Received: 31 August 2020 | Accepted: 13 December 2020

DOI: 10.1111/aphw.12255

ORIGINAL ARTICLE

APPLIED PSYCHOLOGY: Health and Well-Being IAAP

Effects of physical activity and sleep quality on well-being: A wrist actigraphy study during the pandemic

Haien Wang[1,2] | **Ling He**[1,2] | **Yuan Gao**[2] | **Xiao Gao**[2] | **Xu Lei**[1,2]

[1]Sleep and NeuroImaging Center, Faculty of Psychology, Southwest University, Chongqing, China

[2]Key Laboratory of Cognition and Personality, Ministry of Education, Southwest University, Chongqing, China

Correspondence
Xu Lei and Xiao Gao, Sleep and NeuroImaging Center, Faculty of Psychology, Southwest University, Chongqing 400715, China.
Emails: xlei@swu.edu.cn; gaoxiaox@swu.edu.cn

Funding information
National Science Foundation of China, Grant/Award Number: 31971028; Major Project of Medicine Science and Technology of PLA, Grant/Award Number: AWS17J012

Abstract

Previous studies identified the effects of daytime activity, sleep quality and ambient light exposure on individual well-being. These factors have been greatly changed as people are required to stay home during the COVID-19 pandemic; thus, it is necessary to verify whether these factors effect well-being during the pandemic. We recruited 70 adults (females: 46; age range: 31−60) during a high incidence of COVID-19 in China (17–27 February 2020). Both subjective measurements based on self-report scales and objective measurements collected using wrist actigraphy were employed to investigate the effects of night-time sleep and daytime activity on subjective well-being. The actigraphy data show that participants' total sleep time (>8 hr) is sufficient. Self-reported sleep quality was significantly worse than pre-pandemic, and self-reported daytime activity levels significantly decreased during the pandemic. Physical activity was positively related to well-being, both for self-reported daytime activity ($r = .346$, $p = .003$) and for objective measurements ($r = .234$, $p = .051$). Our study found that sleep and daytime activity levels were negatively affected by the pandemic. However, increased daytime physical activity could potentially reduce these negative effects.

Haien Wang and Ling He are contributed equally to this work.

Haien Wang and Ling He are Co-first author

APPLIED PSYCHOLOGY: Health and Well-Being IAAP

KEYWORDS

actigraphy, daytime physical activity, sleep quality, well-being

INTRODUCTION

During the COVID-19 pandemic, to prevent the spread of infection, the governments of many countries have required people to remain at home and practise social distancing in public places. Consequently, individuals' daily lives have been significantly affected by factors such as reduced activity (Ong et al., 2020), decreased light exposure (Leone et al., 2020), worsened sleep quality (Wright, Steptoe, et al., 2020) and altered sleep–wake patterns (Wright, Linton, et al., 2020). In addition, the pandemic has negatively influenced individual well-being (Prime et al., 2020) and may even lead to serious mental health problems (Gao et al., 2020). In the present study, we focused on subjective well-being, because it is widely used as a measure of individual mental health (Costigan et al., 2019). Subjective well-being is affected by several factors. For example, people's well-being tends to increase as income increases (Sacks et al., 2012), and social support is strongly correlated with subjective well-being (Wang, 2016). Recent studies revealed effects of the COVID-19 pandemic such as interruptions in employment (Zhang et al., 2020), decreased income (Nicola et al., 2020) and changes in social support (Cao et al., 2020). Thus, we speculated that the pandemic may negatively affect individual subjective well-being.

Previous studies showed that sleep and activity levels significantly affect physical health (Rosenberger et al., 2016). Reducing physical activity leads to multiple health risks, such as elevated blood pressure and low-density lipoprotein cholesterol (Carson et al., 2013). Moreover, appropriate physical activity can even reduce anxiety and stress (Chodzko-Zajko et al., 2009). Furthermore, physical activity is associated with well-being (Downward & Dawson, 2016), and a higher level of sedentary behaviour is associated with lower subjective well-being (Panza et al., 2017). In another study, light-intensity leisure sport activity was found to be highly correlated with subjective well-being (Downward & Dawson, 2016). As a result, physical activity was recommended as an effective intervention to improve quality of life and well-being (Groessl et al., 2019). During the pandemic, people's daytime physical activity is often restricted, thereby constructing a natural experimental environment in which the relationship between physical activity and well-being can be investigated.

Sleep is another factor crucial to well-being, and its quantity and quality affect all aspects of life (Cellini et al., 2020). Individuals whose sleep is of poor quality and is short in duration have been consistently found to have lower subjective well-being than those who have good sleep quality and receive 7–8 hr of sleep per night (Lemola, Räikkönen, et al., 2013; Steptoe et al., 2008). Inadequate sleep has both short- and long-term effects on individual well-being (for reviews, see, e.g. Owens, 2014). First, sleep duration below seven hours per night may lead to the onset of several physiological diseases (Watson et al., 2015), which may further reduce subjective well-being. Second, sleep quality is directly related to well-being (Fuligni et al., 2018; Lemola, Ledermann, et al., 2013), and efficient, high-quality sleep is essential to maintaining well-being (Noor et al., 2013). Longer, better sleep at night may lead to more positive social responses and higher well-being (Wang & Yip, 2020), while poor sleep correlates with lower well-being (Lemola et al., 2013; Steptoe et al., 2008). According to a statement by the American Academy of Sleep Medicine and the Sleep Research Society, adults should spend at least seven hours in bed every night for optimal health (see, Watson et al., 2015). Due to the impact of the pandemic, people often have more freedom in arranging their schedules, making it easy to get enough sleep. However, it is still unclear whether sleep (quality and duration) has maintained its effects on well-being during the COVID-19 pandemic.

In the present study, we utilized both subjective and objective measurements of daytime activity and night-time sleep. The Pittsburgh Sleep Quality Index (PSQI) (Buysse et al., 1989) and Physical Activity Questionnaire (PAQ; Kowalski et al., 1997) were employed for subjective measurements. Previous studies revealed a strong correlation between the PSQI's sleep quality items and spiritual well-being (Lemola, Räikkönen, et al., 2013). Additionally, physical activity was reported to have a strong correlation with well-being (Garatachea et al., 2009). Currently, behavioural and epidemiological research often uses measurements based on accelerometry to provide objective estimates of physical activity, sedentary behaviour and sleep parameters in various study designs. Compared to questionnaires, accelerometers eliminate recall and reporting bias and may provide more reliable data (Evenson et al., 2008). To better understand individuals' daily lives during the pandemic, it is important to study the complete 24-hr activity cycle (Rosenberger et al., 2016), through which periodic activities, such as physical activity, light exposure and sleep, can be measured using actigraphy.

With the spread of the pandemic, there have been changes to people's working and living environments, and social contact and activities have been restricted. These changes may adversely affect night-time sleep and daytime activity. In the present study, we concentrated on the effects of sleep, physical activity and light exposure on well-being. Specially, we assumed that good sleep (high quality and long duration) and high activity amount during the pandemic could significantly positively predict individual well-being. Furthermore, as some previous studies have indicated that light exposure is linked to well-being (Gabel et al., 2013), we also speculated that individual well-being would be positively correlated with light exposure during the pandemic.

METHODS

Participants

Through an online questionnaire survey, we recruited 70 participants (46 females, 24 males; age range: 31–60; mean ± *SD*: 47.60 ± 5.37). Our study was conducted during a period of growth of the pandemic (from 17 to 27 February 2020) when subjects had adopted home isolation measures in China. The accumulative total number of confirmed cases was over 70,000, with more than 300 new confirmed cases per day during the study (information from the official website of the National Health Commission of the People's Republic of China, http://www.nhc.gov.cn/xcs/yqtb/list_gzbd.shtml). We chose this period because individuals' daily lives were greatly influenced during this time. Most participants were from the southwest of China, such as Sichuan Province and Chongqing Municipality.

Our study was part of the Sleep, Eating behaviours, Emotion, Physical Activity (SEEPA) project, which was conducted during the COVID-19 pandemic in China. The SEEPA project has assessed more than 1,000 participants using four types of questionnaires, focused on sleep disorders, eating disorders, emotional problems and physical activity. Seventy-five participants also wore wrist actigraphy; however, five participants were excluded from analysis because of their incomplete questionnaire data.

Participants were excluded if they had any mental illness or other psychosocial disorders, which was determined through telephone interviews with professional psychological researchers (LH and YG). After completing the experiment, each participant was paid 100 CNY. This study was approved by the local Ethics Committee of Southwest University. Participants provided written informed consent after receiving a detailed explanation of the study protocol. All experimenters followed the guidelines of the Declaration of Helsinki.

Procedure

At the beginning of the experiment (during the COVID-19 pandemic), participants were asked to complete a set of online questionnaires. This included more than 10 scales, on topics related to sleep, eating behaviours, emotion and physical activity. Some scales utilized in the current study are introduced in the following section. Then, the participants who met our inclusion criteria (sleep disorder, mental illness or psychological disorders) were telephone-reviewed.

Participants were asked to wear an actigraphy (wGT3X-BT) for five consecutive days and nights. The devices were worn on the dominant wrist and were only allowed to be removed for short periods of less than half an hour. Participants completed daily diaries, in which they indicated their bedtime, subjective perception of the quality of sleep, the feeling before and after sleep, etc. The actigraph was mailed to the participants before the experiment and take back it in the same way after the experiment. After the experiment, participants mailed the actigraphy back to the experimenter.

Materials

Subjective well-being was assessed by the 9-item Index of Well-being (IWB) (Campbell, 1976), which uses a 7-point scale ranging from 1 (dissatisfying) to 7 (satisfying). Higher total scores indicate better well-being. The scale is psychometrically sound for investigating well-being among Chinese adults (Li, 2000).

Subjective sleep quality was assessed using the PSQI, which has 18 items and 7 dimensions: sleep quality, sleep latency, sleep duration, habitual sleep efficiency, sleep disturbance, use of sleep medication and daytime dysfunction. Participants' sleep quality was measured by total and dimension scores (Buysse et al., 1989); higher scores indicated poorer sleep quality. By adding instructions to indicate the time period as 'before the pandemic' (BP) or 'from the pandemic to now' (FP), we measured PSQI scores for both before and during the pandemic.

A revised version of the PAQ (Kowalski et al., 1997) was used to measure subjective physical activity before and during the pandemic. To adapt the measure for use with adults, some items were changed from 'school' to 'workspace', and some items were deleted because they referred to school activities that were irrelevant to this study's population.

The Mind-Wandering Questionnaire (MWQ; Mrazek et al., 2013) consists of 5 items, each scored on a 6-point scale (range: 0–5), and was used to evaluate participants' trait-level mind wandering before and during the pandemic. Data on participants' daily mental states were collected using the Ford Insomnia Response to Stress Test (FIRST; Drake et al., 2004) and Chalder Fatigue Scale (CFS) (Chalder et al., 1993).

Actigraphy

All objective measurements of daytime activity and night-time sleep parameters were extracted using actigraphy. Actigraphy (wGT3X-BT) (Aggio et al., 2015) was used to detect the amount of participants' movements with a built-in motion sensor. ActiLife software and manufacturer algorithms for detecting sleep based on 60-s epochs were used to generate summary statistics for participants' sleep. Specifically, whether an epoch was scored as 'wake' or 'sleep' was determined by comparing activity counts for the epoch in question and those immediately surrounding it to a threshold value following the formula validated by the Cole–Kripke algorithm (Cole et al., 1992). The actigraphy sleep indices that were derived included average activity amount (counts), average ambient light exposure (lux),

sleep onset time, wake-up time, sleep midpoint and total sleep time. Of the 70 participants who took part in the actigraphy protocol, 69 (98.6%) had measurements for all 5 nights, while 1 (1.4%) had measurements for only 3 nights.

RESULTS

Demographic and questionnaire data

Most participants (44%) had an education level of university or higher (junior high school: 13; senior high school: 26; university or higher: 31). Participants' monthly household income mostly fell within the 1,000 − 20,000 (RMB) range (<1,000:2; 1,000 − 5,000:23; 5,000 − 10,000:20; 10,000 − 20,000:18; ≥ 20,000:7) overall. The mean FIRST score was higher than 16 (17.51 ± 5.40, range: 9–32), indicating that some participants were shown to be at risk of insomnia. Mean CFS score (3.89 ± 3.28, range: 0–13) and IWB score (10.08 ± 2.75, range: 2 − 14) were also calculated.

Effects of the pandemic on subjective sleep parameters

Three scales (PSQI, PAQ and MWQ) were measured twice, and we conducted several paired *t*-tests between scores from before and during the COVID-19 pandemic. The means and standard deviations of the results are listed in Table 1 and illustrated in Figure 1. PSQI-total scores of FP were higher ($t = -2.456$, $p = .017$) than that of BP. Some PSQI sub-dimensional scores increased significantly from BP to FP: subjective sleep quality ($t = -3.000$, $p = .004$), sleep latency ($t = -3.702$, $p < .001$) and sleep disturbance ($t = -2.771$, $p = .007$). However, sleep duration ($t = 2.116$, $p = .038$) scores were significantly lower, and remaining other PSQI sub-dimensions did not show a significant change between BP and FP. Compared to BP, all raw parameters of PSQI were significantly changed at FP: sleep onset time ($t = -4.589$, $p < .001$), sleep onset latency ($t = -3.623$, $p < .001$), wake-up time ($t = -9.115$, $p < .001$), total sleep time ($t = -6.591$, $p < .001$) and midpoint of sleep ($t = -8.250$, $p < .001$). PAQ scores were lower at FP compared with BP ($t = 4.731$, $p < .001$). There was no significant difference between BP and FP MWQ scores.

Objective measures of activity, ambient light and sleep during the pandemic

Actigraphy was used to collect data on physical activity, ambient light and sleep parameters during the pandemic. Participants' average physical activity levels (<1,700 count) and average ambient light exposure (<50 lux) were very low (Table 2). Sleep onset time (22:29 − 5:21) and wake-up time (4:52 − 12:39) were distributed across a large range, while the sleep midpoint was late (3:56). However, participants did not show excessive sleep loss, with a mean total sleep duration over 8 hr.

Correlations between well-being and activity, ambient light and sleep duration

Average physical activity levels were positively correlated with well-being, both in subjective reports (PAQ: $r = 0.346$, $p = .003$) and in objective measurements (actigraphy: $r = 0.234$, $p = .051$), although

TABLE 1 Comparisons of sleep, physical activity and mind wandering between BP and FP

	BP	FP	*t*	*p*
PSQI	4.59 ± 2.86	5.04 ± 3.02	−2.456	.017*
PSQI-subjective sleep quality	0.93 ± 0.85	1.09 ± 0.89	−3.000	.004**
PSQI-sleep latency	0.86 ± 0.83	1.12 ± 0.95	−3.702	<.001***
PSQI-sleep duration	0.46 ± 0.74	0.33 ± 0.76	2.116	.038*
PSQI-sleep efficiency	0.36 ± 0.82	0.43 ± 0.87	−1.150	.254
PSQI-sleep disturbance	0.99 ± 0.44	1.09 ± 0.41	−2.771	.007**
PSQI-sleep medication use	0.07 ± 0.36	0.09 ± 0.37	−0.445	.658
PSQI-daytime dysfunction	0.93 ± 0.83	0.9 ± 0.84	0.363	.718
Usual bedtime	22:41	23:10	−4.589	<.001***
Sleep latency (min)	19	23	−3.623	<.001***
Wake-up time	7:06	8:23	−9.115	<.001***
Sleep efficiency	0.91	0.9	0.961	.340
Sleep duration (total sleep time)	7:36	8:23	−6.591	<.001***
Sleep midpoint	3:03	3:58	−8.250	<.001***
PAQ	2.07 ± 0.77	1.62 ± 0.74	4.731	<.001***
MWQ	10.51 ± 3.844	10.64 ± 4.53	−0.27	.788

Abbreviations: BP, before the pandemic; FP, from the pandemic to now; MWQ, Mind-Wandering Questionnaire; PAQ, Physical Activity Questionnaire; PSQI, Pittsburgh Sleep Quality Index.

***$p < .001$,

**$p < .01$,

*$p < .05$.

the latter was a marginally significant correlation. Greater levels of physical activity were associated with higher well-being. Ambient light exposure was not associated with well-being. In addition, we did not find a correlation between sleep duration and well-being, as illustrated in Figure 2.

DISCUSSION

In this study, based on self-report questionnaires and wrist actigraphy, we found that the COVID-19 pandemic negatively affected both night-time sleep and daytime activity for participants. Multiple sleep parameters showed significant deterioration during the pandemic, compared to before the pandemic, and participants' reported subjective activity decreased significantly as well. Actigraphy data showed that levels of physical activity and ambient light exposure were relatively low in our participants. Although sleep duration and ambient light levels were not shown to be related to well-being, we found physical activity (both subjective and objective) could significantly predict well-being. Our study confirmed that both night-time sleep and daytime activity were negatively impacted during the pandemic. Furthermore, daytime activity was found to be a good predictor of subjective well-being. These results may be useful at both the individual and government policy levels when generating appropriate pandemic response strategies.

During the pandemic, overall sleep quality deteriorated in our sample, and PSQI sub-dimensions scores significantly increased, especially for subjective sleep quality, sleep latency and sleep

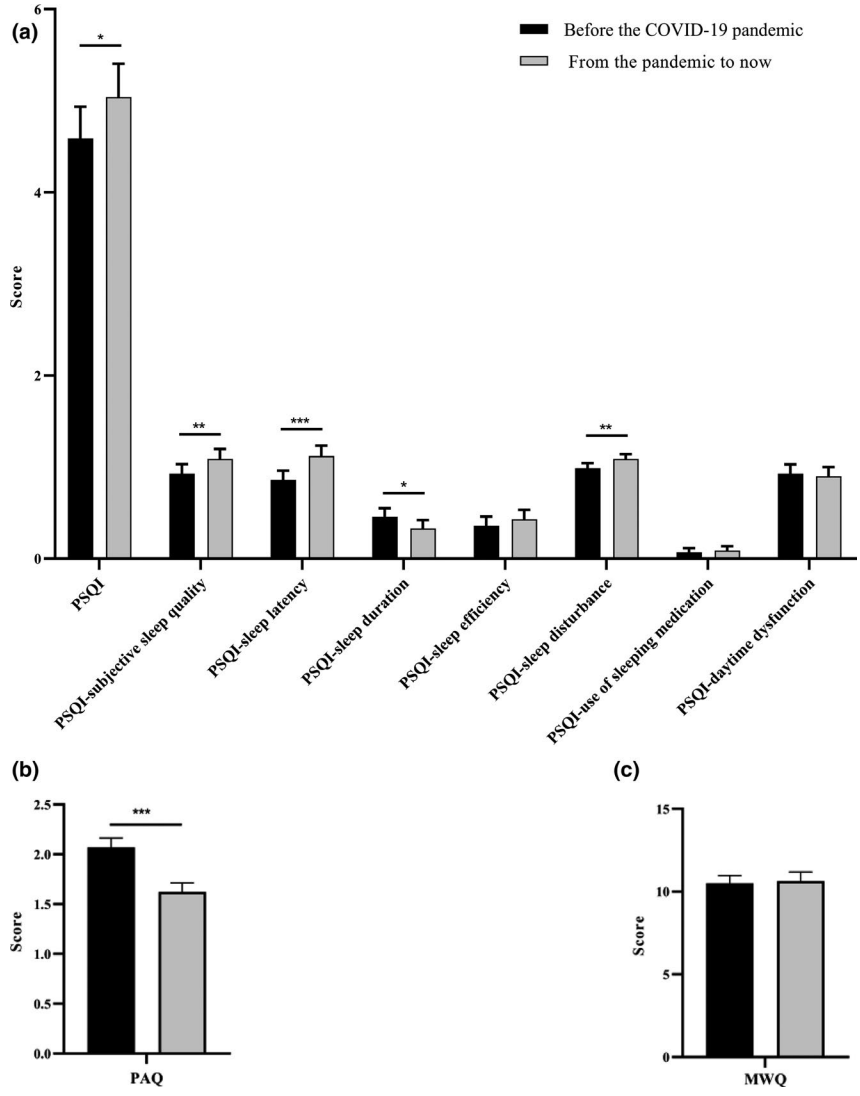

FIGURE 1 Comparison between sleep quality, physical activity and mind wandering before and during the COVID-19 pandemic. Scores for the total PSQI and its sub-dimension (subjective sleep quality, sleep latency, sleep duration and sleep disturbance) were significantly different before the pandemic, compared with FP (a). During the pandemic period, activity questionnaire scores decreased significantly (PAQ) (b). MWQ scores did not change significantly between before and during the pandemic (c) (***$p < .001$, **$p < .01$, *$p < .05$)

disturbance, indicating declines in subjective sleep quality. These results indicated that the pandemic has had a significant adverse effect on individual sleep health. Although sleep duration (total sleep time) scores dropped and the length of sleep time extended, this had a limited impact on the overall deterioration of sleep quality. Increased sleep onset time and frequency of waking during sleep implied there were also possible increases in insomnia during the pandemic. Furthermore, sleep latency during the pandemic significantly increased compared with that in pre-pandemic, which could have led to a lag in sleep onset time. Participants could get up later because they did not have to follow strict schedules, which eventually led to a later sleep midpoint and an increase in total sleep time.

TABLE 2 Actigraphy parameters: night-time sleep parameters and daytime activity and ambient light ($N = 70$)

	M	SD	Range
Average activity (count)	1679.66	546.84	876.46–3918.91
Average ambient light (lux)	37.79	47.24	0.02–326.80
Sleep onset time	23:50	1:25	22:29–5:21
Wake-up time	8:02	1:26	4:52–12:39
Sleep midpoint	3:56	1:19	1:11–9:00
Total sleep time	8:13	1:9	5:46–13:6

We used actigraphy to collect objective data on physical activity levels, ambient light exposure and sleep parameters during the pandemic. The average levels of physical activity and ambient light exposure were relatively low compared with previous studies (Barnett et al., 2016; Hood et al., 2004), indicating that individual levels of physical activity and light exposure may have been negatively affected by the pandemic. However, as we did not collect actigraphy data before the pandemic, it is impossible to perform a quantitative comparative analysis of these objective sleep parameters.

Notably, we found that both subjective and objective activity measurements were positively correlated with subjective well-being, indicating the participants with higher activity levels also had higher well-being, which is consistent with previous studies (Garatachea et al., 2009). Individual physical activity has been restricted during the pandemic; however, physical activity levels still significantly predicted changes in the subjective well-being. Fox has explored the mechanisms underlying the effect of physical activity on psychological well-being, such as biochemical, physiological, psychological, activity-related and dietary interactions, and found that all have an impact on well-being (Fox, 1999). A subsequent study indicated physical activity may help people experience personal achievement and improve their sense of personal control (Stathi et al., 2002). They also pointed out that physical exercise can make an important contribution to mental health, including maintaining mental alertness and avoiding stress. Furthermore, it can help people reduce stress, deal with problems more effectively and feel comfortable and relaxed. This may be the potential reason for higher subjective well-being in individuals with higher physical activity levels. To correct statistical errors, we used Bonferroni correction, and the results still indicated that there was a significant positive correlation between subjective activity levels and subjective well-being ($p = .012$). However, it should be noted that our research was not focused on physical exercise, but on daytime physical activity; thus, whether there is a dose difference between the effects of physical exercise and daytime physical activity on well-being still needs to be explored.

We did not identify any correlations between daytime ambient light exposure and well-being, or between sleep time and well-being, which was inconsistent with previous studies (Gabel et al., 2013; Lemola, Räikkönen, et al., 2013; Steptoe et al., 2008). Hood et al. (2004) reported that 3,000-lux light exposure was a critical limit associated with improved sleep quality; however, mean ambient light (37.79 ± 47.24 lux) in our study was well below the average level of daytime light (554 lux) for adults ($40 - 64$ years) in a normal environment. This indicates that strong light may play a role in individual physical and mental health. We suspected this may have been the main reason why less light exposure during the pandemic did not affect well-being. Our results also showed that participants slept long enough during FP (PSQI-total sleep time: $M = 8$ hr 23 m; PSQI-total sleep time: $M = 8$ hr 13 m) and reached the adult sleep standard of $7 - 9$ hr (Ferrara & Gennaro, 2001), most likely because they did not have to follow their usual schedules and could get adequate sleep during the pandemic. Sleep duration may produce a ceiling effect, therefore weakening its predictive effect on well-being.

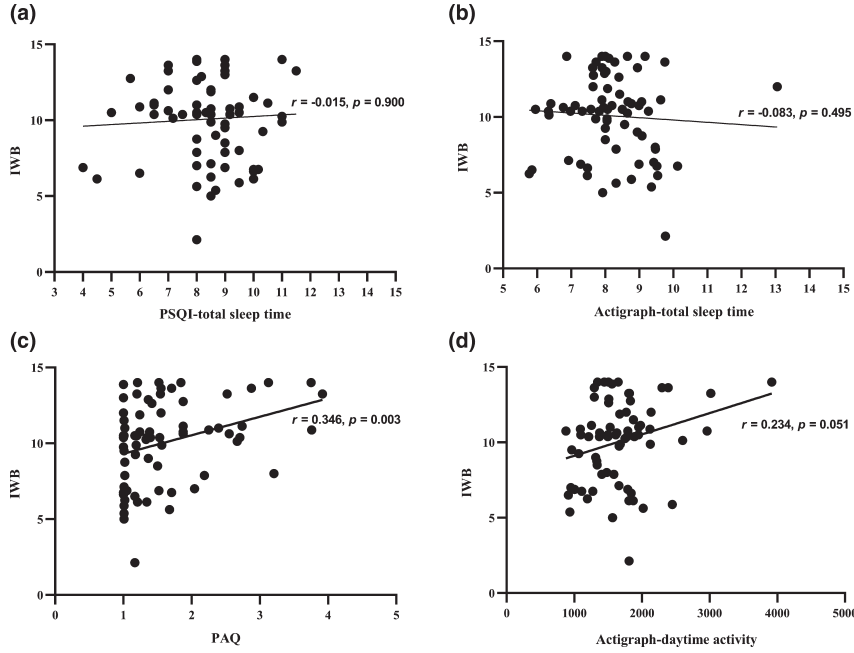

FIGURE 2 Correlations of daytime activity and sleep duration with subjective well-being. Both subject self-reports using the PSQI (a) and PAQ (c) and objective measures (b, d) from actigraphy were utilized

Our study has several limitations. First, the sample size was not large enough, especially for the actigraphy data, which was difficult to collect due to pandemic restrictions. However, the adults in our study were sensitive to changes in daytime physical activity levels, ambient light exposure and night-time sleep before and during the pandemic, which has high representativeness and ecological validity. Second, the threshold of physical activity and ambient light exposure necessary to affect well-being is still uncertain, and different levels of light and activity need to be controlled in subsequent studies. Third, the activity we measured was mainly comprised of daytime activities during the pandemic, rather than sport or exercises in a normal environment, and the potential mechanism of their impact on well-being remains unclear. It will be necessary to compare the differences between sport and daily activities in future studies. Fourth, the actigraphy data were only collected during the pandemic; therefore, it is impossible to objectively determine participants' previous sleep parameters and activity levels. However, we found that the pandemic had negative effects on participants' sleep and physical activity through subjective reports (PSQI and PAQ). Finally, the adapted PAQ used in the present study was not validated; however, participants' activity levels could still be assessed by accumulating raw data, because the questionnaire was designed to investigate the frequency in which adults engaged in multiple activities during the measurement period.

CONCLUSION

Our study found that individual levels of sleep, activity, light exposure and other physical and mental activities were significantly affected by the pandemic. The positive relationship between daytime physical activity and well-being was shown to be stable, even with activity being restricted during the pandemic. In addition, we found that the level of light exposure in the participants' environment was too low, which may have affected their mental and physical health. Thus, governments should

encourage people to increase their amount of outdoor activities while also requiring people to take the necessary preventative measures against COVID-19. Against the backdrop of the global COVID-19 pandemic, governments should call on people to maintain healthy behaviours (e.g. sleep patterns), while also paying attention to individuals' physical and mental health, such as by improving community mental health services and providing individualized psychological and behavioural guidance.

ACKNOWLEDGEMENTS

This work was supported by the National Science Foundation of China (grant number 31971028) and Major Project of Medicine Science and Technology of PLA (AWS17J012).

ETHICAL STATEMENT

The study was approved by the the Ethics Committee of Faculty of Psychology, Southwest University, Chongqing, China.

DATA AVAILABILITY STATEMENT

All data generated or analyzed during this study are included in this article, and the raw data during the study are available from the corresponding author by request.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

ORCID

Haien Wang https://orcid.org/0000-0002-5421-2776
Xu Lei https://orcid.org/0000-0003-2271-1287

REFERENCES

Aggio, D., Smith, L., Fisher, A., & Hamer, M. (2015). Association of light exposure on physical activity and sedentary time in young people. *International Journal of Environmental Research and Public Health*, *12*(3), 2941–2949.

Barnett, A., van den Hoek, D., Barnett, D., & Cerin, E. (2016). Measuring moderate-intensity walking in older adults using the ActiGraph accelerometer. *BMC Geriatrics*, *16*(1), 211.

Buysse, D. J., Reynolds, C. F., Monk, T. H., Berman, S. R., & Kupfer, D. J. (1989). The Pittsburgh Sleep Quality Index: A new instrument for psychiatric practice and research. *Psychiatry Research*, *28*(2), 193–213.

Campbell, A. (1976). Subjective Measures of well-being. *American Psychologist*, *31*(2), 117–124.

Cao, W., Fang, Z., Hou, G., Han, M., Xu, X., Dong, J., & Zheng, J. (2020). The psychological impact of the COVID-19 epidemic on college students in China. *Psychiatry Research*, *287*, 112934.

Carson, V., Ridgers, N. D., Howard, B. J., Winkler, E. A., Healy, G. N., Owen, N., & Salmon, J. (2013). Light-intensity physical activity and cardiometabolic biomarkers in US adolescents. *PLoS One*, *8*(8), e71417.

Cellini, N., Menghini, L., Mercurio, M., Vanzetti, V., Bergamo, D., & Sarlo, M. (2020). Sleep quality and quantity in Italian University students: An actigraphic study. *Chronobiology International*, *37*(11), 1538–1551.

Chalder, T., Berelowitz, G., Pawlikowska, T., Watts, L., Wessely, S., Wright, D., & Wallace, E. P. (1993). Development of a fatigue scale. *Journal of Psychosomatic Research*, *37*(2), 147–153.

Chodzko-Zajko, W. J., Proctor, D. N., Singh, M. A. F., Minson, C. T., Nigg, C. R., Salem, G. J., & Skinner, J. S. (2009). Exercise and physical activity for older adults. *Medicine & Science in Sports & Exercise*, *41*(7), 1510–1530.

Cole, R. J., Kripke, D. F., Gruen, W., Mullaney, D. J., & Gillin, J. C. (1992). Automatic sleep/wake identification from wrist activity. *Sleep*, *15*(5), 461–469.

Costigan, S. A., Lubans, D. R., Lonsdale, C., Sanders, T., & Cruz, B. D. P. (2019). Associations between physical activity intensity and well-being in adolescents. *Preventive Medicine*, *125*, 55–61.

Downward, P., & Dawson, P. (2016). Is it pleasure or health from leisure that we benefit from most? An analysis of well-being alternatives and implications for policy. *Social Indicators Research*, *126*(1), 443–465.

Drake, C., Richardson, G., Roehrs, T., Scofield, H., & Roth, T. (2004). Vulnerability to stress-related sleep disturbance and hyperarousal. *Sleep*, *27*(2), 285-291.

Evenson, K. R., Catellier, D. J., Gill, K., Ondrak, K. S., & McMurray, R. G. (2008). Calibration of two objective measures of physical activity for children. *Journal of Sports Sciences*, *26*(14), 1557–1565.

Ferrara, M., & De Gennaro, L. (2001). How much sleep do we need? *Sleep Medicine Reviews*, *5*(2), 155–179.

Fox, K. R. (1999). The influence of physical activity on mental well-being. *Public Health Nutrition*, *2*(3a), 411–418.

Fuligni, A. J., Arruda, E. H., Krull, J. L., & Gonzales, N. A. (2018). Adolescent sleep duration, variability, and peak levels of achievement and mental health. *Child Development*, *89*(2), e18–e28.

Gabel, V., Maire, M., Reichert, C. F., Chellappa, S. L., Schmidt, C., Hommes, V., & Cajochen, C. (2013). Effects of artificial dawn and morning blue light on daytime cognitive performance, well-being, cortisol and melatonin levels. *Chronobiology International*, *30*(8), 988–997.

Gao, J., Zheng, P., Jia, Y., Chen, H., Mao, Y., Chen, S., & Dai, J. (2020). Mental health problems and social media exposure during COVID-19 outbreak. *PLoS One*, *15*(4), e0231924.

Garatachea, N., Molinero, O., Martínez-García, R., Jimenez-Jimenez, R., Gonzalez-Gallego, J., & Marquez, S. (2009). Feelings of well being in elderly people: Relationship to physical activity and physical function. *Archives of Gerontology and Geriatrics*, *48*(3), 306–312.

Groessl, E. J., Kaplan, R. M., Rejeski, W. J., Katula, J. A., Glynn, N. W., King, A. C., & Pahor, M. (2019). Physical activity and performance impact long-term quality of life in older adults at risk for major mobility disability. *American Journal of Preventive Medicine*, *56*(1), 141–146.

Hood, B., Bruck, D., & Kennedy, G. (2004). Determinants of sleep quality in the healthy aged: The role of physical, psychological, circadian and naturalistic light variables. *Age and Ageing*, *33*(2), 159–165.

Kowalski, K. C., Crocker, P. R., & Kowalski, N. P. (1997). Convergent validity of the physical activity questionnaire for adolescents. *Pediatric Exercise Science*, *9*(4), 342–352.

Lemola, S., Ledermann, T., & Friedman, E. M. (2013). Variability of sleep duration is related to subjective sleep quality and subjective well-being: An actigraphy study. *PLoS One*, *8*(8), e71292.

Lemola, S., Räikkönen, K., Gomez, V., & Allemand, M. (2013). Optimism and self-esteem are related to sleep. Results from a large community-based sample. *International Journal of Behavioral Medicine*, *20*(4), 567–571.

Leone, M. J., Sigman, M., & Golombek, D. (2020). Effects of social isolation on human sleep and chronotype during the COVID-19 pandemic. *SSRN Electronic Journal*. http://dx.doi.org/10.2139/ssrn.3624469

Li, J. (2000). Validation of Index of Well-being in a Sample of Chinese College Students'. *Chinese Journal of Clinical Psychology*, *8*(4), 225–226.

Mrazek, M. D., Phillips, D. T., Franklin, M. S., Broadway, J. M., & Schooler, J. W. (2013). Young and restless: Validation of the Mind-Wandering Questionnaire (MWQ) reveals disruptive impact of mind-wandering for youth. *Frontiers in Psychology*, *4*, 560.

Nicola, M., Alsafi, Z., Sohrabi, C., Kerwan, A., Al-Jabir, A., Iosifidis, C., & Agha, R. (2020). The socio-economic implications of the coronavirus pandemic (COVID-19): A review. *International Journal of Surgery (London, England)*, *78*, 185.

Noor, Z. M., Smith, A., Smith, S., & Nissen, L. (2013). Feasibility and acceptability of wrist actigraph in assessing sleep quality and sleep quantity: A home-based pilot study in healthy volunteers. *Health*, *5*(8A2), 63–72.

Ong, J. L., Lau, T. Y., Massar, S. A. A., Chong, Z. T., Ng, B. K. L., Koek, D., Chee, M. W. L. (2020). COVID-19 Related Mobility Reduction: Heterogeneous Effects on Sleep and Physical Activity Rhythms. *arXiv* arXiv:2006.02100 [PREPRINT]

Owens, J., Adolescent Sleep Working Group (2014). Insufficient sleep in adolescents and young adults: An update on causes and consequences. *Pediatrics*, *134*(3), e921–e932.

Panza, G. A., Taylor, B. A., Thompson, P. D., White, C. M., & Pescatello, L. S. (2017). Physical activity intensity and subjective well-being in healthy adults. *Journal of Health Psychology*, *24*(9), 1257–1267.

Prime, H., Wade, M., & Browne, D. T. (2020). Risk and resilience in family well-being during the COVID-19 pandemic. *American Psychologist*, *75*(5), 631–643.

Rosenberger, M. E., Buman, M. P., Haskell, W. L., McConnell, M. V., & Carstensen, L. L. (2016). 24 hours of sleep, sedentary behavior, and physical activity with nine wearable devices. *Medicine and Science in Sports and Exercise*, *48*(3), 457–465.

Sacks, D. W., Stevenson, B., & Wolfers, J. (2012). The new stylized facts about income and subjective well-being. *Emotion*, *12*(6), 1181.

Stathi, A., Fox, K. R., & McKenna, J. (2002). Physical activity and dimensions of subjective well-being in older adults. *Journal of Aging and Physical Activity*, *10*(1), 76–92.

Steptoe, A., O'Donnell, K., Marmot, M., & Wardle, J. (2008). Positive affect, psychological well-being, and good sleep. *Journal of Psychosomatic Research*, *64*(4), 409–415.

Wang, X. (2016). Subjective well-being associated with size of social network and social support of elderly. *Journal of Health Psychology*, *21*(6), 1037–1042.

Wang, Y., & Yip, T. (2020). Sleep facilitates coping: Moderated mediation of daily sleep, ethnic/racial discrimination, stress responses, and adolescent well-being. *Child Development*, *91*(4), e833–e852.

Watson, N. F., Badr, M. S., Belenky, G., Bliwise, D. L., Buxton, O. M., Buysse, D., & Tasali, E. (2015). Recommended amount of sleep for a healthy adult: A joint consensus statement of the American Academy of Sleep Medicine and Sleep Research Society. *Journal of Clinical Sleep Medicine*, *11*(6), 591–592.

Wright, K. P., Linton, S. K., Withrow, D., Casiraghi, L., Lanza, S. M., de la Iglesia, H., & Depner, C. M. (2020). Sleep in university students prior to and during COVID-19 stay-at-home orders. *Current Biology*, *30*, R797–R798.

Wright, L., Steptoe, A., & Fancourt, D. (2020). Are adversities and worries during the COVID-19 pandemic related to sleep quality? Longitudinal analyses of 45,000 UK adults. *medRxiv*.

Zhang, S. X., Wang, Y., Rauch, A., & Wei, F. (2020). Unprecedented disruption of lives and work: Health, distress and life satisfaction of working adults in China one month into the COVID-19 outbreak. *Psychiatry Research*, *288*, 112958.

How to cite this article: Wang H, He L, Gao Y, Gao X, Lei X. Effects of physical activity and sleep quality on well-being: A wrist actigraphy study during the pandemic. *Appl Psychol Health Well-Being*. 2021;13:394–405. https://doi.org/10.1111/aphw.12255