2.45, 14.99); $\beta = 0.001$	0.02 (−0.13, 0.16); $\beta = 0.001$	6.97 (−1.70, 15.65); $\beta = 0.001$	0.04 (−0.10, 0.19); $\beta = 0.001$
Tools	−20.04 (−50.82, 10.75); $\beta = -0.004$	−0.38 (−0.92, 0.15); $\beta = -0.004$	7.16 (−6.54, 20.86); $\beta = 0.001$	0.06 (−0.16, 0.28); $\beta = 0.001$	3.24 (−0.67, 15.15); $\beta = 0.001$	0.05 (−0.14, 0.25); $\beta = 0.001$
Web browsing	1,153.07* (57.92, 2,248.22); $\beta = 0.23$	1.04 (−1.94, 4.03); $\beta = 0.25$	−82.60 (−173.48, 8.29); $\beta = -0.02$	−1.24 (−2.72, 0.24); $\beta = -0.01$	−71.19 (−164.38, 21.99); $\beta = 0.01$	−1.02 (−2.56, 0.53); $\beta = -0.01$
Games and comics	31.90 (−19.90, 83.70); $\beta = 0.006$	0.65 (−0.25, 1.55); $\beta = 0.007$	−12.29 (−35.11, 10.53); $\beta = -0.002$	−0.15 (−0.51, 0.22); $\beta = -0.002$	−4.96 (−25.88, 15.97); $\beta = -0.001$	0.04 (−0.30, 0.38); $\beta = -0.001$
Multimedia	21.64 (−28.92, 72.20); $\beta = 0.004$	−0.12 (−1.00, 0.76); $\beta = -0.001$	−41.90 (−112.46, 28.67); $\beta = -0.008$	−0.64 (−1.78, 0.50); $\beta = -0.007$	14.84 (−11.85, 41.53); $\beta = 0.003$	0.06 (−0.38, 0.50); $\beta = 0.001$
Health	N/A	N/A	9.40 (−1,048.04, 1,066.83); $\beta = 0.002$	−1.95 (−19.01, 15.12); $\beta = -0.02$	37.94 (−1,050.20, 1,126.09); $\beta = 0.008$	−1.73 (−19.58, 16.12); $\beta = -0.02$
Camera	−3,407.19 (−23,839.59, 17,025.20); $\beta = -0.68$	−83.94 (−439.96, 272.08); $\beta = -0.94$	−1,432.84 (−6,071.19, 3,205.02); $\beta = -0.29$	−18.54 (−94.34, 57.27); $\beta = -0.21$	−43.90 (−224.51, 136.71); $\beta = -0.27$	−0.72 (−3.68, 2.24); $\beta = -0.26$
Total	6.87 (−6.90, 20.63); $\beta = 0.0014$	0.09 (−0.15, 0.33); $\beta = 0.001$	3.42 (−2.58, 9.42); $\beta = 0.001$	−0.003 (−0.10, 0.09); $\beta = -0.00003$	4.07 (−1.42, 9.56); $\beta = 0.001$	0.02 (−0.07, 0.11); $\beta = 0.0003$

Abbreviations: N/A, not applicable; WASO, wake after sleep onset; β, standardized coefficient.

*/ **/ *** significant at 5%/ 1%/ 0.1% level.

TABLE 5 Multilevel regression results (reported as coefficient (95% confidence interval)) of sleep quality on physical activity level (number of participants = 352, number of days = 1,517)

	Secondary school students (number of participants = 123, number of days = 459)		University students (number of participants = 229, number of days = 1,058)	University students (number of participants = 229, number of days = 1,058)	Overall (number of participants = 352, number of days = 1,517)	
	Number of steps	Moderate-to-vigorous physical activity (min)	Number of steps	Moderate-to-vigorous physical activity (min)	Number of steps	Moderate-to-vigorous physical activity (min)
Total sleeping time (h)	−706.06*** (−932.24, −479.89); $\beta = -0.14$	−10.83*** (−15.12, −6.54); $\beta = -0.12$	−569.76*** (−700.71, −438.80); $\beta = -0.11$	−7.95*** (−10.16, −5.74); $\beta = -0.09$	−615.80*** (−730.82, −500.79); $\beta = -0.12$	−8.56*** (−10.58, −6.54); $\beta = -0.10$
Sleep efficiency (%)	−112.44* (12.55, 212.33); $\beta = 0.02$	2.29* (0.34, 4.25); $\beta = 0.03$	−1.82 (−62.24, 58.61); $\beta = -0.0004$	−0.40 (−1.41, 0.61); $\beta = -0.005$	−30.33 (−21.93, 82.59); $\beta = 0.006$	0.33 (−0.60, 1.26); $\beta = 0.004$
Wake after sleep onset (min)	−42.74*** (−65.12, −20.37); $\beta = -0.01$	−0.76* (−1.19, −0.33); $\beta = -0.01$	−15.28* (−29.15, −1.42); $\beta = -0.003$	−0.13 (−0.36, 0.10); $\beta = -0.002$	−22.96*** (−34.86, −11.07); $\beta = -0.005$	−0.29** (−0.51, −0.08); $\beta = -0.003$

Abbreviations: β, standardized coefficient.
*/ **/ *** significant at 5%/ 1%/ 0.1% level.

of our knowledge, all existing studies have relied on self-reported data to determine bedtime smartphone usage. As the validity of self-reports of bedtime smartphone usage requires the accurate recalling of both bedtime and smartphone usage, we questioned the validity of self-report and used an objective measure of sleep onset and smartphone usage to determine bedtime smartphone usage. The invalidity of self-reported bedtime smartphone usage is shown by the disagreement of our results with other existing self-reported results; for example, a Taiwanese study using self-reported data showed that bedtime smartphone usage was very common (95%) among junior college students (Wang et al., 2019), but the current study recorded such usage on less than half of the nights (42.4%). Our results also highlighted the importance of distinguishing between daytime and bedtime smartphone usage, as total sleeping time was negatively related to daytime usage but not related to bedtime usage. We found no association between smartphone usage, both daytime and bedtime, and sleeping efficiency, and these results did not agree with some previous findings (Amra et al., 2017; Carter et al., 2016; Lemola et al., 2015; Mireku et al., 2019). We believe that the effects of smartphone usage and sleep outcomes are still controversial (some other studies found a null association; Demirci et al., 2015) and warrant further investigations, especially through employing well-designed controlled trials. We suspect that, in previous studies, participants might have mixed up bedtime smartphone usage and usage during WASO, as we found that smartphone usage during WASO did improve sleep efficiency. To the best of our knowledge, very few randomized controlled trials have been conducted in this direction, and some found a null association between smartphone usage and sleep outcomes due to small sample size (Dunican et al., 2017).

Besides the time of use, the purpose for which a smartphone is used may also have an impact on sleep outcomes. This study found that only using a smartphone for social network apps and games and comics apps, but not for other types of apps, was associated with total sleeping time. It was hypothesized that interactive smartphone use should have stronger effects on sleep than the passive viewing of a smartphone screen (Dworak et al., 2007). Our results only partially agreed with this hypothesis. Social network app usage can be regarded as passive viewing as its use does not involve frequent touching of the phone. However, the contents of social networks are updated extremely quickly and new updates can be expected to occur every minute. Therefore, users may be anxious about missing out on new content, and such anxiety may cause users to stay awake during the night (Woods & Scott, 2016). Yet, some studies found that social network use was, in fact, positively related to sleep quality (Nursalam et al., 2019), partially because social network sites can help users to connect, make new friends and share their stress (Nursalam et al., 2019). In addition to social network apps, instant messaging apps were also commonly used among our subjects, and we found no association between their use and all sleep outcomes. It was hypothesized that it is difficult to leave a discussion initiated through instant messaging, which thereby delays sleep onset. This hypothesis was supported by the fact that texting was negatively

TABLE 6 Multilevel regression results (reported as coefficient (95% confidence interval)) of sleep quality on daytime smartphone usage (number of participants = 187, number of days = 689)

	Social network (s)	Instant messaging (s)	Tools (s)	Web browsing (s)	Games and comics (s)	Multimedia (s)	Health (s)	Camera (s)	Total (s)
Secondary school students (number of participants = 32, number of days = 92)									
Total sleeping time (min)	1.57 (−2.28, 5.41); $\beta = 0.001$	0.74 (−5.66, 7.13); $\beta = 0.0002$	−0.74 (−3.90, 2.43); $\beta = -0.0004$	0.95 (−0.17, 2.07); $\beta = 0.002$	0.80 (−11.62, 13.22); $\beta = 0.0002$	0.43 (−3.29, 4.16); $\beta = 0.0004$	N/A	0.14 (−0.21, 0.50); $\beta = 0.002$	0.80 (−18.35, 19.96); $\beta = 0.0001$
Sleep efficiency (%)	−57.28, (−163.00, 48.45); $\beta = -3.20$	−54.80 (−219.55, 109.95); $\beta = -1.64$	22.13 (−51.77, 96.02); $\beta = 1.33$	15.51 (−11.40, 42.42); $\beta = 2.97$	−119.35 (−450.26, 211.56); $\beta = -3.68$	27.79 (−61.91, 117.48); $\beta = 2.45$	N/A	−0.88 (−9.15, 7.39); $\beta = -0.98$	−228.25 (−720.28, 263.79); $\beta = -3.47$
Wake after sleep onset (min)	9.92 (−11.63, 31.47); $\beta = 0.006$	15.41 (−18.73, 49.54); $\beta = 0.004$	−5.46 (−21.46, 10.53); $\beta = -0.003$	−0.70 (−6.53, 5.13); $\beta = -0.001$	38.90 (−28.42, 106.22); $\beta = 0.01$	−0.75 (−20.04, 18.53); $\beta = -0.001$	N/A	0.41 (−1.38, 2.19); $\beta = 0.005$	62.58 (−39.75, 164.91); $\beta = 0.01$
University students (number of participants = 155, number of days = 598)									
Total sleeping time (min)	0.15 (−0.84, 1.14); $\beta = 0.0001$	−1.02 (−3.51, 1.47); $\beta = -0.0003$	−1.00 (−2.28, 0.27); $\beta = -0.001$	−0.26 (−0.57, 0.05); $\beta = -0.0005$	1.39 (−0.14, 2.91); $\beta = 0.0004$	0.49 (−0.31, 1.29); $\beta = 0.0004$	0.03 (−0.05, 0.10); $\beta = 0.0003$	0.003 (−0.07, 0.07); $\beta = 0.00004$	−0.78 (−4.90, 3.35); $\beta = -0.0001$
Sleep efficiency (%)	4.69, (−21.19, 30.58); $\beta = 0.26$	−6.82 (−70.00, 56.36); $\beta = -0.20$	−1.39 (−34.45, 31.66); $\beta = -0.08$	−9.42* (−17.50, −1.33); $\beta = -1.80$	22.30 (−17.14, 61.74); $\beta = 0.69$	3.73 (−16.74, 24.40); $\beta = 0.33$	−0.07 (−1.99, 1.85); $\beta = -0.08$	0.89 (−0.82, 2.61); $\beta = 0.99$	−2.80 (−103.16, 108.77); $\beta = 0.04$
Wake after sleep onset (min)	−0.29 (−6.58, 6.01); $\beta = -0.0002$	−0.68 (−16.12, 14.76); $\beta = -0.0002$	−0.24 (−8.29, 7.81); $\beta = -0.0001$	1.10 (−0.87, 3.07); $\beta = 0.002$	−4.34 (−13.96, 5.28); $\beta = -0.001$	1.17 (−3.87, 6.21); $\beta = 0.001$	0.13 (−0.34, 0.59); $\beta = 0.001$	−0.24 (−0.66, 0.17); $\beta = -0.003$	−1.57 (−27.41, 24.27); $\beta = -0.0002$
Overall (number of participants = 187, number of days = 689)									
Total sleeping time (min)	0.23 (−0.80, 1.26); $\beta = 0.0001$	−0.82 (−3.14, 1.49); $\beta = -0.002$	−1.05 (−2.24, 0.14); $\beta = -0.001$	−0.10 (−0.41, 0.21); $\beta = -0.0002$	1.05 (−0.97, 3.08); $\beta = 0.0003$	0.47 (−0.40, 1.34); $\beta = 0.0004$	0.03 (−0.04, 0.09); $\beta = 0.0003$	0.02 (−0.06, 0.09); $\beta = 0.0002$	−0.63 (−4.91, 3.65); $\beta = -0.0001$
Sleep efficiency (%)	−2.72, (−29.61, 24.16); $\beta = -0.15$	−11.92 (−70.63, 46.78); $\beta = -0.36$	−0.27 (−30.99, 30.44); $\beta = -0.02$	−6.74 (−14.80, 1.31); $\beta = -1.29$	13.16 (−39.57, 65.89); $\beta = 0.41$	6.23 (−15.90, 28.36); $\beta = 0.55$	−0.06 (−1.74, 1.61); $\beta = -0.08$	0.61 (−1.21, 2.43); $\beta = 0.68$	−20.29 (−130.30, 89.71); $\beta = -0.31$
Wake after sleep onset (min)	0.90 (−5.50, 7.29); $\beta = 0.001$	1.48 (−12.59, 15.16); $\beta = 0.0004$	−0.74 (−8.07, 6.59); $\beta = -0.0004$	0.93 (−0.99, 2.85); $\beta = 0.002$	0.42 (−12.14, 12.99); $\beta = 0.0001$	0.81 (−4.49, 6.12); $\beta = 0.001$	0.10 (−0.30, 0.51); $\beta = 0.001$	−0.13 (−0.56, 0.31); $\beta = -0.001$	7.34 (−18.94, 33.63); $\beta = 0.001$

Abbreviations: β, standardized coefficient.

*/ **/ *** significant at 5%/ 1%/ 0.1% level.

associated with sleep quality (Exelmans & Van den Bulck, 2016) and its effect on sleep duration was the strongest among other electronic screen usages (Yland et al., 2015). However, we questioned the validity of these results as they relied on self-reported time spent on instant messaging and such data, being recalled data, are inherently unreliable. Our data showed that instant messaging apps were used frequently, at an average of 363.7 times per day, and that each session only lasted for an average of 26 s. We believe that the frequent and short usage of instant messaging apps made the recalling of time spent on them challenging.

It was generally expected that the use of a smartphone would lead to a sedentary and inactive lifestyle due to its sedentary nature (Kenney & Gortmaker, 2017; Lepp et al., 2013). Surprisingly, our data showed that social network, instant messaging, tools and multimedia app usages in the daytime were all positively associated with physical activity level. We believe that there was a bidirectional causation. Those who were more physically active might have spent more time on social network and instant messaging apps to share their photos and information. Similarly, some of the multimedia app usage might have occurred concurrently with physical activity (e.g., playing a video during jogging on a treadmill). On the other hand, our data found no association between games and health app usage and physical activity level. Recently, some augmented reality games developed for smartphones have encouraged walking in the real world (e.g., Pokémon GO), and there is evidence to show that their use is promoting engagement in physical activity (Howe et al., 2016; Wong, 2017). In the current study, too few subjects played Pokémon GO (11 out of 187, 5.9%); therefore, the health-promoting effect of this kind of augmented reality game might have been diluted by the sedentary effect of other kinds of games. Similarly, users of health-related apps, for instance pedometer apps, were found to be more physically active than non-users (Carroll et al., 2017; Ernsting et al., 2017). In the current study, too few subjects used health-related apps (31 out of 187, 16.6%), less than the previously reported percentage (34.1%) in a US sample (Carroll et al., 2017). Most importantly, no secondary school students in our sample used any kind of health-related apps during the measurement period; therefore, we were unable to detect the associations between the usage of health-related apps, sleep quality and physical activity level.

The major limitation of this study lies in the area of sampling and data collection. Only Android users were recruited in this study and caution should be taken when our results are generalized to users of other smartphones. This also explains the small number of adolescent participants in our sample; most of the students in our recruited secondary schools were using an iPhone that is not supported by our tracking app. Nonetheless, our sample has a comparable smartphone usage level (206 min/day) with Korean college students (210 min/day) (Lee et al., 2014) and US adults (159 min/day) (Deng et al., 2019). In our sample, about 10% of the participants owned more than one smartphone. Because the smartphone usage tracking app was only installed in one smartphone of the subjects, we might have underestimated the total smartphone usage. Another limitation was that our smartphone tracking app could not record the usage of some Android default system apps, for example Google Chrome, the default web browser of the Android system, in some versions of the Android operating system. This only affected the measurement of time spent on web browsing and not that on the other usage types. A minor limitation was that different recruitment approaches were used in secondary schools and universities, which might affect the generalizability of our results. It is known that monitoring of PA levels with accelerometers could lead to an increase in PA among older adults (Cooper et al., 2018), but the monitoring has no impact on adolescents (Vanhelst et al., 2017). To the best of our knowledge, we were unable to identify any studies that examine the impact of wearing an accelerometer on sleep quality among adolescents; therefore, we could not determine its impact in our sample. Smartphone usage time during WASO was subjected to error as the phone usage may not have been by the smartphone owner, or the actual waking time could be misclassified as sleep by the ActiGraph (Kushida et al., 2001).

5 | CONCLUSIONS

Time spent on social network apps and games and comics apps in the daytime, social network apps at bedtime and web browsing apps during WASO was associated with total sleeping time. Time spent on social network apps, instant messaging apps and multimedia apps in the daytime was associated with the number of steps and MVPA among Hong Kong Chinese adolescents and young adults. All other types of smartphone usage were not associated with sleep quality and physical activity. The study design could not infer causality and further investigations on these effects employing experimental designs are warranted.

ACKNOWLEDGMENTS

The authors would like to thank Mr Ming Wong (Hong Kong Polytechnic University) for data collection and data management of the current study.

CONFLICT OF INTEREST

The authors declare that there are no known conflicts of interest associated with this publication.

AUTHOR CONTRIBUTIONS

PHL designed the study, obtained the funding, supervised the data collection, conducted the data analysis and drafted the manuscript. ACYT, CSTW and YWM supervised the data collection, managed the research assistants and critically reviewed the manuscript. UL provided critical feedback on data analysis and reviewed the manuscript. All the authors approved the final version of the manuscript.

DATA AVAILABILITY STATEMENT

The dataset(s) supporting the conclusions of this article is(are) available upon request.

ORCID

Paul H. Lee https://orcid.org/0000-0002-5729-6450
Andy C. Y. Tse https://orcid.org/0000-0002-6187-9499

REFERENCES

Amra, B., Shahsavari, A., Shayan-Moghadam, R., Mirheli, O., Moradi-Khaniabadi, B., Bazukar, M., Yadollahi-Farsani, A., & Kelishadi, R. (2017). The association of sleep and late-night cell phone use among adolescents. *Jornal De Pediatria*, *93*(6), 560–567. https://doi.org/10.1016/j.jped.2016.12.004

Benson, V. S., Pirie, K., Schuz, J., Reeves, G. K., Beral, V., Green, J., for the Million Women Study Collaborators (2013). Mobile phone use and risk of brain neoplasms and other cancers: Prospective study. *International Journal of Epidemiology*, *42*(3), 792–802. https://doi.org/10.1093/ije/dyt072

Bohmer, M., Hecht, B., Schoning, J., Kruger, A., & Bauer, G. (2011). *Falling asleep with Angry Birds, Facebook and Kindle – A large scale study on mobile application usage*. MobileHCI '11: Proceedings of the 13th International Conference on Human Computer Interaction with Mobile Devices and Services, Paper presented at the MobileHCI 2011, Stockholm, Sweden. 47–56,https://doi.org/10.1145/2037373.2037383

Cabré-Riera, A., Torrent, M., Donaire-Gonzalez, D., Vrijheid, M., Cardis, E., & Guxens, M. (2019). Telecommunication devices use, screen time and sleep in adolescents. *Environmental Research*, *171*, 341–347. https://doi.org/10.1016/j.envres.2018.10.036

Carroll, J. K., Moorhead, A., Bond, R., LeBlanc, W. G., Petrella, R. J., & Fiscella, K. (2017). Who uses mobile phone health apps and does use matter? A secondary data analytics approach. *Journal of Medical Internet Research*, *19*(4), e125. https://doi.org/10.2196/jmir.5604

Carter, B., Rees, P., Hale, L., Bhattacharjee, D., & Paradkar, M. (2016). Association between portable screen-based media device access or use and sleep outcomes: A systematic review and meta-analysis. *JAMA Pediatrics*, *170*(12), 1202–1208. https://doi.org/10.1001/jamapediatrics.2016.2341

Chittaranjan, G., Blom, J., & Gatica-Perez, D. (2013). Mining large-scale smartphone data for personality studies. *Personal and Ubiquitous Computing*, *17*(3), 433–450. https://doi.org/10.1007/s00779-011-0490-1

Cooper, C., Gross, A., Brinkman, C., Pope, R., Allen, K., Hastings, S., Bogen, B. E., & Goode, A. P. (2018). The impact of wearable motion sensing technology on physical activity in older adults. *Experimental Gerontology*, *112*, 9–19. https://doi.org/10.1016/j.exger.2018.08.002

Demirci, K., Akgönül, M., & Akpinar, A. (2015). Relationship of smartphone use severity with sleep quality, depression, and anxiety in university students. *Journal of Behavioral Addictions*, *4*(2), 85–92. https://doi.org/10.1556/2006.4.2015.010

Deng, T., Kanthawala, S., Meng, J., Peng, W., Kononova, A., Hao, Q., Zhang, Q., & David, P. (2019). Measuring smartphone usage and task switching with log tracking and self-reports. *Mobile Media Commun*, *7*(1), 3–23. https://doi.org/10.1177/2050157918761491

Do, T. M. T., Blom, J., & Gatica-Perez, D. (2011). *Smartphone usage in the wild: A large-scale analysis of applications and context*. ICMI '11: Proceedings of the 13th international conference on multimodal interfaces, Paper presented at the ICMI'11, Alicante, Spain. 353–360, https://doi.org/10.1145/2070481.2070550

Dunican, I. C., Martin, D. T., Halson, S. L., Reale, R. J., Dawson, B. T., Caldwell, J. A., Jones, M. J., & Eastwood, P. R. (2017). The effects of the removal of electronic devices for 48 hours on sleep in elite judo athletes. *Journal of Strength and Conditioning Research*, *31*(10), 2832–2839. https://doi.org/10.1519/JSC.0000000000001697

Dworak, M., Schierl, T., Bruns, T., & Struder, H. K. (2007). Impact of singular excessive computer game and television exposure on sleep patterns and memory performance of school-aged children. *Pediatrics*, *120*(5), 978–985. https://doi.org/10.1542/peds.2007-0476

Ernsting, C., Dombrowski, S. U., Oedekoven, M., O'Sullivan, J. L., Kanzler, M., Kuhlmey, A., & Gellert, P. (2017). Using smartphones and health apps to change and manage health behaviors: A population-based survey. *Journal of Medical Internet Research*, *19*(4), e101. https://doi.org/10.2196/jmir.6838

Exelmans, L., & Van den Bulck, J. (2016). Bedtime mobile phone use and sleep in adults. *Social Science and Medicine*, *148*, 93–101. https://doi.org/10.1016/j.socscimed.2015.11.037

Falaki, H., Mahajan, R., & Estrin, D. (2011). *SystemSens: A tool for monitoring usage in smartphone research deployments*. MobiArch '11: Proceedings of the sixth international workshop on MobiArch Paper presented at the MobiArch'11, Bethesda, Maryland, USA. 25–30, https://doi.org/10.1145/1999916.1999923

Falaki, H., Mahajan, R., Kandula, S., Lymberopoulos, D., Govindan, R., & Estrin, D. (2010). *Diversity in smartphone usage*. Paper presented at the MobiSys'10, San Francisco, California, USA.

Figueiro, M., & Overington, D. (2016). Self-luminous devices and melatonin suppression in adolescents. *Lighting Research & Technology*, *48*, 966–975. https://doi.org/10.1177/1477153515584979

Fobian, A. D., Avis, K., & Schwebel, D. C. (2016). The impact of media use on adolescent sleep efficiency. *Journal of Developmental and Behavioral Pediatrics*, *37*(1), 9–14. https://doi.org/10.1097/DBP.0000000000000239

HKSARG Department of Health (2015). *Health effects on use of internet and electronic screen products*. Retrieved from http://www.studenthealth.gov.hk/english/internet/health_effects.html

Shek, D. T. L., & Yu, L. (2016). Adolescent Internet Addiction in Hong Kong: Prevalence, Change, and Correlates. *J Pediatr Adolesc Gynecol 29* S22–S30.

Howe, K. B., Suharlim, C., Ueda, P., Howe, D., Kawachi, I., & Rimm, E. B. (2016). Gotta catch'em all! Pokémon GO and physical activity among young adults: Difference in differences study. *BMJ*, *355*, i6270. https://doi.org/10.1136/bmj.i6270

Hysing, M., Pallesen, S., Stormark, K. M., Jakobsen, R., Lundervold, A. J., & Sivertsen, B. (2015). Sleep and use of electronic devices in adolescence: Results from a large population-based study. *British Medical Journal Open*, *5*, e006748. https://doi.org/10.1136/bmjopen-2014-006748

John, D., Morton, A., Arguello, D., Lyden, K., & Bassett, D. (2018). "What is a step?" Differences in how a step is detected among three popular activity monitors that have impacted physical activity research. *Sensors*, *18*(4), 1206. https://doi.org/10.3390/s18041206

Kenney, E. L., & Gortmaker, S. L. (2017). United States adolescents' television, computer, videogame, smartphone, and tablet use: Associations with sugary drinks, sleep, physical activity, and obesity. *Journal of Pediatrics*, *182*, 144–149. https://doi.org/10.1016/j.jpeds.2016.11.015

Kushida, C., Chang, A., Gadkary, C., Guilleminault, C., Carrillo, O., & Dement, W. C. (2001). Comparison of actigraphic, polysomnographic, and subjective assessment of sleep parameters in sleep-disordered patients. *Sleep Medicine*, *2*(5), 389–396. https://doi.org/10.1016/S1389-9457(00)00098-8

Kwon, M., Kim, D. J., Cho, H., & Yang, S. (2013). The Smartphone Addiction Scale: Development and validation of a short version for adolescents. *PLoS One*, *8*(12), e83558. https://doi.org/10.1371/journal.pone.0083558

Lee, P. H., & Suen, L. K. P. (2017). The convergent validity of Actiwatch 2 and ActiGraph Link accelerometers in measuring total sleeping period, wake after sleep onset, and sleep efficiency in free-living condition. *Sleep Breath*, *21*(1), 209–215. https://doi.org/10.1007/s11325-016-1406-0

Lee, P. H., & Tse, A. C. Y. (2019). Calibration of Wrist-worn ActiWatch 2 and ActiGraph wGT3X for assessment of physical activity in young adults. *Gait & Posture*, *68*, 141–149. https://doi.org/10.1016/j.gaitpost.2018.11.023

Lee, U., Lee, J., Ko, M., Lee, C., Kim, Y., Yang, S., Yatani, K., Gweon, G., Chung, K.-M., & Song, J. (2014). *Hooked on smartphones: an exploratory study on smartphone overuse among college students. CHI '14: Proceedings of the SIGCHI Conference on Human Factors in Computing*. (2327–2336). https://doi.org/10.1145/2556288.2557366.

Lemola, S., Perkinson-Gloor, N., Brand, S., Dewald-Kaufmann, J. F., & Grob, A. (2015). Adolescents' electronic media use at night, sleep disturbance, and depressive symptoms in the smartphone age. *Journal of Youth and Adolescence*, *44*, 405–418. https://doi.org/10.1007/s10964-014-0176-x

Lepp, A., Barkley, J. E., Sanders, G. J., Rebold, M., & Gates, P. (2013). The relationship between cell phone use, physical and sedentary activity, and cardiorespiratory fitness in a sample of U.S. college students. *International Journal of Behavioral Nutrition and Physical Activity*, *10*, 79. https://doi.org/10.1186/1479-5868-10-79

Mashable (2013). *The 15 countries with the highest smartphone penetration*. Retrieved from https://mashable.com/2013/08/27/global-smartphone-penetration/

Mireku, M. O., Barker, M. M., Mutz, J., Dumontheil, I., Thomas, M. S. C., Röösli, M., Elliott, P., & Toledano, M. B. (2019). Night-time screen-based media device use and adolescents' sleep and health-related quality of life. *Environment International*, *124*, 66–78. https://doi.org/10.1016/j.envint.2018.11.069

Moran, M. (2003). Arguments for rejecting the sequential Bonferroni in ecological studies. *Oikos*, *100*(2), 403–405. https://doi.org/10.1034/j.1600-0706.2003.12010.x

Murdock, K. K., Horissian, M., & Crichlow-Ball, C. (2016). Emerging adults' text message use and sleep characteristics: A multimethod, naturalistic study. *Behavioral Sleep Medicine*, *15*(3), 228–241.

Nursalam, N., Octavia, M., Tristiana, R. D., & Efendi, F. (2019). Association between insomnia and social network site use in Indonesian adolescents. *Nursing Forum*, *54*, 149–156. https://doi.org/10.1111/nuf.12308

Pew Research Center (2015). *Mobile technology fact sheet*. Retrieved from http://www.pewinternet.org/fact-sheets/mobile-technology-fact-sheet/

Pfitzner, R., Gorzelniak, L., Heinrich, J., Von Berg, A., Klumper, C., Bauer, C. P., Koletzko, S., Berdel, D., Horsch, A., Schulz, H., & GINIPlus Study Group (2013). Physical activity in German adolescents measured by accelerometry and activity diary: Introducing a comprehensive approach for data management and preliminary results. *PLoS One*, *8*(6), e65192. https://doi.org/10.1371/journal.pone.0065192

Przybylski, A. K. (2019). Digital screen time and pediatric sleep: Evidence from a preregistered cohort study. *Journal of Pediatrics*, *205*, 218–223. https://doi.org/10.1016/j.jpeds.2018.09.054

Punamaki, R.-L., Wallenius, M., Nygard, C.-H., Saarni, L., & Rimpela, A. (2007). Use of information and communication technology (ICT) and perceived health in adolescence: The role of sleeping habits and waking-time tiredness. *J Adolescence*, *30*(4), 569–585. https://doi.org/10.1016/j.adolescence.2006.07.004

Ryde, G. C., Gilson, N. D., Suppini, A., & Brown, W. J. (2012). Validation of a novel, objective measure of occupational sitting. *Journal of Occupational Health*, *54*, 383–386. https://doi.org/10.1539/joh.12-0091-BR

Sadeh, A., Sharkey, K. M., & Carskadon, M. A. (1994). Activity-based sleep-wake identification: An empirical test of methodological issues. *Sleep*, *17*(3), 201–207. https://doi.org/10.1093/sleep/17.3.201

Shye, A., Scholbrock, B., Memik, G., & Dinda, P. A. (2010). *Characterizing and modeling user activity on smartphones: Summary*. ACM SIGMETRICS Performance Evaluation Review. Paper presented at the SIGMETRICS'10, New York, USA. https://doi.org/10.1145/1811099.1811094.

Soikkeli, T., Karikoski, J., & Hammainen, H. (2011). *Diversity and end user context in smartphone usage sessions*. Paper presented at the Fifth International Conference on Next Generation Mobile Applications and Services. https://doi.org/10.1109/NGMAST.2011.12

Statistista (2015). *Number of smartphone users worldwide from 2014 to 2020 (in billions)*. Retrieved from http://www.statista.com/statistics/330695/number-of-smartphone-users-worldwide/

Toon, E., Davey, M. J., Hollis, S. L., Nixon, G. M., Horne, R. S. C., & Biggs, S. N. (2016). Comparison of commercial wrist-based and smartphone accelerometers, actigraphy, and PSG in a clinical cohort of children and adolescents. *Journal of Clinical Sleep Medicine*, *12*(3), 343–350. https://doi.org/10.5664/jcsm.5580

Twenge, J. M., Hisler, G. C., & Krizan, Z. (2019). Associations between screen time and sleep duration are primarily driven by portable electronic devices: Evidence from a population-based study of U.S. children ages 0–17. *Sleep Medicine*, *56*, 211–218.

Vanhelst, J., Béghin, L., Drumez, E., Coopman, S., & Gottrand, F. (2017). Awareness of wearing an accelerometer does not affect physical activity in youth. *BMC Medical Research Methodology*, *17*, 99. https://doi.org/10.1186/s12874-017-0378-5

Wang, P. Y., Chen, K. L., Yang, S. Y., & Lin, P. H. (2019). Relationship of sleep quality, smartphone dependence, and health-related behaviors in female junior college students. *PLoS One*, *14*(4), e0214769. https://doi.org/10.1371/journal.pone.0214769

Wong, F. Y. (2017). Influence of Pokémon Go on physical activity levels of university players: A cross-sectional study. *International Journal of Health Geographics*, *16*, 8.

Wood, B., Rea, M. S., Plitnick, B., & Figueiro, M. G. (2013). Light level and duration of exposure determine the impact of self-luminous tablets on melatonin suppression. *Applied Ergonomics*, *44*(2), 237–240. https://doi.org/10.1016/j.apergo.2012.07.008

Woods, H. C., & Scott, H. (2016). #Sleepyteens: Social media use in adolescence is associated with poor sleep quality, anxiety, depression and low self-esteem. *Journal of Adolescence*, *51*, 41–49. https://doi.org/10.1016/j.adolescence.2016.05.008

Yland, J., Guan, S., Emanuele, E., & Hale, L. (2015). Interactive vs passive screen time and nighttime sleep duration among school-aged children. *Sleep Health*, *1*, 191–196. https://doi.org/10.1016/j.sleh.2015.06.007

SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section.

How to cite this article: Lee PH, Tse ACY, Wu CST, Mak YW, Lee U. Temporal association between objectively measured smartphone usage, sleep quality and physical activity among Chinese adolescents and young adults. *J Sleep Res*. 2021;30:e13213. https://doi.org/10.1111/jsr.13213