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# Impact of bedding arrangements, pillows, and blankets on particle resuspension in the sleep microenvironment

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ABSTRACT

The risk of exposure to pollutants in mattress dust is enhanced by the extended period that people spend every day in their sleep microenvironments. Epidemiological studies have shown strong associations between exposure to these pollutants and health risks. Blankets, pillows, and mattresses have been considered as major sources of accumulated dust particles, which may become airborne through a process known as resuspension. Therefore, a better understanding of the impact of bedding arrangements on human-induced particle resuspension in the sleep microenvironment is needed. In this investigation, participants performed sets of prescribed movements on an artificially-seeded mattress. Ten different bedding arrangements were examined. Airborne particle number concentrations were measured to estimate size-resolved resuspension rates (RR). Across all particle sizes and bedding arrangements, RRs ranged from $10^{-3}$ *to* $10^{1}$ $h^{-1}$, with higher RRs associated with larger particles. RRs for a seeded pillow were greater than RRs for a seeded blanket or seeded mattress. The use of an additional pillow cover did act as an effective barrier to the penetration of larger particles deposited on the underlying pillow surface. Additionally, blankets were not found to be a significant barrier for particles resuspended from the underlying seeded mattress. Intake fractions (iF) were in the range of $10^{2}$ *to* $10^{4}$ ppm ($10^{-4}$ *to* $10^{-2}$ on a fractional basis), suggesting a significant fraction of released particles can reach the breathing zone region. The highest iF was estimated for an arrangement where both a pillow and a mattress were seeded without a blanket present ($10^{4}$ ppm).

## 1. Introduction

In developed countries, people spend about 90% of their time indoors [1,2]. Thus, exposure to indoor particulate and gaseous pollutants plays a significant role in affecting human health. Additionally, humans spend approximately one-third of their lives sleeping, typically on a mattress or other bedding material. Mattresses, pillows, bedding sheets, blankets, and duvet covers can be major sources of accumulated dust particles, which are dominated by particles smaller than 500 μm in effective diameter [3,4]. Furthermore, field studies have reported dust loads (not size resolved) measured on beds that range from 0.2 to 2.0 g $m^{-2}$ [3,5,6].

Settled mattress dust may contain a spectrum of pollutants, such as: house dust mite (HDM) allergens; bacteria; fungal spores; particle-bound semi-volatile organic compounds (SVOCs), e.g. flame retardants; fabric fibers; and detergent residue, e.g. zeolite particles [5,7–9]. The health risks associated with exposure to these pollutants in the sleep microenvironment are enhanced due to the close proximity of the mattress, pillow, and bedding to a person's airways [10]. Studies have shown that sensitization to HDM allergen is strongly associated with asthma [11,12]. It also has been shown that asthma symptoms in HDM-sensitized individuals are positively related to levels of HDMs in bed, but not to levels of HDMs on the bedroom floor [13,14].

Researchers have focused on the effect of daily vacuum-cleaning of the mattress to lower allergen levels [15–17]. HDM allergen levels can decrease significantly over an eight-week period of daily vacuuming [17]. Another study showed that vacuum cleaning of the mattress more than twice a year significantly lowers the HDM allergen levels [18]. Allergen-impermeable covers on pillows and

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**List of abbreviations**

| | |
|---|---|
| $A_{M,P}$ | seeded surface area (m$^2$); M-mattress, P-pillow |
| $V_c$ | volume of the experimental chamber (m$^3$) |
| $C_{i,\mathrm{BA}}(t)$ | particle number concentration for particle size "*i*" in the bulk chamber air during movement set1 and set2 (#particles m$^{-3}$) |
| $C_{i,\mathrm{BA,CL}}\ (t)$ | average particle number concentration for particle size "*i*" in the bulk chamber air during Clean set (#particles m$^{-3}$) |
| $\overline{C_{i,\mathrm{BZ}}}$ | breathing zone particle number concentration for particle size "*i*" during movement routine on seeded mattress (# particles m$^{-3}$) |
| $\overline{C_{i,\mathrm{BZ,\ Decay}}}$ | breathing zone particle number concentration for particle size "*i*" during decay period (# particles m$^{-3}$) |
| $C_{i,\mathrm{BZ,CL}}\ (\mathrm{t})$ | breathing zone particle number concentration for particle size "*i*" during Clean set (#particles m$^{-3}$) |
| $L_{0,i}$ | initial mattress dust loading for particle size "*i*" (# particles m$^{-2}$) |
| $\overline{L_i}$ | average dust loading throughout the movement set for particle size "*i*" (# particles m$^{-2}$) |
| $L_i(t)$ | continuous mattress loading for particle size "*i*" (# particles m$^{-2}$) |
| $RR_i(t)$ | resuspension rate for particle size "*i*" throughout movement routine (h$^{-1}$) |
| $\overline{RR_i}$ | time-average resuspension rate for particle size "*i*" throughout the movement set (h$^{-1}$) |
| $Q_B$ | volumetric breathing rate (m$^3$ h$^{-1}$) |
| $a$ | chamber air exchange rate (h$^{-1}$) |
| $k_i$ | particle deposition rate for particle size "i" (h$^{-1}$) |
| $iF_i$ | intake fraction for particle size "*i*" (ppm) |
| $\Delta t$ | instrument-specific sampling period (s) |

duvets have been recommended as a way of reducing exposure to allergens [19,20]. Bi-weekly washing of bedding in hot water (over 55 °C) has also been recommended for killing HDMs and removing a settled dust particles [21]. The particle-removal process of washing the bedding can be enhanced by using detergent or detergent with added bleach [21]. On the other hand, using detergents or bleach might lead to skin irritation [22,23].

There is limited research on individual bedding items and their contribution to the total concentration of pollutants in settled dust. Several studies analyzed the concentrations of HDM allergen in houses. Compared to allergen levels in pillows, Mills et al., 2002 [24] reported over a factor of two higher concentrations of allergens in duvets and a factor of four higher concentrations in mattresses.

Mattress foam may contain SVOCs such as flame retardants [25,26]. The amount of SVOCs present in the mattress foam and their emission rate is dependent on numerous factors, including the type of flame retardant, e.g., brominated or organophosphate, the type of foam, and environmental conditions. After being emitted from mattress foam, flame retardants may partition to settled particles and accumulate in mattress dust.

The resuspension of particulate matter from bedding surfaces has not been previously reported in the published literature. Resuspension is defined as a process by which deposited particles detach from a surface and become airborne by applying an external force or forces, e.g., aerodynamic (lift or drag), mechanical (surface vibrations and abrasion), and electrostatic [27]. Particle resuspension is influenced by numerous variables, including the strength of the external force, particle size, particle composition, surface features of the particle and deposition surface, characteristics of the airflow, dust load, and environmental parameters (e.g., relative humidity) [28–31]. The resuspension rate is usually not directly measured and is deduced through modeling based on a mass balance on the concentration of airborne and settled particles and deposition of the particles onto surfaces.

The objectives of this study were to explore the impact of bedding arrangements on resuspension and to evaluate exposure to resuspended particles in the sleep microenvironment. This study is the first to systematically evaluate human-induced particle resuspension from pillows, blankets, and mattresses during a sleep event and may serve as a basis for further evaluation of personal exposure to particles in sleep microenvironments.

## 2. Methods

### 2.1. Experimental setup

Thirty resuspension measurements were performed in a 14.75 m$^3$ chamber at The University of Texas at Austin. Three participants of different body mass and height were involved in this investigation (Table SI1 in the Supplemental Information (SI) section). Each participant wore a protective Tyvex suit with attached hoodie and boots (Model TY122 S, DuPont™), one-use respiratory mask (OSHA and NIOSH N95 rating, Model 8210, 3M™, USA) and single-use nitrile gloves. This protected participants from exposure during the measurements and helped to avoid contamination of particles accumulated on participant's clothing or skin which might interfere with the particle resuspension measurements. The bedding and duvet covers were washed after every use (standard wash cycle), allowed to air dry for a minimum of 48 h, and re-used again.

Polydisperse, 1–20 μm ISO-12103-1-A1 Ultrafine Arizona Test Dust (ATD) (Powder Technology Inc., USA) was used for the seeding procedure. The ATD size distribution is representative of particulate matter commonly found in mattress dust, e.g., fungal spores, bacteria or HDM allergens [3].

Both the experimental mattress and bedding arrangements were prepared and seeded with ATD in a custom-built, full-scale seeding chamber. The seeding chamber was built of extruded polystyrene panels with dimensions 1.2 × 2.1 × 1.4 m, and internally lined with aluminum foil to reduce electrostatic deposition. Six small mixing fans were placed inside the chamber in order to provide uniform mixing conditions during the injection process. The artificial dust was placed, and later injected, through six canisters attached to the removable top of the seeding chamber (canisters developed in Boor et al., 2013 [28]). The canisters were connected to a compressed air line with stable overpressure controlled by a ball valve. Every seeding process was performed with multiple releases of the highly-pressurized air to aerosolize the ATD contained in the canisters. The mixing fans, set to constant 10 V input, were stopped three minutes after the injection. The minimum period for particle deposition in the chamber was set as 24 h. The relative humidity and temperature in the seeding chamber were recorded for each seeding event (HOBO data logger, Model U12-012, HOBOware Pro, Onset Computer Co.).

Nine glass microscope slides were placed at different positions on the mattress (or pillow or blanket, depending on the particular arrangement) during the seeding process to determine the initial dust load and uniformity of deposited particles. The particle loading deposited on microscope slides was measured gravimetrically (Model AB 135-5, Meter-Toledo International Inc.) and was nominally 0.1 g $m^{-2}$ (Table SI1). The value was selected based upon the results of Boor et al. (2014) [32].

A 14.75 $m^3$ stainless-steel chamber was used for the full-scale resuspension experiments. A ventilation system equipped with a HEPA filter provided a constant air exchange rate of 2.9 $h^{-1}$. A stable overpressure of 1.8 Pa was maintained to minimize infiltration of laboratory air. Relative humidity and temperature were monitored with HOBO data loggers and had mean values ($\pm 1\sigma$) of 38 ± 9% and 25.6 ± 0.6 °C across all 30 experiments.

Fig. 1 provides a plan view of the experimental set up in the chamber. Monitoring of airborne particle number concentrations was performed with three Optical Particle Counters (OPCs) (TSI, Models 8220 and 3321) and one Aerodynamic Particle Sizer (APS) (TSI, Model 3321). The sampling frequency of the instruments was: OPC2: 0.1 Hz, OPC3: 0.05 Hz, OPC4: 0.1 Hz, and APS: 1 Hz. In the remaining text each instrument is referred to its sampling location within the chamber (Fig. 1): OPC3 as "bulk air", OPC2 and OPC4 as breathing zone (BZ) left and BZ middle, respectively, and APS as BZ right. The Bulk air sampling location was positioned 83 cm above the mattress surface, at the mid-point between the mattress surface and chamber exhaust. Additionally, an accelerometer (Model LIS302DL, STMicroelectronics) monitored the surface vibrations and was positioned next to the head area for each experiment (10 Hz sampling frequency). The size bins of the OPCs were set to measure five different size ranges: 1–2 μm; 2–3 μm, 3–5 μm, 5–10 μm and 10–20 μm. The APS size ranges were summarized, recalculated and categorized into the same size ranges as the OPCs. We performed an experiment in order to see variability between measurement reading between used Optical Particle Counters. The variation in the total particle concentration (sum of 1–20 μm) among the three OPCs remained below 15%.

Participants were instructed to complete a set of predefined movements during each resuspension event. The movement set consisted of five movements, each performed at the beginning of 2.5-min intervals. During the rest of the 2.5-min interval the participant laid still on the mattress. The first movement was to sit on the edge of the experimental mattress with feet on the floor. The second movement consisted of positioning the body in the center of the mattress in the supine position (and under a blanket for arrangements 3, 4, 5, 6, 8, and 10). During the third movement, the participants rotated carefully on the mattress for a full 360° rotation to return to the supine position (performed beneath the blanket for arrangements 3, 4, 5, 6, 8, and 10). The fourth and fifth movements consisted of 180° rotations to the prone position (movement four) and finally returning to the supine position (movement five) (performed beneath the blanket for arrangements 3, 4, 5, 6, 8, and 10). The first movement set (referred as "clean set") was performed with bedding sheets and mattress that were not artificially seeded, but with the same bed arrangement as the seeded arrangements. The following two identical movement sets were performed with seeded arrangements (in the text referred as set 1 and set 2). The clean set, the set 1 and the set 2 were followed by a 30-min breaks (referred to as decay period 1 and decay period 2, respectively), where participants were not present in the experimental chamber. The breaks served the purpose of calculating particle deposition rates and to represent the levels of resuspended particles a person might be exposed to after cessation of movements during a sleep period. The time allocations of the experimental sequence, together with description of the movements, are described in further detail in Table 1. The whole movement procedure was selected to interpret when occupants go to bed (simulated by the movement M1: sit on the mattress) followed by re-positioning of themselves as they attempt to fall asleep (movements M2-M5). The decay stages simulate the period when a participant falls asleep and lays still.

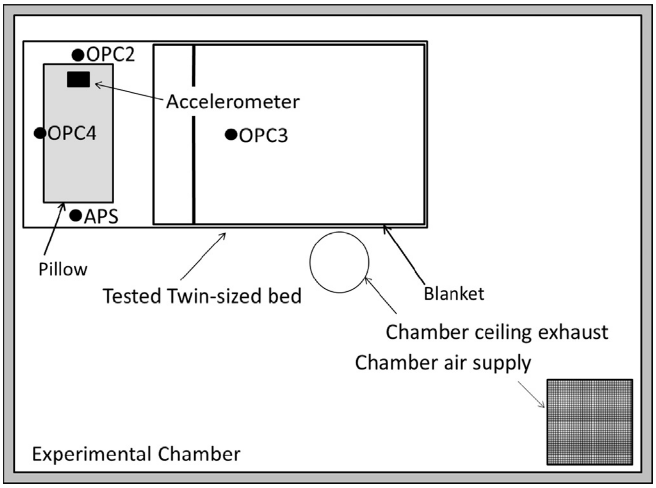

**Fig. 1.** Plan view of the experimental chamber and position of the ceiling air exhaust and chamber air supply element. The sampling OPC3 is located in the center of mattress in height 83 cm above the mattress surface. The APS and OPC2 were located 10 cm above the surface of the mattress and 10 cm from the edge of the mattress. Finally, the OPC4, was located 25 cm above the surface, 10 cm above the mattress surface.

**Table 1**
Time allocation and description of the movements and movement sets.

| Elapsed time (minutes) | | |
|---|---|---|
| 0–30 | Measurement of background concentration | |
| 30–32.5 | Participant enters the exp. chamber | Movement set on the clean mattress |
| 32.5–35 | Movement M1: Sit on mattress | |
| 35–37.5 | Movement M2: Supine position | |
| 37.5–40 | Movement M3: Rotation 360° to supine position | |
| 40–42.5 | Movement M4: Prone position | |
| 42.5–45 | Movement M5: Supine position | |
| 45–47.5 | Stand up and exit the chamber | |
| 47.5–77.5 | Relaxed period with mattress replacement[a] | |
| 77.5–80 | Participant enters the exp. chamber | First movement set |
| 80–82.5 | Movement M1: Sit on mattress | |
| 82.5–85 | Movement M2: Supine position | |
| 85–87.5 | Movement M3: Rotation 360° to supine position | |
| 87.5–90 | Movement M4: Prone position | |
| 90–92.5 | Movement M5: Supine position | |
| 92.5–95 | Stand up and exit the chamber | |
| 95–125 | Decay 1 | |
| 125–127.5 | Participant enters the exp. chamber | Second movement set |
| 127.5–130 | Movement M1: Sit on mattress | |
| 130–132.5 | Movement M2: Supine position | |
| 132.5–135 | Movement M3: Rotation 360° to supine position | |
| 135–137.5 | Movement M4: Prone position | |
| 137.5–140 | Movement M5: Supine position | |
| 140–142.5 | Stand up and exit the chamber | |
| 142.5–175 | Decay 2 | |

[a] Clean mattress with clean bedding sheet is removed and replaced with seeded bedding arrangement.

**Table 2**
Experimental matrix of tested arrangements.

| Arrangement | Mattress | Pillow | Blanket |
|---|---|---|---|
| 1 | Seeded | Seeded | No blanket[c] |
| 2 | Seeded | Unseeded | No blanket[c] |
| 3 | Covered[a] | Seeded | Seeded LB[d] |
| 4 | Covered[a] | Seeded | Seeded HB[e] |
| 5 | Seeded | None[b] | Unseeded LB |
| 6 | Seeded | None[b] | Unseeded HB |
| 7 | Unseeded | Seeded | No blanket[c] |
| 8 | Seeded | Seeded | Unseeded LB |
| 9 | Unseeded | Seeded[g] | No blanket[c] |
| 10 | Covered[a] | Seeded | Seeded FB[f] |

[a] Mattress was present in the seeding chamber and covered by blanket.
[b] The measurements were performed without pillow.
[c] The measurements were performed without any blanket present.
[d] LD-Light Blanket. The light blanket-type was simulated by blanket cover only.
[e] HB-Heavy Blanket. The heavy blanket consisted of fleece blanket protected by blanket cover.
[f] FB-Fleece Blanket.
[g] Pillow was seeded below the pillow cover, and for movement set in the experimental chamber equipped by second layer of pillow cover.

Each participant completed a resuspension experiment for 10 different bedding arrangements (listed in Table 2). The 10 investigated arrangements were either with or without blankets and a seeded or unseeded pillow (50.8 × 71.1 cm plush pillow, 100% polyester fill) or mattress (twin-size coil mattress). A detailed description of the bedding arrangements is presented in Table 2 and Figures A1–A10 in Supplemental Information section. Three types of blankets were tested: (1) light blanket (LB), a duvet cover without an internal blanket; (2) fleece blanket (FB); and (3) heavy blanket (HB), a duvet cover with an internal lining of a fleece blanket.

### 2.2. Resuspension rate estimate

A two-compartment mass balance model was applied for each modeled size range, $i$, as per [30]:

$$V_c\frac{dC_{i,\,\mathrm{BA}}(t)}{dt} = RR_i(t)L_i(t)A_{M,P} - aV_CC_{i,\,\mathrm{BA}}(t) - k_iV_CC_{i,\,\mathrm{BA}}(t) \tag{1}$$

where $C_{i,\mathrm{BA}}(t)$ is the particle number concentration during movements measured in bulk air (Optical Particle counter 3), $V_c$ is the volume of the chamber (m$^3$), $RR_i(t)$ is the resuspension rate for particle size "$i$" throughout movement routine (h$^{-1}$), $L_i(t)$ is the continuous mattress loading for particle size "$i$" (# particles m$^{-2}$), $A_{M,P}$ is the seeded surface area (m$^2$); M-mattress, P-pillow, a is the air exchange rate (h$^{-1}$) and $k_i$ is the particle deposition rate for particle size "$i$" (h$^{-1}$). Further discussion of the model is presented in Boor et al. (2014). Additionally, the particle dust load on the mattress surface was modeled as follows:

$$A_{M,P}\frac{dL_i(t)}{dt} = k_iV_CC_{i,\,\mathrm{BA}}(t) - RR_i(t)L_i(t)A_{M,P} \tag{2}$$

By rearranging Equation (1), the resuspension rate $RR_{(i)}$ can be expressed as:

$$RR_i(t) = \frac{V_C}{L_i(t)A_{M,P}}\left[\frac{dC_{i,\,\mathrm{BA}}(t)}{dt} + (a+k_i)C_{i,\,\mathrm{BA}}(t)\right] \tag{3}$$

Combination of equations (1) and (2) can be used to express $L_{(t)i}$, an input into equation (3):

$$A_{M,P}\frac{dL_i(t)}{dt} = -V_C\left(\frac{dC_{i,\,\mathrm{Bulk\ Air}}(t)}{dt} + aC_{i,\,\mathrm{BA}}(t)\right) \tag{4}$$

By integration of both sides of equation (3), the continuous mattress loading $\mathrm{L}_{(t)\mathrm{i}}$ can be estimated by equation (5):

$$L_i(t) = L_{0,i} - \frac{V_C}{A_{M,P}}\left[\left(C_{i,\,\mathrm{BA}}(t) - C_{i,\,\mathrm{BA,CL}}(t)\right) + a\int_{t0}^{t}\left(C_{i,\,BA}(t) - C_{i,\,\mathrm{BA,CL}}\right)dt\right] \tag{5}$$

where $L_{0,i}$ is the average particle number concentration for particle size "$i$" in the bulk chamber air during Clean set (#particles m$^{-3}$). The background concentration $C_{(t)\mathrm{CL},i}$ was subtracted to account for resuspension of bedding fibers and ambient particles deposited on the bedding during the air-drying process, as well as particle infiltration during the entry of participants. However, this value was generally small relative to airborne particle number concentration during the movement sets. For the second movement set, the last value of $L_{(t)\mathrm{i}}$ from the first movement set was used as an initial mattress load $L_{0,i}$. Simpson's rule was applied to estimate the integral in equation (5):

$$\int_{t0}^{t_i}\left(C_{i,\,BA}(t) - C_{i,\,BA,CL}(t)\right)dt \cong \Delta t\frac{C_{(n-1)i} + 4C_{(n)i} + C_{(n+1)i} - 6C_{i,\mathrm{BA,CL}}}{6} + \int_{t0}^{t_{i-1}}\left(C_{i,\,\mathrm{BA}}(t) - C_{i,\,\mathrm{BA,CL}}(t)\right)dt \tag{6}$$

The mattress loading $L_{(t)i}$ can be estimated by applying Simpson's rule (equation (6)) and substituting it into equation (5). Thus, the resuspension rate $\mathrm{RR}_{(\mathrm{t}+\Delta\mathrm{t})\mathrm{i}}$ for a time-sampling interval $\Delta t$ and size range $i$ can be expressed as follows:

$$RR_i(t+\Delta t) = \frac{V_C}{L_{i,}(t)A_{M,P}}\left[\frac{C_{i,\,\mathrm{BA}}(t+\Delta t) - C_{i,\,\mathrm{BA}}(t)}{\Delta t} + (a+k_i)C_{i,\mathrm{BA}}(t) - C_{i,\mathrm{BA}}(t)\right] \tag{7}$$

The time-sampling interval ($\Delta t$ in equation (7)) was 20 s. A pulse injection and decay of an inert tracer gas ($CO_2$) was used to measure the chamber air exchange rate [32].

### 2.3. Exposure assessment

Evaluating an individual's total inhalation exposure to pollutants should include both the amount of pollutants released into the environment and the fraction of these pollutants that can be inhaled by an individual. Intake fraction (iF) is a metric commonly used to evaluate the exposure to pollutants released from a specific source. The iF is defined as pollutant mass inhaled by an exposed individual per unit pollutant mass emitted from a specific pollution source [33,34]. The mass inhaled is also commonly referred to as the inhalation dose or intake dose. For our particular experiment, the intake fraction is defined as the ratio of the number of inhaled particles during the movement set and the following 30-min decay period to the number of particles resuspended during the movement set. Therefore, size-resolved iFs (expressed as ppm) can be calculated as follows:

$$iF_i = \frac{\int_{t_0}^{t_{\text{set}}=12.5\text{min}} Q_B\left(C_{i,\text{BZ}}(t) - C_{i,\text{BZ,CL}}(t)\right)dt + \int_{t_{t_{\text{set}}=12.5\text{min}}}^{t_{\text{set}}+t_{\text{decay}}=42.5\text{min}} Q_B\left(C_{i,\text{BZ}}(t)\right)dt}{A_{M,P}\int_{t_0}^{t_{\text{set}}=12.5\text{min}} RR_i(t)L_i(t)} \tag{8}$$

where $Q_B$ is an average breathing rate ($m^3\ h^{-1}$), approximated as $0.299\ m^3\ h^{-1}$ for an adult in the sleep or nap activity (U.S. EPA Exposure Factors Handbook 2011) and $C_{i,\text{BZ,CL}}$ is the particle number concentration in the breathing zone during clean set (#particles $m^{-3}$). We applied a simplified expression to compute the average value of iF for the whole experimental sequence. It is defined as total amount of inhaled particles during the movement set and the following decay period to the average number of particles resuspended during the movement set:

$$\overline{iF_i} = \frac{Q_B}{A_{M,P}}\frac{\left(\overline{C_{i,\text{BZ}}} + \overline{C_{i,\text{BZ,Decay}}}\right)}{\overline{L_i RR_i}} \tag{9}$$

where $\overline{C_{i,\text{BZ}}}$ is the time-averaged number concentration of resuspended particles in the breathing zone, $\overline{C_{i,\text{BZ, Decay}}}$ is the time-averaged number concentration of resuspended particles in the breathing zone during the decay period. The concentration in the breathing zone was calculated as the spatial average in the breathing zone region (average BZ left, BZ middle and BZ right), corrected for the concentration measured during the clean set. Additional details on the exposure analysis and modeling assumptions can be found in Boor et al. (2014) [32].

### 2.4. Statistical analyses

Statistical analyses were performed to evaluate the influence of various parameters on resuspension rate and intake fraction. The statistical analyses were performed using statistical software IBM® SPSS® (Ver. 20.0.0, 2011). The resuspension rates and intake fractions for each particle size-range were evaluated by use of non-parametric, two-related samples tests. The results were considered as statistically significant when $p$-values were equal to or below 0.05.

## 3. Results

Thirty experiments for ten different bedding arrangements were performed in the experimental chamber. Actual dust loads were determined gravimetrically by averaging six microscope slides for each experiment with a mean ± SD of $0.097 \pm 0.012\ g\ m^{-2}$ across all experiments. The arithmetic mean of the size-resolved resuspension rates for each bedding arrangement and size-interval are presented in Table 3. The resuspension rates differ by several orders of magnitude. Small particles (1–10 μm) were associated with resuspension rates on the order of $10^{-3}\ h^{-1}$, while large particles (10–20 μm) had resuspension rates as high as $10\ h^{-1}$. Among the tested bedding arrangements, the second movement sets generally exhibited lower resuspension rates compared to the first movement set, aside from arrangements six, seven and nine.

The resuspension rates for bedding arrangements one, two, and nine, categorized by five size ranges and movement sets, are presented in Fig. 2. For all three tested arrangements, the blanket was not present and mattress was either seeded (arrangement 1 and 2) or unseeded (arrangement 9). In order to investigate the impact of a pillow on RR, we used an unseeded pillow in arrangement two and seeded pillow in arrangement one. For arrangement nine, the pillow was seeded and placed below an additional pillow cover layer.

RRs for arrangement 7 (seeded pillow, unseeded mattress) were similar to those for arrangement 1 (seeded pillow and mattress) demonstrating that particles released solely from the pillow can contribute significantly to elevations in airborne particle concentrations.

The difference in RR between the seeded and unseeded pillow (i.e. arrangement 1 and arrangement 2, respectively) was not significant ($p$-values for all size ranges listed in Table SI2 in the Supplemental Information chapter). Both arrangements showed RRs ranging from $10^{-3}$ to $10\ h^{-1}$ depending on particle size. Similar results were obtained for arrangement number nine. No statistically significant differences were observed between arrangements one and two, two and nine or one and nine for both movement sets. The seeded pillow had a positive impact on higher resuspension rates (arrangement 8) compared to the arrangement when a pillow was not present during the procedure (arrangement 5). The resuspension rates were approximately doubled (or higher) when a seeded pillow was present. The highest RRs were obtained for arrangement six. However, the RR for one participant was greater than the RRs of the other two participants. This difference explains the wide range of boxplots for this arrangement (Fig. 3).

**Table 3**
Arithmetic means of estimated resuspension rates ($h^{-1}$) for ten tested bedding arrangements. Each bedding arrangement was performed by three participants.

| | 1–2 μm | | 2–3 μm | | 3–5 μm | | 5–10 μm | | 10–20 μm | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 1. set | 2. set | 1. set | 2. set | 1. set | 2. set | 1. set | 2. set | 1. set | 2. set |
| Bedding arrangement 1 | 3.36E-03 | 1.81E-03 | 1.00E-02 | 5.09E-03 | 2.33E-02 | 9.58E-03 | 9.31E-02 | 3.53E-02 | 7.28E+00 | 2.94E+00 |
| Bedding arrangement 2 | 4.86E-03 | 1.09E-03 | 1.54E-02 | 3.37E-03 | 3.38E-02 | 6.52E-03 | 1.21E-01 | 2.80E-02 | 7.86E+00 | 1.97E+00 |
| Bedding arrangement 3 | 9.35E-03 | 5.03E-02 | 3.29E-02 | 1.67E-02 | 7.82E-02 | 4.20E-02 | 3.39E-01 | 1.93E-01 | 3.04E+01 | 1.21E+01 |
| Bedding arrangement 4 | 4.04E-03 | 1.78E-03 | 1.42E-02 | 5.19E-03 | 3.21E-02 | 1.35E-02 | 1.14E-01 | 6.06E-02 | 9.31E+00 | 1.65E+00 |
| Bedding arrangement 5 | 3.08E-03 | 1.36E-03 | 1.10E-02 | 3.56E-03 | 2.42E-02 | 6.30E-03 | 9.40E-02 | 2.36E-02 | 2.52E+00 | 3.22E+00 |
| Bedding arrangement 6 | 2.00E-02 | 7.00E-03 | 6.77E-02 | 1.89E-02 | 1.55E-01 | 4.28E-02 | 6.40E-01 | 2.19E-01 | 6.40E+00 | 3.42E+00 |
| Bedding arrangement 7 | 5.46E-03 | 5.51E-03 | 1.81E-02 | 1.30E-02 | 4.24E-02 | 2.71E-02 | 2.93E-01 | 1.80E-01 | 3.64E+01 | 1.29E+01 |
| Bedding arrangement 8 | 7.96E-03 | 2.47E-03 | 2.34E-02 | 7.61E-03 | 5.22E-02 | 1.30E-02 | 1.90E-01 | 5.14E-02 | 7.46E+00 | 5.39E+01 |
| Bedding arrangement 9 | 4.15E-03 | 6.33E-03 | 1.28E-02 | 1.46E-02 | 2.84E-02 | 2.77E-02 | 1.05E-01 | 1.30E-01 | 6.66E+00 | 3.59E+01 |
| Bedding arrangement 10 | 2.76E-03 | 1.17E-03 | 1.09E-02 | 3.82E-03 | 3.09E-02 | 1.02E-02 | 1.48E-01 | 2.35E-02 | 4.76E+00 | 2.31E+00 |

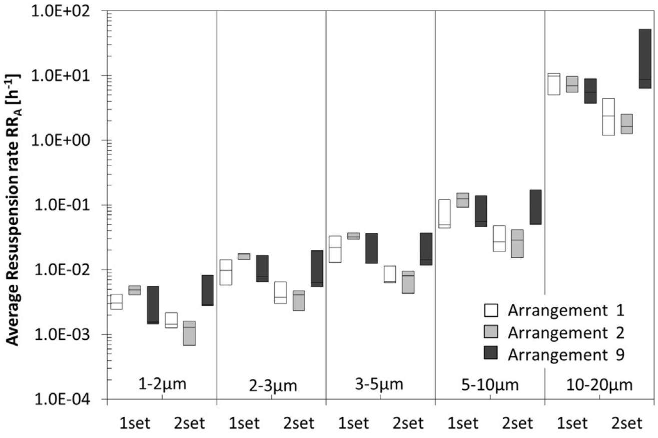

**Fig. 2.** Estimated resuspension rates for five size ranges and two movement sets of arrangements one, two and nine. Arrangement 1: Seeded mattress, seeded pillow and no blanket present; Arrangement 2: Seeded mattress, seeded pillow and no blanket, Arrangement 9: Unseeded mattress, seeded and covered pillow and no blanket. Data ranges (10th and 90th percentiles) are not shown due to the small number of experiments.

To investigate the impact of the type and blanket material three arrangements were compared (Fig. 4). All three arrangements included a seeded pillow and a blanket covered the mattress during the seeding process. The resuspension rates for the light blanket (arrangement three), heavy blanket (arrangement four), and fleece blanket (arrangement ten) did not show statistically significant differences among the tested arrangements for both movement sets. Out of the three tested blankets, the highest RR was estimated for a light blanket with values ranging from 9.4 × $10^{-3}$ to 3.0 × $10^{1}$ $h^{-1}$, and the RRs were approximately two-to-three times higher compared to the other two arrangements. Another impact of the presence of a blanket is shown in Fig. 5, where arrangements three, four and eight are compared. Arrangement eight, in contrast to arrangements three and four, was prepared with a seeded mattress and an unseeded light blanket. Although not significant, RRs for this arrangement were lower compared to the seeded light blanket and higher compared to seeded heavy blanket. Comparing the RRs of all tested arrangements, the highest RRs were observed for arrangements three and six.

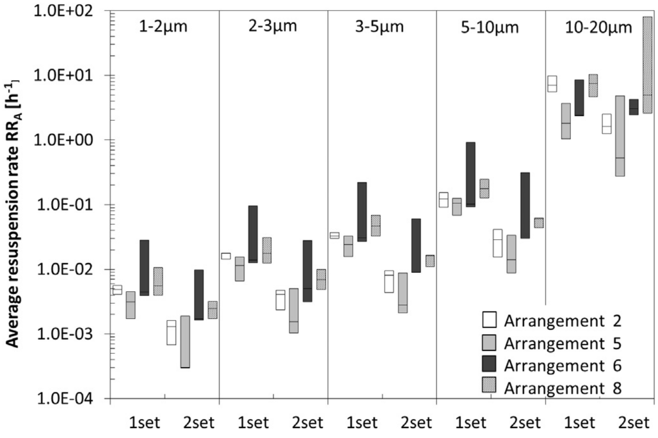

**Fig. 3.** Resuspension rates for five size ranges of five tested arrangements two, five, six and eight. Arrangement 2: Seeded mattress, seeded pillow and no blanket; Arrangement 5-seeded mattress, no pillow and unseeded light blanket; Arrangement 6-seeded mattress, no pillow and unseeded heavy blanket; Arrangement 8-seeded mattress, seeded pillow and unseeded light blanket. Data ranges (10th and 90th percentiles) are not shown due to the small number of experiments.

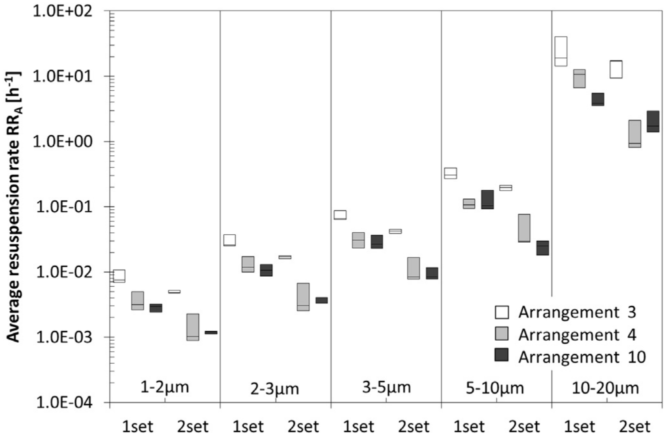

**Fig. 4.** Resuspension rates for five size ranges of arrangements three, four and ten. Arrangement 3-covered mattress (i.e. covered by blanket during the seeding process), seeded pillow and seeded blanket: Arrangement 4-covered mattress, seeded pillow and seeded heavy blanket; Arrangement 10-covered mattress, seeded pillow and seeded fleece blanket. Due to the low number of experiments ($n = 3$) for each arrangement, data ranges are not displayed.

The impact of seeded or unseeded mattress on RR was evaluated by comparing arrangements one, seven, and eight, as shown in Fig. 6. Arrangement one, a seeded mattress with no blanket present, had the lowest RR out of the three investigated arrangements.

Intake fractions for the ten bedding arrangements and five particle size ranges are listed in Table 4. The highest iFs were estimated for small particles (1–5 µm) and ranged from 4 × $10^{3}$ to 8 × $10^{4}$ ppm. The lowest iFs were estimated for large particles (5–20 µm) and ranged from 1 × $10^{2}$ to 2 × $10^{4}$ ppm.

## 4. Discussion

In our previous study [32], we found the impact of body mass, Body Mass Index (BMI), and chamber ventilation rate on RR caused by human-induced movements in a bed to be negligible (although ventilation rate influenced the iF). The peaks in particle number concentrations were associated with peaks in mattress surface vibrations and near-surface air velocity [32]. Dust loading was found to have a small impact on RR. However, in the present study only nominal initial dusts load of 0.1 g $m^{-2}$ was examined. Additionally, RR was also dependent on the type of movement (and movement intensity) performed during the movement set [32].

Higher RRs were observed for larger particles. This result is expected because the magnitude of the various removal forces required to resuspend a deposited particle tends to increase with decreasing particle size. This is in agreement with observations made in resuspension studies by Thatcher and Layton (1995) [31] and Qian and Ferro (2008) [35]. Qian and Ferro (2008) conducted a full-scale walking-induced resuspension chamber study and estimated RRs from $10^{-5}$ to $10^{-2}$ $h^{-1}$ that were three orders of magnitude greater for large particles (5–10 µm) compared to small particles (0.4–0.8 µm). In our study, the RRs for particles in the 5–10 µm range were up to three orders of magnitude higher than RRs for particles in the 1–2 µm range. Furthermore, the RRs in our study tended to be greater for the same particle size range when compared to the results presented by Qian and Ferro (2008). The difference is likely due to elevated removal forces associated with human movements in bed compared to removal forces generated by human footfalls. Indeed, in our previous study, we found RRs to be strongly associated with surface vibrations [32]. The movements measured during this study showed high accelerations (0.1–1 g

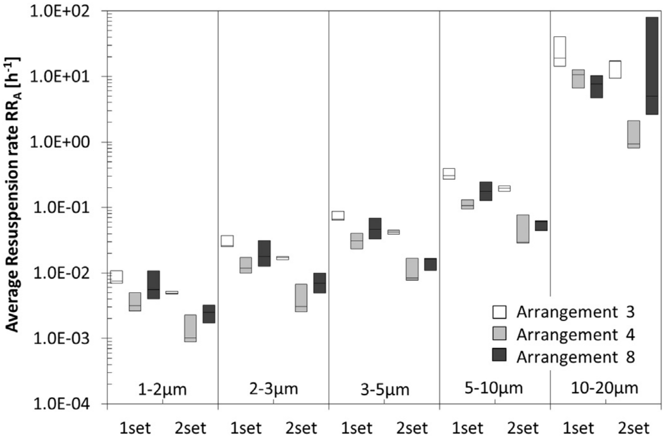

**Fig. 5.** Resuspension rates for five size ranges of five tested arrangements three, four and eight. Arrangement 3-covered mattress (i.e. covered by blanket during the seeding process), seeded pillow and seeded blanket: Arrangement 4-covered mattress, seeded pillow and seeded heavy blanket; Arrangement 8: Seeded mattress, seeded pillow and unseeded light blanket. Due to the low number of experiments ($n = 3$) for each arrangement, data ranges are not displayed.

(9.81 m $s^2$)), whereas vibrations associated with human footfalls have been shown to be typically less than 0.1 g [36].

Large differences in RRs between the first and second movement sets were observed for two test arrangements only (seven and nine). This might be due to the fact that in both arrangements the mattresses were not seeded and only the pillow served as a particle source. During the decay period (30-min break) after the first movement set, resuspended particles may have settled on the surface of both the pillow and mattress. Therefore, during the second movement set the mattress might have served as a source of particles, along with the pillow. However, the change of the seeded area was not considered in the resuspension rate model for the second movement set due to uncertainties in estimating to which surfaces the resuspended particles deposited.

### 4.1. Impact of a pillow

The results obtained in this study showed no significant difference in RRs for arrangements where a pillow was unseeded, seeded or covered in an additional pillow cover. However, the arrangement with the seeded pillow showed higher iFs than the arrangement with an unseeded pillow. High iFs were obtained for the arrangement where a pillow was seeded and covered in an additional pillow cover layer (225-thread count), i.e. the additional pillow cover did not serve as an effective barrier for the penetration of smaller particles resuspended from the underlying pillow surface, but did for larger particles.

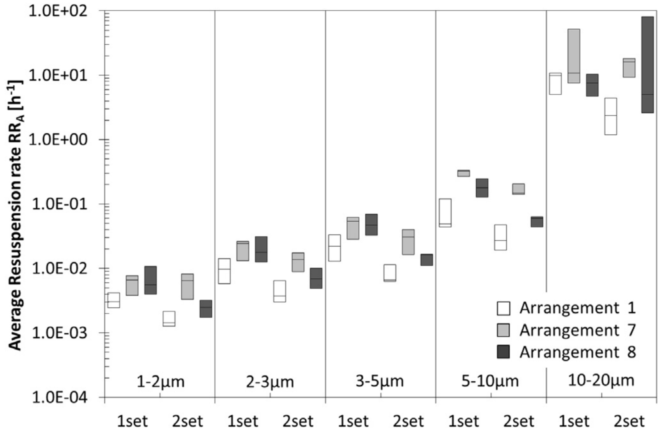

**Fig. 6.** Estimated resuspension rates for five size ranges and two movement sets of arrangements one, seven and eight. Arrangement 1: Seeded mattress, seeded pillow and no blanket present; Arrangement 7: Unseeded mattress, seeded pillow and no blanket present; Arrangement 8: Seeded mattress, seeded pillow and unseeded light blanket. Data ranges (90th and 10th percentiles) are not shown due to the small number of experiments.

### 4.2. Impact of a blanket

Three types of blankets were examined. The resuspension rates were not significantly different ($p$-values displayed in SI2) among the three types of blankets across all five size ranges and both movement sets. However, the lowest RRs occurred for the arrangement with a fleece blanket and the highest for the arrangement with a light blanket. The nature of the light blanket, including its ease of folding and increased porosity, may explain the elevated resuspension rate. The similar levels of resuspension measured for arrangements 4 and 10 suggest that the blanket material (4: duvet cover, 10: fleece) does not have a significant impact on resuspension or adhesion forces. If a pillow is the major source of resuspended particles compared to a blanket, the impact of type of blanket may be negligible. This also explains the insignificant differences among the different blankets when no pillow was present.

### 4.3. Impact of a mattress

Arrangements where the mattress was seeded (arrangements 1, 2, 5, 6 and 8) did not show greater resuspension rates compared to arrangements with an unseeded or covered mattress (i.e. pillow and/or blanket was seeded). Similar results were estimated for the arrangements with mattress covered with a seeded blanket and for seeded mattress covered by an unseeded blanket. The light blanket did not reduce particle resuspension from the underlying mattress. However, the heavy blanket was found to be a more effective barrier to particle resuspension. Similar iFs and RRs estimated for arrangements three and eight indicate that a blanket has a minimal impact on resuspension of particles deposited either on the blanket or under the blanket on the mattress. Neither the RR nor iF showed significant differences across all particle size ranges (Table SI2 and SI3 in the Supplemental Information chapter).

This study also investigated the influence of the presence of a blanket on RRs and iFs. Similar RRs were observed for arrangements without a blanket, seeded pillow and seeded or unseeded mattress. When the mattress was not seeded, the RRs did not increase, however iFs were approximately two times higher. This indicates the importance of a pillow in contributing to resuspension and subsequent transport of the airborne particles into the breathing zone.

### 4.4. Comparison with other studies

We found the highest iF for small particles (1–5 μm) for all test arrangements. The role of particle size on iF is further discussed in Boor et al. (2014). The iFs presented in this study are similar or greater in magnitude compared to previous studies that have reported iFs for indoor sources [34,37]. Taimisto et al. (2011) reported iFs in households equipped with wood heaters of less than or equal to 3.4 ppm. Nazaroff (2008) reported iFs during an episodic indoor emission of approximately 5–6 × $10^3$ ppm (for acrolein and ethylbenzene, respectively). The iFs in the Nazaroff (2008) study were taken over a period of eight hours.

**Table 4**
Estimated intake fraction (ppm) for five size ranges and two movement sets. The values represent arithmetic means.

| | 1–2 μm | | 2–3 μm | | 3–5 μm | | 5–10 μm | | 10–20 μm | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 1.set | 2.set | 1.set | 2.set | 1.set | 2.set | 1.set | 2.set | 1.set | 2.set |
| Bedding arrangement 1 | 13,951 | 7256 | 21,835 | 6204 | 16,353 | 4484 | 9629 | 5277 | 3331 | 444 |
| Bedding arrangement 2 | 11,654 | 58,451 | 7577 | 25,909 | 7445 | 25,929 | 8587 | 20,496 | 660 | 617 |
| Bedding arrangement 3 | 14,195 | 12,220 | 8759 | 8179 | 7534 | 6020 | 5294 | 3747 | 1080 | 5558 |
| Bedding arrangement 4 | 14,291 | 9481 | 8137 | 9490 | 7991 | 6987 | 7092 | 5861 | 1285 | 3487 |
| Bedding arrangement 5 | 33,951 | 24,822 | 14,096 | 14,250 | 8500 | 11,691 | 4785 | 6385 | 2077 | 1286 |
| Bedding arrangement 6 | 13,854 | 15,757 | 8588 | 14,321 | 6301 | 7069 | 4019 | 4677 | 2690 | 1537 |
| Bedding arrangement 7 | 30,626 | 82,255 | 17,113 | 13,372 | 36,533 | 47,426 | 5787 | 3975 | 2761 | 1846 |
| Bedding arrangement 8 | 15,137 | 14,823 | 9817 | 10,450 | 7858 | 9070 | 5618 | 6050 | 3489 | 2295 |
| Bedding arrangement 9 | 25,346 | 13,133 | 15,955 | 12,115 | 11,639 | 9599 | 7675 | 3953 | 1107 | 141 |
| Bedding arrangement 10 | 22,807 | 26,907 | 15,017 | 18,052 | 11,355 | 13,364 | 7623 | 9119 | 2623 | 3174 |

The iFs in this investigation follow the observations of other researchers who focused on the effect of elevated pollutant concentrations and close proximity to the emission sources, e.g., comparing results from stationary and personal monitoring [38–40]. Along with the close spatial proximity of the BZ to the particle deposit, thermal plumes around the human body can help to transport particles upward to the mouth and nose where they can be inhaled [41,42]. On the other hand, exhalation and sleep position are important factors in the dilution of pollutants emitted from sources close to the BZ such as pillows or mattresses [10].

## 5. Conclusion

Resuspension from bedding components is of importance, especially for pillows, given their close proximity to an occupant's breathing zone. The results presented in this paper suggest that the pillow has a strong impact on the resuspension rate. Likewise, as with previous resuspension studies, the larger particles were associated with higher resuspension rates.

Intake fractions estimated from airborne particle concentrations in the breathing zone were found to be highest for small particles across all test arrangements. High intake fractions, i.e., number of inhaled particles per million of particles that resuspend, signify that a significant portion of the resuspended particles may be inhaled. The amount of inhaled particles during a sleep event can become greater due to the lower deposition rate for smaller particles. Resuspension induced by human movements in a bed are comparable in magnitude to resuspension induced by other human activities indoors, such as walking. Future work should further investigate the fundamental mechanisms of particle detachment from bedding fibers and explore the impact of mattress dust particle composition, especially for particles of biological origin, on resuspension.

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## Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.buildenv.2014.06.010.

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