



Influence of indoor air quality on sleep quality of university students in Lisbon

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ABSTRACT

Sleep is a crucial aspect of the human daily life since it allows us to recover from physical and psychological fatigue and its lack can bring several consequences to human health. People spend around one third of their life sleeping but, despite that, their exposure to pollutants during sleep is often neglected. Specifically, students typically change their habits after entering university, due to the freedom that they are allowed at this stage of their lives. These habits often include their sleep patterns, which not only affects their health, but their academic performance as well. This study aimed to assess the indoor air quality (IAQ) that university students are exposed to in their sleeping environment and how it affects their sleep quality.

Firstly, an online survey, based in standardized questionnaires, was conducted to a sample of 1040 individuals to characterize sleep habits and, ultimately, to provide an overview of the sleep quality of the Portuguese population. Students were one of the population groups that showed worse results: only 31% had good sleep quality and only 62% showed good sleep health.

Afterwards, a study to assess sleep quality (by actigraphy and standardized questionnaires) and IAQ (by a monitoring unit based in low-cost sensors) during the sleeping period of two consecutive nights of 13 students in Lisbon university dorms was conducted. Mean levels of CO₂ and VOCs above the established legislation were found during sleep, indicating that ventilation conditions were not sufficient to keep an acceptable IAQ. Temperature was also out of the acceptable comfort range during 44% of the sleeping time.

The perceived sleep quality of students was found to be negatively associated with the number of awakenings and the mean levels of carbon dioxide and relative humidity during the sleeping period. These results confirm previous findings where some IAQ parameters may influence the sleep quality of the individuals, highlighting the importance to focus on the IAQ of sleeping environments as a strategy to improve sleep quality of individuals.

1. Introduction

The unequivocal importance of indoor air quality (IAQ) upon human health and welfare has been established in recent decades (Sundell, 2004). Research efforts have been conducted to understand the IAQ complexity in different micro-environments, such as offices (Mandin et al., 2017), restaurants (Lee et al., 2001) and schools (Almeida et al., 2011; Daisey et al., 2003). However, a specific important

microenvironment has been scarcely studied until recent years: the sleeping environment (Canha et al., 2021).

People spend around one third of their life sleeping, and they stay for a long period of consecutive time on their bedroom while doing so, which aggravates the exposure to pollutants, even if their concentrations aren't as high as in other environments (Canha et al., 2017). However, there are few studies that try to relate the IAQ that people are exposed to during sleep to their sleep quality (Mishra et al., 2018; Strom-Tejsen

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et al., 2016), with most of the studies focusing only on thermal comfort parameters, such as temperature and relative humidity (Okamoto-Mizuno et al., 1999, 2004; Lan et al., 2014; Sewitch et al., 1986).

Sleep plays a crucial role on the human daily life. It allows our body (mainly our brain) to recover from the fatigue accumulated throughout the day. Despite being regulated by natural processes, several external factors can alter the natural process of sleep. Whether it is work obligations and social life (Roenneberg et al., 2003) or the consumption of caffeine (Czeisler, 2013), health problems (Foley et al., 2004) and the use of technological devices, such as mobile phones and laptops prior to sleep (Mohammadbeigi et al., 2016; Demirci et al., 2015). The evening or night exposure to an artificial light also impacts sleep, since it affects not only the circadian cycle, but also the routines and obligations, by allowing us to be active during the night (Czeisler, 2013).

Another factor that has been shown to have some influence in sleep quality is IAQ. Strøm-Tejsen et al. (2016) studied the effect of different ventilation settings on the IAQ of student dormitory bedrooms, as well as its influence on the students' sleep quality. Carbon dioxide (CO₂) levels were lower with the bedroom window open, which promoted improvement of the sleep quality, perceived freshness of bedroom air, next-day sleepiness and performance of the students. Mishra et al. (2018) also monitored young adults' sleep while changing ventilation settings by opening windows or doors. CO₂ levels and temperature were lower for the open setting. Like in the previous study, when CO₂ levels were lower, sleep quality, perception of air quality and next-day performance were improved.

The body temperature is also a major factor in internal sleep regulation. Exposure to unacceptable heat during sleep can increase wakefulness and reduce REM and slow wave sleep (Okamoto-Mizuno and Mizuno, 2012). The effect is aggravated when coupled with high relative humidity (RH), which is the ratio of water vapor in the air and the saturation point (Okamoto-Mizuno et al., 1999).

Upon entering university, students experience a newly found freedom. This freedom, coupled with demands from social and academic life, often leads to a change in their daily habits. Among those habits are the sleeping patterns (Pilcher et al., 1997). Whether it is for partying or studying, students tend to change the amount of sleep that they get, as well their sleep timing. This occurs in highly demanding stage of their lives, from an intellectual point of view, and leads to several sleeping problems (Buboltz et al., 2001; Lund et al., 2010).

Therefore, this study aimed to provide an overview of the sleep quality of the Portuguese population comparing it with the sub-group of university students and, afterwards, to try to understand the influence of IAQ on the sleep quality of such individuals. For the latter, IAQ and sleep quality of university students was assessed in university dorms in Lisbon (Portugal) to obtain a study population with similar conditions and characteristics in order to understand the influence of IAQ upon sleep.

2. Materials and methods

2.1. National survey of sleep quality

In order to obtain an overview of the sleep characterisation of the Portuguese population, a survey was developed based on four standardized sleep tests: 1) the Pittsburgh Sleep Quality Index (PSQI), which assesses sleep quality (Del Rio João et al., 2017); 2) the Satisfaction Alertness Timing Efficiency Duration (SAT-ED) scale, that assesses sleep health (Brandolim Becker et al., 2018) (both of these tests were validated for the Portuguese population); 3) the short version of the Functional Outcomes of the Sleep Questionnaire (FOSQ-10) to check the alertness (Chasens et al., 2009); 4) and the Munich Chronotype Questionnaire (MCTQ) to assess the difference of sleep timing on working and resting days (social jet-lag) (Roenneberg et al., 2003). Additionally, a set of questions focusing on daily sleepiness and on individual demographic characteristics were also applied, in order to gather information about individual life-styles and perceptions of the sleeping environment.

The questionnaire was made available online to all the Portuguese population during a period of two months (April and May of 2019). All answers were conducted anonymously. The objective was to verify which social and environmental conditions affected sleep the most and how university students were placed among the general Portuguese population. The questionnaire got a total of 1040 answers and the general demographic information of the respondents is displayed in Table 1. Table S1 (in the supplementary section) presents the amount of answers obtained by Portuguese district, where is possible to observe that it was obtained answers from all the Portuguese districts.

The evaluation of the results was done considering different factors regarding the sociodemographic data (including professional occupation), school level, practice of physical activity and presence of cardio-respiratory problems) and the sleeping environment (such as, perceived IAQ and room occupation).

2.2. Assessment of indoor air quality during the sleeping period of university students and their sleep quality

2.2.1. Study sites

Two student residencies (A and B) located in the urban metropolitan area of Lisbon (Portugal) were selected and the students attending them were invited to participate in the present study.

Residence A started its functioning in 1998 and it is composed by three blocks: A, B, and C, with three floors each. Overall, this residence has 189 bedrooms, from which 153 are single bedrooms and 36 are double bedrooms. The single bedrooms have 11.2 m² of area while the doubles have 15.3 m².

Residence B started its functioning since 2013 and it has only one block, with 66 single bedrooms and 8 double bedrooms. The single bedrooms have 13.4 m² of area while the doubles bedrooms have an area of 16.7 m².

Fig. 1 provides an example of the single and double bedrooms in both

Table 1

General characterisation of the respondents, where n is the number of individuals in each category.

Characteristics	n	%
Gender		
Male	335	32.2
Female	705	67.8
Age group		
18–20	123	11.8
21–25	227	21.8
26–30	111	10.7
31–35	114	11.0
36–40	167	16.1
41–45	109	10.5
46–50	72	6.9
51–55	49	4.7
56–60	44	4.2
>60	24	2.3
Professional occupation		
Student		304
Unemployed	20	1.9
Employer	77	7.4
Employee	614	59.0
Retired	9	0.9
Fellow		8
Working student	8	0.8
School level		
Middle school	19	1.8
High school	273	26.2
Technical school	43	4.1
Degree	428	41.2
Master		216
PhD	61	5.9



Fig. 1. Example of single (bottom) and double (top) bedrooms at the Residence A (left) and Residence B.

residences. In residence B, all bedrooms have mechanical ventilation (MV) whereas in residence A only block C has this mechanism. All bedrooms in both residences have access to natural ventilation (NV) through a window. In both residences MV is obtained through a fan placed in the bathrooms, which are inside the bedrooms and it is not manually controlled. In residence A it is programmed to work between 7 h and 10 h in the morning and 18 h and 22 h in the evening, while on residence B it is turned on between 8 h and 11 h in the morning and 19 h and 22 h in the evening.

2.2.2. Characterisation of participants

A total of 13 university students from both residences participated voluntarily in the study (nine from the residence A and four from the residence B). The characterization of the participants is summarized in Table 2. During May and June 2019, two nights of sleep were monitored per each volunteer in order to assess IAQ during the sleeping period and its sleep quality (by means of actigraphy), as described in the following sections.

2.2.3. Sleep monitoring

Wrist actigraphy was used to monitor students’s activity/rest cycles, during two consecutive days in order to estimate sleep time and related events. Actigraphy is a well validated method for estimation of sleep parameters (Martin and Hakim, 2011), registering the physical activity of the subject and calculating a sleep score based on computer models. It is not a substitute of more comprehensive methods, as polysomnography, but it is a good complementary method.

An actigraphy set by Condor Instruments was used in the present study (Fig. 2, left). The actigraph ActTrust registers movement levels according to the proportional integration mode (PIM), the time above threshold mode (TAT) and the zero crossings mode (ZCM) as well as other parameters, such as, temperature. Afterwards, the software

ActStudio estimated the sleeping score according to the data registered by the actigraph. To complement the information provided by the actigraph, volunteers were asked to fulfil a sleep diary where they registered what time they went to bed, when they turned out the lights to sleep, woke up, had breakfast, how well they slept the previous night, how many times did they woke up and other aspects about their daily routine.

2.2.4. Indoor air quality monitoring

IAQ of bedrooms was monitored during the two consecutive sleeping periods when sleep was being monitored. During the sleeping period, the windows of the bedrooms were kept closed. In order to avoid problems during the IAQ monitoring due to noise interference on the sleep of the occupants by the use of reference monitoring equipment (Canha et al., 2020), a monitoring unit based on low-cost and noiseless sensors was assembled to be employ for the IAQ monitoring (Fig. 2, right). The monitoring unit allowed to measure the levels of CO₂, volatile organic compounds (VOCs), particulate matter with aerodynamic diameter lower than 2.5 μm (PM_{2.5}) and lower than 10 μm (PM₁₀), air temperature (T) and relative humidity (RH). The monitoring unit had a monitoring frequency of 5 min (the unit monitored with a frequency of 1 min and provided the average of 5 min) and also had a communications module to transmit data to an online platform. The monitoring unit was equipped with the following commercially available sensors:

- SCD30 for CO₂ detection (range: 720–18000 mg·m⁻³);
- SHT31 for measurement of T and RH (typical precision: ±2% RH and ±0.3 °C);
- MiCS-VZ-89TE for VOCs detection (range: 0–2290 μg·m⁻³ in isobutylene);
- HPMA115S0 to measure PM_{2.5} and PM₁₀ (range: 0–1000 μg·m⁻³).

During the monitoring period and regarding the atmospheric daily outdoor conditions, it was registered a mean temperature of 19.0 ± 3.2 °C (ranging from 14.7 to 27.6 °C), a mean relative humidity of 62.5 ± 15.3% (ranging from 24.8 to 94.6%) and a mean wind speed of 6.1 ± 1.4 m·s⁻¹ (ranging from 3.0 to 9.3 m·s⁻¹), with no precipitation verified during that period (Weather Underground, 2021).

2.2.4.1. Calibration of the monitoring unit. The performance and reliability of the monitoring unit was assessed by comparing its monitoring data with the one obtained by reference real-time instruments typically used in IAQ studies (Canha et al., 2020) and, afterwards, by defining correction factors to apply to the raw data assessed by the monitoring unit.

Regarding the reference instruments, two different real-time monitor devices were used:

Table 2

Charaterisation of participants, where S stands for single bedroom, D for double bedroom, NV for natural ventilation and MV for mechanical and natural ventilation.

Subject	Age	Gender	Height (m)	Weight (kg)	Medication	Residence	Block	Bedroom type	Ventilation
1	21	Female	1.57	48	No	A	A	S	NV
2	19	Male	1.87	75	No	A	A	D	NV
3	19	Male	1.80	70	No	A	A	S	NV
4	24	Male	1.62	62	No	A	A	D	NV
5	24	Female	1.58	55	No	A	A	D	NV
6	18	Female	1.74	67	Arthrotec	A	C	D	MV
7	18	Male	1.81	70	No	A	C	D	MV
8	19	Female	1.61	52	Minesse	A	C	D	MV
9	19	Male	1.75	60	No	A	C	D	MV
10	19	Female	1.62	62	No	B	–	S	MV
11	18	Male	1.62	53	No	B	–	S	MV
12	19	Female	1.65	50	No	B	–	S	MV
13	20	Male	1.82	73	No	B	–	S	MV



Fig. 2. (left) Actigraph ActTrust used by the volunteers and (right) the IAQ monitoring unit.

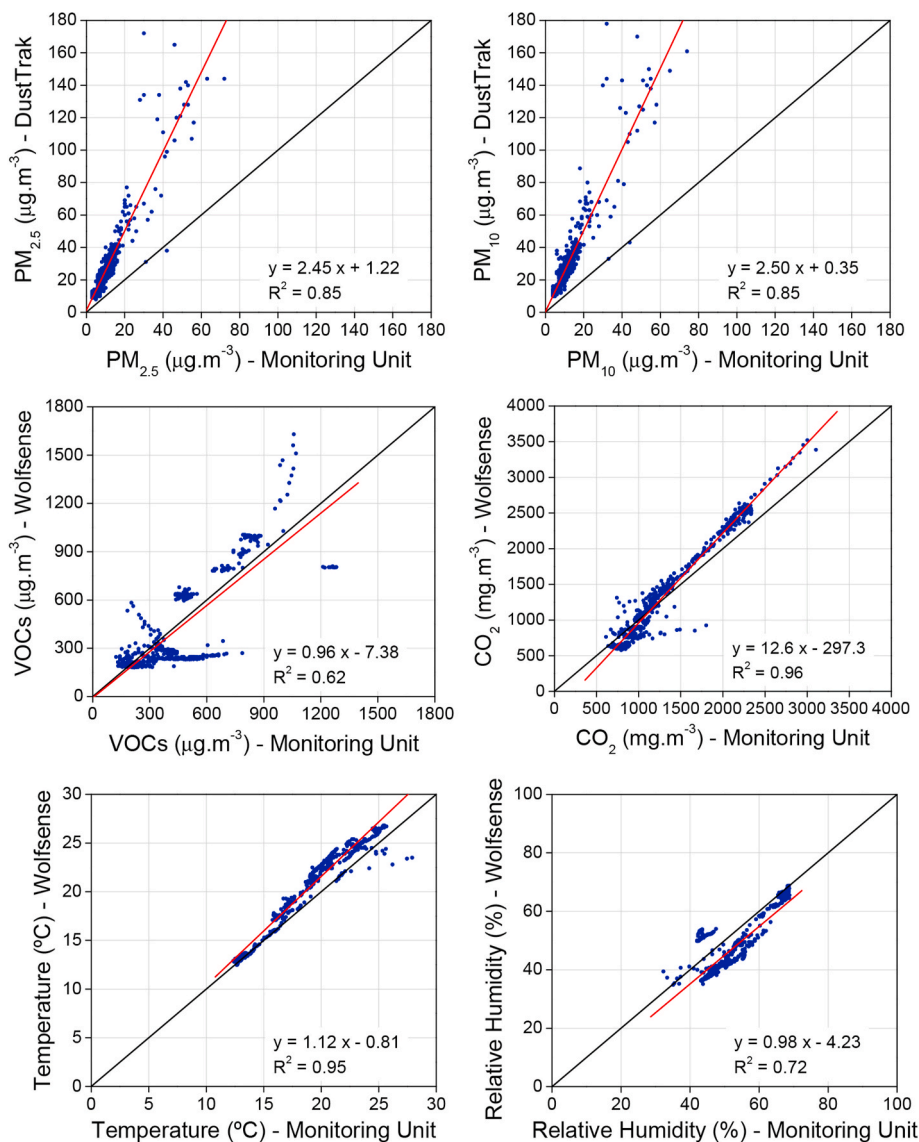


Fig. 3. Performance of the monitoring unit regarding the reference instruments: DustTrak (for PM_{2.5} and PM₁₀) and Wolfsense (for CO₂, VOCs, T and RH). Black dashed line represents the linear association between monitored data obtained from both devices.

- 1) DustTrak DRX monitor (8533 model, TSI, USA) to assess PM_{2.5} and PM₁₀ levels;
- 2) Graywolf (IQ-610 probe, WolfSense Solutions, USA) to assess CO₂, VOCs, T and RH.

All the reference instruments were calibrated according to the manufacturers' specifications and the sampling frequency was set to 5 min. The monitoring devices (reference ones and monitoring unit) were placed next to each other in six different settings (in order to obtain a wide range of levels for the selected parameters): i) indoor of office #1 for a 24 h period with closed window; ii) indoor of office #2 during daytime, with closed window; iii) indoor of office #3 during morning, with closed window; iv) indoor of office #4 during night, with closed window and door; v) bedroom indoor during sleeping period, with closed window and door; vi) outdoor of apartment (balcony) in Lisbon downtown. A total of 59 h of monitored data was gathered from those 6 settings. Fig. 3 provides the performance of the monitoring unit regarding the reference instruments and Table 3 provides the corrections factors for each parameter.

Reasonable to good correlations were obtained between the reference instruments and the monitoring unit (R² ranging from 0.62 – VOCs - to 0.96 – CO₂). Regarding PM_{2.5} and PM₁₀, it was registered an underestimation of the measured values by the monitoring unit especially in higher levels. The data acquired by the monitoring unit was correct based on the linear regression equations shown in Table 3.

2.3. Statistical analysis

The statistical analyses were conducted using Excel and XLSTAT 2014.1.09 software programmes. Analysis of data was conducted by applying non-parametric statistics with a significance level of 0.050. Association between parameters were obtained from Spearman correlations. Statistical differences between two independent samples (e.g. double or single rooms) was assessed using the Mann-Whitney's test. Origin version 7.5 (OriginLab Corporation) was used to plot the results.

3. Results and discussion

3.1. National survey of sleep perception

Fig. 4 provides the overall results of all participants of the survey regarding the sleep questionnaires. The study population may be considered young/adult, with most participants with ages between 18 and 45 years old (with a mean age of 34.2 ± 12.1), mostly females (67.8%) and with a high level of education (67.9% with a degree or above).

Considering the subjective sleep quality assessed by PSQI, only 40.1% of the population reported "good" for sleep quality (with scores ≤5), while 8.0% scored a value above 10, which indicates the presence of a sleep disturbance. More than half (51.9%) of the study population scored between 5 and 10, which means they had a poor sleep quality. These levels of poor sleep quality were higher than the ones found in a specific population of 256 Portuguese anaesthesiologists where 46.1%

Table 3
Correction factors for each environmental parameters monitored by low-cost sensors.

Parameter	Unit	Correlation parameters	
		Equation	R ²
PM _{2.5}	µg.m ⁻³	[DustTrak] = 2.448 × [MU] + 1.224	0.854
PM ₁₀	µg.m ⁻³	[DustTrak] = 2.502 × [MU] + 0.354	0.847
CO ₂	mg.m ⁻³	[WolfSense] = 1.258 × [MU] - 297.254	0.962
VOCs	µg.m ⁻³	[WolfSense] = 0.955 × [MU] - 7.383	0.618
T	°C	[WolfSense] = 1.119 × [MU] - 0.810	0.950
RH	%	[WolfSense] = 0.984 × [MU] - 4.232	0.723

reported poor sleep quality (scores >5) (Valente et al., 2019). Regarding Portuguese children, a study on a group of 1109 individuals reported a mean overall PSQI of 4.14 (significantly lower than the score of 5), indicating that children in this sample had good sleep quality (Gomes et al., 2017).

In the SATED scale, 67.9% of the participants reported a good sleep health, however the amount of people with average sleep health (with scores between 4 and 6) was almost a third of the population (31.0%). Only 1% of the participants reported bad sleep health, based on the SATED scale. A similar trend was found for the FOSQ-10 results that evaluates the alertness, where 63.3% of the participants reported a high alertness state (scores above 15) and 29.5% reported an average alertness state (scores between 11 and 15). However, 7.2% of participants reported a low alertness state (score from 5 to 10).

Based on MCTQ data, 49.2% of the participants showed a tendency to manifest a social jet-lag, since they offset their sleep time more than 1 h in the resting days. A difference between work and free days, is a consequence of a discrepancy between social and biological time and also it is related to a sleep deprivation during the work days (Wittmann et al., 2006).

Regarding the sleepiness, only 35.6% of the participants reported a low daily sleepiness (scores below 4), while the majority of the study population reported an average daily sleepiness (41.5%, with scores between 4 and 6), and 22.9% of the population reporting a high daily sleepiness (scores above 6).

The overall evaluation of the survey results indicates that a part of the study population presents issues regarding their sleep quality. These results are in agreement with the main outcomes found in a study about sleep dissatisfaction in the general population of Portugal, where a total of 1858 Portuguese participants were interviewed by telephone (ages above 18, 52.5% females) (Ohayon and Paiva, 2005). Difficulty initiating sleep was reported by 12.1% of the study population, with 21.0% reporting the prevalence of difficulty maintaining sleep and a total of 10.1% of participants were dissatisfied with their global sleep.

In order to understand how some factors may influence the perception of sleep quality, some specific characteristics of the study population were analysed and are described in the following sub-chapters.

3.1.1. Influence of professional occupation

Fig. 5 provides the sleep quality by the type of professional occupation. One professional occupation that stands out with the worst results regarding sleep is the students and, particularly, working students. No working student reported a sleep of good quality (PSQI), with 12.5% indicating the presence of sleep disturbances. For regular students, only 31.6% reported a sleep of good quality and 62.1% reported a sleep of poor quality. This result agrees with the study conducted on 574 students from Minho University (Portugal) where a total of 64.8% also presented poor sleep quality (Lopes et al., 2013). A study conducted in a sample of 257 students from eight Portuguese universities also concluded that, during weekdays, 65% of students presented poor sleep quality, with 12.1% showing sleep disturbances (Mendes et al., 2019). The percentages of poor sleep quality found in Portuguese university students are similar to the ones found in other countries, such as, in Saudia Arabia (with 62.7% of a total of 440 students) (Mahfouz et al., 2020), in USA (with 65.9% of a total of 1125 students) (Lund et al., 2010) and in Taiwan (with 54.7% of a total of 4318 incoming university students) (Cheng et al., 2012). The remaining occupations reported higher levels of sleep of good quality (ranging from 42.8% for employees to 62.5% for fellows), with sleep disturbances around 10% for unemployed, employee and retired people (10.0%, 9.1% and 11.1%, respectively). Regarding the sleep health assessed by SATED, only 25% of the working students reported a good sleep health, followed by regular students (62.5%) and employers (63.6%), with the remaining occupations reporting a higher good sleep health, ranging from 71.2% (employees) to 88.9% (retired).

Regarding the level of alertness, working students present the worst

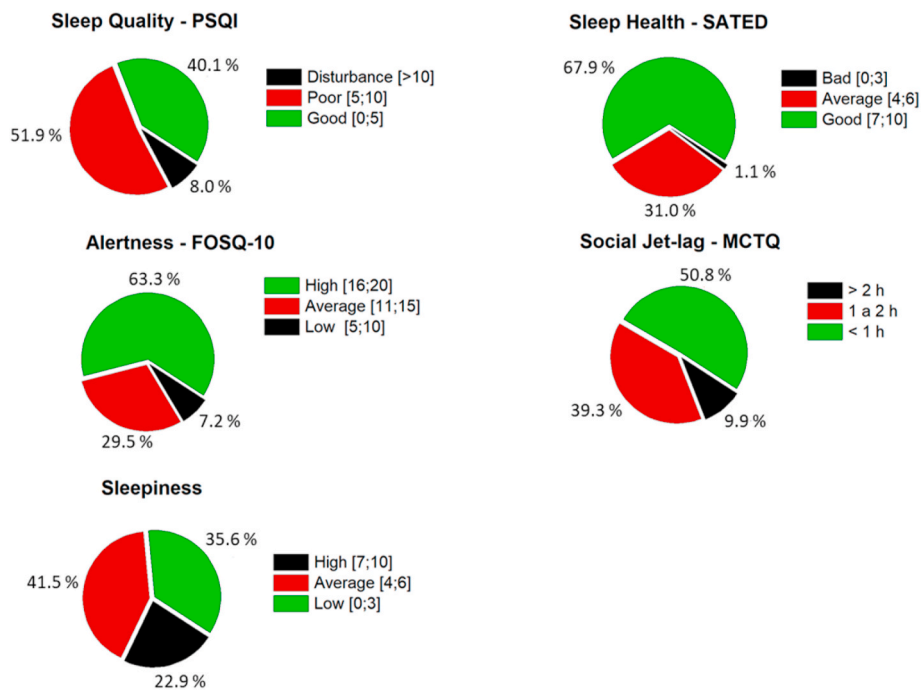


Fig. 4. General results of the survey regarding the perception of sleep quality.

scenario with a percentage of 25% reporting low alertness and the second lowest percentage of high alertness reported with 62.5%, only above to the alertness level of 53.6% found in regular students. Regular students reported the highest percentage of an average level of alertness (40.1%). Regarding the social jet-lag, only 25.0% of the working students did not offset their sleep by more than 1 h on rest days comparing with working days. Regular students were the second professional occupation with the lower percentage of a social jet-lag below 1 h (40.8%) and the higher percentage of a social jet-lag above 2 h (14.1%), only surpassed by working students (37.5%). Overall, regular and working students were the two types of professional occupation that reported social jet-lag above 1 h in more than 50% of the cases.

Considering the sleepiness level, students reported similar levels of high sleepiness (24.7%) as other professional occupations (employee – 20.8%, employer – 26.0%, retired - 33.3%) and lower than unemployed (40%) and working student (50%). The higher percentage of low sleepiness was reported by fellows (75%) with no reporting of high sleepiness.

3.1.2. Influence of bedroom occupancy

Fig. 6 provides the result of the bedroom occupancy on the individual outcomes of sleep quality, namely if it is the only occupant of the bedroom or, if shared, the sleeping occurs on the same or separate beds. Overall, 46% of individuals slept alone in the bedroom, 50% of individuals shared the bedroom and used the same bed, and only 4% of individuals shared the bedroom but not the bed.

Overall, a clear trend between bedroom occupancy and improved outcomes on sleep quality were not found. Regarding the reporting of a sleep of good quality (PSQI), people who have a partner in the same bed indicated better results of a good sleep quality (46.3%), when comparing with the situation of being the single occupant in the bedroom (33.8%) or when sharing a bedroom but in separated beds (34.2%). A good sleep health assessed by SATED scale registered higher percentage (78.9%) in the situation of bedroom sharing with separated beds, when comparing with the other situations: 64.9% for single occupancy and 69.8% for sharing the same bed. When considering alertness, the same group (bedroom sharing with separated beds) registered the lowest percentage of high alertness level (44.7%) among the studied categories, with the

remaining ones registering percentages of 62.7% (single occupancy) and 65.2% (sharing the same bed).

People that shared the same bed had 60.8% of them registering less than 1 h of social jet-lag, while people sleeping in a bedroom with single occupancy registered 41.5% and with shared bedroom but separated beds registered 31.6%. Sleeping in a shared bedroom with separated beds provided the highest percentage of more than 2 h of social jet-lag (23.7%). Only 6% of people that shared the same bed reported a difference of more than 2 h of sleep between working and resting days, while in people sleeping on the same bedroom but in separated beds the highest percentage was reported (with 23.7%). This specific case of bedroom sharing and separated beds is typically the situation of students in university dorms.

Regarding sleepiness, similar high levels were reported in the three categories studied (between 21.1% and 23.2%). However, people that shared bedrooms but used separated beds showed the highest percentage of low sleepiness (42.1%), while people sleeping in a single occupied bedroom showed the highest percentage of average levels of sleepiness (45.2%).

3.1.3. Influence of indoor air quality perception

The perception of indoor air quality (IAQ) in the bedroom was one parameter that was also focused in this survey, in order to understand if low perception of IAQ would be, potentially, a factor of the individuals' perception regarding their sleep quality. Fig. 7 provides the summary of the results regarding the IAQ perception.

Overall, it is possible to observe a trend that a worst perceived IAQ conduct to a worst perception of sleep parameters, except in the case of the social jet-lag (MCTQ). Regarding sleep quality (PSQI), people that reported a perceived good IAQ achieved a high percentage of good sleep quality (47.0%), while people reporting an average or poor perceived IAQ, only around 32% reported a good sleep quality. Regarding the sleep health, 73.6% of the people that perceived a good IAQ had a good sleep health, while 73.7% of the people that perceived a poor IAQ indicated an average sleep health (with only 26.3% having a good sleep health). The same trend was found for the individuals' alertness (FOSQ10), where high alertness levels (70.3%) were found for people perceiving a good IAQ, while people perceiving a poor IAQ indicated the

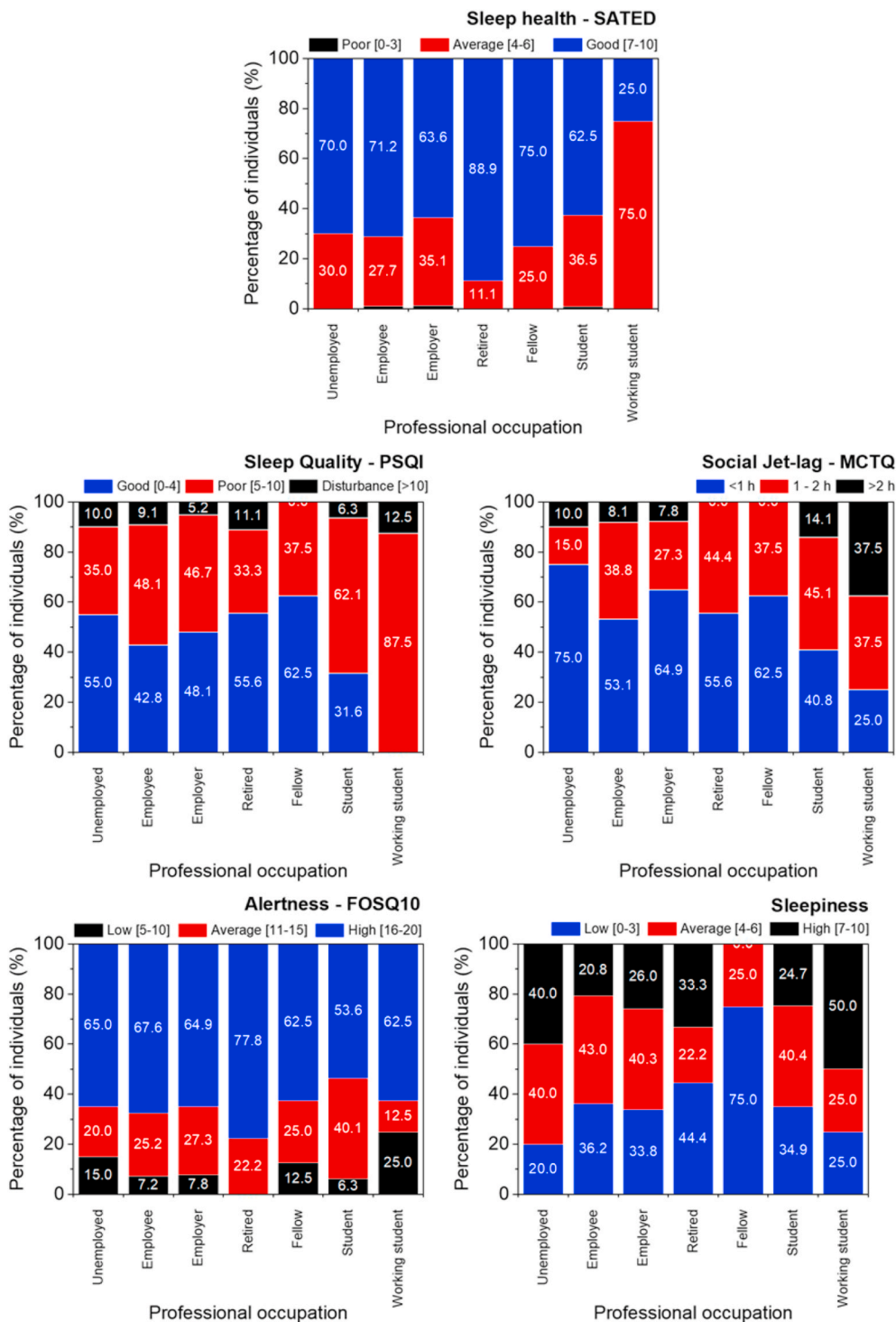


Fig. 5. Sleep outputs per type of professional occupation.

lowest percentage of high alertness (21.1%) and the highest percentage of low alertness among the studied categories (15.8%). Regarding the social jet-lag (MCTQ), no clear influence of the perceived IAQ on the social jet-lag level was observed, with all categories showing percentages between 50.1 and 52.6% of jetlag below 1 h, 38.2–42.1% of jetlag between one and 2 h and 5.3–11.7% of jetlag above 2 h.

A good perceived IAQ also presented higher levels (39.9%) of low daily sleepiness, while a poor perceived IAQ was the category that registered the highest level of high daily sleepiness (with 42.1%), where good and average perceived IAQ resulted in percentages of only 21.2%

and 24.3%, respectively.

These results indicate that people that perceived a good IAQ generally indicate better sleep parameters.

3.2. Sleep monitoring

Using sleep diaries and actigraphy data from the participants, it was possible to obtain information about several sleep parameters, namely the total sleep time (TST), perceived sleep quality (PSQ), the number of awakenings (NA) and activity level during sleep measured by actigraphy

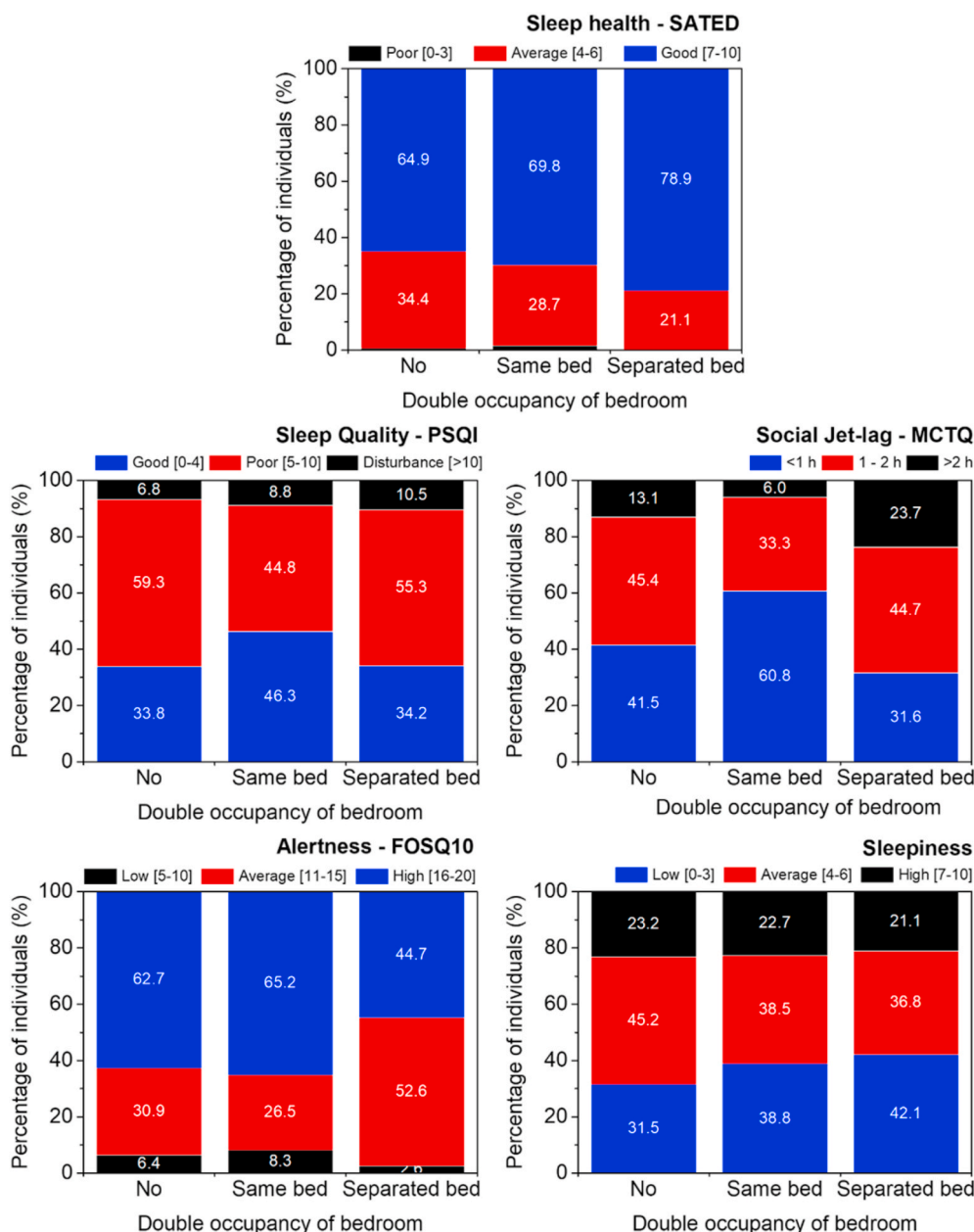


Fig. 6. Influence of the bedroom occupancy in the results of the sleep tests.

(PIM), which is the mode that better correlates with polysomnography (Blackwell et al., 2008). Table 4 provides the results of these parameters for each sleep period. Due to the loss of data by subjects 5 and 12, these subjects were not considered in the sleep monitoring results. The same happened to the second night of subjects 6 and 9.

The students slept, on average, 07:30 ± 01:30 per night, with a minimum value of 03:30 (subject S11, N2) and a maximum value of 10:15 (subject S8, N1). Despite the mean sleeping time is on the adequate range for an adult (between 7 and 8 h), there are high discrepancies between subjects, which is expected considering Pilcher et al. (1997) that studied sleep quality in university students. Regarding the perceived sleep quality, a mean value of 7.0 ± 1.6 (ranging from 4 to 10) was found among the volunteers.

3.3. Indoor air quality monitoring during sleep

Fig. 8 shows the variability between bedrooms of IAQ parameters during the sleep of volunteers and Table 5 provides its summary, along

with its compliance with the limit values (LV) established by the Portuguese legislation (Ordinance n.º 323-A/2013 (2013)) for CO₂, VOCs, PM_{2.5} and PM₁₀, and by the ISO 7730 (2005) for T and RH. Figure S 1 provides an example of IAQ monitoring data of a sleeping period (namely, for the subject 13 during the second night monitored).

Levels of particulate matter, for both PM_{2.5} and PM₁₀, were typically low and below the established limit values by the Portuguese legislation, namely 25 and 50 µg·m⁻³, respectively. PM_{2.5} mean levels were 7.7 ± 2.6 µg·m⁻³ (ranging from 3.7 to 40.4 µg·m⁻³), with only 1% of the measurements above the threshold of 25 µg·m⁻³. However, when considering the lower guideline value of 10 µg·m⁻³ for PM_{2.5}, established by the World Health Organisation (WHO, 2006)(EEA, 2018), around 16% of the measurements were above this threshold. The PM_{2.5} levels observed in this study are below the mean PM_{2.5} levels found during the sleeping period in bedrooms of Lisbon dwellings (Canha et al., 2020), which presented mean PM_{2.5} levels of 15.3 ± 9.1 µg·m⁻³ (ranging from 4.7 ± 3.7 µg·m⁻³ to 36.6 ± 36.8 µg·m⁻³). The PM_{2.5}/PM₁₀ ratio found in the university dorms during sleep was 0.82 ± 0.03

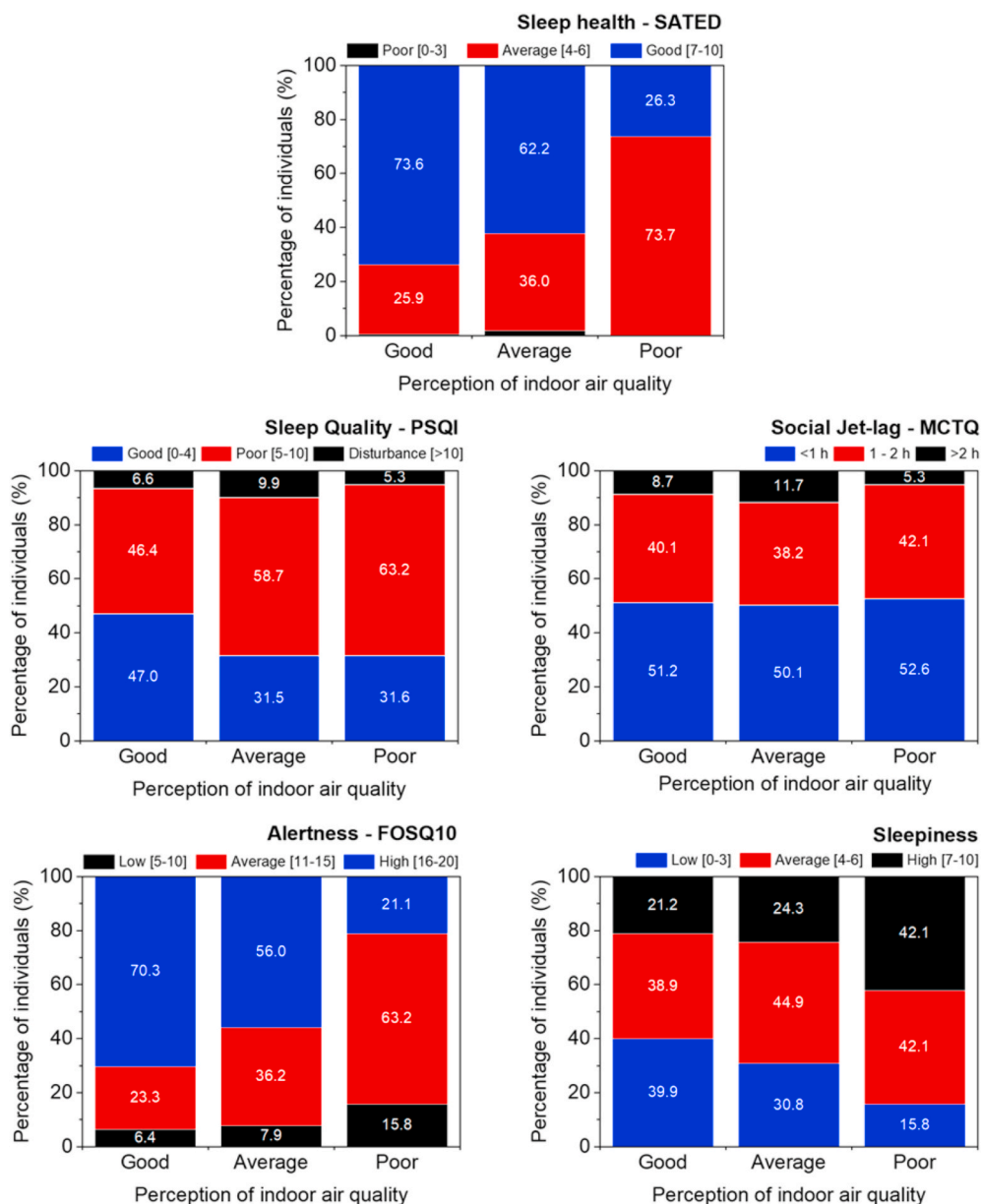


Fig. 7. Influence of the perceived air quality on the results of the sleep tests.

(ranging between 0.78 and 0.87), indicating that a high proportion of PM₁₀ was composed by fine particles. Similar pattern was also found in bedrooms of Lisbon dwellings (where PM_{2.5} accounted between 72% and 84% to PM₁₀ levels) (Canha et al., 2020).

The exposure to PM (E , in $\mu\text{g}\cdot\text{m}^{-3}\cdot\text{h}^{-1}$) can be assessed by multiplying the concentration measured in a specific micro-environment (C_j) by the time spent in it (t_j). Moreover, the potential inhaled dose (D , in μg) can be estimated by multiplying the previous assessed exposure by the inhalation rate (IR , in $\text{m}^3\cdot\text{h}^{-1}$) of the occupants (Faria et al., 2020). For individuals between 19 and 40 years old, the inhalation rate during the sleeping period can be assumed as $0.36\text{ m}^3\cdot\text{h}^{-1}$ (Buonanno et al., 2011).

The exposure and the associated potential inhaled dose to PM levels assessed during the sleeping periods of the subjects of the present study are described in Table S1 (Supplementary Information). Exposures to PM_{2.5} and PM₁₀ were estimated to be $62.9 \pm 24.3\ \mu\text{g}\cdot\text{m}^{-3}\cdot\text{h}^{-1}$ and $76.3 \pm 26.3\ \mu\text{g}\cdot\text{m}^{-3}\cdot\text{h}^{-1}$, respectively. The exposure levels found in this study (university dorms) were below the ones found in bedrooms of couples (with ages between 25 and 45 years old, $113.6 \pm 64.8\ \mu\text{g}\cdot\text{m}^{-3}\cdot\text{h}^{-1}$ for PM_{2.5} and $148.1 \pm 84.8\ \mu\text{g}\cdot\text{m}^{-3}\cdot\text{h}^{-1}$ for PM₁₀) (Canha et al., 2020) and in

children bedrooms in Lisbon dwellings ($141.4\ \mu\text{g}\cdot\text{m}^{-3}\cdot\text{h}^{-1}$ for PM_{2.5} and $177.4\ \mu\text{g}\cdot\text{m}^{-3}\cdot\text{h}^{-1}$ for PM₁₀) (Faria et al., 2020).

Regarding carbon dioxide, 73% of the studied sleeping periods had levels above the limit value of $2250\ \text{mg}\cdot\text{m}^{-3}$ established by the Portuguese legislation, with only three bedrooms registering mean levels below this threshold during the sleeping period (bedrooms of subjects 4, 11 and 12). From these three, only one had a mean value below $1500\ \text{mg}\cdot\text{m}^{-3}$ (bedroom of subject 11), a threshold above which the sleep quality and the next-day performance may be negatively affected as already found in a study in university dorms (Ström-Tejse et al., 2016). In five bedrooms (namely, the bedrooms of subjects S1, S2, S6, S7 and S9), it was found that the levels of CO₂ in the beginning of the sleeping period were already above the established limit value. This indicates clearly that the occupants were at the bedroom previously and did not open the windows to promote natural ventilation before sleep, which should be a good practice in order to avoid such an accumulation of CO₂.

Moreover, the high levels of CO₂ found in most of the bedrooms indicate that the current ventilation conditions are not adequate to promote an efficient dilution of indoor pollutants. It is important to

Table 4

Sleep parameters of each sleep period, where S stands for subject and N for the studied night.

Subject/Night	TST (h)	PSQ	NA	PIM
S1 N1	08:20	8	1	143.9
S1 N2	07:25	8	1	162.6
S2 N1	10:15	5	2	105.0
S2 N2	09:00	5	4	146.7
S3 N1	07:30	7	0	95.8
S3 N2	07:30	7	1	178.5
S4 N1	06:00	9	0	111.4
S4 N2	06:18	10	0	82.6
S6 N1	07:30	6	–	158.1
S7 N1	05:55	4	3	148.2
S7 N2	07:10	6	1	119.9
S8 N1	10:15	9	0	109.3
S8 N2	09:25	7	0	148.7
S9 N1	07:35	7	1	152.9
S10 N1	08:27	6	3	1160.2
S10 N2	07:50	5	2	201.8
S11 N1	05:50	7	3	137.2
S11 N2	03:30	9	1	266.6
S13 N1	07:25	7	1	76.3
S13 N2	06:50	7	2	149.3
Mean ± standard deviation	7:30 ± 1:30	7.0 ± 1.6	1.4 ± 1.2	192.8 ± 231.8
Minimum - Maximum	[3:30–10:15]	[4–10]	[0–4]	[76.3–1160.2]
Median	7:30	7	1	147.5

highlight that CO₂ is known to be a cognitive inhibitor in humans (Satish et al., 2012) and can cause headaches, discomfort, nausea and eye and throat irritation (Schwarzberg, 1993; Yang et al., 1997).

A similar trend was found for VOCs with only two bedrooms registering mean levels below the limit value of 600 µg·m⁻³ established by the Portuguese legislation (bedrooms of subjects 1 and 4). VOCs are a group of pollutants that are emitted by common household products (such as cleaning and consumer products) and building materials (such as paints and varnishes) (Chin et al., 2014). VOCs are highly irritating to the eyes and respiratory tracts (WHO, 2008) and can damage organs such as liver and kidneys and cause cancer (Wickliffe et al., 2020). High levels of these pollutants were also found in bedrooms of Lisbon dwellings (Canha et al., 2020), showing that ventilation conditions were also not enough to promote their dilution and that this is a common problem found in bedrooms (Canha et al., 2021).

Regarding comfort parameters, six bedrooms (out of 13) registered mean temperatures above the temperature range of 23–26 °C established for occupants' comfort during the warm season (ISO 7730:2005, 2005). Overall, the mean temperature registered in all bedrooms was 26.0 ± 1.4 °C, ranging from 23.2 ± 0.1 °C (bedroom of subject 1) to 28.8 ± 0.3 °C (bedroom of subject 3). This reflects a trend of higher temperatures than the established range during sleep, with a total 44% of the monitored data outside that range. Taking into account that temperature is a known and important determinant of sleep quality (Okamoto-Mizuno and Mizuno, 2012; Pan et al., 2012), a special effort should be done to improve this issue in the studied bedrooms.

Mean levels of relative humidity were always within the recommended range of 30–70% for the occupants' comfort in indoor environments (ISO 7730:2005, 2005), with a mean value of 51.7 ± 9.5%, ranging from 32.8 ± 4.1 (bedroom of subject 11) to 67.5 ± 5.0 (bedroom of subject 2).

3.3.1. Influence of bedrooms' characteristics

In order to understand if the type of ventilation of the bedrooms and their type of occupancy influenced the levels of the different IAQ parameters, statistical differences were assessed by Mann-Whitney's test, as displayed in Table S2 (Supplementary Information).

The type of ventilation did not show any statistical difference for any of the IAQ parameters. This fact may indicate that the set-up and settings

of the mechanical ventilation are not enough to provide improved levels of IAQ, when comparing to the use of natural ventilation as it would be expected (Canha et al., 2016). The lack of influence of mechanical ventilation is probably due to the timing and low frequency that is activated, as well as its location, since it is located in the bathrooms and not directly where the occupants sleep. Therefore, improvements should be done to provide a traditional mechanical ventilation setting in the bedrooms, which are expected to improve IAQ.

Bedrooms with double occupancy had levels of CO₂, RH and VOCs significantly higher than single occupied bedrooms. Bedrooms with double occupancy registered mean levels of 5930 ± 3040 mg·m⁻³ for CO₂, 1012 ± 419 µg·m⁻³ for VOCs and 57.5 ± 9.4% for RH, while single occupied bedrooms registered mean levels of 2900 ± 1250 mg·m⁻³ for CO₂, 672 ± 169 µg·m⁻³ for VOCs and 47.3 ± 8.6% for RH, respectively. The higher levels of these parameters are probably due to the double occupancy during the sleeping period, since all can be promoted by exhaled human breath. However, this fact also highlights that the current ventilation settings are not suitable to promote a proper dilution of these parameters.

3.4. Influence of indoor air quality on sleep

The influence of the different IAQ parameters into the sleep quality of the occupants was assessed based on the Spearman's correlations, which are shown in Table 6.

Considering only the sleep parameters, it was found that the perceived sleep quality (PSQ) was negatively correlated with the number of awakenings (NA) during the sleeping period.

The activity levels (PIM) of the occupants during the sleeping period were positively correlated with both PM_{2.5} and PM₁₀ levels, which was expected since movement of the occupant during sleep promotes the resuspension of particles that were previously settled in the bed clothing and mattress (Canha et al., 2017).

The total time of sleep (TST) was positive correlated with the levels of CO₂ and RH during sleep. This was expected because the only source of CO₂ and RH during sleep is the exhaled breath of the occupants (confirmed by the correlation between these two parameters) and, therefore, the longer period of time that people sleep, the longer they are exhaling CO₂ and water vapor. Without proper dilution by ventilation, these parameters will continuously increase during the sleeping period.

VOCs levels were also correlated with CO₂ levels, highlighting their common source, namely via exhalation of the occupants, as already shown previously (Sun et al., 2017; Sun and Yang, 2013).

The perceived sleep quality was found to be negatively correlated CO₂ and RH, which agrees with previous findings that high levels of CO₂ have a negative impact on sleep quality. A study in Australian dwellings with 48 individuals showed that deep sleep percentage was negatively related to CO₂ levels during sleep, with a 4.3% decrease for every 180 mg·m⁻³ CO₂ increase in the mean CO₂ levels (Xiong et al., 2020). In 20 single bedrooms of Danish university dorms, reducing CO₂ levels during sleep conducted to improved perceived freshness of the bedroom air, improvement of sleep efficiency and decrease of the next-day reported sleepiness (Strøm-Tejsten et al., 2016). Lower CO₂ levels were also found to promote better sleep depth, lower number of awakenings and better sleep efficiency of individuals sleeping in 17 Dutch single bedrooms (Mishra et al., 2018). A study conducted with 104 individuals in Chinese dwellings showed that CO₂ levels during sleep were positively associated with the number of awakenings and negatively associated with subjective sleep quality (Zhang et al., 2021).

The influence of RH on PSQ found in this study agrees with the fact that humidity can promote heat stress during sleep, which can, by its turn, impact on sleep quality (Okamoto-Mizuno and Mizuno, 2012).

3.5. Considerations

Despite the present study allowed to identify a negative influence of

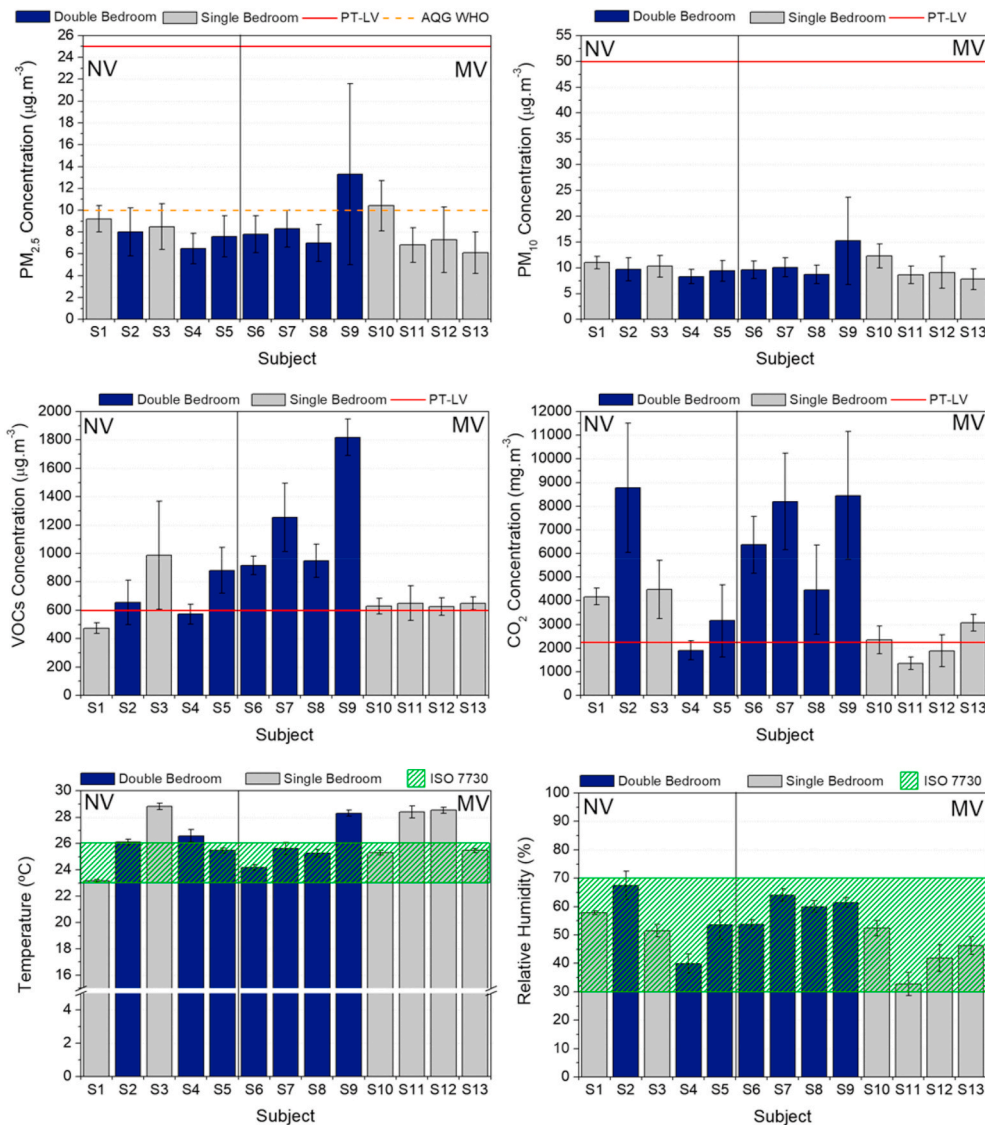


Fig. 8. Indoor air quality during the sleeping period of the 13 volunteers, with indication of typology of bedroom (single or double), type of mechanical ventilation (NV – natural ventilation or MV – mechanical ventilation) and established limit values and guidelines (Portuguese legislation – red line - and WHO – orange dash line) and optimum range of comfort parameters (ISO 7730 – green listed area).

Table 5

Descriptive analysis of pollutants and comfort parameters during the sleep periods in the 13 bedrooms. n is the percentage of time during sleep where the limit values were surpassed.

	Pollutants				Comfort parameters	
	PM _{2.5} (µg.m ⁻³)	PM ₁₀ (µg.m ⁻³)	CO ₂ (mg.m ⁻³)	VOC (µg.m ⁻³)	T (°C)	RH (%)
Limit value	25	50	2250	600	[23–26]	[30–70]
Mean ± SD	7.7 ± 2.6	9.5 ± 2.6	3830 ± 2490	825 ± 260	26.0 ± 1.42	51.7 ± 9.46
Minimum -Maximum	[3.7–40.4]	[5.4–42.9]	[730–15760]	[398–2193]	[22.7–29.4]	[27.3–76.4]
Median	6.12	7.86	3060	744	25.5	53.1
n (%)	0.96	0.00	72.5	74.5	43.5	6.6

CO₂ and RH levels during sleep into the perceived sleep quality of the occupants, this study was focused on very similar sleeping environments, namely university dorms. Real life settings in dwellings should be studied in the future to consider the greater variability that can exist regarding bedrooms. Moreover, future efforts should also focus on a greater number of individuals to obtain a more representative sample and to study potential individual characteristics' influence on sleep. The combined use of questionnaires and actigraphy to assess sleep quality is

a good and viable strategy as seen in this work but efforts should be done to also apply polysomnography, since it provides time-resolved data and it can identify several sleep patterns allowing the quantitative characterization of macro and micro sleep structure.

4. Conclusions

Initially, this study aimed to understand how was the sleep quality of

Table 6

Correlation between parameters of sleep quality and indoor air quality. Bold indicates that it is significant correlation (p-value < 0.050).

	Variable	Sleep quality				Indoor air quality					
		PIM	TST	PSQ	NA	PM _{2.5}	PM ₁₀	VOCs	CO ₂	T	RH
Sleep quality	PIM	1	0.01	-0.20	0.32	0.68	0.68	0.05	-0.20	-0.10	-0.01
	TST		1	-0.27	-0.02	0.33	0.33	0.09	0.45	-0.36	0.57
	PSQ			1	-0.63	-0.35	-0.35	-0.31	-0.52	0.10	-0.57
	NA				1	0.28	0.28	-0.18	0.06	-0.02	0.20
Indoor air quality	PM _{2.5}					1	1.00	0.18	0.27	-0.22	0.43
	PM ₁₀						1	0.18	0.27	-0.22	0.43
	VOCs							1	0.49	0.31	0.39
	CO ₂								1	-0.21	0.86
	T									1	-0.32
	RH										1

the Portuguese population, based on a sample of 1040 individuals. New and relevant information about sleep quality and sleep problems in the Portuguese population was found, specifically in university students. This study highlighted that worst perceived IAQ conducted to a lower perception of parameters that assessed the perception of the individuals toward their sleep quality. This fact reinforces previous findings that IAQ affects sleep quality, and that the sleeping environment may play an important role on human health and well-being, highlighting the importance and need to focus on this topic.

Around 50% of the Portuguese population reported to have poor sleep quality and one third reported not having a good sleep health. Only 50% of individuals slept in their preferred timing during working days, 37% did not have a high alertness state during the day, and only 35.6% reported low sleepiness during the day. University students stand out, obtaining worse indicators in almost all tests when compared to other professional occupations.

Focusing on this specific group of the population, the assessment of IAQ during the sleep of students in university dorms revealed that students were exposed to mean levels of CO₂ and VOCs higher than the established limit values during sleep, indicating that ventilation conditions were not sufficient to keep an acceptable IAQ. Temperature also was out of the acceptable comfort range during 44% of the sleeping time, which may condition the sleep of the individuals. Despite some of the bedrooms having mechanical ventilation, it was showed that its settings were not optimized since it provided similar results to naturally ventilated bedrooms. Bedrooms with double occupancy promoted levels of CO₂, RH and VOCs significantly higher than single occupied bedrooms.

Regarding the sleep assessment by actigraphy and questionnaires, the students within this study showed highly irregular sleep patterns between them, evidencing the lack of sleep quality reported by the 312 students and working students that answered the online survey.

This study highlighted that the perceived sleep quality of individuals was negatively associated with the number of awakenings and the mean levels of CO₂ and RH during the sleeping period. These outputs confirms previous findings where some IAQ parameters may influence the sleep quality of the individuals, highlighting the importance of this topic and the need for further studies focusing on other groups of population, with bigger samples and using complementary techniques for both IAQ and sleep assessments.

Credit author statement

João Ramos - management of volunteers, data sampling and monitoring, data analysis, original draft, writing of the original draft, writing (review and editing). Joana Belo - funding acquisition, conceptualization, data sampling and analysis. Dário Silva - data sampling and monitoring. Carlos Diogo - data sampling and monitoring. Susana Marta Almeida - conceptualization, writing (review and editing). Nuno Canha - conceptualization, data sampling and monitoring, data analysis, original draft, writing (review and editing)

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.apr.2021.101301>.

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