Can air purification improve sleep quality? A 2-week randomised controlled crossover pilot study in healthy adults

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RESEARCH ARTICLE

Can air purification improve sleep quality? A 2-week randomised-controlled crossover pilot study in healthy adults

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Summary

Insufficient quantity and quality of sleep is a public health concern that can be addressed by interventions for improving sleep outcomes. Environmental factors such as poor air quality are a potential target for intervention, particularly in light of associations between air pollution and worse sleep. The aim of this pilot study was to investigate the effects of using an air purifier on sleep outcomes and mood in 30 healthy adults. There were two conditions: (i) air purifier with a high-efficiency particulate air filter; (ii) air purifier with a placebo filter. Participants undertook both conditions, each over 2 weeks with a 2-week washout, following a counterbalanced, double-blind design. Daily sleep outcomes were measured with actigraphy watches and sleep diaries, whilst daily mood was assessed with the Positive and Negative Affect Schedule. The Insomnia Severity Index, the Pittsburgh Sleep Quality Index, and symptoms of anxiety and depression were measured pre- and post-. The purifier filter was associated with increased total sleep time for an average of 12 min per night, and increased total time in bed for an average of 19 min per night relative to the placebo. There were several sleep and mood outcomes for which no changes were observed, and time awake after sleep onset was higher for the purifier filter. Air quality was better during the high-efficiency particulate air filter condition. These findings offer positive indications that environmental interventions that improve air quality can have benefits for sleep outcomes in healthy populations who are not exhibiting clinical sleep disturbances.

KEYWORDS
actigraphy, air cleaners, air pollution, air purification, air purifier, air quality, high-efficiency particulate air, mood, sleep, sleep diary, sleep quality, sleep watches

1 | INTRODUCTION

Insufficient sleep is a prevalent, global, public health concern (Chattu et al., 2018). In addition to the daily impact and distress of poor sleep, long-term sleep disturbance has also been widely associated with physical and mental wellbeing (Grandner, 2019). For example, there are established associations with cardiovascular health (Makarem et al., 2019), obesity (Hargens et al., 2013), smoking and substance abuse (Hasler et al., 2012), cognitive, emotional and behavioural dysregulation (Palagini et al., 2019), poorer academic performance, work

success and learning capacity (Barnes & Watson, 2019; Hershner, 2020), deficits to affective functioning including mood disorders, suicidal behaviour and self-harm (Lyall et al., 2018). Given the prevalence and widespread impact of insufficient sleep amongst young people and adults globally, sleep disturbances presents not only as a significant public health problem, but also an economic burden on society.

An appropriate sleep environment is crucial for good sleep quality, and can be influenced by a range of environmental factors, including noise, traffic, temperature, lighting and air quality (Caddick et al., 2018). Air pollution is one environmental factor that has been widely associated with a number of health conditions, including reduced life span, cardiovascular disease (Cai et al., 2018), diabetes (Yang et al., 2020) and depression (Fan et al., 2020), and data from the Global Burden of Disease Study spanning 1990–2015 indicate that a measure of air quality (particulate matter 2.5; $PM_{2.5}$) was the fifth-ranking mortality risk factor in 2015 (Cohen et al., 2017). In a systematic review, Cao et al. (2021) examined the association between ambient air pollution and sleep quality, identifying 15 studies across 10 different countries. They reported that most studies found one or more air pollutants as having negative influences on sleep. Furthermore, indoor air quality has been associated with various sleep outcomes as reported in a review of 22 field studies that assessed exposure to main indoor air pollutants during the sleeping period (Canha et al., 2021).

In light of the associations between air quality and sleep, interventions that improve air quality may have positive effects for sleep outcomes. There is strong evidence for effective psychological treatment of sleep disturbances caused by psychological factors, such as stress, and evidence of secondary benefits on mental wellbeing (Gee et al., 2019). However, very little is known about interventions targeting environmental causes of sleep disturbance, and any associated benefits of this. Whilst some environmental factors are harder to control, such as external air pollution, street noise and lighting, there are solutions that can be implemented within the home and bedroom environment to improve indoor air quality (Cooper et al., 2021). A review by Johnson et al. (2018) concluded that given clear evidence of environmental factors being associated with insufficient sleep and sleep disorders, interventions that target changes in the environment and promote better sleep need to be developed, tested and evaluated, as a means to reducing insufficient sleep and the associated health concerns. Increasing bedroom ventilation by opening windows and reducing CO_2 has been associated with better sleep outcomes (Mishra et al., 2018; Strøm-Tejsen et al., 2016), however it remains unknown whether interventions targeting the reduction of bedroom air pollutants such as particulate matter, volatile organic compounds (VOCs) and NO_2 can improve sleep outcomes. Therefore, the primary aim of this pilot study was to investigate the effects of using an air purifier (air cleaner) for 2 weeks on sleep outcomes in a sample of healthy adults. Secondary aims were to explore effects on subjective mood, and measures of air quality.

2 | METHODS

2.1 | Participants

Thirty participants aged 25–65 years were recruited. One withdrew for personal reasons, leaving a final sample of $n = 29$ (21 females and 8 males). The mean age was 35 years (s.d. 10) and mean body mass index was 23 kg m^{-2} (s.d. 3.6 and range 17–29, calculated from self-reported height and weight). Ethnicities varied, including White British ($n = 8$), other White background ($n = 7$), Chinese ($n = 4$), other Asian background ($n = 4$), Black African ($n = 2$), Mixed White and Black Caribbean ($n = 1$), other mixed background ($n = 1$), and prefer not to say ($n = 2$). Twelve participants shared a bed with a partner, and five participants shared a room with one other person. Exclusion criteria were diagnosed sleep disorders, regularly taking medication that affected sleep or mood, any mental health diagnosis, children < 5 years in the household, living within 5 miles of an airport, night shift workers, currently using purifiers or humidifiers, or pregnancy. Participants were recruited through advertising in the local community, and received a £100 honorarium upon completing the study.

2.2 | Design

The design was a double-blind, randomised-controlled, crossover trial with two conditions: (i) a purifier filter condition with a high-efficiency particulate air (HEPA) filter; and (ii) a placebo filter condition that consisted of the same fabric as the filter condition, but the fabric was slit to allow the air to pass through unfiltered. Therefore, the placebo condition was identical in appearance, shape and weight to the HEPA filter condition. Each arm lasted 2 weeks. Double-blinding was achieved with an independent researcher at the University of Reading who prepared the purifiers in advance by inserting the placebo or purifier filter according to the randomisation schedule created with www.randomization.com using seed 4437. The prepared purifier was given to the lead researcher who took the equipment to participants' homes. Participants were asked not to open the purifier, and the screen was covered with tape to ensure blinding of participants to the purifier readings (e.g. air quality). Following an initial screening session where exclusion criteria were checked and demographic data were collected, participants were randomly assigned to the purifier or the placebo for the first arm of the study. A 2-week washout period separated the two conditions. Data collection occurred between May and September 2021.

2.3 | Sleep measures

Subjective and objective measures of sleep were collected. Objective sleep measurement was examined via Actigraphy Sleep Watches (Motionwatch 8), and subjective measurement was examined via self-reported Consensus Sleep Diaries (Carney et al., 2012). Both

measures were used to assess the following daily sleep parameters: sleep-onset time (SOT); sleep-onset latency (SOL); wake-up time (WUT); total sleep time (TST); wake after sleep onset (WASO); and sleep efficiency (SE). As is standard with actigraphy data collection, sleep diary data were examined to check and correct any errors in the daily actigraphy output. In addition to these daily measures, at the beginning and the end of each arm, general sleep quality was collected with the Insomnia Severity Index (ISI; Morin, 1993) and the Pittsburgh Sleep Quality Index (PSQI; Buysse et al., 1989). The PSQI consists of 18 items that are used to calculate seven domains of sleep, including subjective sleep quality, sleep latency, sleep duration, SE, sleep disturbance, use of sleeping medication, and daytime dysfunction. These component scores are then summed to create a global PSQI score representing overall sleep quality. Amongst participants without medical comorbidities, a global score of > 5 suggests problematic sleep that may require clinical investigation. A systematic review and meta-analysis of the psychometrics of the measure revealed good reliability and validity (Mollayeva et al., 2016). The ISI is a seven-item scale assessing the perceived severity of insomnia symptoms (initial, middle, terminal), satisfaction with sleep, interference with daytime functioning, noticeability of impairment, and concern caused by the sleep problems, over the past 2 weeks. The items are rated on a Likert-scale from 0 to 4. The ISI has also been found to have good reliability and validity amongst adults (Bastien et al., 2001).

2.4 | Wellbeing and other measures

Daily mood was assessed with the Positive and Negative Affect Schedule (PANAS; Watson et al., 1988), producing a score out of 50 for Positive Affect and Negative Affect, with higher scores indicating higher levels of affect. Symptoms of depression, anxiety and stress were collected at the beginning and end of each arm with the Patient Health Questionnaire Depression Scale (PHQ-8; Kroenke et al., 2009), Generalised Anxiety Disorder Scale (GAD-7; Spitzer et al., 2006) and Perceived Stress Scale (PSS-10; Cohen et al., 1983), respectively. The PSS-10 was adapted to reflect the previous 2 weeks in line with the other measures. In order to capture subjective feedback relating to factors such as noise and the experience of using the air purifier, participants answered a series of questions at the end of the study via an online questionnaire outlined in Table 4 (see Results), which had "yes", "no" or "not sure" answers.

2.5 | Air quality assessment

Data relating to air quality were collected by the purifier continuously whilst it was turned on and automatically uploaded the data to a secure cloud for the following variables: overall air quality (OAQ); particulate matter 2.5 ($PM_{2.5}$ fine particles) and particulate matter 10 (PM_{10} coarse particles); humidity; temperature; VOCs; and

TABLE 1 Means (se) for daily outcome measures with the sleep diary and actiwatch, for the 2-week purifier arm and the 2-week placebo arm (data are per day, averaged across 14 days; $n = 29$)

Variable	Purifier ($n = 29$)	Placebo ($n = 29$)	Condition sig.	Order sig.	Condition* order interaction sig.
TST diary	7:15 (10)	7:03 (8)	0.06	0.11	0.046*
TST watch	6:47 (9)	6:42 (8)	0.53	0.88	0.024*
Total TIB diary	8:43 (10)	8:24 (9)	0.007**	0.24	0.38
Total TIB watch	8:16 (11)	8:06 (8)	0.22	0.42	0.08
SE^ % diary	83.4 (1)	84.6 (1)	0.12	0.46	0.049*
SE^ % watch	82 (1)	83 (1)	0.14	0.24	0.046*
SOL diary	16 (2)	16 (2)	0.72	0.67	0.64
SOL watch	18 (3)	20 (3)	0.54	0.82	0.051
WASO diary	9 (2)	9 (3)	0.64	0.26	0.41
WASO watch	67 (5)	59 (4)	0.003**	0.06	0.24
SOT diary	12:34 (13)	12:41 (14)	0.34	0.98	0.9
SOT watch	12:16 (12)	12:29 (14)	0.12	0.61	0.15
WUT diary	7:56 (12)	7:55 (13)	0.82	0.4	0.12
WUT watch	8:11 (12)	8:11 (13)	0.99	0.28	0.17
Positive affect	24.1 (1.7)	23.5 (1.6)	0.41	0.25	0.86
Negative affect	12.4 (0.7)	12.2 (0.6)	0.62	0.27	0.18

Note: Analysis model was a 2 × 2 ANOVA with condition as a repeated variable (purifier and placebo) and order as a between-groups variable (purifier first, placebo first). Degrees of freedom = 27. Data are clock time or minutes unless stated. ^Calculated as TST/total TIB. For Positive and Negative Affect, a higher score indicates greater levels of positive and negative affect.

Abbreviations: SE, sleep efficiency; SOL, sleep-onset latency; SOT, sleep-onset time; TIB, time in bed; TST, total sleep time; WASO, wake after sleep onset; WUT, wake-up time.

*$p < 0.05$.**$p < 0.01$.

nitrogen dioxide (NO_2). OAQ was automatically calculated from the $PM_{2.5}$, PM_{10}, VOC and NO_2 data using an algorithm.

2.6 | Procedures

Interested participants undertook an online screening session with the research team during which exclusion criteria were checked and demographic data collected (see Section 2.1 "Participants"). During screening, participants provided informed consent and the first test session was arranged for between 1 and 3 weeks later. The day each arm commenced, participants were provided with the purifiers, the relevant filter, the watches and a questionnaire pack containing the questionnaires described in Section 2.3 "Sleep measures". Standardised instructions for setting up and using the purifier, connecting it to the internet and using the actiwatch were provided by the researcher via an online meeting, and additional paper instructions were included in the questionnaire pack. Participants were asked to place the purifier in their bedroom and turn it on at least an hour before going to sleep, and to keep the windows and doors closed whilst the air purifier was on. To ensure blinding to the conditions, the screen on the purifier was covered by the research team and participants were instructed to operate the purifier with a remote control. Use of the purifier app was not permitted. Participants were encouraged to maintain their exercise and dietary habits and their bedtime routines for the duration of both arms. At the end of each arm, all equipment and the questionnaire pack were collected by the researcher. At the end of arm 1, the 2-week washout commenced. Participants were not given any instructions regarding their sleeping habits during the washout. The purifiers were provided by Dyson Technology Ltd UK. The study was registered with Research Registry (ref 6887). Ethical approval was obtained from the University of Reading, School of Psychology Research Ethics Committee (ref 2021-047-DL).

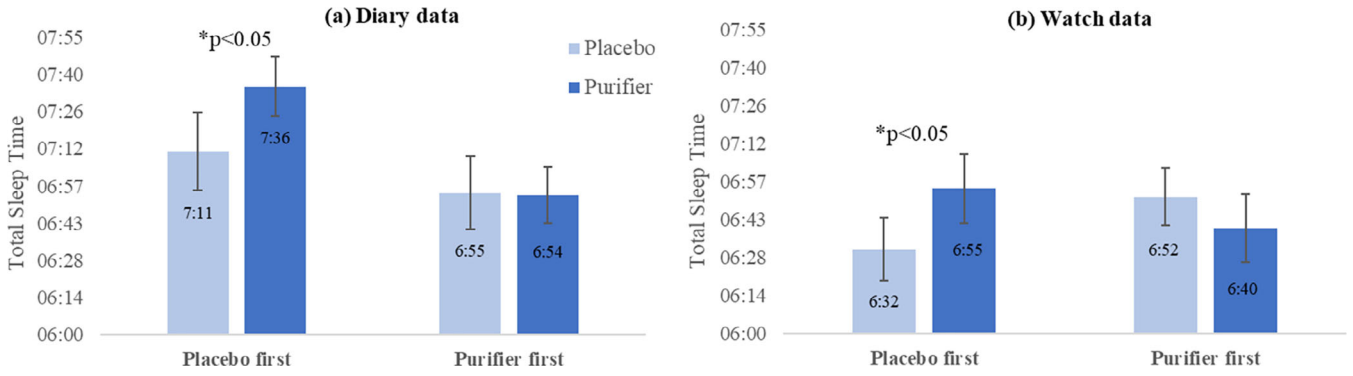

FIGURE 1 Means (se), total sleep time (TST; hr:min) according to (a) the diary and (b) the watch. Data are presented for an 2 × 2 ANOVA model with condition (purifier and placebo) as a repeated-measures variable and order (placebo first and purifier first) as a between-groups variable. A significant condition*order interaction was observed for diary data ($F_{1,27} = 4.38$, $p < 0.05$) and the watch data ($F_{1,27} = 5.72$, $p < 0.05$). Post hoc paired *t*-tests were performed with Bonferroni correction for multiple comparisons, two-tailed. Mean values shown within each bar

TABLE 2 Means (se) for outcome measures collected at the beginning and the end of each 2-week arm for the purifier and placebo ($n = 29$)

Variable	Purifier baseline	Purifier follow-up	Placebo baseline	Placebo follow-up	Condition sig.	Time sig.	Condition* time sig.
PSQI[a]	5.7 (0.4)	5 (0.3)	5.4 (0.5)	4.9 (0.4)	0.4	0.08	0.72
ISI[b]	6.2 (0.7)	5.7 (0.7)	6.8 (0.9)	6.2 (0.8)	0.35	0.29	0.81
Depression (PHQ-8)[c]	5.2 (0.7)	4.3 (0.7)	5.3 (0.9)	4.2 (0.8)	0.98	0.015*	0.7
Anxiety (GAD-7)[c]	4.5 (0.8)	3.5 (0.6)	4.6 (0.8)	3.7 (0.6)	0.76	0.006**	0.94
Stress (PSS)[c]	14.2 (1.4)	13.8 (1.3)	14.9 (1.5)	13.3 (1.3)	0.87	0.11	0.41

Note: Analysis model was a 2 × 2 ANOVA with condition (purifier and placebo) and time (beginning of arm, end of arm) as repeated-measures variables. The inclusion of order (purifier first, placebo first) as a between-groups variable in the model did not produce any additional significant outcomes or change any of the outcomes from the original model, thus the original model is presented here. Degrees of freedom = 27, two-tailed.

[a]Pittsburgh Sleep Quality Index (PSQI), a higher score indicates worse sleep.

[b]Insomnia Severity Index (ISI), a higher score indicates worse sleep.

[c]For these variables, higher scores indicate greater levels of depression, anxiety and stress (PHQ-8, Patient Health Questionnaire Depression Scale; GAD-7, Generalised Anxiety Disorder Scale; PSS, Perceived Stress Scale).

*$p < 0.05$.

**$p < 0.01$.

2.7 | Analysis

For variables collected daily (actigraphy, sleep diaries, Positive and Negative Affect, and air quality outcomes), data were averaged across each 2-week period for an average daily value, and the analysis model was a mixed ANOVA with Condition as a repeated-measures independent variable with two levels (purifier and placebo), and Order as a between-groups variable with two levels (purifier first or placebo first). For variables collected at the beginning and the end of each arm (ISI, PSQI, depression, anxiety and stress), the analysis model was a repeated-measures ANOVA with Condition as a repeated-measures variable with two levels (purifier and placebo), and Time as a repeated-measures variable with two levels (baseline and 2 weeks). Initially, Order was also included in this analysis model; however, there were no significant main effects or interactions with Order. Therefore, the data for this model are reported without Order in the analysis (to improve statistical power). Where significant interactions were observed, post hoc *t*-tests were performed with Bonferroni corrections for multiple comparisons. All *t*-tests were two-tailed. For the air quality data, participants with *z*-scores of 2.5 or greater were considered outliers, as this corresponds to a probability of < 0.01 when there were fewer than 20 degrees of freedom for error (Tabachnick et al., 2007). This resulted in between one and four participants being excluded depending on the air quality DV (see Results). There was also missing data due to internet connection failure for four participants for OAQ, VOC and NO_2, and six participants for $PM_{2.5}$, PM_{10}, temperature and humidity.

TABLE 3 Means (se) for daily outcome measures of air quality as an average per day for the 2-week purifier arm and the 2-week placebo arm with paired samples *t*-test (two-tailed)

	Purifier	Placebo	*t*-test sig.
Air quality^ ($n = 21$)	92.2 (10.8)	117 (15.5)	0.036*
$PM_{2.5}$ ($n = 23$)	2.16 (0.39)	4.79 (0.66)	0.00004**
PM_{10} ($n = 23$)	2.29 (0.42)	5.02 (0.72)	0.00003**
VOCs ($n = 21$)	88.5 (10.5)	103.8 (15.3)	0.15
NO_2 ($n = 21$)	20.8 (2.6)	20.8 (2.6)	0.99
Temperature (°C) ($n = 19$)	23.3 (0.4)	22.6 (0.5)	0.24
Humidity % ($n = 19$)	60.2 (1.4)	61.3 (1.7)	0.53

Note: $PM_{2.5}$, particulate matter 2.5; PM_{10}, particulate matter 10; VOCs, volatile organic compounds.
^Calculation needed.
*$p < 0.05$.
**$p < 0.01$.

3 | RESULTS

As shown in Table 1, participants spent on average 19 min longer in bed per night during the purifier arm relative to the placebo arm according to the diary as shown by a significant main effect of Condition ($F_{1,27} = 8.39$, $p < 0.01$). This translated into 12 min longer total sleep duration for the purifier arm according to the diary based on a main effect of Condition, which approached significance ($F_{1,27} = 3.92$, $p = 0.058$). There was evidence for an impact of Order on TST as shown by significant Condition*Order interactions according to the diary ($F_{1,27} = 4.38$, $p < 0.05$) and the watch ($F_{1,27} = 5.72$, $p < 0.05$). As shown in Figure 1, Bonferroni-corrected *t*-tests showed that when participants had the placebo during the first arm, TST increased by 24 min per night during the purifier arm according to the diary ($t = 3.19$, df = 13, $p < 0.05$) and 22 min per night according to the watch ($t = 2.79$, df = 13, $p < 0.05$). This effect was not present when participants had the purifier arm first and the placebo arm second.

As shown in Table 1, there was not an overall difference between the purifier and the placebo for SE; however, there was a significant Condition*Order interaction according to the diary ($F_{1,27} = 4.24$, $p < 0.05$) and the watch ($F_{1,27} = 4.38$, $p < 0.05$). Further Bonferroni-corrected *t*-tests indicated that a difference was present for participants who had the purifier first. Specifically, in this group, SE was 2.8% better for the placebo relative to the purifier according to the diary ($p < 0.05$), and 2.2% better according to the watch ($p < 0.05$).

TABLE 4 Responses to the end of study questionnaire ($n = 28$ as one participant did not complete this)

Question	Yes	No	Not sure
Did you notice the air purifier noise disturbed your sleep?	10	15	3
If yes, which phase was noisier?	Purifier = 3	Placebo = 7	
Would you consider using a purifier in other rooms/ at other times of the day?	17	4	7
Would you consider using a purifier in your bedroom?	16	8	4
If you had the air flow directed at you, did you feel a cooling benefit?	24	4	–
Did you notice any impact on your breathing during the night?	3	16	9
Did you feel your sleep environment was more comfortable due to the air purifier?	14	5	9
Did you sleep with a partner?	12	16	–

The only other significant effect for the sleep outcome measures was that according to the watch, WASO was greater for the purifier relative to the placebo as shown by the main effect of Condition ($F_{1,27} = 10.48$, $p < 0.01$; Table 1). As shown in Table 2, the main effects of Time showed that both arms were associated with reductions in symptoms of depression by a score of 1 (se. 0.34) for the PHQ-8 ($F_{1,28} = 6.77$, $p < 0.05$) and reductions in anxiety by a score of 1 (se. 33) for the GAD-7 ($F_{1,28} = 8.68$, $p < 0.01$). However, no differences in mood outcomes were seen between the purifier and the placebo. As shown in Table 3, OAQ was significantly better during the purifier condition relative to the placebo condition ($t = 0.224$, df = 20, $p < 0.05$). Both fine ($PM_{2.5}$) and coarse particulate matter (PM_{10}) were significantly reduced by the purifier related to the control ($t = 5.31$, df = 22, $p < 0.001$ and $t = 5.14$, df = 22, $p < 0.001$). For all other air quality variables there were no significant differences between the purifier and the placebo. As shown in Table 4, 10 participants (33%) reported that noise from the air purifier disrupted their sleep and, interestingly, seven of these reported that the placebo condition was nosier. The majority of participants ($n = 24$, 86%) felt a cooling benefit of the purifier, and 50% ($n = 14$) indicated that the sleep environment was more comfortable due to the air purifier.

4 | DISCUSSION

The primary aim was to investigate the effects of using an air purifier for 2 weeks on sleep outcomes in a sample of healthy adults. Relative to a control condition with a placebo filter, the purifier was associated with some benefits for sleep outcomes. Specifically, total time in bed (TIB) increased by an average of 19 min per night relative to the placebo filter, and there was increased TST by an average of 12 min per night, although this latter effect only approached statistical significance, and increased wakefulness was also reported for the purifier according to the actiwatch. Nevertheless, for those who are not achieving an optimal amount of sleep, a habitually maintained increase of 12 min per night may have benefits for health outcomes and other aspects of life, given the associations between sleep duration and physical and mental wellbeing (Grandner, 2019), cardiovascular health (Makarem et al., 2019), obesity (Hargens et al., 2013), academic performance and work capacity (Barnes & Watson, 2019; Hershner, 2020). However, it is important to acknowledge that for healthy adults already obtaining an optimal amount of sleep, an increase of 12 min per night is unlikely to convey significant health benefits. When considering the impact of the design of the study, it was notable that significant benefits for TST were only observed when the placebo filter was used for the initial 2-week period, followed by the purifier for the second 2-week period. This indicates that there may have been a period of adjustment in which participants acclimatised to using the air purifier in their bedrooms. If this acclimatisation occurred during the placebo arm, then participants were able to experience benefits when they subsequently introduced the purifier filter. However, if the acclimatisation process occurred during use of the purifier filter, TST remained similar during the subsequent 2-week period when using the placebo filter. This has implications for future studies. For example, it may be sensible to introduce a run-in period during which participants familiarise themselves with any equipment being used or to any adjustments to the environment such as the introduction of an air purifier.

It is important to acknowledge that there were a number of sleep outcomes for which no changes were observed. This is perhaps unsurprising in the context of a healthy sample with a mean baseline PSQI score of 5 who demonstrated good sleep characteristics across both conditions. For example, TST was in the healthy range (approximately 7 hr; 7–9 hr is recommended; Hirshkowitz et al., 2015), SOL was within the normal amount of time that it takes to fall asleep (up to 30 min; Ohayon et al., 2017) and SE was only just below the optimum window of 85%–90% (Ohayon et al., 2017). Interestingly, whilst there were no differences in SE overall between the air purifier and the placebo filter, the interaction with order showed that SE was slightly better for the placebo relative to the purifier for those who had the purifier during the first 2-week period. This order effect further emphasises the importance of an acclimatisation period. SE was calculated as TST/TIB. Therefore, this efficiency effect should be considered in the context of overall increased total TIB and increased TST for the purifier arm. This illustrates that SE can reduce even when there are ostensibly benefits overall as observed here where both variables show improvements. For example, the increase in total TIB was greater than the increase in TST (as observed here when comparing the purifier with the placebo), thus SE was lower (for the purifier relative to the placebo). Therefore, in this context with a healthy TST, the slight reduction in SE is not necessarily a negative outcome because overall, sleep duration is longer during the purifier condition.

The data from the actiwatch showed that there was a greater amount of WASO for the purifier relative to the placebo, which may also have contributed to the SE effect. Again, this should be considered in the context of longer sleep duration and greater TIB, which offers more opportunities for periods of wakefulness. Perhaps of more importance is that WASO was the only variable for which there was a discrepancy between the sleep diary and the actiwatch; the sleep diary showed no differences. It is plausible that the actiwatch is overestimating time spent awake after falling asleep, consistent with research comparing actigraphy with polysomnography (Quante et al., 2018), suggesting a bias in the actigraphy rather than the self-report. Therefore, the wakefulness data should be treated with caution and require further investigation. A broader positive finding is that the symmetry between the consensus sleep diary and the actiwatch data indicates a good level of reliability, and this shows that these techniques can be utilised in a free living environment for a 4-week period (albeit as two blocks of 2 weeks with a washout period). The subtle differences in the data between the two approaches (e.g. wakefulness) support the importance of utilising both methods of data collection in a free living environment.

As expected, air quality was better during the air purifier condition, which was driven by lower levels of fine and course particulate matter ($PM_{2.5}$ and PM_{10}), whilst no differences were observed for NO_2, which was within the expected range for normal indoor air, as

were levels of VOCs (WHO, 2010). Whilst it is tempting to postulate that improvements in air quality were causally related to sleep benefits, this study does not have sufficient statistical power to directly examine this relationship, nor was it designed to do so. It would certainly be of interest to explore this hypothesis. Evidence exists for a relationship between air quality and sleep outcomes (for recent reviews, see Canha et al., 2021 and Cao et al., 2021); however, further data are required to understand the mechanisms by which air purification and associated improvements in air quality may directly lead to improvements in sleep outcomes. Improving ventilation by opening windows has been shown to reduce levels of CO_2 and improve sleep outcomes (Mishra et al., 2018; Strøm-Tejsen et al., 2016), and introduction of cleaner, less polluting cookers has been shown to reduce levels of $PM_{2.5}$ and improve sleep outcomes in children (Accinelli et al., 2014). Cao et al. (2021) propose two possible mechanisms. Particulate matter and other gaseous particles may directly affect the upper and lower respiratory system causing swelling, inflammation and increased oxidate stress at a cellular level, all of which may elevate resistance in the airway and reduce breathing capacity, which could subsequently affect sleep. Secondly, there is evidence in rodents that particulate matter may interact with the central nervous system (CNS) by entering the brain and crossing the blood–brain barrier (BBB) via the olfactory nerve (Oberdörster et al., 2004). A number of direct and indirect pathways have been proposed by which fine particles and air pollution may disrupt the BBB and contribute to oxidative stress in the brain and neuroinflammation (Block & Calderón-Garcidueñas, 2009; Peters et al., 2019). It is plausible that this disruption to the CNS could affect sleep outcomes, for example, oxidative stress and endothelial dysfunction have been associated with sleep apnea (Orrù et al., 2020).

If pathways for air quality impacting neuronal process and regulation of neurotransmitters can be identified, it opens up interesting considerations for the role of air quality in the bidirectional relationship between sleep quality and psychological factors such as general mood, stress, anxiety and depression. For example, serotonin is implicated in the regulation of mood states (Pourhamzeh et al., 2021) and the sleep–wake cycle (Cespuglio, 2018). However, in the present study, there were no observable benefits of using the purifier filter for general mood state, stress, anxiety or depression compared with the placebo. Interestingly, it was evident that simply having the purifier in the bedroom (with either the placebo or purifier filter) was associated with a small reduction in symptoms of depression and anxiety, even in a sample with low levels of symptoms and normal levels of stress. One plausible mechanism is that the process of introspection for sleep and mood measures led to improvements in mood outcomes, or more simply participants experienced expectancy effects. For example, there is evidence from neuroimaging studies that beliefs and expectations can markedly modulate neurophysiological and neurochemical activity in brain regions involved in emotional processing (Beauregard, 2007). If participants believe that they are experiencing a physiological benefit from the purifier then this could translate into improvements in mood states. The overall absence of condition-specific effects for mood in this study indicates that the sleep benefits associated with the purifier were not mediated by changes in mood. Similarly, temperature and humidity were consistent across both arms, although CO_2 was not assessed, which has previously been associated with sleep outcomes (for review, see Canha et al., 2021). A limitation of introducing air purification to the bedroom is that any noise associated with the product may impact sleep. Here, the subjective feedback indicated noise was not particularly problematic for participants, with at least half the sample reporting that noise associated with the purifier did not affect their sleep, that they would use a purifier in their bedroom in future, and that the sleeping environment was enhanced by the purifier. Taken together, this indicates that mechanical air purification is acceptable in a real word sleeping environment over a period of several weeks. Nevertheless, 10 participants did report that the noise of the purifier affected their sleep. It would be interesting to further explore how participants perceive the sleeping environment to change following air purification. For example, 24 participants indicted that the cooling benefit of the purifier was welcomed, whilst only three reported that the purifier impacted their breathing. This suggests that any mechanisms associated with the respiratory system were not explicitly noticed by participants, and perhaps increased air flow may enhance sleep outcomes, particularly during the summer months when data collection occurred here (May–September). However, these subjective data were collected retrospectively with multiple choice answer format and therefore should be interpreted with caution.

In summary, this crossover intervention in healthy adults shows that using an air purifier in the bedroom over a 2-week period is associated with some benefits to sleep outcomes, specifically increased TST and TIB relative to a purifier with a placebo filter. However, increased periods of wakefulness were also reported for the purifier relative to the placebo according to the actiwatch only. There were no benefits for mood outcomes relative to the placebo and, as expected, air quality was higher during the active purifier arm as indicted by lower levels of $PM_{2.5}$ and PM_{10}. There were indications that an acclimatisation period following the introduction of a purifier to the bedroom environment would enable a more sensitive investigation of the impact of such interventions on sleep outcomes. Future studies should explore whether direct associations can be observed between improvements in air quality and sleep outcomes, and whether interventions to improve environmental factors such as air quality are beneficial for populations with sleep disturbance.

AUTHOR CONTRIBUTIONS

DL and FO designed the research and primarily managed the project. SG and SC contributed to conceptualisation of the study, and SG assisted in the management of the project. EB collected the data and undertook day to day management of the project. DL and EB undertook the data analysis. DL, FO and EB wrote the manuscript. SG and SC reviewed the manuscript.

CONFLICT OF INTEREST

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study maybe available on request from the corresponding author. The data are not publicly available due to commercial restrictions.

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