Crowdsourced smartphone data reveal altered sleep/wake pattern in quarantined Chinese during the COVID-19 outbreak

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Abstract

The Chinese Government quarantined Wuhan on 23rd January 2020 and thereafter the Hubei province, affecting a total of 59 million citizens, to cease the spread of the coronavirus disease in 2019 (COVID-19). The effects of this lockdown on the psychological and mental health of both the affected and unaffected Chinese are largely unknown currently. We utilized one of the largest crowdsourced databases (Sleep as Android) that consisted of 15,681 sleep records from 563 users in China to estimate the change in the sleep pattern of Chinese users during the span of 30th December 2019 to 8th March 2020 with reference to 64,378 sleep records of 1,628 users for the same calendar period of years 2011-2019. The sleep pattern in China changed drastically after 23rd January 2020 when the law of quarantine and suspension of Wuhan became effective. The two major findings are: (1) Chinese people increased their sleep duration by an average of 20 min and delayed their sleep onset by an average of 30 min weekdays, while they maintained a similar sleep duration weekends, and (2) larger changes were found in several subgroups, including those in Wuhan (80 sleep records from 3 users), female subjects, and those aged ≤ 24 years. Overall, Chinese people slept later and longer than usual during the COVID-19 pandemic quarantine.

Keywords: COVID-19 pandemic confinement; Altered sleep duration and pattern, Wuhan China; Sleep as Android App; Crowdsourcing

INTRODUCTION

The outbreak of the new coronavirus disease in 2019 (COVID-19) quickly became pandemic. Since its first confirmed case on 17th November 2019 (Zhao et al. 2020), the number of cases quickly increased to 10,586,381 by 1st July 2020. The Chinese Government implemented several policies and restrictions to cease the spread of the virus and to maximize the social distance between people. One of the heaviest restrictions, announced the night of 22nd January 2020, was that Wuhan, the documented origin of the COVID-19 pandemic in China, would be quarantined and all public transport connecting Wuhan would be suspended on next day, January 23rd. The restrictions were rapidly implemented thereafter in all 15 cities in Hubei province by 29th January 2020, affecting a total of 59 million citizens, thereby constituting the largest lockdown recorded in human history (Reuters 2020). While previous studies (Hawryluck et al. 2004; Johal 2009) well-document the impact of infectious disease outbreaks on psychological and mental health, most of them involved the severe acute respiratory syndrome (SARS) outbreak in 2003 for which the scale of disease outbreak was smaller than that of COVID-19.

Herein we utilize one of the largest crowdsourced databases of sleep records obtained from Sleep as Android app (methodological details of the app provided in the Methods section below) to obtain insights on how the government-mandated COVID-19 quarantine affected people’s sleep pattern. This app was launched in 2011, and data collection has been continuous thereafter; thus, its database allows us to examine changes in sleep pattern during the COVID-19 outbreak with reference to sleep records before the outbreak.

MATERIAL AND METHODS

Sleep as Android

The Sleep as Android smartphone application (https://sleep.urbandroid.org/) is developed for the Android operating system as a smart alarm clock that awakens the user according to his/her sleep cycle. Sleep onset time can be identified using two methods, i.e., manual assignment and objective detection. Nearly all (99.6%) of the users selected the first method, by which sleep onset was defined as the moment when the "start sleep tracking" button was pressed in the app. The remaining 0.4% of users used the automatic sleep tracking function that detects sleep onset of users via different sources, including external wearable wristbands, the built-in accelerometer in the smartphone, sleep sounds such as snores, and contactless ultrasonic tracking (Chaudhry 2017). The awake time was defined as the moment when the person terminated the tracking manually, interacted with the phone, talked near the phone, and detected by the app or the light sensor of the phone, >60 lux after the sunset time of the geographical location. This research conforms to international ethical standards (Portaluppi et al. 2010). The app has accumulated more than 300,000 reviews in Google Play and is one of the most reviewed and highest rated apps for sleep analysis (Ong and Gillespie 2016; Choi et al. 2018).

Data retrieval

Data of only users who agreed to share information were retrieved. Sleep as Android began to collect data in 2010; however, the sample size then was small; therefore, we decided to analyze the sleep data of 1st January 2011 until 8th March 2020, when the diagnosis of new cases of COVID-19 in China had become stable (reduced to 45 new cases). A total of 33,786,868 sleep records (hereby denoted as n_s) from 141,509 users (hereby denoted as n_u) were retrieved. Variables available in the dataset including the date of the sleep records, sleep duration (calculated by the difference between sleep onset time and awake time), sleep onset time, self-rating of sleep quality (from 1 to 5 in 0.25 steps), and time zone obtained from the smartphone's system. Geographical coordinates, age, and sex were also collected but were available only for some sleep records.

Data processing

Outliers of sleep duration were removed from the analysis. These included sleep duration of <3h or >13h, and sleep onset time between 06:00 and 18:00h. Furthermore, we treated all sleep records with sleep onset time between 00:00 and 06:00h as sleep that occurring the previous day (for example, sleep onset at 2 January 01:00h was treated as sleep occurring on 1 January).

Our analysis of sleep records during the COVID-19 pandemic started on 30 December 2019 (the day when Dr. Li Wanliang, the whistleblower of COVID-19, who shared the warnings about the outbreak through WeChat). All sleep records from China, classified as time zones of Asia/Chongqing, Asia/Chungking, Asia/Harbin, Asia/Hong_Kong, Asia/Macao, Asia/Macau, Asia/Shanghai, and Asia/Taipei, were included. Similar to a previous report using data from Sleep as Android, the system time zone, instead of geographical coordinates, was used to classify user location due to missing data (Anýž et al. 2019). A total of 15,681 sleep records from 563 users were available for analysis.

Sleep records for users in China during the COVID-19 pandemic quarantine period were compared with the following three sleep records, namely: (1) users in China before the COVID-19 pandemic (n_s =121,846 sleep records from n_u=2,265 users), (2) users outside of China during the COVID-19 pandemic (n_s=1,125,188 sleep records of n_u=30,904 users), and (3) users outside of China before the COVID-19 pandemic (n_s=8,235,073 sleep records of n_u=98,843 users). In total, our data analysis comprised n_s=9,497,788 sleep records of n_u=102,839 users, corresponding to a valid sleep record rate of 28.1%. Among them, rating of sleep quality was available in n_s =3,252,861 sleep records of n_s = 63,969 users.

Statistical analysis

Three sleep parameters, i.e., sleep duration, sleep onset time, and subjective sleep quality, were analyzed in the current study. For comparison, we also computed the expected value of these variables using linear regression, controlling for time zone, the month of the record, and day of the record (S/M/T/W/T/F/S). These variables were associated with sleep patterns in crowdsourcing sleep data (Walch et al. 2016; Anýž et al. 2019). Deviations between the actual and expected sleep parameters, as well as the standard error of these deviations, were produced in regression analysis. The SPSS version 25 (IBM Corp. Released 2017. IBM SPSS Statistics for Windows, Version 25.0. Armonk, NY: IBM Corp.) was used to conduct the data analysis.

We analyzed the above-stated three sleep parameters before (30th December until the 8th March for the years 2011 to 2019, n_s=64,378 sleep records) and during the COVID-19 outbreak from 30 December 2019 to 8 March 2020 (n_s=15,681 sleep records). Additional subgroup analyses were performed to analyze sleep patterns of the following subgroups: Wuhan, the city identified as the origin of the COVID-19 pandemic, versus outside Wuhan (n_s=8,911 who provided consent to allow access to the smartphone-measured geographical location with distance from the Wuhan Hankou Railway Station calculated using the haversine formula (Inman 1948), n_u=331), sex (n_s=4,456, n_u=143), and age groups (n_s=4,370 subjects who provided their date of birth, n_u=143). All group differences were examined with the t-test and generalized estimating equation (GEE) that adjusted for within-subject correlation.

RESULTS

Figure 1 shows the sleep duration of subjects in China. Before the COVID-19 outbreak, the actual and expected sleep duration, respectively, was in the range of 410 to 430 min per night except for the dates of 9th, 28th, and 29th of February (Figure 1A). During the COVID-19 outbreak, the sleep duration pattern differed according to the quarantine and suspension of Wuhan, which was announced on the night of 22nd January 2010 and became effective at 10:00h of 23rd January (Figure 1B). The actual and expected sleep duration coincided before 23 January, while the sleep duration positively deviated from the expected duration afterwards. The actual sleep duration after 23rd January was ~420 to 430 min per night weekdays and ~450 to 460 min per night weekends. Deviation from the expected duration was largest on the 26th and 27th of January 2020 (47 and 46 min, respectively, both p <0.001, Figure 1C), which was the second and third day of the Chinese Lunar New year. Deviations per other weekday and weekend nights ranged from 15 to 30 min and 0 to 10 min per night, respectively. Overall, the expected weekday-weekend difference in sleep duration was reduced during the COVID-19 outbreak. As a reference, deviations of sleep duration before the COVID-19 outbreak were all within 10 min. Graphs of the sleep duration of subjects outside China are found in the online supplementary material (Figure S1).

Figure 2 shows the sleep onset time of subjects in China. Before the COVID-19 outbreak, the actual and expected sleep onset was in the range of 01:00 to 01:10h, except 31st December, 28th February, and 29th February (Figure 2A). Similar to the change in the pattern of sleep duration during the COVID-19 outbreak, sleep onset also differed after 23rd January. The sleep onset time on weekdays was delayed from 01:00 to 01:20-01:30h (Figure 2A). The average deviations of sleep onset time on weekdays and weekends after 23rd January were ~30 min and -5 min, respectively (Figure 2C). Similar to the pattern found for sleep duration, the expected weekday-weekend difference of sleep onset time was also reduced during the COVID-19 quarantine. Graphs of the sleep onset time of subjects outside China are found in the online supplementary material (Figure S2).

Figure 3 shows the sleep rating of subjects in China. No special pattern was found both before and during the COVID-19 outbreak, except that the actual rating on 24th January 2020 was slower than the expected one, which is of near statistical significance, i.e., p= 0.06 (Figure 3C).

Three subgroup analyses were conducted on the sleep records of Chinese residents during the COVID-19 outbreak that were complete for relevant data (location, sex, and age). First, we compared the sleep pattern of subjects in Wuhan (n_s=80, n_u=3) versus other locations in China outside Wuhan (n_s=8,831, n_u=328). Figures S4 and S5 show the sleep duration and sleep onset time of the Chinese according to the location of residence. The majority of the records were from people located in the largest cities of China, such as Beijing, Shanghai, Chongqing, Shenzhen, Guangzhou, Hong Kong, and Taipei. The comparison of the change in sleep duration and sleep onset by location in China is reported in Table 1. The records of Chinese who resided outside Wuhan indicate sleep duration increased during the pandemic period by 11 min (t-test $p < 0.001$, GEE-adjusted $p = 0.001$) weekdays after 23rd January 2020. The records of the Chinese who resided in Wuhan indicated sleep duration before 23rd January 2020 was about 8 h 40 min and was reduced during confinement to 7 h 46 min. Change in sleep onset was found in the sleep records of Wuhan residents weekdays; it was 39 min earlier during confinement (t-test $p = 0.08$, GEE-adjusted $p < 0.001$). To summarize, during the COVID-19 outbreak, sleep duration weekdays and weekends for those residing in Wuhan did not differ, while the weekday-weekend difference in sleep duration was reduced for those residing outside of Wuhan.

The second subgroup analysis compared the gender difference in the change of sleep pattern (n_s=4,456, n_u=143). Table 2 shows only the sleep duration of males was affected (increased 11 min, p=0.002). In addition, males showed small, while females showed large changes in sleep onset time, in particular, during weekends, when sleep commenced on average 37 min earlier than expected (p=0.03). To conclude, females experienced a larger change than their male counterparts in sleep pattern during the COVID-19 outbreak.

The third subgroup analysis compared the change in sleep pattern by age group (n_s=4,370, n_u=143). The largest deviation from expected sleep duration was in those aged ≤ 24 y (Table 3). Persons of this age group lengthened their sleep duration by 19 min weekdays and delayed their sleep onset by 34 min weekends. Those aged ≥ 25 showed little change in sleep duration during the COVID-19 outbreak; although, those aged 45-54 increased their sleep duration by 25 min on weekdays (p=0.02) In terms of sleep onset time, no change was found weekdays and some changes were found on weekends. Those aged ≤ 24 y slept ~34 min later (p=0.005), while those aged 45-54 y delayed their sleep onset for 1 h 18 min (p<0.001).

DISCUSSION

We examined the sleep pattern in China during the COVID-19 outbreak using crowdsourced smartphone-measured sleep data (Sleep as Android) of nearly one million records of more than a hundred thousand subjects. We found the sleep pattern in China changed drastically after 23rd January 2020 when the law of quarantine and suspension of Wuhan became effective. First, Chinese people increased their sleep duration by an average of 20 min and delayed their sleep onset by an average of 30 min weekdays, while they maintained a similar sleep duration weekends. Second, larger changes were found in certain subgroups, including those who resided in Wuhan, female subjects, and those aged ≤ 24 y. At the time of quarantine, all employees were required to work from home except those who had to work at their office, such as healthcare professionals or police. This mode of work might be the main driver of this change in sleep pattern, since those under quarantine were not required to work at scheduled hours, and such a change in work mode increased the proportion of healthy sleep duration, i.e., 7 to 9 h per day (Wang S et al. 2017; Sun et al. 2018), from 40.3% to 44.6%. This change was a short-term one, and the long-term impact on future sleep patterns and mental health warrant investigation.

The advantages of using crowdsourced data are large sample size, representation of participants from all regions of the world, and ease of participation. Also, with a large number of sleep records before the COVID-19 outbreak both in and outside China, we were able to estimate the expected sleep pattern during the non-outbreak period, thus determining the change in sleep pattern during the quarantine of the COVID-19 outbreak. This evaluation is difficult to accomplish using a traditional longitudinal design, since the sleep patterns before and during the outbreak have to be both measured (Robbins et al. 2020).

A major limitation of our study is the unknown measurement error of the Sleep as Android app. The first source of measurement error is the measurement of sleep onset time, because the delay between the time of pressing the "start sleep tracking" button and exact sleep onset was not measurable. The second source of measurement error is the calibration algorithm of the subjective sleep onset and awake detections. The sensitivity of such detections varies across smartphone devices and with certain environmental factors (Robbins et al. 2020), and it is almost impossible to be adjusted for in this large-scale study. Another major limitation is the composition of our sample. Given the large amount of missing data for variables of location, age, and sex, the representativeness of our sample in terms of age-sex and population-location distributions could not be evaluated. Also, is likely users of the Sleep as Android app are younger and wealthier than the non-users (Krebs and Duncan 2015). Furthermore, information specific to emerging research questions could not be implemented in the smartphone system, and some important variables were missed. Moreover, the impact of the disease outbreak on sleep patterns and mental health problems of the healthcare workers, patients, and the general population are expected to be different (Bai et al. 2004; Chua et al. 2004; Maunder 2004; McAlonan et al. 2007; Wang C et al. 2020), but we were unable to identify the job of the subjects whose sleep records were analyzed.

An online survey conducted in China between 31st January and 2nd February 2020 showed the general public were suffering from various types of psychological conditions, including depression, anxiety, and stress (Wang C et al. 2020). The results of the present study additionally indicate the general public in China also experienced change in sleep pattern. It is well-known that change in sleep habits and quantity is linked to mental health problems (Wang S et al. 2017), and Chinese under the quarantine and suspension were concurrently experiencing increase in sleep duration and mental health problems. It is worth investigating the concurrent role in the same cohort of persons both alterations in sleep habits and mental health status.

Large-scale studies revealed that sleep patterns can be affected by national events. A previous study using the same source of data as the current study (Sleep as Android) found sleep duration was reduced the night immediate following national events, such as Brexit vote and US presidential election (Anýž et al. 2019). Sleep duration was reduced because people might have spent some of the span typically devoted to sleep time on other activities, e.g., social media and news. Similarly, information on COVID-19 is also spreading as fast as the virus, itself, with an estimated basic reproduction number R_0 of 3.4 on YouTube and 4.6 on

Twitter (Cinelli et al. 2020). It is believed that such rapid spread of news leads to fear (Chiolero 2020) and reduces sleep duration; however, our results do not support this postulation.

Other countries of the world besides China are also experiencing the outbreak of COVID-19, including the Republic of Korea (or South Korea), Iran, Italy, Spain, and USA. The change of sleep pattern reported among Chinese as found in this study may or may not be generalizable to other populations. Although citizens in these regions outside of China shared similar lockdown policies and fear of infection, China is regarded as the origin of the transmission of COVID-19 and the stigma on Chinese has been common worldwide. Studies on the sleep pattern in quarantined residents of all affected countries should also be conducted.

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CONFLICT OF INTERESTS: None declared.

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FIGRE CAPTION

Figure 1. (A) Actual and expected sleep duration in China before the COVID-19 outbreak, using sleep records of the Sleep as Android app for years 2011 – 2019. Solid line represents the daily means of actual sleep duration during the span of 30 Dec – 8 Mar for years 2011 – 2019, and dotted line represents the daily means of expected sleep duration estimated using regression controlling for time zone, month of record, and day of record (S/M/T/W/T/F/S). (B) Actual and expected sleep duration in China during COVID-19 outbreak, 30 Dec 2019 – 8 Mar 2020. Solid line represents the daily means of actual sleep duration for 30 Dec 2019 – 8 Mar 2020, and dotted line represents the daily means of expected sleep duration. (C) Deviation from the expected sleep duration in China before and after COVID-19 outbreak. Deviation from expected sleep duration per given day is defined as difference between actual and expected sleep duration. Error bars represent the 95% confidence interval of the deviation.

Figure 2. (A) Sleep onset in China before COVID-19 outbreak, using sleep records of the Sleep as Android app for years 2011 – 2019. Solid line represents daily means of actual sleep onset for 30 Dec – 8 Mar of years 2011 – 2019, and dotted line represents daily means of expected sleep onset estimated using regression controlling for time zone, month of record, and day of record (S/M/T/W/T/F/S). (B) Actual and expected sleep onset in China during COVID-19 outbreak, 30 Dec 2019 – 8 Mar 2020. Solid line represents daily means of actual sleep onset for 30 Dec 2019 – 8 Mar 2020, and dotted line represents daily means of expected sleep onset. (C) Deviation from expected sleep onset in China before and after COVID-19 outbreak. Deviation from expected sleep onset per given day is defined as difference between actual and expected sleep onset. Error bars represent the 95% confidence interval of the deviation.

Figure 3. (A) Sleep rating in China before COVID-19 outbreak, using sleep records of Sleep as Android app for years 2011 – 2019. Solid line represents daily means of actual sleep rating 30 Dec – 8 Mar for years 2011 – 2019, and dotted line represents daily means of expected sleep

onset estimated using regression controlling for time zone, month of record, and day of record (S/M/T/W/T/F/S). (B) Actual and expected sleep onset in China during COVID-19 outbreak, 30 Dec 2019 – 8 Mar 2020. Solid line represents daily means of actual sleep onset for the period of 30 Dec 2019 – 8 Mar 2020, and dotted line represents daily means of expected sleep onset. (C) Deviation from expected sleep onset in China before and after COVID-19 outbreak. Deviation from expected sleep onset per given day was defined as difference between actual and expected sleep onset. Error bars represent the 95% confidence interval of the deviation.


A
Sleep duration in China before the COVID-19 outbreak
Actual sleep duration
Expected sleep duration
Sleep duration (min)
400
410
420
430
440
450
460
470
Date
B
Sleep duration in China during the COVID-19 outbreak
Actual sleep duration
Expected sleep duration
Sleep duration (min)
400
410
420
430
440
450
460
470
Date
C
Sleep duration in China before and after the COVID-19 outbreak
Before the COVID-19 outbreak (Year 2011-2019)
During the COVID-19 outbreak (30 Dec 2019 - 8 Mar 2020)
Deviation from the expected sleep duration (min)
-40
-20
0
20
40
60
Date


A
Sleep onset in China before the COVID-19 outbreak
Actual sleep onset
Expected sleep onset
Sleep onset (hh:mm)
Date
B
Sleep onset in China during the COVID-19 outbreak
Actual sleep onset
Expected sleep onset
Sleep onset (hh:mm)
Date
C
Sleep onset in China before and after the COVID-19 outbreak
Before the COVID-19 outbreak (Year 2011-2019)
During the COVID-19 outbreak (30 Dec 2019 - 8 Mar 2020)
Deviation from the expected sleep onset (hh:mm)
Date


A
Sleep rating in China before the COVID-19 outbreak
Actual sleep rating
Expected sleep rating
Sleep rating
3.4
3.3
3.2
3.1
3.0
2.9
12-30 12-31 1-1 1-2 1-3 1-4 1-5 1-6 1-7 1-8 1-9 1-10 1-11 1-12 1-13 1-14 1-15 1-16 1-17 1-18 1-19 1-20 1-21 1-22 1-23 1-24 1-25 1-26 1-27 1-28 1-29 1-30 1-31 2-1 2-2 2-3 2-4 2-5 2-6 2-7 2-8 2-9 2-10 2-11 2-12 2-13 2-14 2-15 2-16 2-17 2-18 2-19 2-20 2-21 2-22 2-23 2-24 2-25 2-26 2-27 2-28 2-29 3-1 3-2 3-3 3-4 3-5 3-6 3-7 3-8
Date
B
Sleep rating in China during the COVID-19 outbreak
Actual sleep rating
Expected sleep rating
Sleep rating
3.4
3.3
3.2
3.1
3.0
2.9
12-30 12-31 1-1 1-2 1-3 1-4 1-5 1-6 1-7 1-8 1-9 1-10 1-11 1-12 1-13 1-14 1-15 1-16 1-17 1-18 1-19 1-20 1-21 1-22 1-23 1-24 1-25 1-26 1-27 1-28 1-29 1-30 1-31 2-1 2-2 2-3 2-4 2-5 2-6 2-7 2-8 2-9 2-10 2-11 2-12 2-13 2-14 2-15 2-16 2-17 2-18 2-19 2-20 2-21 2-22 2-23 2-24 2-25 2-26 2-27 2-28 2-29 3-1 3-2 3-3 3-4 3-5 3-6 3-7 3-8
Date
C
Sleep rating in China before and after the COVID-19 outbreak
Before the COVID-19 outbreak (Year 2011-2019)
During the COVID-19 outbreak (30 Dec 2019 - 8 Mar 2020)
Deviation from the expected sleep rating
0.5
0.0
-0.5
12-30 12-31 1-1 1-2 1-3 1-4 1-5 1-6 1-7 1-8 1-9 1-10 1-11 1-12 1-13 1-14 1-15 1-16 1-17 1-18 1-19 1-20 1-21 1-22 1-23 1-24 1-25 1-26 1-27 1-28 1-29 1-30 1-31 2-1 2-2 2-3 2-4 2-5 2-6 2-7 2-8 2-9 2-10 2-11 2-12 2-13 2-14 2-15 2-16 2-17 2-18 2-19 2-20 2-21 2-22 2-23 2-24 2-25 2-26 2-27 2-28 2-29 3-1 3-2 3-3 3-4 3-5 3-6 3-7 3-8
Date

Table 1. Comparison of the change in sleep duration and sleep onset before suspension of Wuhan by location in China (n_s=8,911, n_u=331)

		Sleep duration (SD)			Sleep onset (SD)		
Location[1]	Weekday/Weekend	Before suspension (30 Dec 2019 to 22 Jan 2020)	After suspension (23 Jan 2020 to 8 March 2020)	Difference (p-value)	Before suspension (30 Dec 2019 to 22 Jan 2020)	After suspension (23 Jan 2020 to 8 March 2020)	Difference (p-value)
Outside Wuhan	Weekday	6h 54m (1h 28m) (n_s=2,555, n_u=290)	7h 5m (1h 28m) (n_s=3,982, n_u=245)	11m (t-test: <0.001; GEE-adjusted: 0.001)	01:11 (1h 50m) (n_s=2,555, n_u=290)	01:15 (1h 50m) (n_s=3,982, n_u=245)	4m (t-test: <0.001; GEE-adjusted: 0.002)
	Weekend	7h 18m (1h 39m) (n_s=797, n_u=202)	7h 27m (1h 34m) (n_s=1,497, n_u=198)	9m (0.04; GEE-adjusted: 0.053)	01:27 (1h 51m) (n_s=797, n_u=202)	01:34 (1h 51m) (n_s=1,497, n_u=198)	7m (t-test: 0.18; GEE-adjusted: 0.26)
Wuhan	Weekday	8h 44m (1h 44m) (n_s=25, n_u=3)	7h 47m (55m) (n_s=33, n_u=1)	-57m (t-test: 0.009; GEE-adjusted: <0.001)	01:09 (1h 26m) (n_s=25, n_u=3)	00:30 (1h 18m) (n_s=33, n_u=1)	-39m (t-test: 0.08; GEE-adjusted: <0.001)
	Weekend	8h 41m (1h 16m) (n_s=8, n_u=3)	7h 46m (56m) (n_s=14, n_u=1)	-55m (t-test: 0.07; GEE-adjusted: <0.001)	00:23 (50m) (n_s=8, n_u=3)	00:27 (1h 47m) (n_s=14, n_u=4)	4m (t-test: 0.92; GEE-adjusted: 0.82)

[1] A sleep record was defined as located in Wuhan if the geographical distance between the smartphone and Wuhan Hankou Railway Station was within 50km

n_s and n_u denote the number of sleep records and number of users, respectively

Table 2. Comparison of the change in sleep duration and sleep onset before suspension of Wuhan by male and female subjects in China (n_s=4,456, n_u=143)

		Sleep duration (SD)			Sleep onset (SD)		
Sex	Weekday/Weekend	Before suspension (30 Dec 2019 to 22 Jan 2020)	After suspension (23 Jan 2020 to 8 March 2020)	Difference (p-value)	Before suspension (30 Dec 2019 to 22 Jan 2020)	After suspension (23 Jan 2020 to 8 March 2020)	Difference (p-value)
Male	Weekday	6h 48m (1h 31m) (n_s=1,130, n_u=115)	6h 59m (1h 30m) (n_s=1,830, n_u=98)	11m (t-test: 0.002; GEE-adjusted: 0.01)	01:03 (1h 50m) (n_s=1,130, n_u=115)	01:12 (1h 45m) (n_s=1,830, n_u=98)	9m (t-test: 0.04; GEE-adjusted: 0.13)
	Weekend	7h 17m (1h 39m) (n_s=359, n_u=83)	7h 22m (1h 39m) (n_s=699, n_u=88)	5m (t-test: 0.41; GEE-adjusted: 0.35)	01:09 (1h 51m) (n_s=359, n_u=83)	01:35 (1h 56m) (n_s=699, n_u=88)	26m (t-test: <0.001; GEE-adjusted: 0.002)
Female	Weekday	7h 6m (1h 43m) (n_s=141, n_u=14)	7h 5m (1h 25m) (n_s=183, n_u=13)	-1m (t-test: 0.90; GEE-adjusted: 0.92)	01:13 (1h 35m) (n_s=141, n_u=14)	01:32 (1h 15m) (n_s=183, n_u=13)	19m (t-test: 0.049; GEE-adjusted: 0.26)
	Weekend	7h 54m (1h 48m) (n_s=43, n_u=8)	7h 38m (1h 58m) (n_s=71, n_u=8)	-16m (t-test: 0.48; GEE-adjusted: 0.29)	01:30 (1h 28m) (n_s=43, n_u=8)	02:07 (1h 25m) (n_s=71, n_u=8)	37m (t-test: 0.03; GEE-adjusted: 0.009)

n_s and n_u denote the number of sleep records and number of users, respectively

Table 3. Comparison of the change in sleep duration and sleep onset before suspension of Wuhan by age groups in China (n_s=4,370, n_u=143)

		Sleep duration (SD)			Sleep onset (SD)		
Sex	Weekday/Weekend	Before suspension (30 Dec 2019 to 22 Jan 2020)	After suspension (23 Jan 2020 to 8 March 2020)	Difference (p-value)	Before suspension (30 Dec 2019 to 22 Jan 2020)	After suspension (23 Jan 2020 to 8 March 2020)	Difference (p-value)
24 or below	Weekday	7h 15m (1h 32m) (n_s=263, n_u=31)	7h 34m (1h 29m) (n_s=412, n_u=24)	19m (t-test: 0.007; GEE-adjusted: 0.01)	01:14 (1h 42m) (n_s=263, n_u=31)	01:30 (1h 29m) (n_s=412, n_u=24)	16m (t-test: 0.04; GEE-adjusted: 0.25)
	Weekend	7h 46m (1h 49m) (n_s=85, n_u=19)	7h 54m (1h 41m) (n_s=158, n_u=19)	8m (t-test: 0.57; GEE-adjusted: 0.51)	01:22 (1h 49m) (n_s=85, n_u=19)	01:56 (1h 21m) (n_s=158, n_u=19)	34m (t-test: 0.005; GEE-adjusted: 0.004)
25-34	Weekday	6h 52m (1h 36m) (n_s=330, n_u=39)	6h 59m (1h 36m) (n_s=505, n_u=34)	7m (t-test: 0.28; GEE-adjusted: 0.35)	00:52 (1h 43m) (n_s=330, n_u=39)	00:59 (1h 50m) (n_s=505, n_u=34)	7m (t-test: 0.40; GEE-adjusted: 0.62)
	Weekend	7h 10m (1h 43m) (n_s=103, n_u=26)	7h 23m (1h 39m) (n_s=192, n_u=27)	13m (t-test: 0.27; GEE-adjusted: 0.22)	00:57 (1h 42m) (n_s=103, n_u=26)	01:05 (1h 50m) (n_s=192, n_u=27)	8m (t-test: 0.56; GEE-adjusted: 0.63)
35-44	Weekday	6h 44m (1h 29m) (n_s=508, n_u=42)	6h 51m (1h 27m) (n_s=799, n_u=40)	7m (t-test: 0.18; GEE-adjusted: 0.26)	01:09 (1h 52m) (n_s=508, n_u=42)	01:15 (1h 49m) (n_s=799, n_u=40)	6m (t-test: 0.32; GEE-adjusted: 0.39)
	Weekend	7h 23m (1h 45m) (n_s=153, n_u=34)	7h 23m (1h 43m) (n_s=297, n_u=37)	0m (t-test: 0.999; GEE-adjusted: 0.998)	01:24 (1h 44m) (n_s=153, n_u=34)	01:44 (1h 49m) (n_s=297, n_u=37)	20m (t-test: 0.07; GEE-adjusted: 0.09)
45-54	Weekday	6h 6m (1h 33m) (n_s=108, n_u=15)	6h 31m (1h 26m) (n_s=188, n_u=8)	25m (t-test: 0.02; GEE-adjusted: 0.08)	00:58 (2h 5m) (n_s=108, n_u=15)	01:11 (1h 29m) (n_s=188, n_u=8)	13m (t-test: 0.27; GEE-adjusted: 0.51)
	Weekend	6h 58m (1h 23m) (n_s=40, n_u=9)	7h 2m (1h 37m) (n_s=78, n_u=9)	4m (t-test: 0.85; GEE-adjusted: 0.83)	00:42 (2h 1m) (n_s=40, n_u=9)	02:00 (1h 27m) (n_s=78, n_u=9)	1h 18m (t-test: <0.001; GEE-adjusted: 0.03)

55 or above	Weekday	7h 16m (1h 4m) (n_s=44, n_u=5)	6h 57m (49m) (n_s=65, n_u=4)	-19m (t-test: 0.09; GEE-adjusted: 0.35)	00:27 (1h 19m) (n_s=44, n_u=5)	00:25 (1h 1m) (n_s=65, n_u=4)	-2m (t-test: 0.91; GEE-adjusted: 0.79)
	Weekend	7h 11m (1h 42m) (n_s=15, n_u=4)	7h 9m (37m) (n_s=27, n_u=3)	-2m (t-test: 0.93; GEE-adjusted: 0.95)	00:27 (51m)(n_s=15, n_u=4)	00:15 (1h 15m) (n_s=27, n_u=3)	-12m (t-test: 0.57; GEE-adjusted: 0.47)

n_s and n_u denote the number of sleep records and number of users, respectively