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Title:

Sensor-Based Sleep Quality Index (SB-SQI): A New Metric to Examine the Association of Office Workstation Type on Stress and Sleep

Short title:

Sensor-Based Sleep Quality Index (SB-SQI)

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Sensor-Based Sleep Quality Index (SB-SQI): a New Metric to Examine the Association of Office Workstation Type on Stress and Sleep

Abstract

Study Objective: This study examined office workstation types' impact on objective health-related metrics including stress, physical activity (PA), and sleep quality. We propose a sensor-based sleep quality index (SB-SQI) to fill a needed gap for objective sleep quality measurement over short time scales.

Methods: We monitored 231 office workers using chest-worn sensors for 72 hours, yielding 11,736 hours of usable data from 163 participants (mean age 43.4, 56% women). SB-SQI was based on a validated algorithm estimating sleep-onset latency, total sleep time, and sleep efficiency, using the scoring method from the Pittsburg Sleep Quality Index (PSQI). We examined the relationships between SB-SQI, office workstation type (open-bench seating, cubicle, and private office), work-hours stress (standard deviation of heart rate variability), and after-work PA (relative duration of moderate-to-vigorous activity).

Results: The sensor-derived poor-sleep ratio of the private office workers was higher than with other office workstation types (81% vs. 66.1%, $p = 0.023$). PSQI revealed a similar but insignificant trend with a lower effect-size. Among good-sleepers, open-bench seating workers had 22% ($p = 0.018$) less stress during work hours than others. A significant association between work-hours stress and after-work hours PA ($r = 0.331$, $p = 0.000$) was observed irrespective of office workstation type, with the highest PA level observed for open-bench seating workers.

Conclusions: Office workstation type had a significant impact on work-hours stress, affecting PA after work hours, which influenced sleep quality. SB-SQI could be more sensitive than PSQI in determining the impact of office workstation types on sleep quality.

Brief Summary *(120 words or less)*

Current Knowledge/Study Rationale: *(two sentences summarizing why the study was done)*

There is increasing evidence that office design influences quality-of-life measures related to stress, physical problems, vitality, and overall sleep quality. However, the lack of an objective measure to capture changes in sleep quality over short time scales makes it difficult to establish relationships between attributes of office design and sleep outcomes.

Study Impact: *(two sentences summarizing how the study impacts the field)*

This study suggests benefits to sleep outcomes from open-bench seating via reducing stress during work hours leading to increased activity after work hours. In addition, we propose an innovative sensor-based sleep quality index (SB-SQI), which enables superior sensitivity in tracking sleep quality over short time scales compared to self-reported sleep quality for calculating relationships between office workstation types and sleep outcomes.

Key words: Sleep, Office workers, office workstation, wellbeing, stress, physical activity, wearables, digital health, sleep quality index, tracking sleep quality, workstation types, accelerometry, heart rate variability.

Introduction

Accurate assessment of sleep quality in office workers is critical since poor sleep quality is a major occupational health concern worldwide.[1] However, the impact of interior office design on sleep quality is often underestimated or poorly documented.[2, 3] A major obstacle to evaluating the impact of interior office design attributes on sleep quality is the lack of a method to measure those outcomes objectively.

Sleep problems among office workers are widespread, affecting an estimated 23 percent of workers in the United States.[4] It is well established that poor sleep is associated with a range of significant short-term impairments such as headaches, memory loss, and diminished attention, as well as long-term health consequences such as obesity, coronary heart disease, diabetes, hypertension, gastrointestinal problems, mental health, and depression[5-7]. Economic consequences of poor sleep quality could be also substantial. According to the Centers for Disease Control and Prevention (CDC), $226.4 billion could be added to the U.S. economy if individuals who slept under six hours started sleeping six to seven hours.[8] Several studies have also demonstrated the negative effects of poor sleep for economic impacts on employers. For example, Rosekind and colleagues[9] examined the impact of sleep disturbances on work performance/productivity by surveying over 4000 employees at four US corporations. Their results suggest that workers with insomnia had significantly worse productivity, performance, and safety outcomes. The same study reported $54 million ($1967/employee) in annual economic losses because of poor sleep for the entire work population at the participating companies. Poor sleep also increases health care services utilization, leading to $15 billion in health care costs each year,[10] as well as many other negative consequences such as greater absenteeism, increased use of sick leave, and poor job satisfaction.[11]

A wealth of evidence supports the link between occupational factors (e.g., prolonged sitting, indoor air quality, daylight/window, and work related stress) and sleep quality.[12-14] However, the effects of office design and their contributing factors on sleep quality are poorly understood possibly in part because of lack an objective tool with sensitivity to track changes in sleep quality over short time scales. Many prior studies linking workplace to sleep quality are based on questionnaires or surveys. Such assessments have several major limitations such as subjectivity, lack of sensitivity over short time scales, and ceiling problems. Since changes in office design may lead to subtle, often imperceptible, and cumulative effects, these tools are unable to fully capture the impact of individual design decisions.

Advances in wearable technologies, biomechanical modeling of the human body, digital connectivity, and signal processing have opened new avenues for developing objective metrics to monitor wellbeing of individuals in real world conditions. Wearable technologies not only enable assessing wellbeing metrics (e.g., stress, physical activities, etc) during work and after work hours, but also allow quantifying sleep parameters and tracking daily fluctuations in sleep patterns. Recent advances in signal processing and sensor technology have also improved accuracy of measuring sleep parameters, such as sleep onset latency, sleep efficiency, and time-in-bed compared to the gold standard of a sleep lab assessment (i.e., polysomnography or PSG), opening up the opportunity to accurately determine sleep quality outside the sleep lab.[15] Such technologies have been successfully examined the effect of indoor environment (e.g., air quality, light) on sleep quality.[2, 3, 13] However, these studies only focused on one or two independent sleep-related parameters. In other words, no method to date has been proposed to combine objectively measured sleep parameters of interest into an overall sleep quality index.

In this study, we propose a sensor-based sleep quality index (SB-SQI) inspired by the Pittsburgh Sleep Quality Index (PSQI),[16] merging several different sensor-based sleep-related parameters to calculate overall sleep quality. Using this objective metric, we examined relationships among office workstation types (open-bench seating, cubicle, and private) on sleep quality. We hypothesized that office workstation type impacts stress during work hours leading to sedentary behavior after work hours, which in turn results in poor sleep quality.

Methods

Participants

White-collar workers involved in a variety of office-based roles for the US government

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were recruited across four federal office buildings in the Northeast and Southern regions of the United States. Inclusion criteria included any ambulatory volunteer working in one of the designated federal office buildings and committed to compliance with the protocol of the study. Exclusion criteria included pregnancy, volunteers unable to participate over the full duration of the study (three consecutive days), and those with a pacemaker or insulin pump. Participants provided informed consent prior to this study and then completed orientation and training. The study was approved by the University of Arizona institutional review board.

Participants wore a light-weight (26 grams, width: 62.3 mm, height: 38.6 mm, and depth: 11.5 mm) chest sensor (EcgMove 3, movisens GmbH, Karlsruhe, Germany) for three consecutive days, including two consecutive nights. In our previous studies, we demonstrated that this duration would be sufficient to extract reliable data about activity monitoring and yield the highest adherence to wearing the sensor at all times.[17, 18] The sensor includes a tri-axial accelerometer, a uni-channel electrocardiography (ECG), and a temperature sensor. This sensor configuration, together with validated algorithms designed by our team, enabled assessment of adherence to wearing the sensor (using a combination of temperature and accelerometers),[19] physiological stress response (using the ECG sensor),[20] physical activities (using the accelerometer sensor),[21-23] and nighttime sleep quality (using the accelerometer sensor).[21]. Based on the participant's preference, the sensor was attached with either two standard ECG electrodes adhering directly to the subject's skin or a chest-worn ECG belt. Participants were asked to wear the sensor continuously, except when showering, swimming, or if they experienced discomfort. Participants were instructed on how to reattach the sensor if it was removed for any reason. Using a validated algorithm,[17] adherence to wearing the sensor was objectively monitored and data associated with sensor-detachment were excluded from final data analysis. The study coordinator verified the sensor's placement on a daily basis during work hours and provided additional instructions if needed. The battery life of the sensor supported continuous monitoring for three days without recharge.

Office Workstation Types

While many office design factors could contribute to health and wellbeing of office workers, this study focused on association between office workstation type and measures of stress, physical activity, and sleep. We hypothesized that office workstation types characterized by more open and less compartmentalized planning might encourage social and collaborative interaction, which in turn could reduce stress, enhance physical activity, and contribute to improved sleep quality. In this study, participants worked at three different office workstation types: (1) private offices (completely walled enclosure), (2) cubicles (high-walled partitions that one cannot see over while seated, and (3) open-bench seating (no partitions or partitions that are readily seen over while seated).

Wellbeing Parameters of Interest

To quantify the impact of office workstation type on wellbeing, we objectively quantified physiological stress responses, physical activity, and sleep quality using the wearable sensor. We hypothesized that those working at open-bench seating workstations (the office design than may encourage social and collaborative interaction) have less stress during work hours compared to those in other office workstation types, leading to less sedentary physical activity after work hours and an increased likelihood of high sleep quality. Sleep quality was assessed objectively using sensor-derived sleep parameters and subjectively using PSQI. Other assessments included perceived stress, anxiety, and office air quality, including relative humidity, CO_2, CO, temperature. But these additional assessments were not considered for the purpose of this study.

Objective Quantification of Sleep: Sensor-Based Sleep Quality Index (SB-SQI)

Our team designed a validated algorithm[15] to extract sleep quality parameters of interest from the chest-worn sensor, including sleep onset latency, sleep duration, and sleep efficiency. According to our previous study, in comparison with polysomnography in a controlled sleep lab, these parameters could be extracted with an average accuracy of 86 percent, which is higher than wrist-worn sensors due to the added value of body posture and body acceleration.[15] To calculate sleep quality from the independently measured sleep parameters, we used the suggested PSQI benchmarks to score each parameter (Figure 1). The PSQI includes seven major components, three of which (sleep onset latency, sleep duration, and sleep efficiency) are similar to senor-measurable parameters. In the PSQI, these sleep components are categorized based on participants' self-reported values. Because we objectively measured three sleep components, we graded these sleep components using actual values instead of self-reported numbers. Each sleep component was then weighted on a 4-point scale ranging from 0 (no problem) to 3 (severe problem) as suggested by PSQI benchmarks. For example, sleep duration was graded as 0, 1, 2, and 3, if the measured duration of sleep was over 7 hours, between 6 to 7 hours, between 5 to 6 hours, and below 5 hours,[16] respectively (Figure 1). We merged these three measured sleep parameters into a single index—the sensor-based sleep quality index (SB-SQI)—with a range of 0 to 9 points, where 0 indicates no problems and 9 indicates severe problems. To determine good sleep and poor sleep, we used a linear interpolation to match the SB-SQI scale (0-9) to the cutoff point score of 5 or greater based on the PSQI scale (0-21).[16] This interpolation resulted in a cutoff score of 2 or greater for the SB-SQI. To verify this cutoff point, the interpolated value was compared to the median value of SB-SQI estimated from all participants. We also estimated semi-PSQI, which includes all PSQI components except the three measurable components (sleep onset latency, sleep duration, and sleep efficiency) replaced by SB-SQI. A chi-square test was used to calculate significant differences between the two evaluation methods for determining poor sleepers. Furthermore, the correlation between PSQI global score and a semi-PSQI was analyzed. To examine interactions between stress during work hours, activity level after work hours, and sleep quality, we calculated sleep quality using SB-SQI during the night before and the night after work hours.

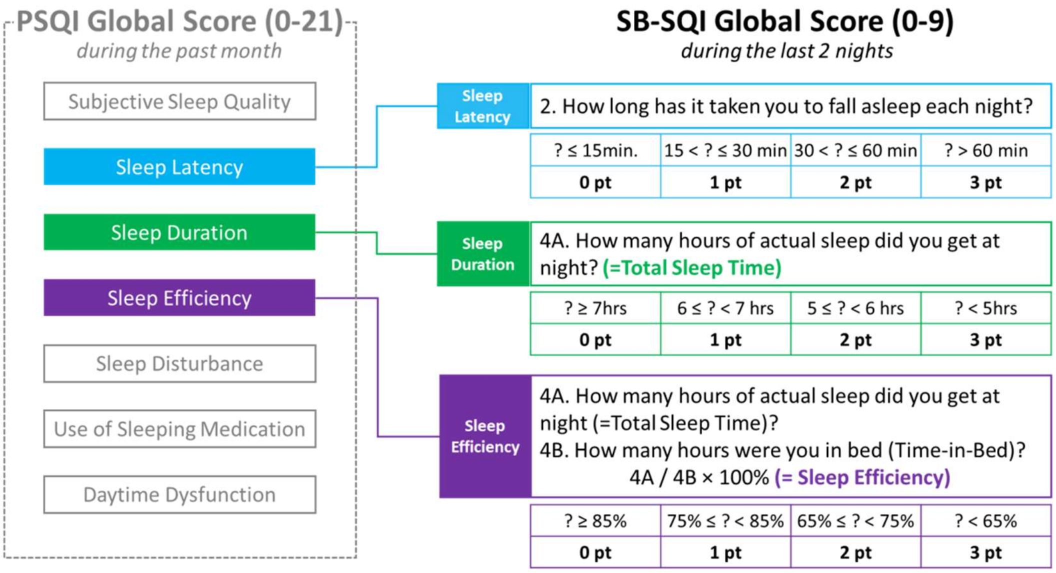

Figure 1. Definition of the Sensor-Based Sleep Quality Index (SB-SQI) Score from the Benchmark Suggested by the Pittsburg Sleep Quality Index (PSQI)

Measuring the Physiological Stress Response

To quantify the physiological stress response during work hours, we used ECG signal recorded by the chest-worn sensor. The physiological stress response was quantified by a standard time-dependent measure of heart rate variability (HRV), in particular, the mean of the 5-minute standard deviation of the normal-to-normal sinus RR intervals (SDNN index) in the ECG signals.[24] HRV was extracted using validated algorithms described in our previous studies.[20, 25] The SDNN index measures autonomic influence on HRV[26] and is regarded as a marker of cardiovascular risk (e.g., hypertension, cholesterol, congestive heart failure), sleep apnea, diabetes, and psychological health outcomes (depression).[27-33] Lower SDNN values indicate the presence of a physiological (sympathetic nervous system) stress response while higher SDNN values are considered healthier.[34]

Measuring Physical Activity

To quantify physical activity levels after work hours, three-axis accelerometer data were collected from chest-worn sensors using the algorithms described in previous studies.[21, 22] The physical activity levels were then quantified to four categorical activity levels (sedentary, light, moderate, and vigorous activities) for each 6-second segment using a validated algorithm and recommendations described in previous studies.[35, 36] Finally, the percentage of moderate-to-vigorous (MtoV) activity levels after work hours and before bedtime was calculated for each day for each participant.

Statistical Analyses

Statistical analyses were conducted to examine relationships between office workstation types and sleep quality. The chi-square test was performed to assess the likelihood of poor sleep in three different office workstation types for two nights. Analysis of variance (ANOVA) was performed to assess (1) the effect of office workstation types on sleep quality and (2) the effect of MtoV activity level after work hours on sleep quality for different office workstation types. Two reciprocal effects were analyzed: (1) the effect of stress at work on sleep quality that night (data for day 1-2 and night 1-2 were examined) and (2) the effect of sleep quality on stress at work the next day (data for night 1-2 and day 2-3 were analyzed). We applied Pearson's correlation to assess the relationship between stress on work and MtoV activity level after work hours for different office workstation types (data for day 1-2 were considered for analysis). ANOVA and correlation analyses were controlled for age, BMI, gender, and the season during which participants were observed. Statistical significance was considered at $p < 0.05$, and effect sizes (Cohen's *d*) were also calculated for group comparisons.

Results

Descriptive Statistics

A total of 231 white-collar office workers participated in this study and 163 (70.6%) of these participants were considered for the purpose of this study after the data with missing demographic information and unusable sensor data were excluded. Participants' demographic characteristics are described in Table 1.

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Table 1. Demographic Characteristics

Variables	Values	Units
Participants, *n* (%)	231 (100)	
Missed, *n* (%)	68 (29.7)	
Analyzed, *n* (%)	163 (70.6)	
Gender		
Female, *n* (%)	90 (55.2)	
Male, *n* (%)	73 (44.8)	
Age, mean (SD)	44.3 (12.0)	yrs
BMI, mean (SD)	27.6 (5.6)	kg/m^2
Season		
Spring & Fall, *n* (%)	47 (28.8)	
Summer, *n* (%)	65 (39.9)	
Winter, *n* (%)	51 (31.3)	
SDNN index at work		
Day 1, mean (SD)	51.6 (17.2)	ms
Day 2, mean (SD)	50.9 (16.5)	ms
Day 3, mean (SD)	52.0 (17.7)	ms
MtoV activity after work hours		
Day 1, mean (SD)	6.9 (5.8)	%
Day 2, mean (SD)	6.5 (5.6)	%
PSQI global score (of 21), mean (SD)	6.3 (3.2)	
SB-SQI score (of 9), mean (SD)		
Night 1, mean (SD)	2.4 (1.4)	
Night 2, mean (SD)	2.5 (1.7)	

Agreement between SB-SQI and PSQI

A high agreement was observed between PSQI global scores and the semi-PSQI global scores (r = 0.704, p < 0.001, Figure 2). Using a linear interpolation technique and considering the cut point of 5 on the 21-point PSQI scale for defining poor sleepers, a cut point of 2.1 on the 9-point SB-SQI was selected for estimating poor sleepers. The median SB-SQI global score calculated from all participants was 2.0, which was close to the cut-point value of 2.1 estimated using a linear interpolation. According to the PSQI data, 71.2% (116 of 163) of our participants had poor sleep quality. Using SB-SQI and the cut point estimated above, 73.7% (132 of 179) and 67.9% (114 of 168) of participants were

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classified as poor sleepers in the night 1 and night 2 measurements, respectively. A significant agreement ($r = 0.70$, $p < 0.001$, Figure 2) was observed between PSQI and semi-PSQI. When poor and good sleepers were classified using PSQI, a significant between groups difference ($p = 0.043$) was also observed for SB-SQI. Taken together, the results suggest an agreement between the two sleep quality instruments to identify poor sleepers.

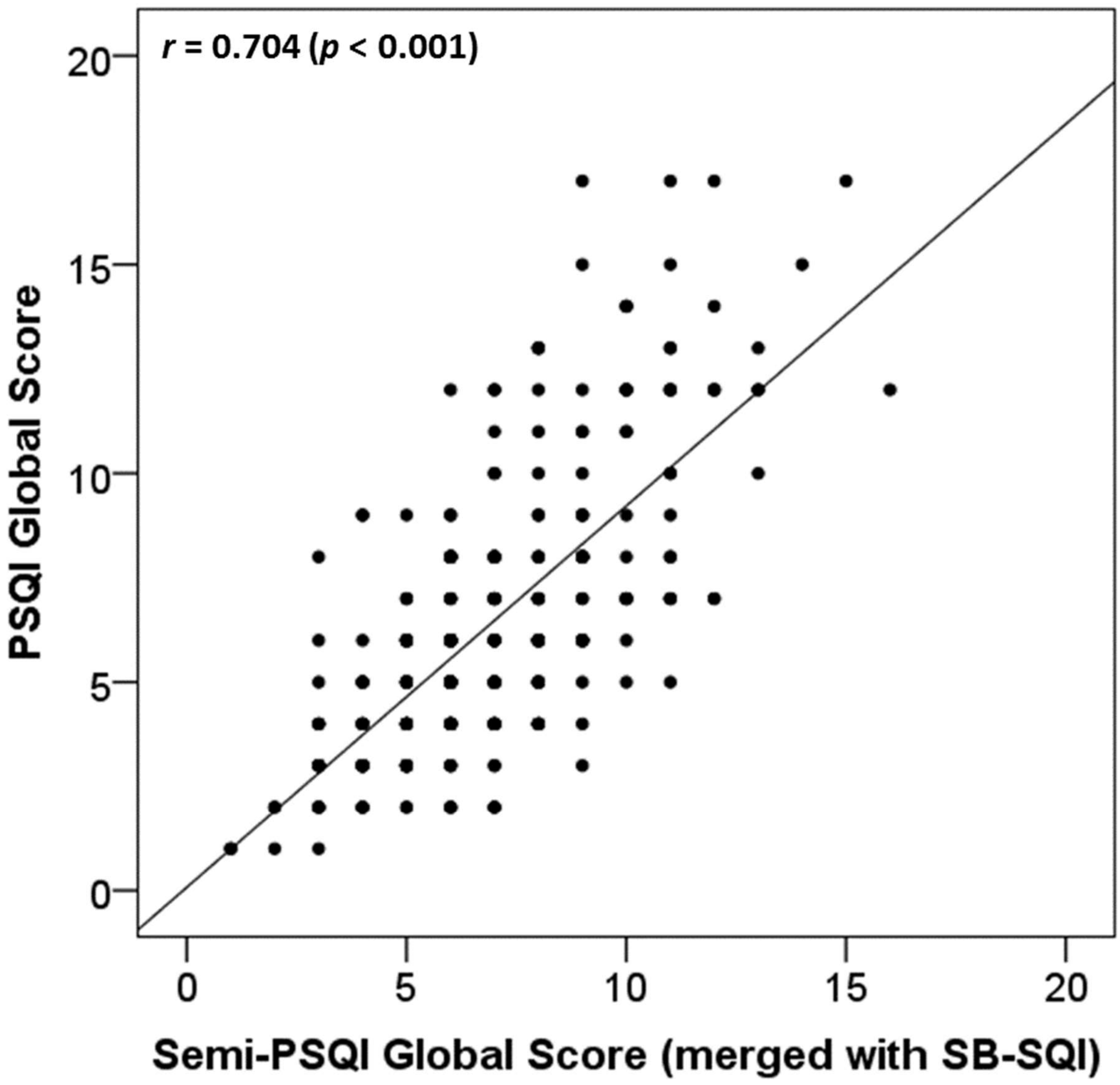

Figure 2. Significant agreement between PSQI and semi-PSQI Global Score (sensor-derived PSQI)

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Sleep Quality and Office Workstation Types

Overall, irrespective of office workstation types and type of instruments used, more than 60% of participants had poor sleep (Figure 3). Results, however, revealed that the likelihood of poor sleepers may increase depending on office workstation type. The difference between office workstation type is more pronounced when poor sleepers are classified using SB-SQI, with significantly higher likelihood of poor sleep for those who are working in private office workstations compared to other office workstation types (81.0% vs. 66.1%, $p = 0.023$, Figure 3b).

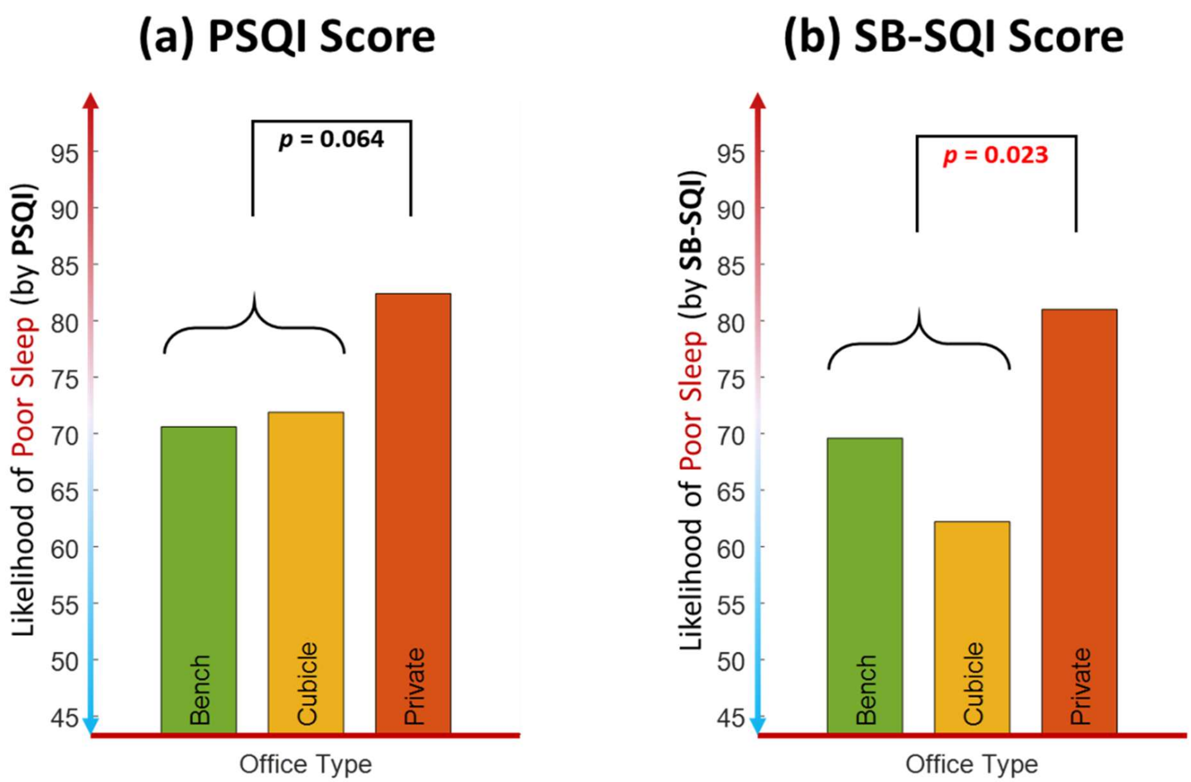

Figure 3. Likelihood of Poor Sleep as a Function of Office Workstation Type. SB-SQI is more sensitive for discriminating between private office workers and other office workstation type workers

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The Impact of Sleep Quality during the Preceding Night on Stress during Work Hours

Figure 4 illustrates the effect of sleep quality (quantified using SB-SQI during the night before) on objective stress (quantified by SDNN index) during work hours. Results suggest that those who had poor sleep quality the night before work had 9.3% higher stress during work hours (p = 0.012, d = 0.35, Figure 4a). Interestingly, those who were working in open-bench seating exhibited less stress than those in other office workstation types, a finding that was driven by the difference in stress only among good sleepers (Figure 4b). Overall, the association between office workstation type and stress level during work hours was dependent on sleep quality during the preceding night. Specifically, open-bench seating workers who had good sleep had a significantly higher SDNN index (less stress) during work hours (p = 0.018, d = 0.65) than open-bench seating workers with poor sleep quality. A similar trend was observed for cubicle workers (p = 0.065, d = 0.39). The largest effect size was observed between open-bench seating workers and private office workers when both groups had good sleep quality (d = 0.78). A similar trend was observed between cubicle workers and private office workers, with an effect size of d = 0.54, when both groups had good sleep quality.

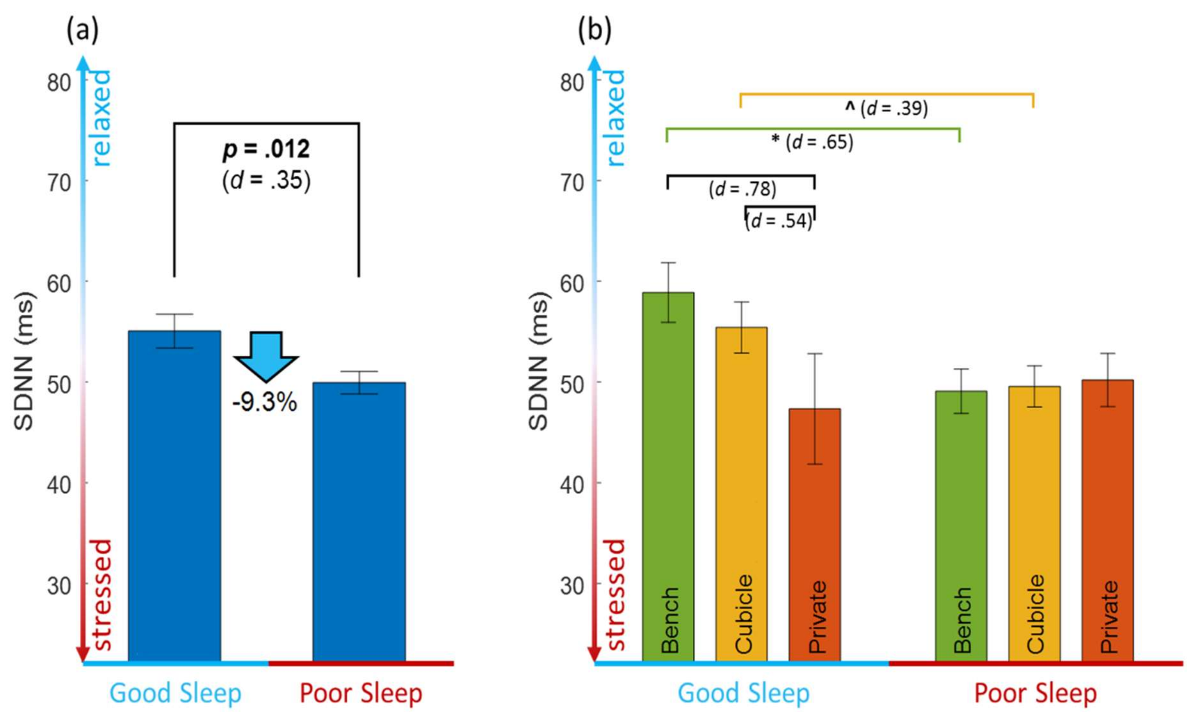

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Figure 4. Effect of Sleep Quality on Stress during Next Day Work Hours (a) stress during work hours was higher among poor sleepers. (b) The negative impact of poor sleep quality on stress is independent of office workstation type. However, office workstation type could negatively impact stress levels in good sleepers. All results were adjusted for participants' demographics and season.

The Impact of Sleep Quality during the Preceding Night on Activity Levels after Work Hours

Figure 5 illustrates the association between sleep quality the previous night and activity levels after work hours. Results suggest that poor sleepers tend to have on average 15% less MtoV after work hours compared to good sleepers. But after adjustment for participants' demographics (i.e. age, gender, and BMI) and season, the between group difference didn't achieve a statistically significant level in our sample (p = 0.127, d = 0.24, Figure 5a). Poor sleepers also had a lower level of MtoV activities after work hours irrespective of office workstation type (Figure 5b). However, office workstation type had a noticeable effect on after work hours MtoV activities among good sleepers. In particular, open-bench seating workers who had good sleep quality tended to be more active after work hours compared to other groups. The largest effect size was observed between open-bench seating and cubicle workers (d = 0.57), when both groups had good quality of sleep.

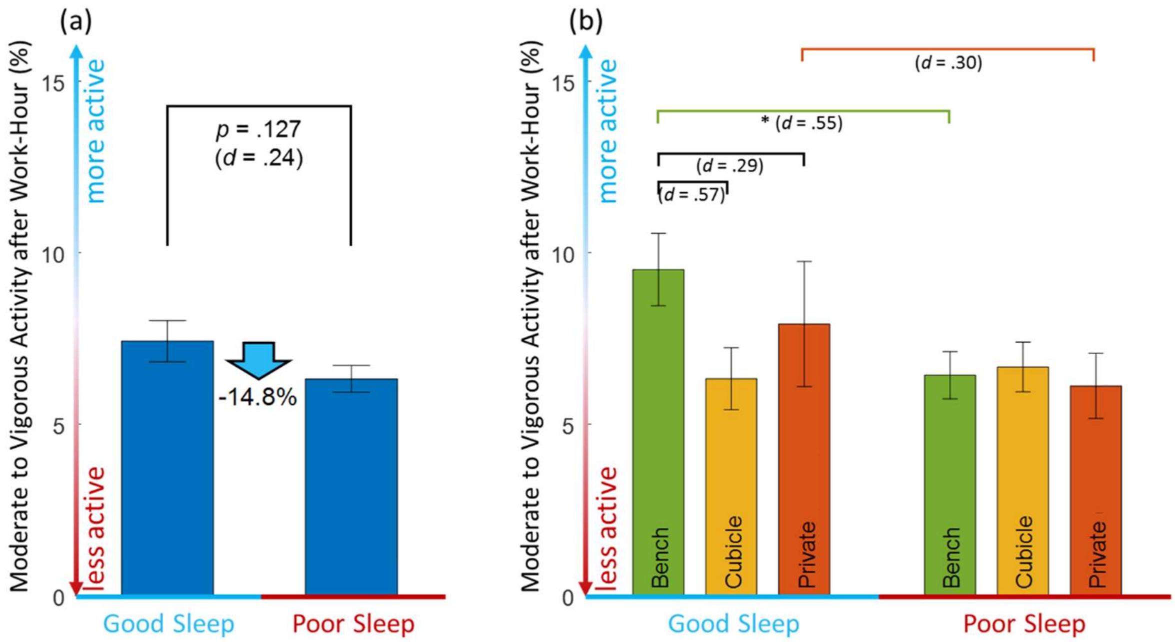

Figure 5. Effect of Sleep Quality during Previous Night on Activity after Work Hours: (a) Poor sleepers were less active the next day than those with good sleep quality and (b) poor sleep negatively impacted the level of activity after work hours irrespective of office workstation type after adjustments for participants' demographics and season. Open bench seating workers with good sleep quality were the most active group in our sample.

The Impact of Stress at Work on Physical Activity Levels after Work Hours

Figure 6 illustrates the association between stress at work and physical activity level after work hours. Overall a significant correlation was observed between stress at work and MtoV activity after work hours after adjustment for participants' demographics and season ($r = 0.331$, $p < 0.001$, Figure 6). The results confirm that lower stress during work hours is associated with a higher physical activity level after work hours. This association is slightly stronger among open-bench seating workers ($r = 0.383$, $p < 0.001$) and weaker among private office workers ($r = 0.247$, $p = 0.059$).

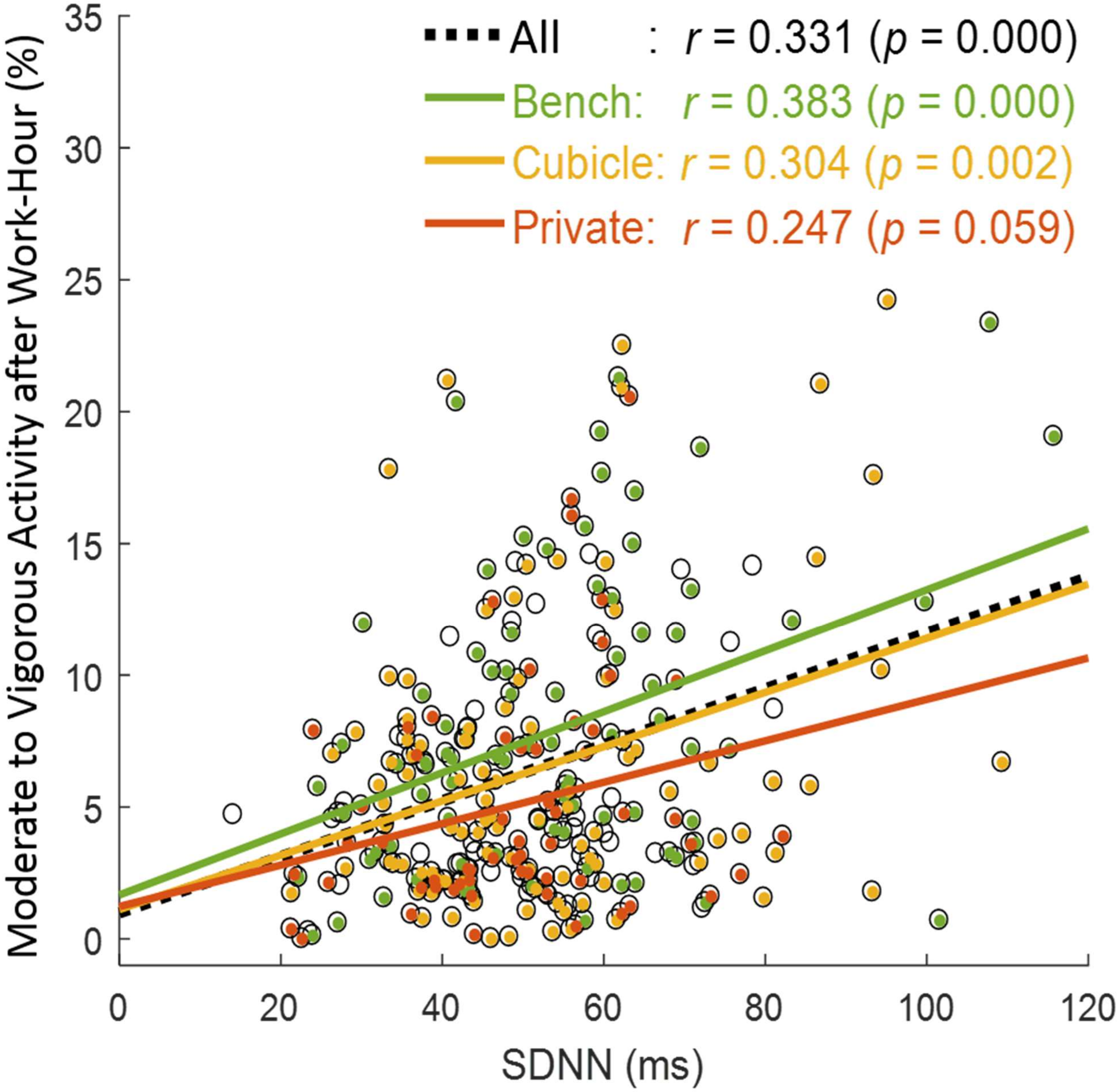

Figure 6. Association between Stress at Work and Moderate-to-Vigorous Activity after Work Hours

The Impact of Stress at Work on Same Night Sleep Quality

Figure 7 demonstrates the impact of stress during work hours on sleep quality for the same night. Results suggest that those who had good sleep after work had 8.4% less stress at work (p = 0.018, Figure 7a). In addition, among good sleepers after work, the level of stress during work hours was lowest among open-bench seating workers compared to workers in cubicles and private offices (Figure 7b).

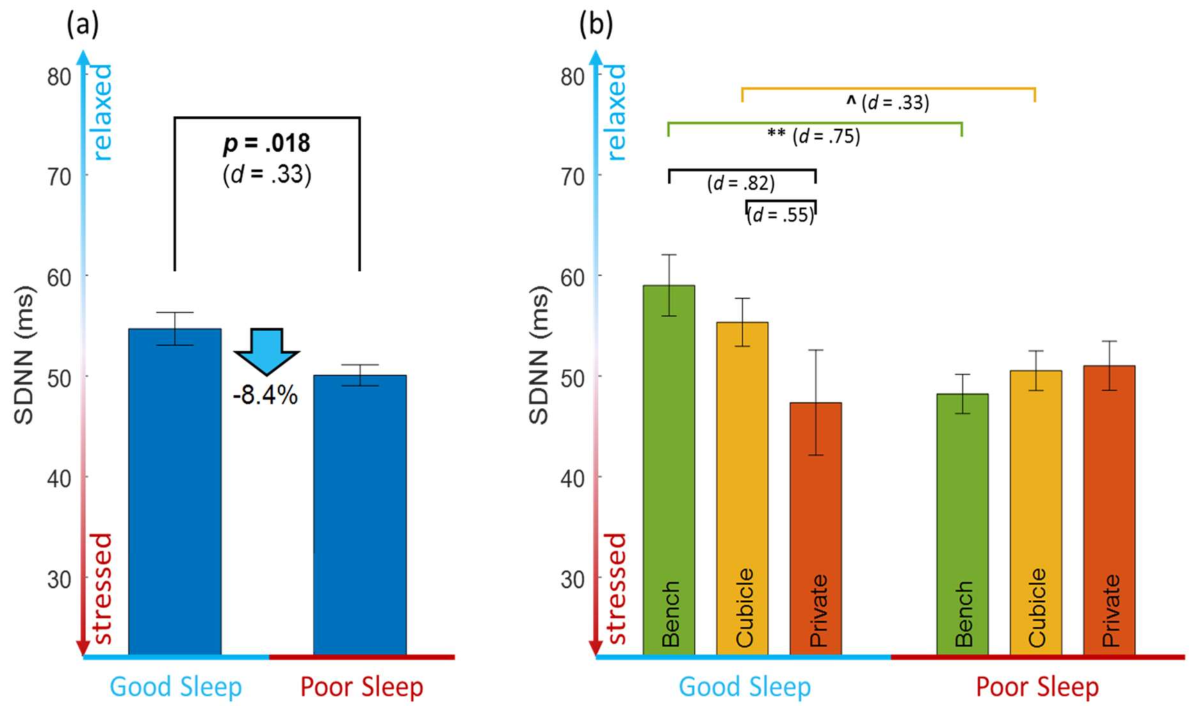

Figure 7. Effect of Stress at Work on the Sleep Quality that Night: (a) those with higher stress tend to have poorer sleep quality (b) Among good sleepers, stress level was lowest in open-bench seating workers.

Discussion

This study proposed the sensor-based sleep quality index (SB-SQI) as a new method to objectively quantify sleep quality using a wearable sensor and also tested this method's ability to examine the effect of workplace design on sleep quality. We found that assessing sleep quality by SB-SQI is comparable to PSQI but with greater sensitivity to reveal the impact of interior office design on sleep quality.

Using this new sleep quality assessment method (SB-SQI), we analyzed the impact of office workstation type on sleep quality over short time scales (i.e., night to night). To our knowledge, there is no existing literature investigating the association between work hours stress, after work hours physical activity, and sleep quality for workers in different office workstation types. This study showed that the sleep quality of office workers in open-bench seating and cubicles was significantly better than those in private offices. This difference appears to be linked to level of stress during work hours, which was the lowest among open-bench seating workers in our sample. We speculate that working in open-bench seating may encourage shorter unbroken sitting bouts. This may be due to several factors, including the need to move to different types of work stations for different types of work (e.g. quiet room, conference room) and higher likelihood of unplanned socialization with coworkers compared to workers in cubicles and private offices. This in turn may help reduce stress during work. Less stress during work may lead to more motivation for physical activity after work hours, which promotes better quality of sleep. These hypotheses are supported by the following findings in our study.

First, the results revealed that the likelihood of having poor sleep is higher among those who were working in private offices (Figure 3b). Among those who slept well the previous night, private office workers had the highest level of stress and open-bench seating workers had the lowest level of stress during work hours (Figure 4b). Those who had good sleep had significantly lower stress during same day work hours (Figure 7a). These observations are in line with previous findings suggesting that stressful experiences on the job are associated with poor sleep quality,[37] and that poor sleepers experience higher levels of stress.[38] Together, we speculate that office workstation type may impact stress levels during work hours, which in turn may impact sleep quality. Because this study was observational, we cannot confirm causality and, thus, this hypothesis needs to be confirmed in a prospective intervention study over a longer period of monitoring.

Second, having lower stress during work hours was associated with higher physical activity levels after work hours (Figure 6). Physical activity level after work hours was also affected by the office workstation type, particularly among good sleepers and those who worked in open-bench seating (Figure 5b). Furthermore, those who had better sleep the night before tended to have higher physical activity levels after work hours. Together, the association between stress during work hours and sleep quality could be explained by physical activity level after work hours. This observation may also explain the effect of office workstation type on sleep quality. For instance, according to our results summarized above, working in open-bench seating may help to reduce stress during work hours (Figure 4b), and lower stress could also motivate more physical activity after work hours (Figure 6), which in turn may lead to better sleep quality after work. These observations are consistent with the findings of previous researchers who demonstrated a significant association between physical activity and sleep quality.[39, 40] At the same time, however, high stress during work hours may affect workers' sleep quality, thus negating any benefits of office workstation type. Therefore, the results indicate that there is a potential for a deleterious cycle of negative health consequences fueled by high stress and poor sleep quality. This hypothesis needs to be validated in prospective studies over longer monitoring periods.

Compared with prior literatures, the current study extends sleep assessment beyond qualitative and perceived assessment tools (e.g., PSQI). In this study, we demonstrated that, in agreement with self-reported PSQI, SB-SQI, which enables objective quantification of sleep quality, also distinguishes between poor and good sleepers. However, our results suggest that SB-SQI is more sensitive in detecting the effects of office workstation types on sleep quality. In particular, it enables tracking sleep quality over short time scales (e.g., night to night v. 30 days in PSQI). In future studies, SB-SQI derived from the chest-worn sensors could include additional measurable sleep related features not yet explored in this study, such as heart rate variability during sleep time, respiration rate, and body temperature. These additional sensor-derived parameters may enable estimating other key sleep parameters, such as sleep stages and light/deep sleep.[15] Furthermore, the sensor enables automatic tracking of both physical and physiological parameters (e.g., stress) over the span of the entire night, unlike perceived sleep assessment tools which require respondents to consider their past month of sleep. Using objective assessments instead of self-report could be an especially critical improvement in sleep quality assessments for populations with cognitive impairments, who may be unable to self-report. For instance, previous studies have shown that the current perceived sleep assessment tools are not significantly associated with the gold-standard sleep assessment (PSG).[15, 41-43] Our previous study suggested that the sleep parameters measured by the chest-worn sensors are significantly correlated with similar parameters measured in a sleep lab by PSG.[15] Thus SB-SQI based on the chest-worn sensor is therefore valuable for objective assessment of daily sleep quality and is more sensitive to change than perceived sleep quality assessment (e.g., PSQI).

Although this study has shown the benefits of using SB-SQI for objective assessments of sleep quality, several limitations remain. First, the usable data samples were limited due to low signal quality of the sensor in several participants. Some of participants' data were missing due to the sensor being detached by the user, or had a low quality signal (in particular, the ECG data) due to motion artifacts or electrode malfunction. Some of the subjects also failed to complete the PSQI survey or complete demographic information (e.g., age, gender, or BMI). A further study with increased sample size is needed to generalize the results. Second, the results were not adjusted for job description of participants (e.g., managerial, technical, computer-dominant). The type of work may have some impact on stress, sleep quality, and activity level, which were not controlled in this study. Third, while the results were adjusted by season, we did not control for geographical location because of the small sample size. Geographical location of participants may bias some of our observations. For instance, those working in the South may have different seasonal physical activity behavior than those who are working in the Northeast. Fourth, the duration of monitoring (two nights and three days) may not be sufficient to truly highlight the effect of office workstation type on sleep quality. However, it may help to understand potential short time scale (night to night) interaction between sleep quality, stress during work hours, and physical activity levels after work hours. Finally, future studies are needed to explore the causal relationship between interior office designs and sleep quality using interventional study designs, over a longer period of monitoring.

In conclusion, we proposed an objective tool for assessing sleep quality (SB-SQI) using a chest-worn sensor with workers at three different office workstation types. This study suggests that SB-SQI could be used as an objective tool to evaluate sleep quality over short time scales (e.g., night to night), which in turn may assist in objective tracking sleep quality changes in response to daily events (e.g., stress during day time) without the need for any questionnaires or daily diaries. From an application standpoint, the proposed SB-

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SQI is applicable to wearable platforms, such as mobile app (e.g., smartphone or smartwatch) with the chest-worn sensor. Utilizing SB-SQI in conjunction with the methods already developed for measuring PA and HRV, our results suggest that workers' stress, physical activity, and sleep are all related, yet office workstation type seems to affect this relationship in good sleepers. Specifically, those working in open-bench seating had the least stress during work hours, leading to more physical activity after work hours and better quality of sleep than workers in cubicles or private offices. Finally, our study provides important insights for wellbeing in office workers that may affect both short- and long-term health outcomes, and their associated economic impacts.

Abbreviations:

SB-SQI: Sensor-Based Sleep Quality Index

PA: Physical activity

PSQI: Pittsburg Sleep Quality Index

CDC: Centers for Disease Control and Prevention

PSG: Polysomnography

ECG: Electrocardiography

BMI: Body Mass Index

CO2: Carbone Dioxide

CO: Carbon Monoxide

HRV: Heart Rate Variability

RR: Beat to Beat interval

SDNN: Standard Deviation of the Normal-to-Normal sinus RR intervals

MtoV: Moderate to Vigorous

ANOVA: Analysis of Variance

SD: Standard Deviation

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