Association between Indoor Air Quality and Sleep Quality

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ABSTRACT

The association between indoor air quality (IAQ) and sleep quality was investigated in this study. A total of 27 participants (14 males and 13 females, 20-33 yrs.) without any sleep disorders and chronic diseases were recruited and divided into two groups: a polysomnography (PSG) group and a non-PSG group. The IAQ was changed by opening or closing windows. There were two phases for the experiment and two nights in each phase including one adaptive night and one test night, and around one-week washout period between two phases. A questionnaire, Fitbit and home PSG – the Nox A1 (from Resmed) were used for measuring sleep quality. Bed temperature, ambient temperature, relative humidity, CO_2 levels, TVOCs, $PM_{2.5}$ and noise were recorded by different sensors during sleep. Mann-Whitney *U* tests and multivariate linear regression models were used for statistical analyses and individual differences between two phases were also analyzed. Higher ambient temperature, RH and CO_2 levels were monitored with the window closed compared to it open. The participants had on average a 0.87 point higher score on the Groningen sleep quality scale (GSQS) sleeping with the window open than with it closed. Higher $PM_{2.5}$ levels were associated with time awake (β, 95% CI: 1.546, 0.124 - 2.968; *p*-value < 0.035), percentage awake (β, 95% CI: 0.342, 0.091 - 0.592; *p*-value < 0.010) and sleep efficiency (β, 95% CI: -0.342, -0.592 - -0.091; *p*-value < 0.010). Higher ambient temperature was associated with the number of awakenings (β, 95% CI: 3.074, 0.331 - 5.816; *p*-value < 0.030). In conclusion, the participants reported better sleep quality sleeping with quieter surroundings (windows closed). Higher $PM_{2.5}$ level was associated with more time awake, higher percentage awake and lower sleep efficiency. Higher ambient temperature was associated with an increased number of awakenings.

KEYWORDS

Indoor air quality; Field study; Sleep quality; Fitbit; Polysomnography

1. INTRODUCTION

Human beings spend one-third time of a day sleeping. Although some people have a relaxed mood, and sleep in the bedrooms with low noise, moderate light and appropriate temperature, they cannot sleep well probably because of poor air quality.

There are only a few studies about indoor air quality (IAQ) and sleep quality, although some of them conclude that IAQ is related to sleep quality (Mishra et al., 2018; Strom-Tejsen et al., 2016). Mishra et al. (2018) conducted a field experiment where the IAQ was changed by opening and closing doors/windows and obtained that questionnaire-based depth of sleep ($p = 0.002$) and actigraphy-based sleep phase ($p = 0.003$) were significantly different between open and closed conditions. Better sleep depth, sleep efficiency, and fewer number of awakenings were found with lower CO_2 levels (Mishra et al., 2018). Strom-Tejsen et al. (2016) controlled the IAQ via opening and closing windows in a pilot experiment, while turning on and off the fans in a follow-up experiment. Sleep latency was significantly better with the window open ($p < 0.0480$) and sleep efficiency with the fan in operation ($p < 0.0494$). Also, subjective assessment of sleep quality improved.

Psychologic states and dietary habits are also significantly associated with sleep quality. Depressed mood is contributing to decreased overall sleep quality and sleep latency (Menefee et al., 2000; Owens and Matthews, 1998). Alcohol, coffee, tea and tobacco are all associated with sleep quality. The degree of correlation might be varied by important confounders, like dietary habits and lifestyles (Ogilvie et al., 2018). Regarding IAQ, higher ventilation rates indicate good IAQ and CO_2 could be an indicator for bedroom ventilation. In addition, indoor comfortable parameters, such as temperature (T) and relative humidity (RH) influence sleep quality (Caddick et al., 2018).

Indoor environmental parameters of ambient T, RH, CO_2, total volatile organic compounds (TVOCs), $PM_{2.5}$, noise and bed T would be monitored between the window closed and open. Meanwhile, both subjective and objective assessments would use to test the participants' sleep quality. The purpose of this study is to confirm the association between IAQ and sleep quality.

2. METHOD

A self-controlled case series method was used for two conditions with the window open or closed during sleep. Indoor environmental parameters were recorded by several types of indoor air monitors and also assessed by the participants via questionnaires. Fitbit, home polysomnography (PSG) and the Groningen Sleep Quality Scale (GSQS) were used to measure the participants' sleep quality. The abbreviated Profile of Mood States (POMS) and the Perceived Stress Scale (PSS) were performed at the test nights via a night questionnaire. In addition to sleep environment, the GSQS, the Karolinska Sleepiness Scale (KSS), and other questions were filled on the next day morning after the test nights via a morning questionnaire.

2.1. Study design

There were two phases for the whole test, two nights in each phase (the first an adaptive night and the second the test night) and around one-week washout period between two phases (Heo et al., 2017). Participants were divided into 2 groups: a polysomnography (PSG) group and a non-PSG group due to the limited number of PSG-monitors available. There were 4 participants doing the sleep tests at each night – two of them were in the PSG group and the other two were in the non-PSG group. Participants were asked not to have alcohol, caffeine drinks, tea, tobacco and intensive physical activities at least 12 hours prior to their bedtimes at the test nights.

2.2. Participants and base

The online questionnaires of the Pittsburgh Sleep Quality Index (PSQI) were sent to all the tenants that lived in the university dorm with the help from the dorm manager. Those interested in this sleep test filled and submitted the PSQI. 28 participants were selected based on 3 selection criteria - the PSQI score was less than or equal to 5, non-smokers, and no sleep disorders nor any chronic diseases. Four rooms furnished uniformly next to each other were rented in the same university dormitory in April 2019. IAQ was controlled by opening or closing the windows during sleep (two rooms with windows open and the other two with windows closed). We paid the participants from the non-PSG (PSG) groups €50 (€75) each after the experiment.

2.3. Indoor environment and bed temperature

Ambient T, RH, CO_2, TVOCs, $PM_{2.5}$, noise and bed T were monitored during the experimental period. Table 1 shows the brands, types, accuracies, measuring ranges and recorded intervals of all the devices used. The adjustable waist band with the temperature data logger inside is shown in Figure 1. The participants wore the bands underarm with the temperature data logger in front of the chest for the purpose of measuring the bed T.

Table 1: The details of the air monitoring devices used

Parameter	Device/Sensor	Accuracy	Measuring range	Recorded interval
Ambient temperature	Netatmo	± 0.3 °C	0-50 °C	5 min
Relative humidity		± 3 %	0-100 %	
CO_2		± 50 ppm (from 0 to 1,000 ppm) ± 5% (from 1,000 to 5,000 ppm)	0-5000 ppm	
Noise		-	35-120 dB	
TVOCs	Awair	± 10 %	175-3500 ppb	
$PM_{2.5}$		± 15 %	0-500 µg/m³	
Bed temperature	HOBO U12-012	± 0.35 °C	-20-70 °C	

Figure 1: Adjustable waist band with the temperature data logger (HOBO U12-012) inside

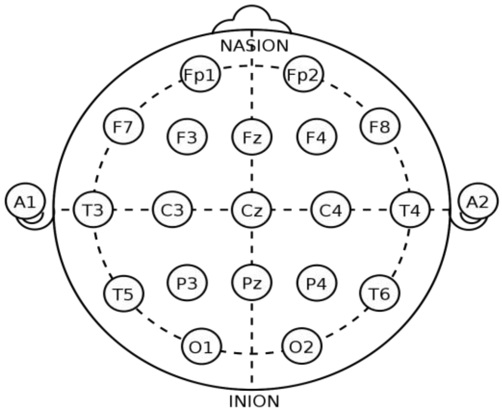

Figure 2: Electrode locations of the international 10-20 system for EEG (originated from WIKIPEDIA)

2.4. Assessments of the sleep quality

Both subjective and objective assessments were applied to test sleep quality, including the GSQS, Fitbit and PSG. The KSS was used to measure sleepiness. Other sleep-related factors, such as mood and stress, were measured via the POMS and PSS questionnaires respectively.

2.4.1 Objective assessments of sleep quality. We used two kinds of devices for sleeping tests: two sets of the home polysomnography (PSG) – the Nox A1 from Resmed company (only for half of the participants) and four Fitbit Charge 2 smartwatches. Each participant would wear the Fitbit (and PSG) during both adaptive and test nights.

The Nox A1 contains Electroencephalography (EEG), Electrocardiography (ECG) and chin Electromyography (EMG). The EEG of the Nox A1 includes 10 channels (electrodes). Each electrode placement site has a letter to identify the lobe, or area of the brain it is reading from pre-frontal (Fp), frontal (F), temporal (T), parietal (P), occipital (O), and central (C). Figure 2 shows the electrode locations of the international 10-20 system for EEG. Among those locations, C3, C4, F3, F4, A1, A2, O1 and O2 were used in the Nox A1. The Nox A1 was set up via the Noxturnal software system beforehand. Electrodes and sensors were attached to the participants' heads 1-2 hours before the bedtimes of them. Afterward, the Noxturnal tablet app was used to perform bio-calibration and impedance checks next to the subjects. The sleeping results were analyzed automatically by the Noxturnal software system. Sleep scoring includes analysis start time, analysis stop time, total sleep time (TST), analysis duration (TRT), sleep latency (SL), REM latency, Wake After Sleep Onset (TRT-SL-TST), sleep efficiency (TST/TRT*100). Sleep stages include N1, N2, N3, REM and wake. Interruptions of sleep last

3 to 15 seconds were defined as arousals (ASAA, 2019). Arousal parameters include arousal index (AI; in TST), arousal count (in TST) and arousal count in wake (the arousal lasts more than 15 seconds).

The Fitbit Charge 2 smartwatch shows sleep quality based on 3 sleep stages: light, deep and REM. These stages are estimated based on heart rate and limb movement. Sleep start time, sleep end time, asleep, awake, time in bed (TIB), REM, light sleep, deep sleep and SL could be obtained from the Fitbit. Light sleep contains sleep stages N1 and N2, whereas deep sleep corresponds to N3.

2.4.2 Subjective assessments of sleep quality. The GSQS (in the morning questionnaire) which measures sleep quality for a single night was used for the self-evaluation of sleep quality in the next morning after the test nights. It includes 15 true or false questions and the answers are summed into a single number indicator. The score is from 0 to 14 and the maximum score indicates poor sleep quality the night before.

2.5. Morning questionnaire

In addition to the GSQS, the KSS and questions about sleep environment were also included in the morning questionnaire filled by the participants the morning after the test nights. Sleep environment was assessed by applying a similar method as Strom-Tejsen et al (2016) used. The KSS is a tool to evaluate subjective sleepiness and verified to be closely correlated to the results electroencephalogram (Kaida et al., 2006). Sleepiness is evaluated by a 9-point scale from 1 (extremely alert) to 9 (extremely sleepy). In addition, other questions were included – pajamas, earplugs, eye mask, and socks worn, how many times the participants woke up and why, and also the bedtime and get up time were reported by themselves. The analysis start time and stop time of PSG were also adjusted based on the self-reported bedtime and get up time.

2.6. Night questionnaire

As the mood and stress influence sleep quality, the abbreviated POMS and the PSS were used to test them. The abbreviated POMS contains 40 items where five negative subscales and two positive subscales including anger, fatigue, depression, confusion, esteem-related affect and vigor. Total Mood Disturbance (TMD) is calculated by summing the totals for the negative subscales and then subtracting the totals for the positive subscales (Grove et al., 2013). The higher the score of TMD, the worse the mood. The PSS contains 10 questions to test the stress during the last month. Scores ranging from 0–13, 14–26 and 27–40 respectively indicate low, moderate and high perceived stress.

2.7. Statistical analyses

First, the Kolmogorov-Smirnov test was used to measure if the data were normally distributed. If so, the T-test was used. In the other case, Mann-Whitney U tests were used to test significant differences among all indoor environmental parameters between two window/PSG conditions. Second, Spearman correlation coefficients (r) were calculated for all the factors which showed significant differences in the T-test/Mann-Whitney U test. One factor in the pairs was excluded if the r was higher than 0.4 (p-value < 0.05) and the remaining factors were included in the multivariate linear regression models to test the associations between sleep parameters and those factors. All multivariate linear regression models were adjusted by sex, age and BMI. The differences of all the parameters from the window closed to open were calculated individually for each participant. Subsequently, Mann-Whitney U tests were used to analyze if the differences were significantly different with zero. SPSS 22.0 (SPSS Ltd., USA) was used in all statistical analyses. All analyses were considered statistically significant when *p*-values were less than 0.05.

3. RESULTS

Table 2 shows the demographic characteristics and study information of the participants. A total of 28 participants were recruited but one of them quit. There were 13 females and 14 males among the remaining participants and the age ranged from 20 to 33 years. The majority of participants had body mass index (BMI) within the normal range 18.5–25.0. However, two of them were underweight and had the BMI less than 18.5, three were overweight with the BMI between 25.0 and 29.9, and one had the BMI in the obese range higher than 30.0. All of them had good sleep quality during the past month with the PSQI scores less than or equal to 5. Four rooms were numbered from A to D. The first condition of the windows of Room A and C were open whereas Room B and D closed. Room A and B were the PSG rooms used for the participants from the PSG group.

Table 2: Demographic characteristics and study information of the participants (N=27)

No.	Room No.	Sex	Age (years old)	Height (cm)	Weight (kg)	BMI	PSQI	Windows first condition	PSG used
1	A	Male	25	185	80	23.4	3	Open	Yes
2	A	Male	27	175	58	18.9	4	Open	Yes
3	A	Male	22	193	82	22.0	3	Open	Yes
4	A	Male	27	178	65	20.5	2	Open	Yes
5	A	Male	26	173	93	31.1	2	Open	Yes
6	A	Male	27	163	62	23.3	5	Open	Yes
7	A	Female	21	167	61	21.9	4	Open	Yes
8	B	Female	27	163	50	18.8	5	Closed	Yes
9	B	Male	23	178	65	20.5	5	Closed	Yes
10	B	Male	23	164	56	20.8	5	Closed	Yes
11	B	Male	26	168	74	26.2	3	Closed	Yes
12	B	Male	24	183	72	21.5	4	Closed	Yes
13	B	Female	25	160	52	20.3	5	Closed	Yes
14	B	Female	28	165	50	18.4	3	Closed	Yes
15	C	Male	28	169	67	23.5	4	Open	No
16	C	Female	31	160	61	23.8	0	Open	No
17	C	Female	28	159	62	24.5	5	Open	No
18	C	Female	22	166	67	24.3	4	Open	No
19	C	Female	21	166	60	21.8	3	Open	No
20	C	Male	33	172	67	22.6	4	Open	No
21	C	Male	20	180	95	29.3	4	Open	No
22	D	Female	24	157	68	27.6	3	Closed	No
23	D	Female	33	162	50	19.1	3	Closed	No
24	D	Female	22	167	53	19.0	4	Closed	No
25	D	Female	25	172	58	19.6	5	Closed	No
26	D	Female	25	162	48	18.3	3	Closed	No
27	D	Male	26	178	75	23.7	5	Closed	No

BMI, body mass index; PSQI, Pittsburgh sleep quality index; PSG, polysomnography.

Table 3 lists the average and the 95th percentile of concentrations of indoor parameters between two window/PSG conditions during sleep. The data of night-time indoor parameters from bedtimes to get up times of the participants were used. Both the average and the 95th percentile of ambient T, RH and CO_2 were significantly different between the two window conditions (*p*-value < 0.05). According to means, the average ambient T with the window closed were averagely 1.6 °C higher than that with the open condition and the RH was 4.5% higher. The average 95th percentile of ambient T was 0.9 °C higher with the window closed than that with the window open and 0.8 °C higher in the PSG rooms than that in the non-PSG rooms. The average 95th percentile of RH was 4.5% higher with the window closed compared to that with the window open. Besides, both the mean and the 95th percentile of CO_2 with the window closed were around 2.6 times higher on average than those with the window open. The average mean of $PM_{2.5}$ and the average 95th percentile of noise in the PSG rooms were significantly higher than those in the non-PSG rooms. Bed T and TVOCs did not show any significant different results between the two window/PSG conditions.

Table 3: Average and the 95th percentile of concentrations of indoor parameters between two window/PSG conditions during sleep

Items	N^a (%)	Mean ± Std.	5th	25th	50th	75th	the 95th	*p*-value ^{b}
Average ambient T in total and stratified by the window/PSG conditions (°C)								
Total	105 (100)	21.8 ± 1.4	19.2	21.0	22.1	22.7	23.8	
Window closed	50 (47.6)	**22.6 ± 0.8**	20.9	22.2	22.5	22.9	24.2	**< 0.001**
Window open	55 (52.4)	**21.0 ± 1.3**	18.8	20.0	21.1	21.9	23.0	
No PSG	49 (46.7)	21.5 ± 1.4	18.5	20.9	21.7	22.5	23.5	0.092
PSG	56 (53.3)	22.0 ± 1.3	19.2	21.1	22.3	22.7	24.1	
The 95th percentile of ambient T in total and stratified by the window/PSG conditions (°C)								
Total	105 (100)	22.5 ± 1.2	20.2	21.9	22.6	23.3	24.5	
Window closed	50 (47.6)	**23.0 ± 1.0**	21.2	22.5	22.9	23.3	25.0	**0.001**
Window open	55 (52.4)	**22.1 ± 1.3**	19.6	21.3	22.2	23.2	23.8	
No PSG	49 (46.7)	**22.1 ± 1.3**	19.4	21.5	22.2	23.1	23.7	**0.001**
PSG	56 (53.3)	**22.9 ± 1.0**	20.6	22.4	22.9	23.4	24.7	
Average RH in total and stratified by the window conditions (%)								
Total	105 (100)	40.8 ± 5.8	29.5	36.3	42.0	44.9	49.4	
Window closed	50 (47.6)	**43.1 ± 5.2**	32.5	40.4	43.8	46.5	51.7	**< 0.001**
Window open	55 (52.4)	**38.6 ± 5.6**	28.5	34.8	38.8	43.6	46.4	
No PSG	49 (46.7)	40.2 ± 6.0	29.3	35.7	41.4	44.5	50.6	0.407
PSG	56 (53.3)	41.2 ± 5.7	29.2	37.2	42.2	45.0	49.5	
The 95th percentile of RH in total and stratified by the window/PSG conditions (%)								
Total	105 (100)	42.1 ± 5.8	32.0	37.5	43.0	46.0	51.0	
Window closed	50 (47.6)	**44.5 ± 5.3**	33.6	42.0	45.0	47.3	52.9	**< 0.001**
Window open	55 (52.4)	**40.0 ± 5.5**	30.8	35.0	40.0	45.0	48.4	
No PSG	49 (46.7)	41.8 ± 6.1	31.0	36.5	43.0	46.0	52.0	0.607
PSG	56 (53.3)	42.4 ± 5.6	32.0	38.3	43.5	47.0	51.0	
Average CO_2 in total and stratified by the window/PSG conditions (ppm)								
Total	105 (100)	1122.6 ± 618.6	468.0	584.4	840.7	1550.4	2451.5	
Window closed	50 (47.6)	**1656.4 ± 449.4**	929.5	1323.5	1546.1	1960.2	2489.1	**< 0.001**
Window open	55 (52.4)	**637.3 ± 223.9**	449.0	531.9	586.4	660.4	1279.2	
No PSG	49 (46.7)	1107.0 ± 600.1	462.0	604.1	769.6	1524.1	2450.2	0.842
PSG	56 (53.3)	1136.2 ± 639.5	473.0	568.2	917.1	1637.9	2461.2	
The 95th percentile of CO_2 in total and stratified by the window/PSG conditions (ppm)								
Total	105 (100)	1258.9 ± 673.4	523.0	659.8	1035.8	1814.4	2637.2	
Window closed	50 (47.6)	**1843.7 ± 457.3**	1215.7	1507.7	1810.1	2188.5	2671.6	**< 0.001**
Window open	55 (52.4)	**727.3 ± 281.0**	493.6	598.9	673.4	773.5	1373.1	
No PSG	49 (46.7)	1242.9 ± 669.7	487.8	685.3	824.1	1814.4	2646.7	0.888
PSG	56 (53.3)	1273.0 ± 682.3	528.5	646.3	1076.2	1830.9	2636.3	
Average $PM_{2.5}$ in total and stratified by the window/PSG conditions (μg/m³)								
Total	79 (100)	23.5 ± 4.1	15.0	21.3	24.2	26.1	29.9	
Window closed	39 (49.4)	23.8 ± 3.2	18.5	22.0	24.2	25.5	29.9	0.845
Window open	40 (50.6)	23.2 ± 4.7	11.9	21.2	24.2	26.4	30.9	
No PSG	24 (30.4)	**21.5 ± 5.7**	11.8	18.0	21.6	26.2	32.3	**0.040**
PSG	55 (69.6)	**24.4 ± 2.7**	19.6	22.4	24.5	25.9	30.1	
Average noise in total and stratified by the window/PSG conditions (dB)								
Total	105 (100)	42.5 ± 6.1	35.6	36.3	46.0	48.2	50.1	
Window closed	50 (47.6)	42.5 ± 6.0	35.4	36.1	46.0	48.0	50.2	0.090
Window open	55 (52.4)	42.5 ± 6.2	35.8	36.7	38.0	48.4	50.4	
No PSG	49 (46.7)	**36.4 ± 0.7**	35.3	36.1	36.2	36.8	37.9	**< 0.001**
PSG	56 (53.3)	**47.7 ± 3.0**	37.6	47.1	48.2	48.7	51.0	
The 95th percentile of noise in total and stratified by the window/PSG conditions (dB)								
Total	105 (100)	43.7 ± 5.6	36.0	38.0	46.0	49.0	51.0	

Window closed	50 (47.6)	43.3 ± 5.9	36.0	37.0	46.0	48.0	51.0	0.100
Window open	55 (52.4)	44.0 ± 5.4	36.4	39.0	43.0	49.0	51.4	
No PSG	49 (46.7)	**38.3 ± 2.2**	36.0	36.4	38.0	39.1	43.4	**< 0.001**
PSG	56 (53.3)	**48.4 ± 2.7**	40.8	47.3	49.0	50.0	52.2	

[a] some samples missed if the total sample size is less than 108; [b] calculated by Mann-Whitney *U* tests. Bold indicates *p*-value < 0.05. T, temperature; RH, relative humidity; PSG, polysomnography.

From the results of the morning questionnaire between the window closed and open during sleep, the participants reported the air with the window open was 1.7 scores fresher compared to it with the window closed, while they felt noisier. Regarding the subjective sleep quality assessment, we did not find any significant results between two window conditions. Moreover, the participants in the non-PSG group had higher PSS score than those had in the PSG group before sleep at the test nights. Regarding the sleep parameters from the PSG between two window conditions for all nights and only test nights, no significant results were found. As for the sleep parameters from the Fitbit between two window/PSG conditions, considering all the nights, the participants had significantly longer sleep latency with the window open compared to those who slept with the window closed, while this significant result disappeared from the results of only test nights. The participants from the non-PSG group had an increased number of awakenings than those from the PSG groups at all nights and only test nights. No significant results were found among the other factors from the Fitbit.

From the results above, the participants had different feelings of air freshness and noise between two window conditions. Also, the average and the 95th percentile of ambient T, RH and CO_2 were significantly different between window open and closed nights. As for the PSG and non-PSG rooms, some indoor parameters including the 95th percentile of ambient T, the average $PM_{2.5}$, the average and the 95th percentile of noise were higher than those in the non-PSG rooms.

Table 4 shows β and 95% confidence interval (CI) from multivariate linear regression analyses of sleep parameters and window/PSG conditions related factors. The participants that slept with more noise (self-reported) had 0.294 higher score of GSQS than those that slept with less noise, herein the change of higher and lower noise levels (independent variable) was one unit (the same as follows). Regarding the sleep parameters from Fitbit, those higher-stressed participants had significantly 5.009 minutes more time asleep, 5.590 minutes more TIB and 2.435 minutes more REM sleep time than the lower-stressed participants. Participants sleeping with higher levels of $PM_{2.5}$ had significantly 1.546 minutes more time awake, 0.342 % more awake percentage and 0.342 % lower sleep efficiency than those who slept with lower levels of $PM_{2.5}$. Those slept with higher the 95th percentile of ambient T had significantly 3.074 times higher number of awakenings than those who slept with lower the 95th percentile of ambient T.

Table 4: β and 95% confidence interval (CI) of sleep parameters and window/PSG conditions related factors from multivariate linear regression analyses

Items	Window/PSG related	β (95% CI)	*p*-value
GSQS and window-conditions related factors			
GSQS	Average CO_2	-0.001 (-0.002 - 0.001)	0.297
	Noise	**0.294 (0.016 - 0.572)**	**0.039**
Sleep parameters from Fitbit and PSG-conditions related factors			
Asleep (min)	**Stress**	**5.009 (0.831 - 9.186)**	**0.021**
	The 95th percentile of ambient T	7.943 (-13.902 - 29.788)	0.456
	Average $PM_{2.5}$	-2.318 (-7.642 - 3.006)	0.374
	The 95th percentile of noise	-2.141 (-7.099 - 2.818)	0.378
Awake (min)	Stress	0.582 (-0.534 - 1.698)	0.289
	The 95th percentile of ambient T	1.294 (-4.541 - 7.13)	0.648
	Average $PM_{2.5}$	**1.546 (0.124 - 2.968)**	**0.035**
	The 95th percentile of noise	-0.969 (-2.294 - 0.355)	0.142
Number of awakenings	Stress	0.366 (-0.158 - 0.891)	0.160

(times)	**The 95th percentile of ambient T**	**3.074 (0.331 - 5.816)**	**0.030**
	Average $PM_{2.5}$	-0.026 (-0.694 - 0.642)	0.936
	The 95th percentile of noise	-0.448 (-1.07 - 0.175)	0.149
	Stress	**5.590 (0.903 - 10.278)**	**0.022**
TIB	The 95th percentile of ambient T	9.237 (-15.272 - 33.747)	0.440
(min)	Average $PM_{2.5}$	-0.772 (-6.745 - 5.201)	0.790
	The 95th percentile of noise	-3.11 (-8.673 - 2.453)	0.256
	Stress	**2.435 (0.183 - 4.688)**	**0.036**
REM sleep	The 95th percentile of ambient T	-0.367 (-12.146 - 11.413)	0.949
(min)	Average $PM_{2.5}$	-2.481 (-5.351 - 0.39)	0.086
	The 95th percentile of noise	-0.216 (-2.89 - 2.458)	0.867
	Stress	0.023 (-0.174 - 0.22)	0.811
Sleep efficiency	The 95th percentile of ambient T	-0.063 (-1.092 - 0.966)	0.900
(%)	**Average $PM_{2.5}$**	**-0.342 (-0.592 - -0.091)**	**0.010**
	The 95th percentile of noise	0.142 (-0.091 - 0.376)	0.218
	Stress	-0.023 (-0.22 - 0.174)	0.811
Awake	The 95th percentile of ambient T	0.063 (-0.966 - 1.092)	0.900
(%)	**Average $PM_{2.5}$**	**0.342 (0.091 - 0.592)**	**0.010**
	The 95th percentile of noise	-0.142 (-0.376 - 0.091)	0.218

GSQS, Groningen sleep quality scale; T, temperature; TIB, time in bed; PSG, polysomnography.

From the results of the individual differences from the window closed to open, air freshness, noise, the average and the 95th percentile of ambient T, RH, and CO_2 also shows the similar trends of results as the overall results between the window closed and open mentioned above. However, the GSQS, the KSS and the number of awakenings show significant results, which are different from the overall results between the window closed and open.

4. DISCUSSION

In this study, the association between sleep environment and sleep quality with the window closed and open was investigated.

The recommended values of indoor air parameters established by the Flemish government (VR 2018, 3003) or reviewed by Caddick et al. (2018) are shown in Table 5. The average ambient T reached the recommended range for both window conditions. There were at least 5% (window closed) and 50% (window open) nights with the average RH lower than the recommended range. The average CO_2 levels with the window open were less than the recommended value of 800 ppm for at least 75% nights, while all the nights with the window closed exceed 800 ppm. Those indoor air parameters were all significantly different between the window closed and open, and the CO_2 levels had the highest difference between two window conditions among those parameters. Only less than 5% nights reached the average $PM_{2.5}$ levels less than 10 µg/m^3 for both the window closed and open.

The average CO_2 level with the window open was quite similar to the value in the previous study from Strom-Tejsen et al. (2016) (660 ppm). Also, we had the same situation as another study indicated - the CO_2 levels with the window and door open were largely under 1000 ppm (Mishra et al., 2018). However, the results were different for the window closed from the previous studies. Strom-Tejsen et al. (2016) indicated that the average CO_2 level was 2585 ppm with the window closed, while it was 1656 ppm in this study. Mishra et al. measured largely under 1500 ppm of CO_2 levels but with the peak of over 3000 ppm. Different building characteristics lead to different building sealing, which might be the major reason for the different results among those studies.

Table 5: Recommended values of indoor air parameters established by the Flemish government (VR 2018, 3003) or reviewed by Caddick et al. (2018)

Items	Recommended values
Temperature (T)	17 – 28 °C (Caddick et al., 2018)
Relative humidity (RH)	40 – 60 % (Caddick et al., 2018)
CO_2	< 800 ppm (VR 2018, 3003)
$PM_{2.5}$	10 μg/m³ (VR 2018, 3003)
TVOCs	-

From the results of multivariate linear regression analyses of the GSQS and sleep parameters and window/PSG conditions related factors, the indoor environmental parameters of the 95th percentile of ambient T and $PM_{2.5}$ were both related to a few sleep parameters from Fitbit. Mishra et al. (2017) found that the number of awakenings recorded by the Sensewear Armband was negatively associated with ambient T but positively with CO_2 levels. That is opposite with the result in this study that the number of awakenings recorded by Fitbit increased with the higher 95th percentile of ambient T. The reason might be that the cover in this study was warmer than that in the study of Mishra et al. (2017), thus within the recommended range of ambient T, the participants had an increased number of awakenings in this study but a decreased number sleeping with the higher ambient T in the study of Mishra et al. (2017). Also, Strom-Tejsen et al. (2016) indicated that the sleep latency improved with the window open and the sleep efficiency was better with the fan on (lower CO_2 levels). However, CO_2 was not a significant factor to influence sleep quality comparing to this study. Potentially, this is because the lower CO_2 levels were under the window open condition, which could also lead to higher noise levels. Although Mishra et al. (2017) also used the method of the window/door open and closed to change the air quality in the bedrooms, the outdoor noise might not be the same in this study. Some participants reported that there were several groups of people going pass by the street beside the bedrooms and talking loudly in this study.

The $PM_{2.5}$ levels were higher in the PSG rooms than the non-PSG rooms. The time I stayed in the PSG rooms was much more than the time I stayed at the non-PSG rooms since I had to prepare the materials for using PSG, set up PSG monitors and help to wear PSG for around one hour each time each person. My indoor activities induced an increase of $PM_{2.5}$ levels before participants' bedtimes and then the starting points of $PM_{2.5}$ levels in the PSG rooms must be higher than those in the non-PSG rooms. Also, $PM_{2.5}$ was positively associated with the time and percentage of awake and negatively associated with sleep efficiency recorded by Fitbit. Shen et al. (2018) investigated the association of $PM_{2.5}$ with sleep-disordered breathing (SDB) among 4312 healthy participants and indicated that exposure to $PM_{2.5}$ was associated with SDB. There was a study also concluding that $PM_{2.5}$ was strongly associated with sleep disorder symptoms in females (2−17 yrs.) (Lawrence et al., 2018). SDB and sleep disorder symptoms might be the reason to increase awakenings and decrease sleep efficiency.

From the results of the individual differences from the morning questionnaire, the participants felt the air to be fresher, but reported the noise to be higher, they felt worse, had higher GSQS (worse sleep quality) and felt less alert the next morning when they slept with the window open the night before, whereas the subjects reported less sleepy the next morning after the test night with the window open in the study of Strom-Tejsen et al. (2016). Again, the reason is that the outdoor noise levels might be much lower in the study of Strom-Tejsen et al. (2016) than the noise in this study. Besides, the participants had an increased number of awakenings recorded by Fitbit with the window open and this is consistent with the findings from Laverge and Janssens (2011) where the reports were from the subjects' feedback.

5. CONCLUSIONS

The participants reported better sleep quality sleeping with quieter surroundings (windows closed). Higher $PM_{2.5}$ level was associated with more time awake, higher percentage awake and lower sleep efficiency. Higher ambient temperature was associated with an increased number of awakenings.

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7. REFERENCES

Ailshire, J. A., Crimmins, E. M., 2014. Fine Particulate Matter Air Pollution and Cognitive Function Among Older US Adults. American Journal of Epidemiology. 180**,** 359-366.

An, R., Yu, H., 2018. Impact of ambient fine particulate matter air pollution on health behaviors: a longitudinal study of university students in Beijing, China. Public Health. 159**,** 107-115.

ASAA (American Sleep Apnea Association), 2019. https://www.sleepapnea.org/treat/getting-sleep-apnea-diagnosis/sleep-study-details/

Auchincloss, A. H., et al., 2008. Associations between recent exposure to ambient fine particulate matter and blood pressure in the Multi-Ethnic Study of Atherosclerosis (MESA). Environmental Health Perspectives. 116**,** 486-491.

Caddick, Z. A., et al., 2018. A review of the environmental parameters necessary for an optimal sleep environment. Building and Environment. 132**,** 11-20.

Heo, J. Y., et al., 2017. Effects of smartphone use with and without blue light at night in healthy adults: A randomized, double-blind, cross-over, placebo-controlled comparison. Journal of Psychiatric Research. 87**,** 61-70.

Kaida, K., et al., 2006. Validation of the Karolinska sleepiness scale against performance and EEG variables. Clinical Neurophysiology. 117**,** 1574-1581.

Laverge, J., Janssens, A., 2011. Analysis of the influence of ventilation rate on sleep pattern. In: Indoor Air 2011. ISIAQ; 2011.

Lawrence, W. R., et al., 2018. Association between long-term exposure to air pollution and sleep disorder in Chinese children: the Seven Northeastern Cities study. Sleep. 41**,** 1-10.

Menefee, L. A., et al., 2000. Self-reported sleep quality and quality of life for individuals with chronic pain conditions. Clinical Journal of Pain. 16**,** 290-297.

Mishra, A. K., et al., 2018. Window/door opening-mediated bedroom ventilation and its impact on sleep quality of healthy, young adults. Indoor Air. 28**,** 339-351.

Ogilvie, R. P., et al., 2018. Sleep indices and eating behaviours in young adults: findings from Project EAT. Public Health Nutrition. 21**,** 689-701.

Owens, J. F., Matthews, K. A., 1998. Sleep disturbance in healthy middle-aged women. Maturitas. 30**,** 41-50.

Shen, Y. L., et al., 2018. Association of $PM_{2.5}$ with sleep-disordered breathing from a population-based study in Northern Taiwan urban areas. Environmental Pollution. 233**,** 109-113.

Strom-Tejsen, P., et al., 2016. The effects of bedroom air quality on sleep and next-day performance. Indoor Air. 26**,** 679-686.