Indoor Environmental Quality and its Effects on Human Sleep Quality

Hagen Fritz Kerry Kinney, PhD David Schnyer, PhD

Student Member ASHRAE

Zoltan Nagy, PhD

Associate Member ASHRAE

Abstract

Sleep is essential for multiple aspects of a person’s well-being and can be affected by components of a person’s physical and mental states in addition to the environment they sleep in. To date, the majority of research analyzing the relationship between a person’s sleep quality and indoor environment focuses on environmental parameters such as temperature, relative humidity, light, and noise. However, in recent years, a few key studies have identified indoor air quality (IAQ) as a potential contributor to sleep quality. The recent interest in IAQ’s effect on sleep quality has been sparked by the introduction of multiple affordable sensing technologies in both the IAQ and sleep quality fields. In this study, we combine five, commercially available IAQ sensors into one device that we provide to participants to measure their IAQ in addition to temperature, relative humidity, and light. Participants are provided with wearable sleep monitoring devices and are also asked to fill out four-question surveys in the morning to get a sense of two types of sleep quality: device-monitored and self-reported. We found that certain pollutants such as NO2, CO, and PM2.5 altered device-monitored sleep metrics like sleep efficiency when comparing nights with low versus high pollutant concentrations. When considering self-reported sleep metrics, we found that participants rated their sleep as more restful when CO2 concentrations were low, but we did not see this relationship with any other measured pollutant. Results from our study indicate that there is merit in measuring both types of sleep quality in regard to multiple air pollutants rather than just CO2, which is the pollutant focused on in other, similar studies of IAQ’s effect on sleep quality.

introduction

Achieving an adequate amount of good-quality sleep is essential for human health and well-being, including physiological processes, emotion regulation, physical development, quality of life (Hirshkowitz et al., 2015), and improving next-day performance (Gomes et al., 2011; Pereira et al., 2015). Lack of and disturbed sleep have been linked to negative health outcomes including obesity (Beccuti and Pannain, 2011), cardiovascular-related diseases (Cappuccio and Miller, 2017), and reduced life expectancy (Cappuccio et al., 2010). Achieving and maintaining sleep is a complex process that involves a variety of neurotransmitters and other signaling chemicals in conjunction with multiple organs in the human body. The primary internal influences affecting sleep include physical ailments like head and body aches in addition to a person's mental state such as feeling stressed, anxious, or depressed (Tsuno et al. 2005; Uhde et al., 2009). Primary environmental factors known to affect sleep include light, noise, and thermal comfort. Light's negative effect on sleep is a well-known phenomenon (Cho et al., 2013) as is the effect noises - soft, loud, constant, and intermittent - have on sleep (Hume et al., 2012). The relationship between thermal comfort and sleep also garners a considerable amount of attention including topics such as bedding insulation (Amrit, 2007), the relative humidity and temperature of the air (Lan et al., 2017), and a person’s internal body temperature (Kubota et al., 2002).

A potential external factor affecting sleep that has only recently received attention is indoor air quality (IAQ). Proper IAQ is paramount to the health of building occupants especially when considering people in developed nations spend, on average, 87% of their time indoors (Klepeis et al., 1995). Indoor air is comprised of a mixture of pollutants generated indoors from a variety of processes and those from outdoor environments that penetrate indoors via infiltration, natural ventilation, and/or mechanical infiltration. Pollutant profiles in the indoor environment can be quite different than those outside because of unique indoor sources and the amount of ventilation with outdoor air that is provided. In general, poor IAQ can exacerbate or induce many illnesses relating to the respiratory (Lévesque et al., 2018) and cardiovascular systems (Chuang et al., 2017) in addition to negatively affecting occupants' moods (Hummelgaard et al., 2007), and productivity (Mujan et al., 2019).

Under the current recommendation of 7 to 9 hours of sleep per night for adults, nearly one-third of a person's life is spent in a bedroom environment. Therefore, both acute exposures to air pollutants each night and the cumulative effects of these exposures are concerning. Recent studies have focused on characterizing the bedroom's IAQ by looking at chemicals and compounds emitted from bedding materials (Boor et al., 2017), the IAQ near the sleeping individual (Licina et al., 2017), and the concentration of pollutants in the bulk air (Zhang et al., 2018). These studies acknowledge the need for research that links the bedroom's environmental quality to the occupants' sleep qualities, but only a handful of studies have attempted to address this issue (Laverge and Arnold, 2011; Strom et al., 2016; Mishra et al., 2018; Liao et al., 2019; Xiong et al. 2020). Many common pollutants associated with the indoor and outdoor environment can inflame airways affecting respiration while sleeping leading to the development or increase in severity of breathing-related sleep disorders. Additionally, some pollutants can alter the development and/or structure of the brain (Lucchini et al., 2012; Costa et al., 2019) which might alter sleep architecture and quality.

There are two methods by which researchers can understand a subject's sleep quality: (1) through self-report measures like diaries or questionnaires administered before and/or after sleep, or (2) by using devices to derive key metrics of the subject's sleep. The gold standard for measuring sleep quality is through the use of polysomnography (PSG) which gives detailed information about a person's neurophysiological and cardio-respiratory state while sleeping. This information can be used to determine wake-fullness, rapid-eye-movement (REM) stages, and various non-REM stages. While PSG provides the most accurate measures of sleep quality, the method involves bulky machinery that may disrupt participants’ sleep, requires training to interpret the results, and is costly to conduct. To combat these issues, various companies have developed affordable wearable devices capable of measuring sleep quality. Newer products couple heart rate monitoring with movement detection to help estimate a few key sleep stages. These devices can provide useful insight into a subject's overall and gross sleep quality parameters (Haghayegh et al., 2019). In a similar fashion, rapid development of affordable sensing technologies has made measuring indoor environmental quality (IEQ) easier than ever before, sparking interest in measuring conditions within the bedroom microenvironment. Recent studies highlight that new, commercially available IEQ sensors can be distributed at scale (Bekö et al., 2010; Cheng and Li, 2018) and can be useful when measuring conditions over extended periods of time as they require less power and maintenance to operate than higher-grade instruments.

In this paper, we leverage commercially available sensing technologies to measure both IEQ and sleep quality to understand the relationship between these fields amongst college-aged students living in Austin, TX. We start by describing the IEQ monitor that combines many of these low-cost sensors into an all-in-one device. We continue by describing the study where these devices along with wearable fitness trackers are distributed to participants who are asked to rate their own sleep. Data from this study is presented and used to probe the question of IAQ's effect on both measured and self-report sleep quality. Our research is novel in that we are measuring multiple components IAQ the study population, which helps account for any confounding factors that might compromise the effects of IAQ on various sleep metrics measured by unobtrusive sleep-monitoring devices and ecological momentary assessments (EMAs).

Methodology

This research project was a subset of a larger study aimed at understanding student’s behaviors and environmental exposures throughout the course of their day using numerous affordable and mobile sensing technologies. Student participants were recruited across all disciplines from the University of Texas at Austin (UT) and underwent an initial screening before being consented into the study. By May 1st, 2020, a total of 71 participants were initially enrolled with two participants opting to drop out during the course of the study. Following enrollment, various devices were shipped to subsets of participants with instructions provided on how to set up and/or use them. Participants were instructed to go about their normal behaviors as devices passively collected data or participants were notified of surveys to complete. The study concluded when participants scheduled an exit interview with a study coordinator in early September 2020 and returned study materials back to UT.

Environmental Quality Monitoring

A one-time questionnaire was administered to participants to get an initial impression of their indoor environment such as pollutant exposures at home (smoking/vaping practices, pets, floor type, etc.) and cleaning habits (portable air cleaner use, disinfecting practices, etc.). To monitor the IEQ of the participants’ bedrooms during the study period, we developed, calibrated, and deployed our own open source, research-oriented monitoring device called the Building EnVironment and Occupancy (BEVO) Beacon. We distributed 30 of these devices to a subset of the original 71 participants. The BEVO Beacon, pictured in Figure 1, includes a single-board micro-computer wired to six affordable, commercially available sensors; one 250 mm X 250 mm (1” X 1”) cooling fan; and a battery-powered clock which keeps time if the device is not connected to the internet. The micro-computer is housed in a separate chamber from the sensors where a fan provides cooling to the processing unit. The six IEQ sensors are either exposed directly to the ambient air or have inlets that pull from outside the wooden housing. The sensors on the BEVO Beacon measure temperature, relative humidity (RH), light levels, carbon dioxide (CO2), particulate matter with aerodynamic diameters less than 2.5 (PM2.5) and 10 (PM10) micrometers, total volatile organic compounds (TVOCs), nitrogen dioxide (NO2), and carbon monoxide (CO). Each sensor attempts to take 5 readings over a period of 10 seconds, logs the average of these readings, and then sleeps for 50 seconds providing data at a one-minute resolution. Data are stored locally on the micro-computer but can be accessed remotely as long as the device is connected to WiFi.

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**Figure 1** Our all-in-one IEQ-monitoring device, the BEVO Beacon, and its five main IAQ sensors. Temperature and relative humidity are measured by the Carbon Monoxide and Nitrogen Dioxide sensors.

BEVO Beacons were shipped to participants on a rolling basis beginning June 1st, 2020 with the first device reaching its destination on June 3rd. After receiving the device, participants were asked to power-on the devices immediately. The BEVO Beacons were returned on a rolling basis starting September 1st, 2020.

Sleep Monitoring

As part of the study, all 71 participants were asked to download and use a smartphone application. The application is an open research platform (Torous et al. 2016) that provides digital phenotyping in the form of data collected from smartphone sensors and responses from EMAs. EMAs were sent to participants four times a week, twice a day: once in the morning at 9:00 am and again in the evening at 7:00 pm. Both EMAs asked participants to rate various components of their mood on a four-point scale. The morning EMAs also included four questions to help determine self-report sleep metrics, asking participants to estimate their total sleep time (TST), sleep onset latency (SOL), number of awakenings (NAW), and restfulness on a four-point scale (0 – not very restful; 3 – very restful).

Commercial fitness tracking devices were distributed to the same 30 participants who received a BEVO Beacon. Participants were asked to create or use their existing accounts, which were linked to a secure server. This particular fitness tracker included a heart rate monitor in addition to the standard accelerometer which helps to more accurately track sleep. Measurements obtained from the fitness tracker were used directly in addition to a few metrics derived from the sleep stage estimates produced by the fitness tracker. The primary sleep metrics include sleep efficiency (SE) defined as the percentage of time asleep when in bed and the ratio of REM stage sleep to all other stages i.e., non-REM (nREM).

Pre-Processing IEQ Data

When BEVO Beacons were returned, 3 sensors onboard each of the devices were calibrated jointly in a house environment against laboratory grade monitors including the CO2, NO2, and PM (of all sizes). From the calibration, a linear model was fit to help correct measurements from these three sensors.

For this study we were only interested in data collected during periods when participants were home and in their bedrooms. The fitness trackers log sleep data, including the start and stop time for any sleep event that the devices detect lasting a minimum of 3 hours. We used the start and stop timestamps to restrict the IEQ data from BEVO Beacons to only these periods. However, the fitness tracker is worn around the wrist and travels with the participant whereas the BEVO Beacon remains fixed in participants’ bedrooms. There could be instances where participants sleep in an environment other than the one the BEVO Beacon is monitoring. To correct for this, we cross referenced the addresses provided by the participants with GPS traces from the participants’ phones logged by the open research platform. We were then able to further filter the IEQ dataset to only include nights when the participants were asleep at their homes i.e., the same location the BEVO Beacon was monitoring.

Results

IEQ and Device-Monitored Sleep Quality

By filtering the IEQ dataset to only include nights with device-monitored sleep and GPS traces to confirm that participants were home, the dataset consists of a total of 278 nights of IEQ and sleep quality measurements across 15 unique participants. A significant amount of data was lost because participants might not have logged data from one of the three modalities (GPS from phone app, IEQ from BEVO Beacon, or sleep measurements from wearable), invalidating the remaining data from other modalities. Figure 2 shows the number of nights measured by each of the BEVO Beacons in addition to which sensors collected data for each of those nights.



**Figure 2** Number of nights of measurements for each of the 15 BEVO Beacons after filtering for device-monitored sleep events and GPS traces confirming participants and BEVO Beacons are co-located.

By looking on an aggregate basis, we can see if the distributions of device-monitored sleep metrics differ for nights when a measured parameter is low or high based on established or assumed thresholds given in Table 1. We determine if the measurement for a certain parameter is low or high depending on the median value measured during an individual’s sleep event. Figures 3 and 4 show the distributions of sleep efficiency and REM:nREM ratios, respectively, for each of the pollutants measured by the BEVO Beacon in addition to temperature. Numbers above each of the violin plots indicate the p-value from a t-test of means between the distributions. Values less than or equal to 0.05 are highlighted.

Table 1. Pollutant Thresholds for Determining Low/High Pollutant Levels

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  | Threshold | Organization | Notes | Citation |
| Temperature | 27°C /80.6°F |  | Median nightly concentration from study |  |
| TVOC | 200 ppb | WHO | Twice the sensory irritation limit | WHO, 2010 |
| CO2 | 1100 ppm | ASHRAE | Based on standard 62.2 | ASHRAE, 2019 |
| CO | 4 ppm | WHO | Based on minimum 24-hour exposure limit | WHO, 2010 |
| NO2 | 25 ppb | EPA and WHO | Half the EPA NAAQS (to account for indoors) and WHO 1-hour exposure limit | US EPA, 2010; WHO, 2010 |
| PM2.5 | 1.5 |  | Median nightly concentration from study |  |



**Figure 3** Distributions of SE for nights when IEQ parameters are below or above thresholds in Table 1. Values above the violin plots indicate p-values from a t-test on the difference of means between the two distributions.



**Figure 4** Distributions of REM:nREM for nights when IEQ parameters are below or above thresholds in Table 1. Values above the violin plots indicate p-values from a t-test on the difference of means between the two distributions.

IEQ and Self-Report Sleep Quality

Since EMAs were only administered four times a week and incur a larger burden on the participants relative to a wearable device, there are fewer observations when participants are home, asleep, and completed the EMA the following morning. Data availability is shown for the 192 nights across 16 participants in Figure 5. An additional participant is present compared to the device-monitored dataset because one of the sleep-monitoring devices was using an older operating system which invalidated the sleep metrics. However, the device was still able to detect the start and stop times of sleep events accurately.



**Figure 5** Number of nights of measurements for each of the 15 BEVO Beacons after filtering for device-monitored sleep events, GPS traces confirming participants and BEVO Beacons are co-located, and EMAs completed upon waking.

For the self-reported sleep metrics, we focus on two of the possible four: SOL, or the amount of time participants reported it took them to fall asleep, and self-reported restfulness on a 4-point scale. Following a similar analysis to that conducted for device-monitored sleep metrics, Figure 6 highlights any significant differences in the distributions of self-reported SOL for nights when concentrations of the measured IEQ parameters were low or high.



**Figure 6** Distributions of self-reported SOL ratios for nights when the given IEQ parameter value is below or above the thresholds given in Table 1. P-values from a t-test on the difference of means between the two distributions are given above the corresponding IEQ parameter.

Rather than look at restfulness on a four-point scale, we combine scores of 0 and 1 into a “negative” rating while 2 and 3 constitute “positive” ratings. Figure 7 shows how the measurements of the IEQ parameters from the BEVO Beacon differ for nights when participants rate their restfulness as either negative or positive.



**Figure 7** Distributions of median pollutant and temperature measurements for nights when participants rate their restfulness as either negative (0 and 1) or positive (2 and 3) on the morning EMA when they awaken. Only results where t-statistics on the means could be calculated between the distributions are included with p-values given above each violin plot.

Discussion

Effect of IEQ on Sleep Quality

**Device-Monitored Sleep.** When considering device-monitored sleep metrics, there appears to be a significant decrease in SE, according to the data in Figure 2, when concentrations of NO2, CO, and PM2.5 are elevated. There are no studies that explicitly study indoor NO2 or CO and device-monitored sleep quality, but PM2.5 has been studied and shown to negatively affect sleep efficiency according to PSG (Liao, 2019), confirming results found here. Alternatively, we see a significant increase in sleep efficiency at elevated temperatures which contrasts well-established knowledge and results in a recent, similar study (Xiong et al., 2020).

Based on results in Figure 3, TVOCs seem to increase the relative percentage of time spent in REM sleep compared to non-REM. TVOCs represent a complex and often unknown mixture of compounds so understanding the relationship between TVOCs on sleep quality is more nuanced, however recent studies indicate TVOCs do not produce significant changes in sleep quality when compared to PSG (Liao, 2019). Although some studies have hypothesized that NO2 could disrupt normal sleep architecture by interfering with neurotransmitters in the brain, the results here show no significant differences in the ratio of REM:nREM under low and high concentration nights. We do see that PM2.5 concentrations tend to reduce the ratio of REM:nREM sleep suggesting that perhaps PM2.5 is altering sleep architecture by either increasing severity of breathing-related sleep disorders or those associated with signaling in the brain. Important to note is that CO2 shows no significant differences in SE or REM:nREM ratios under low and high conditions which contradicts many of the results found in similar studies (Strom et al., 2016; Mishra et al., 2018; Xiong 2020) that use devices to monitor sleep quality. CO2 tends to be a good proxy for ventilation so we would expect some significant differences in sleep metrics especially considering other pollutants in our study exhibited significant differences between sleep metrics at low and high concentrations. Lastly, temperature show a significant decrease in the time spent in REM, which was recently corroborated (Xiong, 2020).

**Self-Reported Sleep.** Measurements of SOL proved to be lower amongst nights with elevated measurements of CO2, PM2.5, and temperature according to the data presented in Figure 6. This relationship suggests that people are able to fall asleep quicker when the concentrations of CO2 are elevated which is probable considering increased CO2 concentrations are known to cause subjective and objective indicators of drowsiness (Snow et al., 2018). Like CO2, PM has been implicated in causing fatigue in multiple studies of indoor environments, most notably offices (Nezis et al., 2019). While cooler temperatures might promote more efficient sleep, warming prior to bed has been shown to decrease SOL in young adults free of known sleep conditions (Raymann et al., 2007).

The effect of CO2 on sleep quality is significant when considering the restfulness scores from the EMAs. Figure 7 highlights that nights when participants rate their restfulness as poor, the median CO2 concentration for that night is significantly higher than when they rate their sleep more restful. The same relationship is apparent when considering the CO distributions although the difference in shape of the distributions is not nearly as dramatic as those of the CO2 results. Strom et al. (2016) reported significant improvements in participants’ restfulness scores when the CO2 concentrations were lower, while Mishra et al. (2018) found that increased concentrations of CO2 reduced the self-report depth of sleep but had no correlation to self-reported restfulness. Xiong et al. (2020) report no correlation between any self-reported sleep metric and CO2. When considering temperature and TVOCs, there is not significant difference between the distributions of measurements during negative and positive restfulness nights. For the remaining two pollutants, t-statistics could not be calculated and are not shown.

Conclusion

In this study we highlighted the importance of a properly controlled indoor environment as it relates to sleep quality. Many common indoor air pollutants like CO2 and particulate matter, which have been hypothesized to affect sleep through direct or indirect means, have been shown here to alter both device-monitored and self-reported sleep amongst a healthy, young adult population sleeping in their normal environment free from bulky monitoring equipment that might bias results. We also show that other, less-studied pollutants, like NO2 and CO might have equally important consequences on sleep quality. There also appears to be differences in IAQ’s effect on sleep quality when considering the type of sleep quality (device-monitored or self-report) measured implicating that studies should be conducted analyzing both measurements of sleep quality. We plan to continue to probe the relationship between indoor air pollution and sleep quality by monitoring different groups of individuals with more robust instrumentation to see if certain individuals’ sleep qualities are more or less susceptible to indoor air pollution.

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