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Reductions in exposures to simulated respiratory aerosols by a ceiling-mounted HEPA air filtration unit

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ABSTRACT

Supplemental air filtration can reduce indoor exposure to hazardous aerosols without requiring modifications to building heating, ventilation, and air conditioning (HVAC) systems. Portable air cleaners were widely used during the COVID-19 pandemic, but they can have drawbacks including noise, space obstruction, and electrical cord safety considerations. Built-in air filtration units are an alternative to provide supplemental air filtration. We conducted a case study of a HEPA air filtration unit installed in the ceiling of a conference room using radial laminar flow or square cone ceiling air supply diffusers. A respiratory aerosol simulator exhaled aerosol particles (0.3 to 10 μm), and the particle concentrations were measured in the personal breathing zones of three breathing simulators representing a speaker and two meeting participants. For the speaker, using one square cone supply diffuser reduced inhalation exposure by 49 % to 81 % while using two square supply diffusers reduced exposure by 68 % to 93 %. For the participants, the exposures were reduced by 23 % to 64 % with one square supply diffuser and 58 % to 86 % with two square supply diffusers. Results when using the radial supply air diffusers were more variable and more dependent on the simulator layouts. Combining the use of cloth face masks on all simulators with the ceiling unit reduced the speaker's exposure by 87 % to 99 % and the participants' exposures by 84 % to 97 %. In most cases the ceiling air filtration unit provided protection against simulated respiratory aerosol particles comparable to that seen previously with portable air cleaners.

1. Introduction

Infectious respiratory viruses such as SARS-CoV-2 are spread by aerosols and droplets of respiratory fluids that are expelled by infected people when they cough, breathe, talk, sing and sneeze [1–5]. A variety of interventions are recommended to reduce the indoor transmission of SARS-CoV-2, including increasing ventilation rates, upgrading ventilation system filters, adding portable air filtration systems, maintaining a larger physical distance between people, limiting the number of people in indoor settings, and the universal wearing of well-fitting face masks, respirators, or other types of face-worn products (called universal masking) [6–9]. Improving ventilation and filtration are of particular interest as methods to reduce the aerosol transmission of diseases because they can be implemented by building operators without requiring the people in the buildings to take individual actions or comply with mandates. Increasing the amount of outdoor air drawn into a building by the heating, ventilation, and air conditioning (HVAC) system can be an effective means of reducing exposure to indoor aerosols. However, increasing the use of outdoor air can substantially increase energy and can increase exposure to outdoor pollutants [10]. Reducing aerosol exposure by increasing air filtration and recirculation through the HVAC system can also be effective, but this often requires the installation of air filters with higher minimum efficiency reporting value (MERV) ratings, which can add costs and increase the air flow resistance that must be overcome by the ventilation system [9,11]. In addition, increasing ventilation or filtration with an existing HVAC

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system often is not possible if the HVAC systems does not have the extra capacity needed to increase the use of outdoor air or well-filtered recirculated air.

As an alternative to increasing ventilation or filtration by modifying an existing HVAC system, supplemental air filtration systems such as portable air cleaners can reduce the exposure of the occupants to indoor aerosols. Supplemental air filtration systems are typically less expensive than HVAC system renovations and usually can be implemented more quickly and easily. Portable air cleaners were widely used during the COVID-19 pandemic and have been shown to be an effective method for reducing exposure to respiratory aerosols [12–14]. Wall or ceiling mounted air filtration systems are a less common method to reduce exposure to indoor aerosols outside of specialized settings, likely because they are typically more expensive than portable air cleaners and require installation. However, built-in air filtration systems can have significant advantages: they are usually quieter and less obtrusive than portable air cleaners, they do not require electrical cords in the room, they can be more easily integrated into a building's environmental control system, and, since the units are fixed in place, they can provide greater and more consistent control over air movements within a room.

The purpose of this study was to examine the efficacy of a built-in ceiling-mounted high-efficiency particulate air (HEPA) filtration system at reducing the exposure of conference room occupants to simulated respiratory aerosols. Our study primarily focused on reducing the aerosol exposure for a teacher or lecturer at the front of the room with an infected student exhaling aerosol particles directly at them, as this was a particular concern during the COVID-19 pandemic. The results of these experiments provide a case study of the performance of a built-in air filtration system. The results also illustrate some of the considerations when designing such a system and when deciding between the installation of a built-in air filtration system and alternative methods for reducing exposure to indoor aerosols.

2. Materials and methods

2.1. Summary

A ceiling HEPA air filtration unit was installed in a conference room with the filtered air supply diffusers positioned toward the front of the room and the air exhaust return grille positioned in the middle (Fig. 1). A respiratory aerosol simulator (the source) and three breathing simulators (a speaker and two meeting participants) were placed in the conference room to simulate a meeting or class in which one meeting participant is exhaling respiratory aerosols into the room and the speaker and other participants are being exposed to those aerosols. The exposure of the speaker and participant simulators to the respiratory aerosols from the source was measured by monitoring the aerosol particle concentrations in the personal breathing zones of the speaker and participants and at other locations in the room. The exposure reductions resulting from the use of the ceiling HEPA air filtration unit were measured while using one or two air supply diffusers of two different designs. Experiments were also conducted with cloth face masks on all the simulators (universal masking) to study the effects of a combination of face masks and the ceiling HEPA air filtration unit on aerosol exposure. A list of the experimental parameters is shown in Table 1.

2.2. Conference room

Experiments were conducted in a 164 m^3 conference room (6.6 m wide x 9.1 m long x 3 m tall) described in detail previously [12]. The room HVAC system was operated at a constant supply air flow of 0.1 m^3/s (1.9 air changes/hour (ACH)) for all experiments. Supply air from the HVAC system entered the room through six 0.6 m x 1.2 m (24″ x 48″) slot inlets forming the perimeters of the fluorescent light fixtures. Return air flowed from the room into a ceiling plenum through three 0.6 m x 1.2 m slot outlets. The locations of the HVAC supply and return air slots are shown in Fig. S5 in the supplemental materials. The temperature and humidity in the room were recorded using a relative humidity/temperature transmitter (HMT333, Vaisala Oyj, Vantaa, Finland).

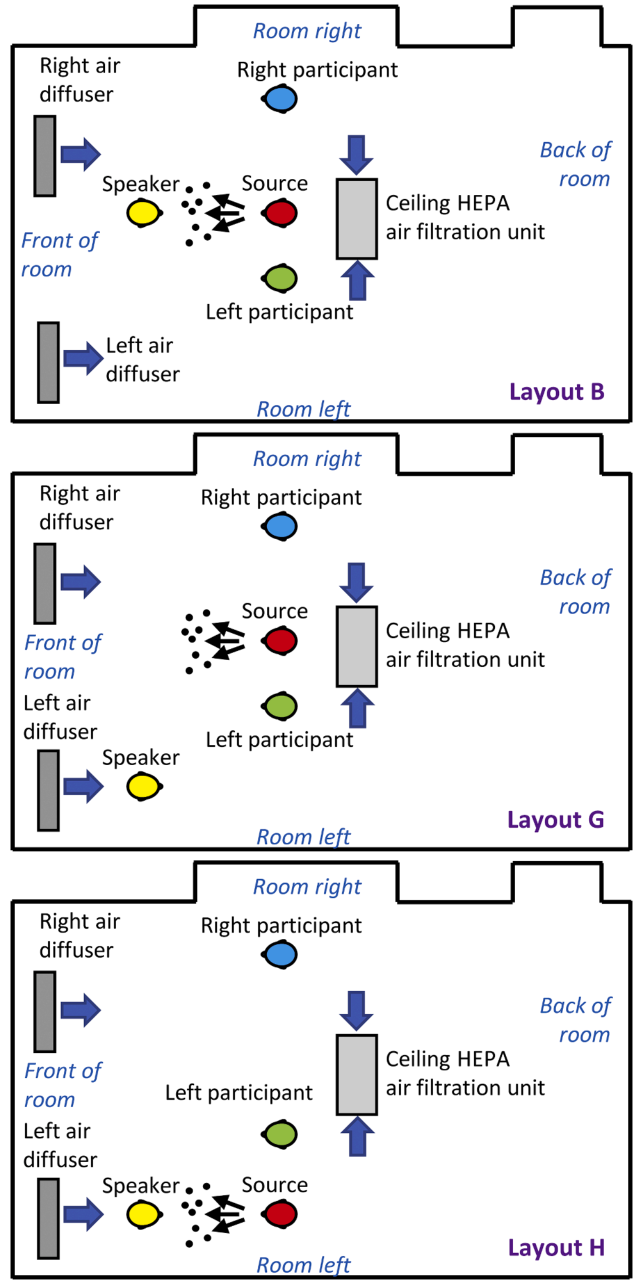

Fig. 1. Schematics of the room showing the layouts of the simulators, ceiling diffusers, and ceiling air filtration unit for the three different simulator layouts used in the experiments. Air is drawn out of the room at the ceiling unit where it passes through a HEPA filter. The air then flows through ducts in the ceiling to the diffusers, and back into the room. Photographs and scale drawings with dimensions are shown in Figs. S1 to S7 in the supplemental materials.

2.3. Ceiling HEPA air filtration unit

A ceiling-mounted HEPA air filtration unit (Puraflo, Price Industries, Inc., Suwanee, GA) was installed in the conference room. The unit has two clean air ducts that lead to two air supply diffusers and one 0.6 m x 1.2 m air return in the base of the unit. A valve was added to one clean air duct to allow it to be shut off for experiments using only one air supply diffuser. The system was tested using one or two of two types of

Table 1
Experimental parameters used in the study. Four experiments were performed for each combination of parameters, for a total of 120 experiments (3 simulator layouts x 2 mask conditions (worn and not worn) x 5 diffuser combinations x 4 replicates each).

Parameter	*Values tested*
Layouts of simulators in room	Layout B
	Layout G
	Layout H
Use of face masks	Not worn
	Worn by all simulators
Air supply diffusers	Not used
	1 Radial diffuser (left side only)
	2 Radial diffusers (left & right)
	1 Square cone diffuser (left side only)
	2 Square cone diffusers (left & right)

ducted air supply diffusers: a 0.3 m x 1.2 m (12″ x 48″) radial flow diffuser (1-way Half Radial Flow Diffuser, Price Industries) that provides a low face velocity air flow across a broad area, or a 0.61 × 0.61 m (24″ x 24″) square cone 4-way diffuser (Model 4MJV3, Grainger, Lake Forest, IL) that provides a higher velocity air flow. The air supply flowrates through the diffusers were measured using a balometer (Alnor Model EBT731, TSI, Shoreview, MN) and are shown in Table 2. A schematic of the locations of the diffusers and HEPA filtration unit are shown in Fig. 1. Photographs and dimensional locations of the installation and diffusers are shown in Figs. S1 to S7 in the supplemental materials.

2.4. Air change rate

The air change rate is the number of times per hour that the room air is replaced. If the air in the room is completely and continuously mixed, the ACH can be calculated by dividing the airflow into the room over an hour of time by the room volume. In reality, the air may not be well mixed, and thus the actual rate of air exchange may be lower than the rate calculated from the airflow. In addition, while HEPA filters collect virtually all the aerosol particles that flow into them, other filters with lower ratings do not collect all aerosol particles, which can also reduce the apparent ACH of a filtration system. Because of these two factors, the effective ACH provided by an air filtration system can be less than the rate calculated from the airflow. We measured the effective ACH for the room as a whole using the aerosol concentration-decay rate method (also called the pull-down method) [15]. The room was loaded with aerosol particles for 20 min using a 3-jet Collison nebulizer with a 14 % KCl solution. A large fan was used to ensure that the aerosol was evenly distributed throughout the room. The nebulization was then stopped, and the aerosol concentrations were measured for 20 min at eight symmetrically spaced locations using aerosol optical particle sizers (OPS; Model 3330, TSI, Inc., Shoreham, MN) sampling at one-second intervals. The particle number concentrations for the three smallest size bins (0.3–0.4, 0.4–0.5, and 0.5–0.65 μm) were aggregated for each instrument and used to determine the decay rate. The smallest size bins were used for decay rate measurements because these particles have the lowest settling velocities, which minimizes the confounding effects of settling on the particle concentrations. Each test was repeated three times, and the results were averaged among all the OPSs to determine the overall effective air change rate for the room with the ceiling air filtration unit off, using one diffuser, and using two diffusers. Because the measured effective ACH also includes the reduction in aerosol concentration due to the room HVAC system, the effective ACH measured with the ceiling unit off was subtracted from the ACH measured when the unit was on to determine the effective ACH due to the ceiling unit alone.

2.5. Respiratory aerosol simulator

A respiratory aerosol simulator was used to simulate a person (referred to here as the source) who was exhaling aerosol particles into the conference room as described previously [12]. The simulator uses an elastomeric bellow driven by a computer-controlled linear motor to reproduce human breathing air flows. The source simulator has a headform with pliable skin (Hanson Robotics, Plano, TX) that mimics the depth and elasticity of human skin so that masks and respirators fit the headform much like they would fit a human head [16]. The simulator headform has the dimensions of the NIOSH medium headform described by Zhuang, Benson and Viscusi [17]. The mouth of the respiratory aerosol simulator was 1 m (40″) above the floor, simulating an adult who is seated. The simulator was calibrated to a ventilation rate of 15 L/min with a breathing rate of 12 breathes/min and a tidal volume of 1.25 liters, which corresponds to the ISO standard for a female performing light work [18]. The flow calibration was performed using an ultrasonic spirometer (Easy-on PC, NDD Medical Technologies, Inc., Andover, MA, USA). The locations used for the respiratory aerosol simulator are shown in Figs. 1 and S6 and S7 in the supplemental materials.

The test aerosol was produced using a solution of 14 % potassium chloride (KCl) in a single-jet Collison nebulizer (BGI, Butler, NJ) at 103 kPa (15 lbs./in^2). The aerosol passed through a diffusion drier (Model 3062, TSI, Shoreview, MN), mixed with 15 L/min dry filtered air, and was neutralized using a bipolar ionizer (Model HPX-1, Electrostatics, Hatfield, PA).

2.6. Speaker and participant breathing simulators

Three breathing simulators were used to simulate a speaker at the front of the room (speaker) and meeting participants to the side of the source simulator (left participant and right participant) as shown in Figs. 1 and S6 and S7. The breathing simulators have a similar design to that of the respiratory aerosol simulator and have been described previously [12]. As with the respiratory aerosol simulator, the breathing simulators breathed at 12 breaths/minute with a tidal volume of 1.25 L

Table 2
Air flowrates and air change rate (ACH) through the ceiling air filtration unit supply diffusers. The square cone diffusers had less airflow resistance than the radial diffusers and thus produced a higher flowrate at each power setting. For experiments using only one diffuser, the power to the HEPA unit blower was reduced so that the airflow through the single diffuser approximately matched the airflow that was measured through that diffuser when two diffusers were used and the HEPA unit power was 100 %. The calculated ACH is based on the flowrate from the diffusers divided by the room volume. The effective ACH is the ACH due to the ceiling filtration unit measured for the entire room using the concentration decay method. The ACH due to the HVAC system (1.9 ACH) was subtracted from the total effective ACH values to give the ACH due to the ceiling unit alone shown as in the table.

Air supply diffusers	*Left diffuser flowrate (L/s)*	*Right diffuser flowrate (L/s)*	*Total diffuser flowrate (L/s)*	*Calculated ACH*	*Effective ACH*	
					Mean	*SD*
Not used	0	0	0	0	0	0.15
1 Radial diffuser	175	0	175	3.8	2.7	0.05
2 Radial diffusers	177	127	305	6.7	4.9	0.09
1 Square cone diffuser	195	0	195	4.3	4.5	1.51
2 Square cone diffusers	202	146	348	7.6	6.2	0.06

and a ventilation rate of 15 L/min. The breathing simulator headforms (Respirator Testing Head Form 1 – Static, Crawley Creatures Ltd, Buckingham, UK) have the dimensions of the ISO Respiratory Protective Device medium headform [19] and have pliable skin that mimics the depth and elasticity of human skin [16]. The mouth of the speaker simulator was 1.5 m (60″) above the floor, simulating a person who is standing. The mouths of the participant simulator were 1 m (40″) above the floor, simulating seated adults.

2.7. Face masks and fit testing

For some experiments, cloth face masks with 3 layers of cotton fabric and ear loops (Defender model, HanesBrands Inc., Winston Salem, NC) were placed on the simulators. Experiments were conducted either with no face masks on any of the simulators or with face masks on all the simulators (universal masking). After the mask was placed on the headform, the fit factor was measured using a standard respirator fit testing device (Model 8038 PortaCount® Pro Plus; TSI, Shoreview, MN) in class 100 mode (also called N99 mode) as described previously [20]. The fit factor is the ratio of the aerosol concentration outside the mask to the concentration inside the mask (a more detailed explanation is given in the supplemental materials). Note that, because the cloth face masks do not have a high filtration efficiency, the fit factor measurement reflects a combination of particles penetrating through the mask material and flowing around the mask through face seal leaks, rather than only measuring face seal leaks as would be the case with a respiratory protective device [20]. Fit factor results are shown in Table S4 in the supplemental materials.

2.8. Noise measurements

Five noise dosimeters (Spartan 730, Larson Davis, Depew, NY, USA) were used to measure the decibel A-weighted (dBA) noise levels produced by the ceiling air filtration unit at five locations evenly distributed in the room (Fig. S8 in the supplemental materials). For comparison, the noise levels produced by a pair of portable HEPA air cleaners (Honeywell 50,250-S, Kaz Inc., Memphis, TN, USA) operating at a combined flowrate of 236 L/s were also measured. The ceiling filtration unit was tested using one and two square cone diffusers. The room HVAC system was set at a constant 1.9 ACH for all noise measurements and all doors were closed to the room. Sound level readings were averaged over two minutes and were performed three times.

2.9. Aerosol exposure measurements

To measure the exposure of the speaker and participant breathing simulators to the simulated respiratory aerosols from the source, OPS's were connected to straight stainless steel probes passing through each breathing simulator headform that collected aerosol samples from alongside the mouth. The probes were located such that, if the simulator was wearing a face mask, the particle counter collected aerosol samples from inside the mask (i.e., the particle counter measured the concentration of the aerosol being inhaled by the simulator). The optical particle counters reported the number of aerosol particles detected per cm^3 of air ($\#/cm^3$) at 1 Hz in 16 logarithmically spaced size bins from 0.3 to 10 μm. Before each test, the background aerosol number concentration was measured during the three minutes before source breathing was initiated and was subtracted from the concentrations measured afterward.

The aerosol samples were collected from within the personal breathing zones of the speaker and participant simulators (the region around the nose and mouth). Note that different fields use different definitions for the breathing zone; this is discussed in more detail in the supplemental materials.

2.10. Experimental procedure

Before each experiment, the source, speaker, and participant simulators were positioned in the conference room. Masks were placed on the simulators when needed and the fit factors were measured. The room HVAC system was set to its maximum ventilation rate (9 ACH) to reduce the background aerosol concentration to a minimum. The room HVAC system was then set to 1.9 ACH, the ceiling air filtration unit was set to the appropriate flow rate for the test, and the speaker and participant breathing simulators were started. After two minutes, the background aerosol concentrations were measured for three minutes, and the aerosol exhalation by the respiratory source simulator was then started. Aerosol concentration measurements continued for 60 min. The experimental parameters are shown in Table 1. Four replicates were performed for each set of experimental conditions for a total of 120 experiments.

2.11. Theory and calculation

2.11.1. Theoretical analysis

If a well-mixed room is initially clean of aerosol particles, and a source emitting aerosol particles at a constant rate is then introduced into the room, then the aerosol concentration in the room at time t is given by [15]:

$$C(t) = \frac{F}{q}\left(1 - e^{-\frac{q}{V}t}\right)$$

Where:

F = the rate of introduction of aerosol into the room (μg/sec)
q = ventilation flow rate (m^3/sec)
V = volume of room (m^3)
C = concentration (μg/m^3)

Note that C(0) = 0 and C(∞) = F/q and that the effects of gravitational settling are ignored.

The mean of the aerosol concentration over the time span t = 0 to t = T is then:

$$C_{mean}(T) = \frac{\int_0^T C(t)dt}{T} = \frac{F}{q}\left[1 + \frac{V}{qT}\left(e^{-\frac{q}{V}T} - 1\right)\right] \quad (1)$$

This theoretical mean concentration for a well-mixed room can be compared to the mean concentration calculated from the experimental data. The mean concentrations can be used to calculate the reduction in aerosol concentration due to each intervention, which is equivalent to the reduction in exposure to the aerosol. For example, if the mean aerosol concentration in the personal breathing zone of a simulator is 200 μg/m^3 when the ceiling unit is off and 80 μg/m^3 when the ceiling unit is on, then the reduction in exposure due to the ceiling unit is (200 – 80)/200 = 0.6, or 60 %.

2.11.2. Experimental data analysis

The mass of the aerosol in each size bin per m^3 of air (mass concentration) was calculated by multiplying the particle count by the volume of an individual particle with the mean diameter of the size bin (assuming the particles were spherical) and by 1.984 g/cm^3 (the density of KCl). Note that this conversion from particle counts to particle mass is commonly used but is an approximation [21].The total aerosol mass/m^3 (total aerosol mass concentration) was found by summing the aerosol mass concentrations across all the size bins. The mean mass concentration was found by averaging the total mass concentration over 60 min starting from the time of the initiation of the source breathing. The data for each experiment are shown in Tables S3 and S4 in the supplemental materials.

2.11.3. Statistical analysis

The total mass concentration data were first assessed for normality and homogeneity of variance across groups. Lack of both indicated that an analysis of variance (ANOVA) on the rank of the total mass concentration data was necessary for valid statistical comparison. The full data were subset by Layout (B, G, or H) and individually run with a two-way ANOVA to test the effects of Diffuser type, Masking condition, and their interaction. The analysis was run on each layout subset since comparisons across diffuser within a layout were of interest rather than across layout. A Tukey HSD post-hoc analysis with the Tukey-Kramer p-value adjustment for multiple comparisons was done for full pairwise comparison across all levels of diffuser and masking condition. Results were considered significant if $p \leq 0.05$. All analyses were conducted using the R programming language [22]. Detailed results of the statistical analysis are shown in Tables S5 to S8 in the supplemental information.

3. Results

The mean aerosol concentrations in the personal breathing zones of the speaker and meeting participant simulators under each test condition are shown in Figs. 2–4. The addition of the ceiling HEPA air filtration unit reduced the exposure of the speaker and the participants to the simulated respiratory aerosols exhaled by the source. However, the amount of exposure reduction varied from as little as 9 % to as much as 99 %, depending upon the layout of the simulators, the type of diffuser, the number of diffusers, and the use of face masks (Tables S1 and S2).

For the speaker, using one square cone diffuser reduced the inhalation exposure by 81 % for layout B ($p < 0.001$), but did not significantly reduce exposure in layouts G and H (Figs. 2 and S9-S11). Using two square cone diffusers reduced exposure by 68 % to 93 %, depending upon the simulator layout ($p < 0.001$ for all layouts). For the two meeting participants, the baseline exposures without operation of the ceiling air filtration unit were lower than for the speaker because the participants were to either side of the source rather than in front (Fig. 1).

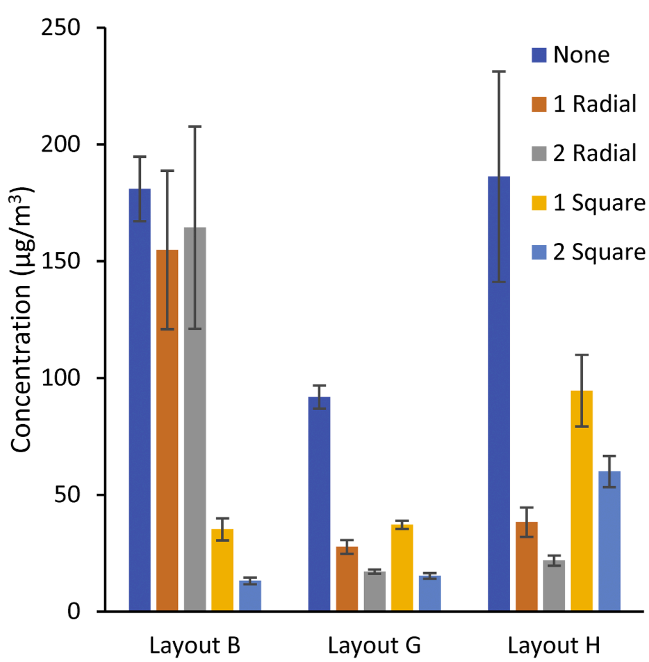

Fig. 2. Mean aerosol concentration for the speaker with different layouts and air supply diffusers. Each bar is the mean of four experiments. Error bars indicate the standard deviation.

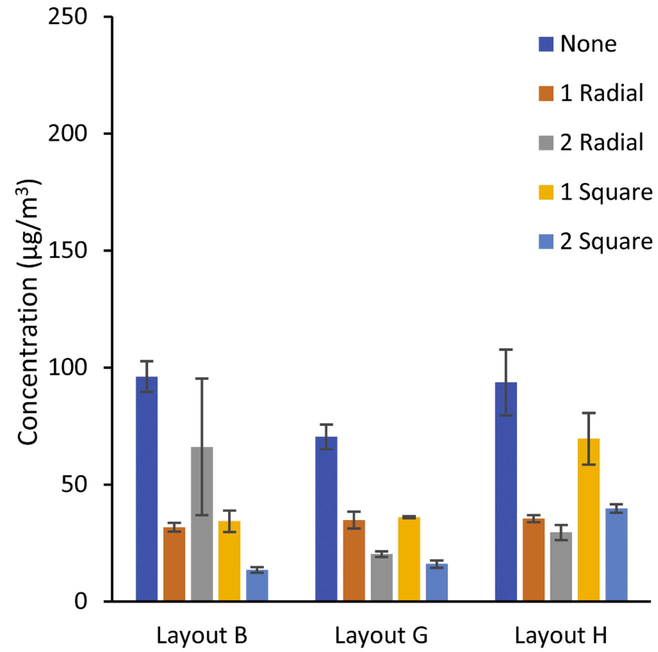

Fig. 3. Mean aerosol concentration for the left participant with different room layouts and air supply diffusers. Each bar is the mean of four experiments. Error bars indicate the standard deviation.

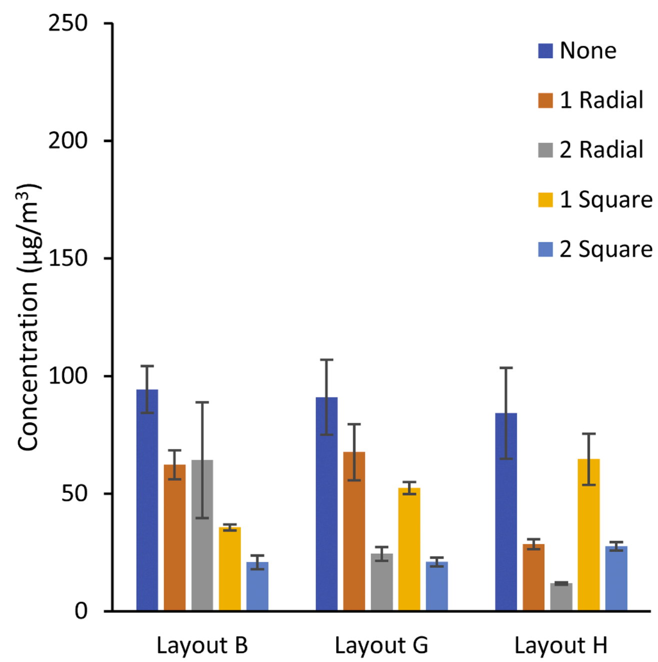

Fig. 4. Mean aerosol concentration for the right participant with different room layouts and air supply diffusers. Each bar is the mean of four experiments. Error bars indicate the standard deviation.

Additionally, the exposure reductions due to the ceiling unit generally were not as high for the participants compared with the speaker. For the left participant, the exposures were reduced by 64 % in layout B ($p = 0.003$) and 49 % in layout G ($p = 0.029$) when using one square diffuser, and 58 % to 86 % while using two square diffusers ($p \leq 0.002$ for all layouts; Figs. 3 and S9-S11). For the right participant, the exposure was reduced 62 % in layout B ($p < 0.001$) and 42 % in layout G ($p = 0.001$) with one square diffuser, and 67 % to 78 % with two square diffusers ($p < 0.001$ for all layouts; Figs. 4 and S9-S11).

The results with the radial diffusers were influenced more by the simulator layouts than were the square cone results. The radial diffusers were more effective at protecting the speaker when the speaker was standing directly in front of a diffuser (layouts G and H) but were much less effective when the speaker was standing between them (layout B). For layout G, the exposure was reduced by 70 % when using one radial diffuser ($p = 0.001$) and 81 % when using both ($p < 0.001$), and in layout H the exposure was reduced by 79 % when using one radial diffuser ($p < 0.001$) and 88 % when using both ($p < 0.001$; Fig. 2). However, when the speaker was in layout B, the speaker was located between the two radial diffusers, and in this case the exposure was only reduced by 14 % when using one radial diffuser and 9 % when using two, and neither reduction was significant.

For the two meeting participants, use of the radial diffusers provided mixed results compared with the square diffusers, with greater exposure reductions in some layouts and less in others (Figs. 3, 4, and S9-S11). For the left participant, across all layouts, the exposures were reduced 51 % to 67 % with one radial diffuser ($p \leq 0.029$ for all; Fig. 3). With two radial diffusers, the left participant saw reductions of 71 % in layout G and 69 % in layout H ($p < 0.001$ for both), but the reduction for layout B was not significant. For the right participant, with one radial diffuser, the exposure reductions were 34 % in layout B ($p = 0.011$; Fig. 4) and 66 % in layout H ($p < 0.001$), but was not significant for layout G. With two radial diffusers, the reductions for the right participant were 32 % in layout B ($p = 0.045$), 73 % in layout G ($p < 0.001$), and 86 % for layout H ($p < 0.001$).

Without the ceiling air filtration unit, cloth face masks worn by all four simulators reduced respiratory aerosol exposure by 84 % to 89 % for the speaker and 78 % to 86 % for the meeting participants across all layouts ($p < 0.001$ for all). The combination of masking and the ceiling air filtration unit was more effective than either intervention alone for both the speaker and participants and for all diffusers and layouts (Fig. 5 and Table S2). The combination of masking and the ceiling filtration unit

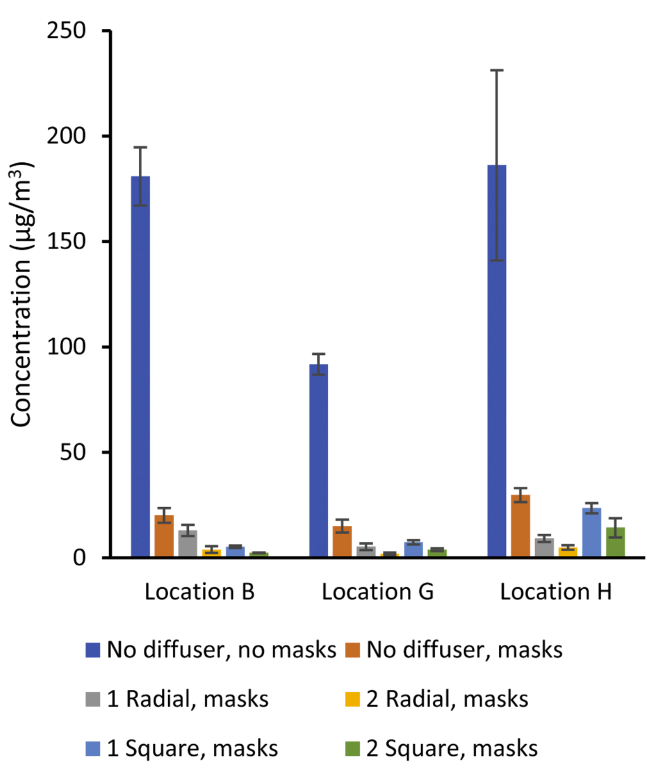

Fig. 5. Mean aerosol concentration for the speaker with universal masking. The first bar indicates the concentration when no masks were worn and the ceiling unit was off. The remaining bars show the results when all simulators were wearing cloth face masks. Results for all simulators are shown in Table S2.

reduced the speaker's exposure by 87 % to 99 % depending upon the diffusers and layout ($p < 0.001$ for all). For the participants, masking combined with the ceiling filtration unit reduced exposure by 84 % to 97 %, again depending upon the diffusers and layout ($p < 0.001$ for all).

The room air change rates that were calculated based on the flow rates from the diffusers and the effective ACH measured using the concentration decay method are shown in Table 2. The average room temperature during the experiments was 21 °C (SD 0.8) and the average relative humidity was 50 % (SD 14). The relative humidity remained below the deliquescence relative humidity for KCl (85 %; [23]) for all simulator experiments, indicating that the KCl particles remained desiccated.

The average background noise level in the room was 43.7 dBA (Table 3). With the ceiling air filtration unit, the average noise level was 54.7 dBA when using one diffuser and 59.0 dBA when using two diffusers. With the two HEPA air cleaners, the average noise level was 64.1 dBA.

4. Discussion

The COVID-19 pandemic provided a stark demonstration of the importance of reducing respiratory disease transmission using interventions aimed at removing or deactivating airborne viruses. One intervention that has garnered increased attention is the use of air filtration to remove airborne infectious particles before they are able to infect others. Increasing air filtration in indoor settings has been shown to decrease the amount of indoor aerosol particles both in simulation studies [24] and in classrooms [25,26]. Increases in ventilation and air filtration were shown in two school studies to reduce the incidence of respiratory infections [25,27]. Portable air cleaners are one effective way to supplement existing HVAC systems and bring down aerosol concentrations. However, they can have drawbacks such as noise, the need to occupy floor space, and aesthetic issues. Thus, in some settings, built-in air filtration units may be preferable.

The primary motivation for our research was to examine methods for protecting workers such as teachers who are lecturing a class that may include students with infectious respiratory illnesses. During the COVID-19 pandemic, there was tremendous concern for the well-being of teachers because the disease had a much greater impact on older adults compared with children, particularly adults with underlying health issues. Previously, we tested the efficacy of commercial portable air cleaners and do-it-yourself air cleaners at reducing the exposure of room occupants to simulated respiratory aerosols [12,28,29]. In this study, we have used the same experimental set-up to test a built-in ceiling air filtration system as an alternative to portable air cleaners.

Overall, the ceiling air filtration unit effectively reduced exposure to simulated respiratory aerosols. The effectiveness varied depending upon

Table 3
Noise measurements (dBA) with the ceiling air filtration unit operated with one and two square diffusers and with two portable air cleaners. A diagram of the dosimeter locations is shown in Fig. S8 in the supplemental materials.

Condition	*Location in room*						
	Left front	*Right front*	*Left rear*	*Right rear*	*Center of room*	*Average*	*SD*
Background	43.3	44.8	43.1	44.2	42.7	43.7	0.77
	43.5	44.8	43.2	44.3	42.8		
	43.5	44.8	43.2	44.3	42.8		
Ceiling unit with one diffuser	55.0	54.4	53.7	54.3	56.2	54.7	0.87
	55.0	54.3	53.7	54.3	56.2		
	55.0	54.4	53.8	54.4	56.2		
Ceiling unit with two diffusers	59.0	58.5	58.4	58.6	60.3	59.0	0.72
	58.9	58.5	58.4	58.6	60.3		
	58.9	58.5	58.4	58.7	60.3		
Portable air cleaners	63.9	65.3	65.0	63.2	63.6	64.1	0.84
	63.8	65.1	65.0	63.1	63.5		
	63.7	65.0	65.0	63.1	63.4		

the type of diffuser used, the number of diffusers (with corresponding differences in flowrate), the layout of the simulators in the room, and the use of face masks. Because we were particularly interested in methods to protect workers like teachers from infected students, the source simulator was always in the audience; we did not test scenarios where the speaker may have been infected. Consequently, because the source was exhaling toward the front of the room where the speaker was located, the speaker exposures to respiratory aerosols were noticeably higher than the participant exposures when the ceiling unit was not used. Overall, reductions in exposure due to the ceiling air filtration unit were more pronounced for the speaker than the participants.

We tested two types of air supply diffusers in this study: radial diffusers and square cone diffusers. The radial diffusers are designed to provide a high clean air flow volume with a low velocity across a broad grill. Radial diffusers are typically used in cleanrooms to provide laminar air flow with little air mixing. In contrast, square cone diffusers are used to provide a higher velocity air flow and to promote mixing. Square cone diffusers are commonly used in indoor spaces such as offices and classrooms. Our expectation was that the radial diffusers would provide a broad sheet of air flowing from the front of the room toward the air return, and therefore that the radial diffusers would consistently perform better than the more traditional square diffusers at protecting the speaker. In fact, the radial diffusers protected the speaker better than the square diffusers when the speaker was directly in front of one of the diffusers (layouts G and H) but performed worse when the speaker was between the diffusers (layout B; Figs. 6 and S9-S11). When using two radial diffusers, the aerosol concentration was only 9 % lower than the concentration when the ceiling filtration unit was turned off. This likely occurred because, by design, the radial diffusers do not promote air mixing. A smoke visualization test (not shown) indicated that our set-up created an air circulation dead zone between the radial diffusers into which the source was exhaling aerosol particles. Thus, particles were only slowly removed from the personal breathing zone of the speaker when the speaker was between the radial diffusers (layout B).

For the participants, in some cases, the radial diffuser performed better while in other cases the square diffuser was better; neither style of diffuser was universally superior. For example, with the simulators in layout B, using one radial diffuser reduced aerosol exposure for the right participant by 34 % while one square diffuser reduced it by 62 % (Figs. 8 and S9). On the other hand, with the simulators in layout H, using one radial diffuser reduced the right participant's exposure by 66 % while one square diffuser reduced it by only 23 % (Figs. 8 and S11).

Using two square diffusers instead of one diffuser (with a corresponding 78 % increase in air flow) resulted in a lower aerosol concentration in the personal breathing zones of the speaker and both participants in all cases. This is a logical outcome given the additional clean airflow and improved room air mixing resulting from the two square diffusers. For the radial diffusers, increasing the number of diffusers from one to two and increasing the air flow by 74 % reduced exposures for all three simulators when they were in layouts G and H (Figs. 6–8 and S10-S11). However, for layout B, although using one or two radial diffusers always reduced the aerosol exposure below the baseline condition, using two diffusers did not reduce the exposure more than using just one diffuser for any of the simulators (Figs. 6–8 and S9). Again, this most likely was due to the lack of air mixing and the creation of dead zones when using the radial diffusers. It is worth noting that the room had a width of 5.74 m (18′ 10″) at the front, while the two radial diffusers each had a width of only 1.2 m (48″) and therefore together only provided air flow across 42 % of the span. The addition of more radial diffusers at the front might have provided a more even air flow and eliminated the dead zones that were seen in our study, which may have improved their performance. An important lesson is that air flows in a room can be more complex than anticipated, and that ventilation systems, including supply diffusers and exhaust grilles, should be carefully designed and then tested after installation. For example, ensuring that speaker position or lectern was within the protected zone of the radial diffuser would be important during periods of heightened exposure concern.

As seen in our previous studies [12,28,29], the universal use of face masks was the most consistent and, overall, most effective strategy at reducing respiratory aerosol exposure, and the combination of supplemental air filtration and masking was substantially more effective than

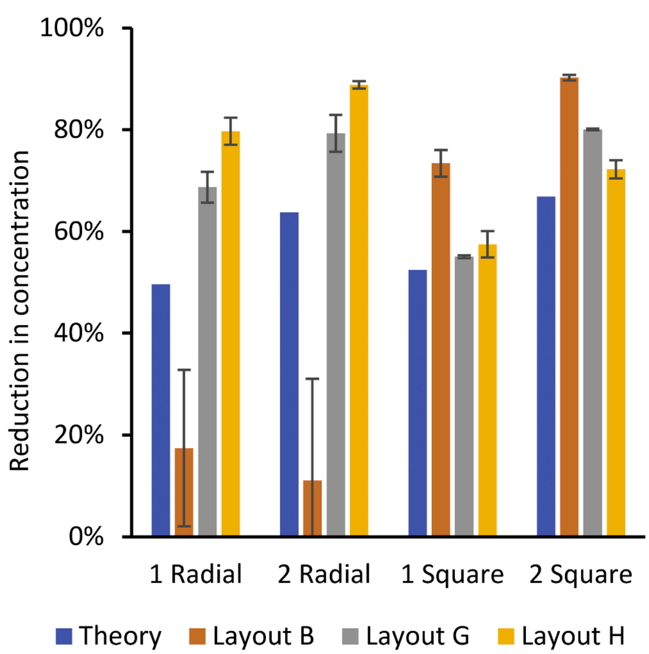

Fig. 6. Theoretical and experimental reduction in aerosol concentration in the personal breathing zone of the speaker. The first bar (blue) indicates the theoretical reduction that would be expected from Eq. (1) based on the airflow through the diffuser and assuming a well-mixed room. The remaining bars show the actual reductions observed during the experiments. To avoid issues with particle losses due to settling, only the experimental data for particles from 0.3 to 0.5 μm were used for the comparison. The reductions were calculated relative to the case where the ceiling unit was off for each layout.

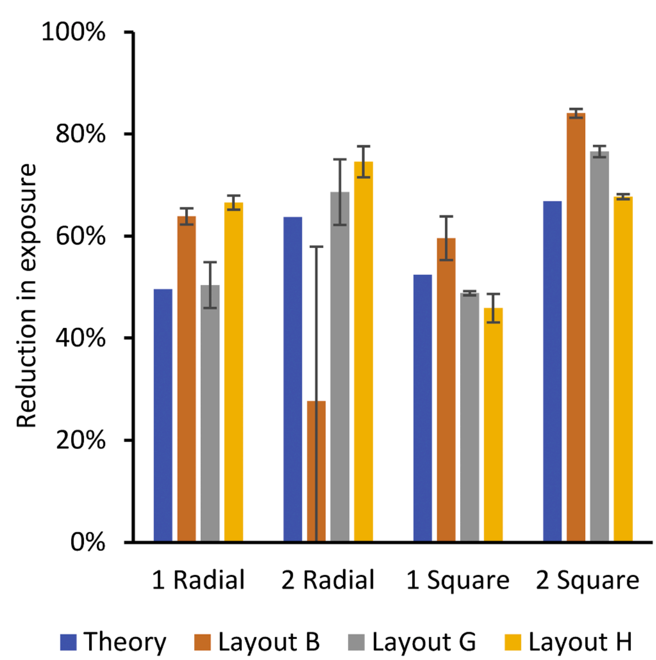

Fig. 7. Theoretical and experimental reduction in aerosol concentration in the personal breathing zone of the left participant.

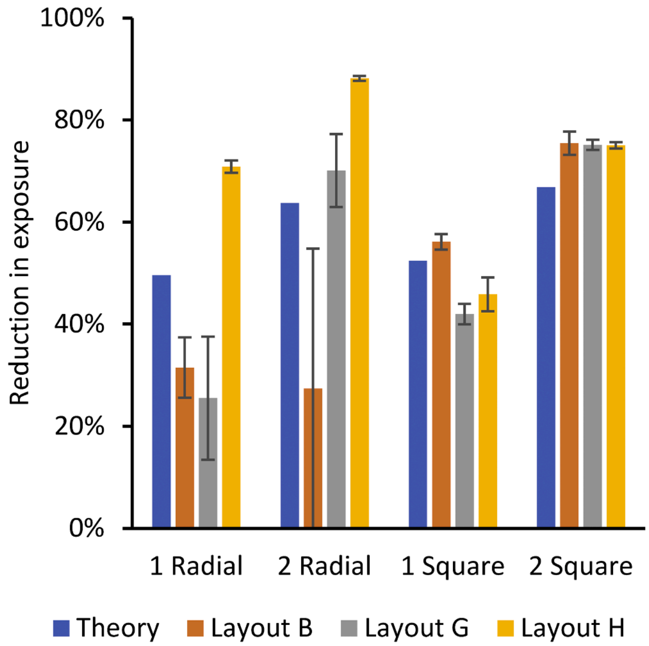

Fig. 8. Theoretical and experimental reduction in aerosol concentration in the personal breathing zone of the right participant.

either intervention alone (Fig. 5 and Table S2). However, face masks can also be uncomfortable and interfere with communications, and their use can be very unpopular. Interventions like increased ventilation or supplemental air filtration are less obtrusive, do not require occupant cooperation, and generally can be implemented without raising strong objections from the public.

In our room, the diffusers were placed at the front of the room behind the speaker while the ceiling unit with the air return was placed in the center of the room. Our intention was to create an airflow from the speaker toward the participants in order to help protect the speaker from respiratory aerosols emitted by the source. It is instructive to compare our results with those that would be expected based on the commonly-used assumption of a well-mixed room (Eq. (1)). Fig. 6 shows the theoretical reduction in exposure that would be expected in a well-mixed room based on the airflow out of the diffusers (Table 2), and the actual reductions seen during our experiments for the speaker. For the radial diffusers, the reduction in exposure was higher than the well-mixed case when the speaker was in front of the diffusers, but much lower when the speaker was in the dead zone between the radial diffusers. For the square diffusers, which provide more mixing, the exposure reduction is similar to or higher than the theoretical well-mixed case. Thus, it is possible that the exposure reduction was enhanced by the directionality of the airflow for the speaker. For the participants, the differences were inconsistent and less pronounced (Figs. 7 and 8).

It is also of interest to compare the results of this study to our previous studies of portable commercial and do-it-yourself (DIY) air cleaners [12,28,29], which were done in the same room. In the current study, with the simulators in layout B, using the ceiling unit with a single square diffuser reduced the speaker's exposure to respiratory aerosols by 81 %, while using two diffusers reduced exposure by 93 %. In our previous study, with the same layout, using two commercial air cleaners that provided 5.2 ACH total reduced the speaker's exposure by 47 % to 67 % depending upon the locations of the air cleaners [12,28]. In a later study, using two Corsi-Rosenthal DIY air cleaners providing 6.2 to 14.3 ACH reduced the speaker's aerosol exposure by 53 % to 75 % depending upon the filter width, fan model, and fan speed [29]. Thus, the ceiling air filtration unit with the square diffusers reduced the speaker's aerosol exposure more than did the portable air cleaners. For the two meeting participants, the reductions were similar for all three interventions.

One common complaint about portable air cleaners, especially in classrooms, is that they are noisy. The American National Standards Institute (ANSI) recommends that classroom background noise should not exceed 35 dBA [30]. In this study, we found that the ceiling air filtration unit was noticeably quieter than the portable air cleaners. Compared with the portable HEPA air cleaners, the ceiling air filtration unit produced a noise level that was 5.2 dBA lower with two diffusers and 9.4 dBA lower when using one diffuser (Table 3). This is likely because the blower for the ceiling unit is above the ceiling rather than in the room as with a portable air cleaner.

Finally, we must acknowledge that any simulation cannot fully reproduce real-world conditions, and thus our study has several limitations. The simulators were tested in a limited number of layouts and did not move around the room. The simulators were at room temperature and did not exhale warm air that would create a thermal plume, which could influence the airflow pattern and aerosol dispersion [31]. Our study was conducted in a single conference room with its own unique airflow patterns, and different results would likely be seen in different rooms. The room did not contain furniture, which could affect the aerosol dispersion. Our aerosol monitors measured aerosol particles from 0.3 μm to 10 μm in diameter, which is the size range of bioaerosol particles that can remain airborne for longer time but are large enough to carry pathogens. However, humans do produce respiratory aerosol particles across a much broader size range [1,32]. Finally, the transmission of infectious diseases by aerosols is complex and involves numerous factors, many of which are not well understood. Exposure to respiratory aerosols is only one factor, and the reported exposure reductions in this paper should not be directly interpreted as actual reductions in risk of transmission.

5. Conclusions

Supplemental air filtration provides a way to reduce aerosol exposure in indoor spaces and potentially reduce the aerosol transmission of infectious diseases without requiring modifications to the building HVAC system [9]. Portable air cleaners are a common way to add supplemental air filtration to a room, but they may not be the best choice for all settings. Ceiling-mounted HEPA air filtration units offer an alternative means to increase air filtration in a meeting room or classroom. In our case study of a built-in filtration unit in a conference room, the ceiling unit provided as much or more protection against simulated respiratory aerosol particles compared with our previous results with portable air cleaners. The ceiling unit was also quieter than the portable air cleaners and did not occupy floor space or require electrical cords. On the other hand, the ceiling air filtration unit was considerably more expensive than a pair of portable air cleaners and required professional installation, and the unit cannot be moved from room to room as needed. Thus, the choice of a ceiling air filtration unit or portable air cleaners will depend upon the circumstances. In addition, the installation of any supplemental air filtration should be carefully planned and executed, especially if diffusers providing laminar flow are being used.

6. Abbreviations

ACH: Air changes per hour
ANSI: American National Standards Institute
ASHRAE: American Society of Heating, Refrigerating, and Air-conditioning Engineers
CDC: Centers for Disease Control and Prevention
COVID-19: Coronavirus disease 2019
DIY: Do-it-yourself
HEPA: High-efficiency particulate air
HVAC: Heating, ventilation, and air conditioning
KCl: Potassium chloride
MERV: Minimum Efficiency Reporting Value
NIOSH: National Institute for Occupational Safety and Health

OPS: Optical particle sizer
SARS-CoV-2: Severe acute respiratory syndrome coronavirus 2
SD: Standard deviation

7. Disclaimers

The authors declare no competing interests. The findings and conclusions in this report are those of the authors and do not necessarily represent the official position of the National Institute for Occupational Safety and Health (NIOSH), US Centers for Disease Control and Prevention (CDC). Mention of any company or product does not constitute endorsement by NIOSH, CDC.

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CRediT authorship contribution statement

William G. Lindsley: Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Raymond C. Derk:** Writing – review & editing, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Jayme P. Coyle:** Writing – review & editing, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Francoise M. Blachere:** Writing – review & editing, Investigation, Data curation, Conceptualization. **Theresa Boots:** Writing – review & editing, Validation, Methodology, Formal analysis. **Stephen B. Martin:** Writing – review & editing, Supervision, Methodology, Formal analysis, Conceptualization. **Kenneth R. Mead:** Writing – review & editing, Supervision, Methodology, Conceptualization. **John D. Noti:** Writing – review & editing, Supervision, Methodology, Conceptualization.

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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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.buildenv.2025.112611.

Data availability

Experimental data is included in the supplemental materials.

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Reductions in exposures to simulated respiratory aerosols by a ceiling-mounted HEPA air filtration unit

Supplemental information

Figure S1: Radial air supply diffuser.

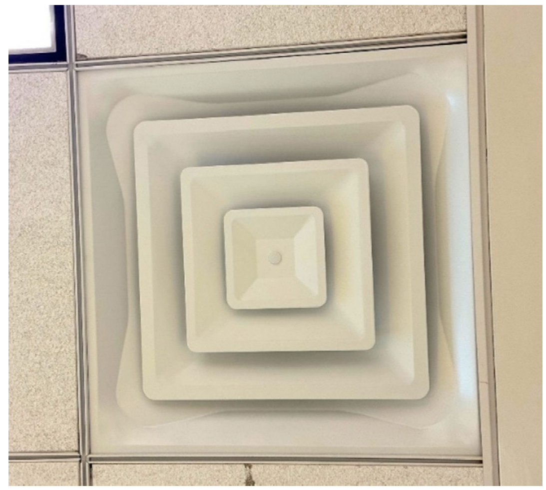

Figure S2: Square cone air supply diffuser.

Figure S3: Air return and HEPA filter.

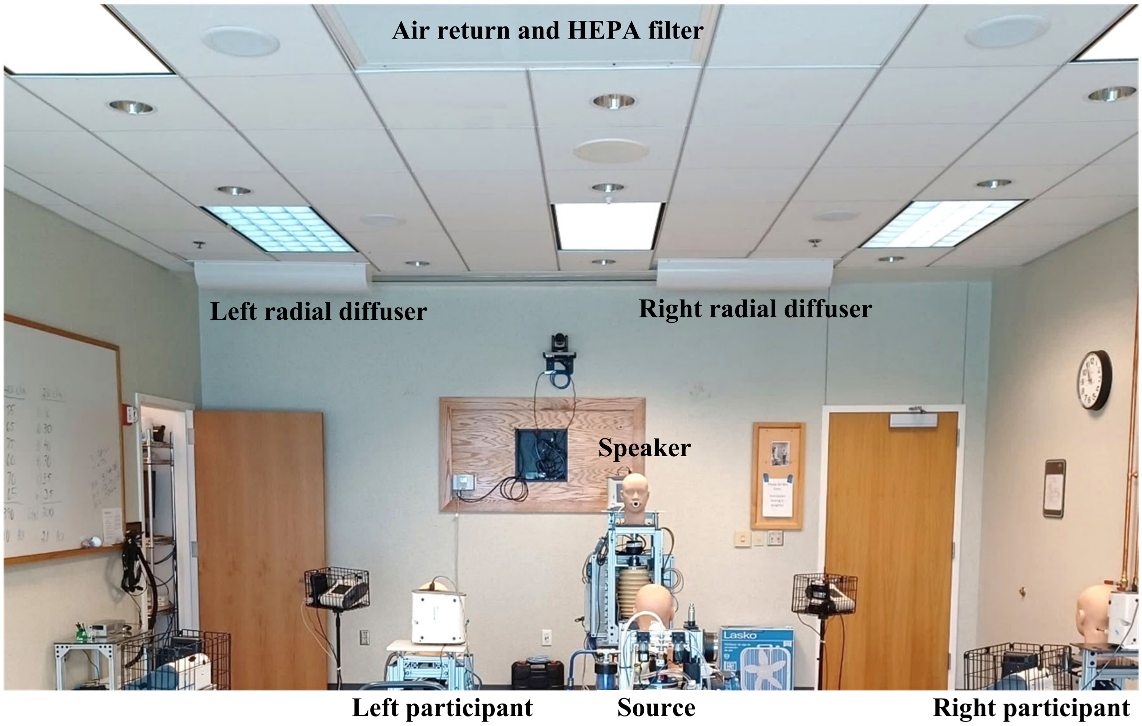

Figure S4: Room layout showing simulators and ceiling air filtration unit with radial diffusers installed.

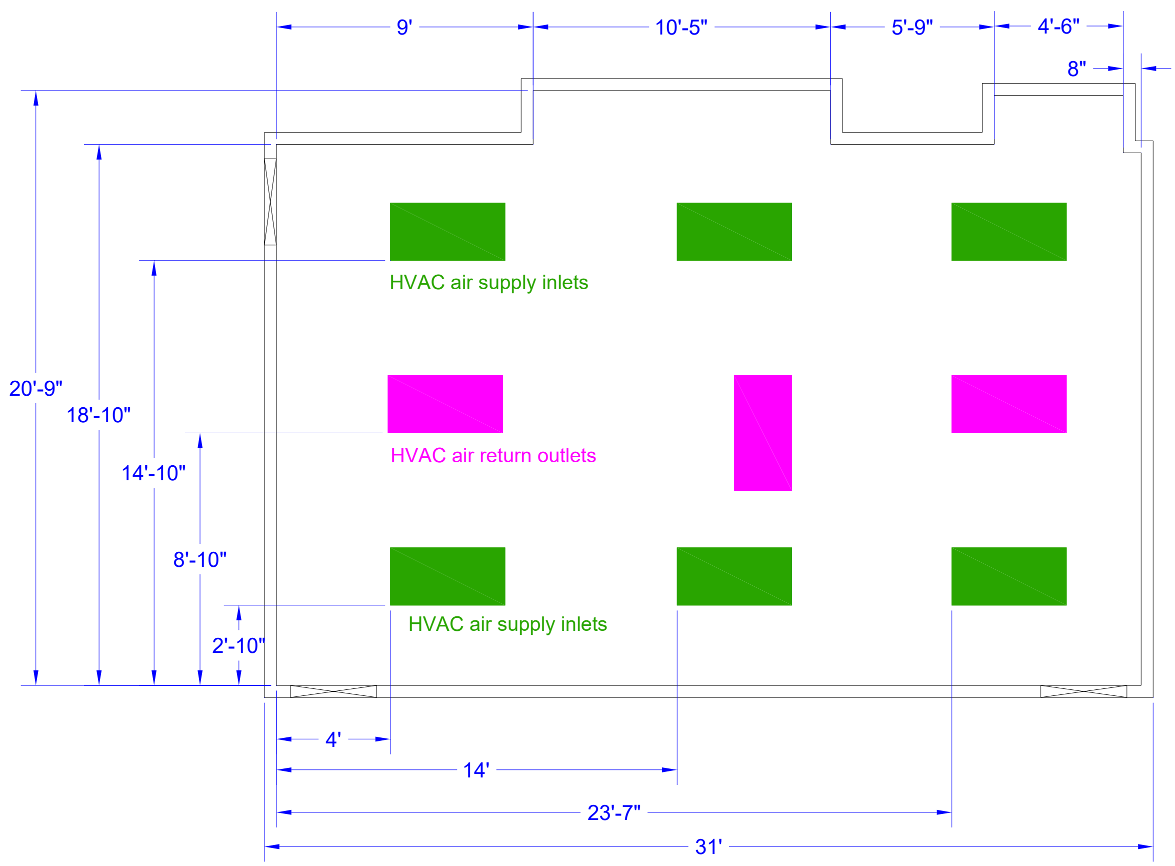

Figure S5: Room layout with dimensions showing HVAC system air supply (green) and return (magenta) locations in the ceiling.

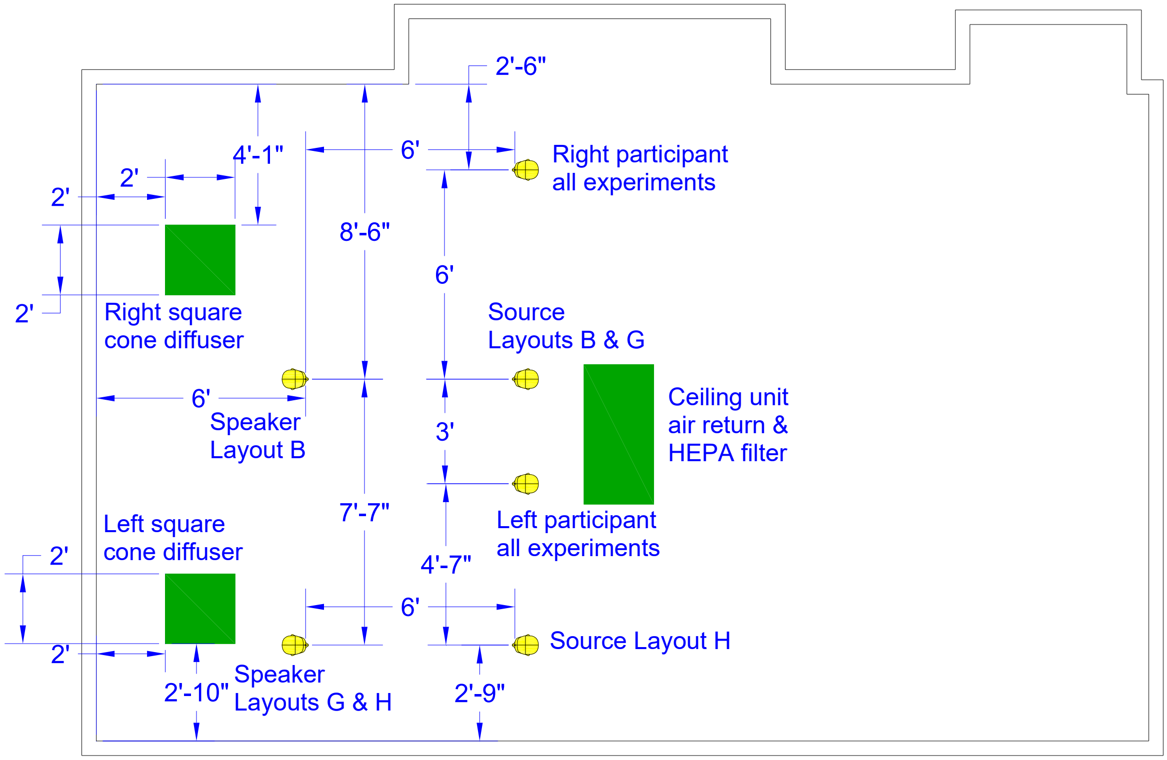

Figure S6: Room layout showing ceiling air filtration unit with square cone diffusers. Yellow heads show the locations of the simulators. Green boxes show the locations of the diffusers and air return for the ceiling air filtration unit. During the COVID-19 pandemic, protecting teachers from infected students was a significant issue, and continues to be of great concern both for seasonal respiratory infections and for future pandemics. The experimental layouts were chosen to represent a scenario like a teacher lecturing at the front of a room and a student in the class with a respiratory infection who was exhaling infectious aerosol particles. Layouts B and H were designed to represent a worst-case scenario where an infected student was expelling aerosol directly at the teacher. The 6-foot (1.8 meter) distance from student to teacher was chosen because that was the recommendation in the United States for physical distancing during the pandemic. Layout B represents a teacher in the center front of the room, and that location was also between the diffusers. Layouts G and H represented a teacher lecturing from the side of the room and directly in front of a diffuser. In layout G, the student was not exhaling directly at the teacher so that we could study how much the relative positions of the teacher and infected student affected the exposure.

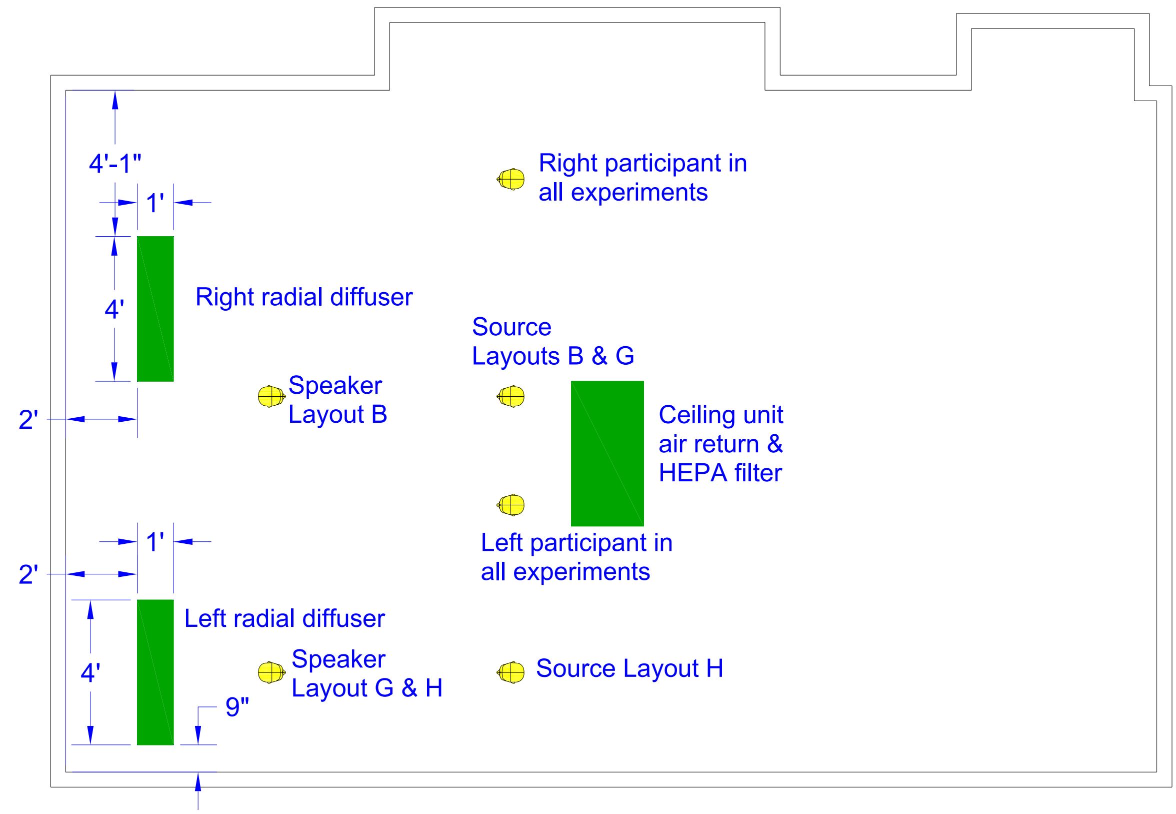

Figure S7: Room layout showing ceiling air filtration unit with radial diffusers.

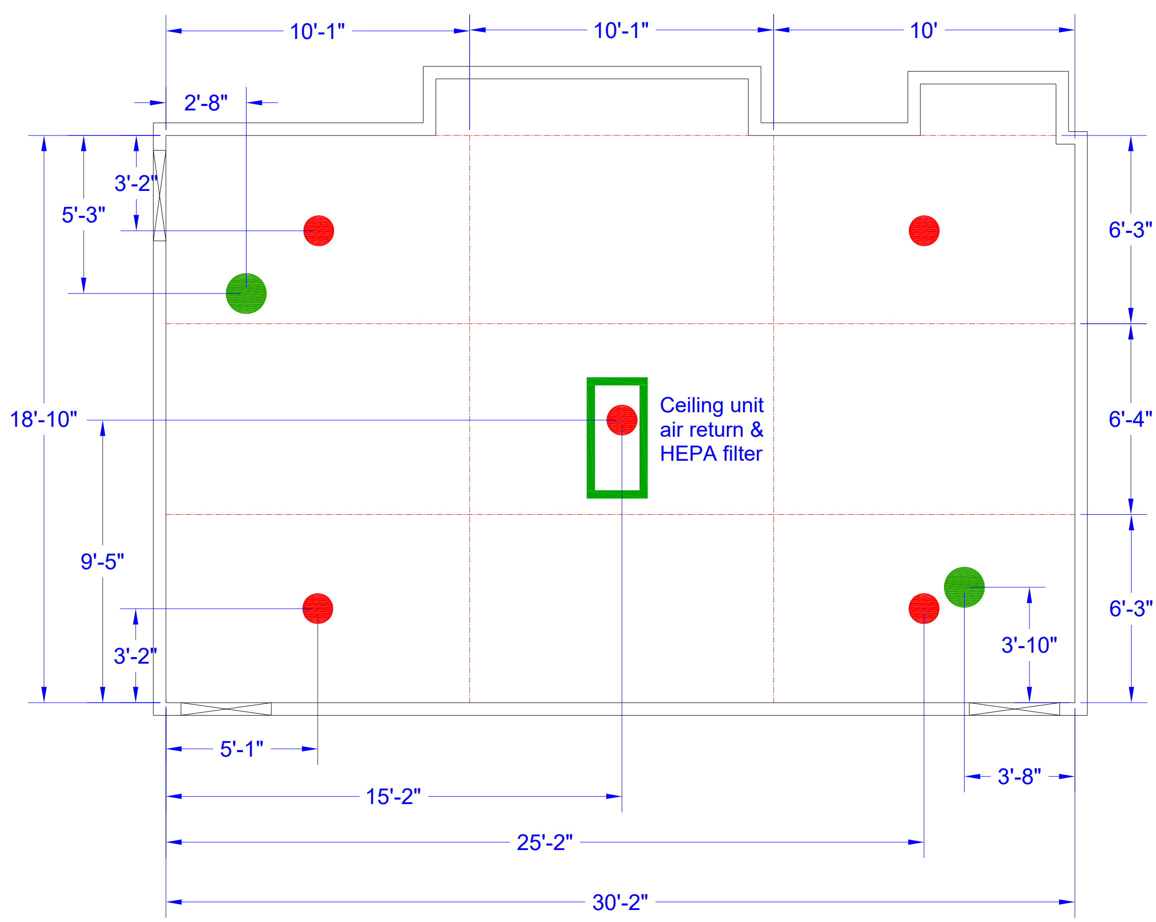

Figure S8: Room layout showing locations of noise dosimeters (red circles), portable HEPA air cleaners (green circles), and ceiling air filtration unit (green rectangle) during noise measurements.

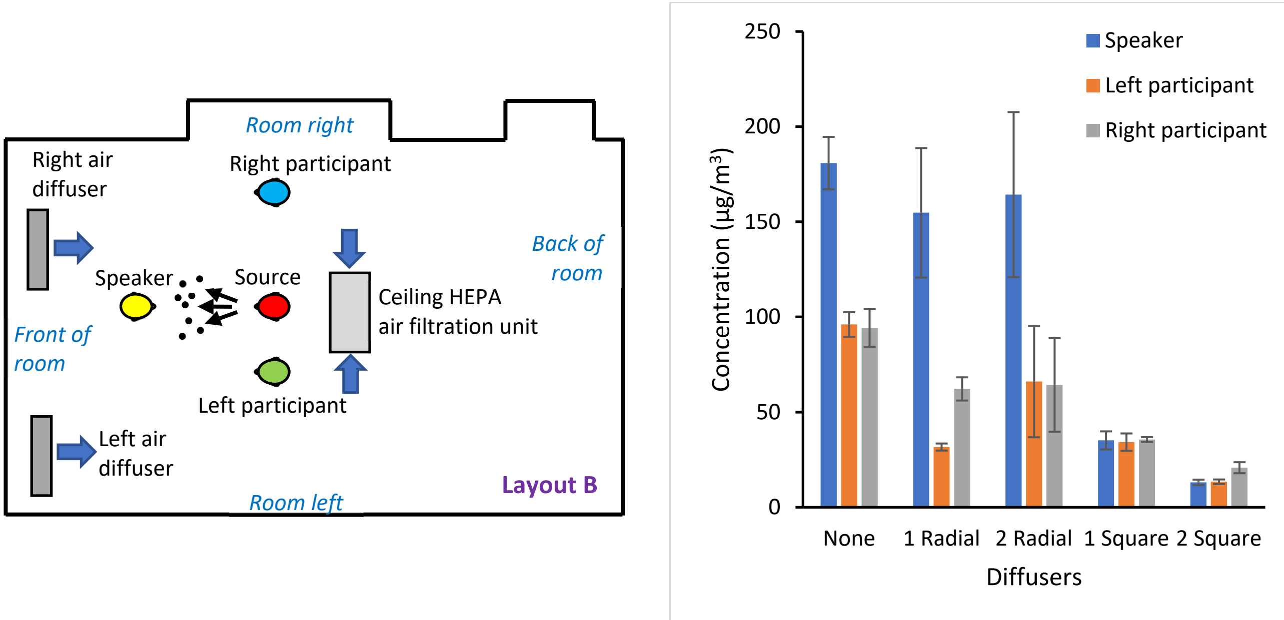

Figure S9: Mean aerosol concentrations for Layout B. Each bar is the mean of four experiments. Error bars indicate the standard deviation.

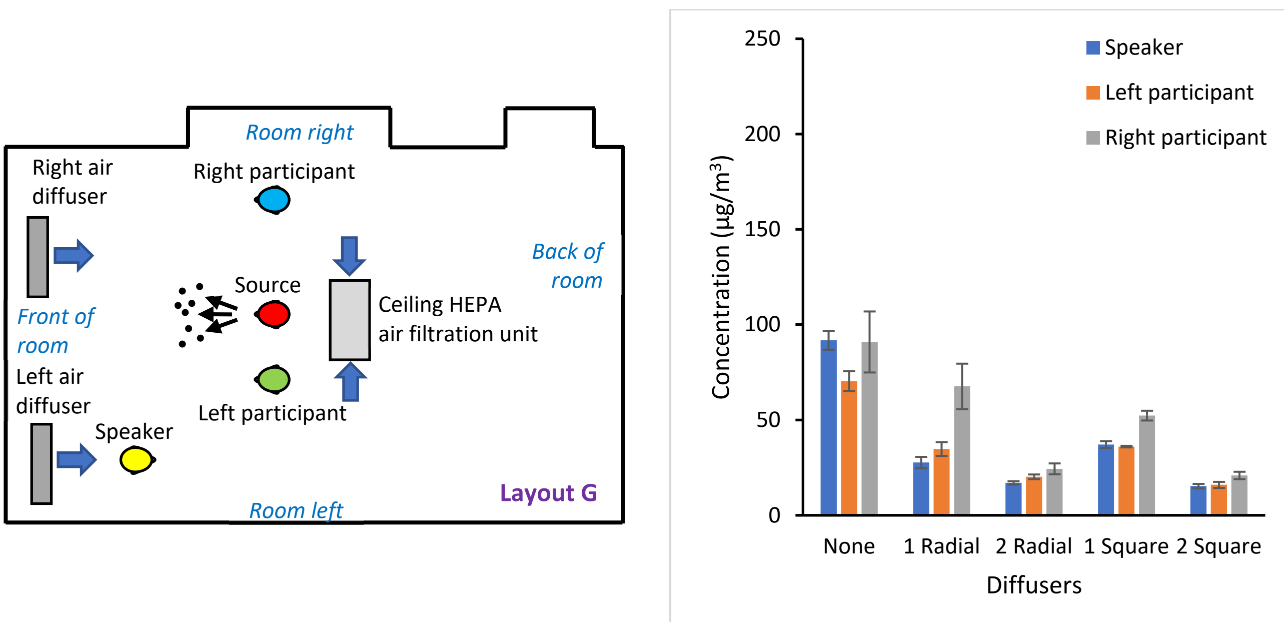

Figure S10: Mean aerosol concentrations for Layout G. Each bar is the mean of four experiments. Error bars indicate the standard deviation.

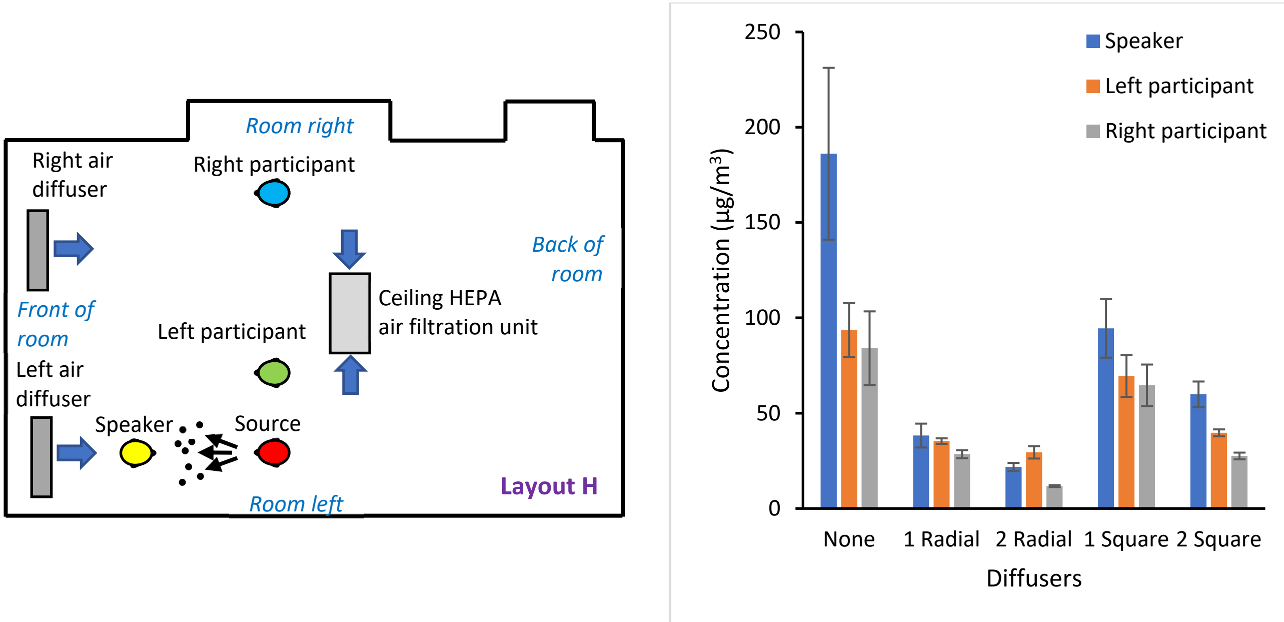

Figure S11: Mean aerosol concentrations for Layout H. Each bar is the mean of four experiments. Error bars indicate the standard deviation.

Table S1: Percentage reduction in aerosol concentration within the personal breathing zone of each simulator for each layout and diffuser combination and with no face masks. The reductions are relative to the control experiments in which the ceiling air filtration unit was off.

	Diffusers	Layout B		Layout G		Layout H	
		Mean	SD	Mean	SD	Mean	SD
Speaker	*1 Radial*	14% (ns)	19.9%	70%	3.6%	79%	6.0%
	2 Radial	9%*	25.0%	81%	1.4%	88%	3.1%
	1 Square	81%	3.0%	60% (ns)	2.9%	49% (ns)	14.8%
	2 Square	93%	1.0%	83%	1.6%	68%	8.6%
Left participant	*1 Radial*	67%	2.9%	51%	6.3%	62%	5.9%
	2 Radial	31% (ns)	30.8%	71%	2.8%	69%	5.9%
	1 Square	64%	5.3%	49%	3.8%	26% (ns)	16.2%
	2 Square	86%	1.6%	77%	2.8%	58%	6.7%
Right participant	*1 Radial*	34%	9.5%	26% (ns)	18.5%	66%	8.2%
	2 Radial	32%	27.1%	73%	5.7%	86%	3.3%
	1 Square	62%	4.2%	42%	10.5%	23% (ns)	21.9%
	2 Square	78%	3.9%	77%	4.6%	67%	7.8%

NS denotes cases where reductions were not statistically significant at p = 0.05.

Table S2: Percentage reduction in aerosol concentration within the personal breathing zone of each simulator for each layout and diffuser combination with face masks worn by all simulators. The reductions are relative to the control experiments in which the ceiling air filtration unit was off and no masks were worn. All reductions were statistically significant at p = 0.05.

	Diffusers	Layout B		Layout G		Layout H	
		Mean	SD	Mean	SD	Mean	SD
Speaker (masked)	*Not used*	89%	2.1%	84%	3.4%	84%	4.3%
	1 Radial	93%	1.5%	94%	1.8%	95%	1.5%
	2 Radial	98%	0.9%	98%	0.7%	97%	0.9%
	1 Square	97%	0.4%	92%	1.2%	87%	3.3%
	2 Square	99%	0.2%	96%	0.7%	92%	3.1%
Left participant (masked)	*Not used*	80%	4.3%	78%	3.1%	80%	4.1%
	1 Radial	91%	1.4%	89%	2.3%	88%	2.4%
	2 Radial	97%	0.2%	95%	1.7%	90%	2.2%
	1 Square	95%	0.8%	91%	1.8%	84%	2.8%
	2 Square	97%	0.2%	94%	1.1%	91%	3.2%
Right participant (masked)	*Not used*	79%	3.6%	86%	3.7%	78%	5.3%
	1 Radial	86%	2.4%	85%	4.1%	93%	1.8%
	2 Radial	97%	0.5%	97%	1.3%	96%	1.0%
	1 Square	95%	0.6%	93%	2.2%	88%	3.1%
	2 Square	96%	0.7%	96%	1.2%	95%	2.0%

Definition of Breathing Zone

The aerosol samples were collected from within the personal breathing zones of the speaker and participant simulators. In the industrial hygiene field, the term breathing zone is used to refer to the region in close proximity to the nose and mouth from which a person inhales and is used in the context of personal exposure to airborne materials. For example, NIOSH defines the breathing zone as "a hemisphere of radius 0.3 m extending in front of the human face, centered on the midpoint of a line joining the ears; the base of the hemisphere is a plane through this line, the top of the head and the larynx" [1]. However, in the building ventilation field, it is common to describe the breathing zone as the region in an entire room that is within certain heights and distances from the wall; in this case, the term "breathing zone" is being used in the context of overall indoor air quality. For example, ASHRAE defines the breathing zone as "a region within the dwelling-unit habitable space between planes 3 and 72 inches (75 and 1800 mm) above the floor and more than 2 feet (600 mm) from the walls or fixed air-conditioning equipment" [2]. For this study, we are using breathing zone in the industrial hygiene sense and we refer to it as the "personal breathing zone" to emphasize that we mean the region immediately around the nose and mouth of a person.

Fit factor

The manikin fit factor [3] was measured by performing a respirator fit test [4] for each device using a respirator fit tester (PortaCount® Pro+ Model 8038, TSI, Shoreview, MN). The PortaCount was used in Class 100 mode (also called N99 mode), in which the tester measures the concentration of aerosol particles from 0.02 to 1.0 µm at the mouth of the headform (inside the mask) and in the ambient air (outside the device) [5, 6]. The aerosol samples at the mouth of the headform were collected through a sampling port in the headform; thus, it was not necessary to install a sample port in the source control device as is done when performing fit tests with people. The fit factor (FF) was calculated as [5, 7]:

$$FF = \frac{C_B + C_A}{2C_R}$$

Where:

C_B = particle concentration in an ambient aerosol sample collected before the mask sample was taken.

C_A = particle concentration in an ambient aerosol sample collected after the mask sample was taken.

C_R = particle concentration in the aerosol sample collected at the mouth inside the mask.

The fit factor is normally used to determine how well a respiratory protective device fits the wearer by measuring the degree to which aerosol particles can enter through gaps between the wearer's face and the respirator (face seal leaks). It is determined by placing the device on a person or on a manikin headform and measuring the ratio of the aerosol concentration outside the respirator to the aerosol concentration inside the respirator [3]. For example, a fit factor of 10 means that the ambient aerosol concentration is 10 times higher than the concentration inside the respirator. Fit factor measurements are not intended to test the filtration efficiency of the device itself. In fact, the calculation of the fit factor for a respirator assumes that any ambient aerosol particles passing through respirator material are filtered out and that any particles detected inside the respirator are due to face seal leaks, not penetration of particles through the filter material [8]. For example, a fit factor of 10 is interpreted as indicating that 90% of the air inside the respirator has passed through the respirator filtration media (with aerosol particles being completely removed) and that 10% of the air bypassed the media and entered through face seal leaks.

It is important to note, however, that this assumption is not correct when using the fit tester with cloth masks. The filtration efficiencies of most cloth masks are much lower than those of respirators, and ambient particles therefore can penetrate more easily through the cloth material. Thus, the fit factor for a cloth mask is not a true measurement of face seal leakage alone; instead, it represents a combination of face seal leakage and particle penetration through the mask material [9].

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Table S3: Experimental data dictionary

Field name on data page	Field definition
Experiment	Identification number of the experiment.
Location	Positions of simulators
Masking	Indicates whether face masks were worm by simulators during experiment
Diffusers	Indicates which type of air supply diffusers and how many were in operation during the experiment
Speaker	Mean aerosol mass concentration in the breathing zone of the speaker simulator during the experiment minus the background concentration, in µg/m3
Left_participant	Mean aerosol mass concentration in the breathing zone of the left participant simulator during the experiment minus the background concentration, in µg/m3
Right_participant	Mean aerosol mass concentration in the breathing zone of the right participant simulator during the experiment minus the background concentration, in µg/m3
Source_Fit	Fit factor measured for cloth mask worn by source simulator. NA indicates that a mask was not used for this experiment.
Speaker_Fit	Fit factor measured for cloth mask worn by speaker simulator.
Left_Fit	Fit factor measured for cloth mask worn by left participant simulator.
Right_Fit	Fit factor measured for cloth mask worn by right participant simulator.

Table S4: Experimental data

Experiment	Layout	Masking	Diffusers	Speaker	Left_participant	Right_participant	Source_Fit	Speaker_Fit	Left_Fit	Right_Fit
NC-SC-KCL-001	B	None	Not_Used	182.538	95.028	101.381	NA	NA	NA	NA
NC-SC-KCL-002	B	None	Not_Used	191.142	105.485	104.11	NA	NA	NA	NA
NC-SC-KCL-004	B	None	Not_Used	188.782	90.722	84.092	NA	NA	NA	NA
NC-SC-KCL-005	B	None	Not_Used	160.89	93.007	87.546	NA	NA	NA	NA
NC-SC-KCL-006	B	Masked	Not_Used	23.97	23.403	22.975	2.0	4.3	4.3	3.8
NC-SC-KCL-007	B	Masked	Not_Used	22.06	20.569	21.052	2.0	4.3	4.3	3.8
NC-SC-KCL-008	B	Masked	Not_Used	17.614	15.209	18.856	1.7	4.3	4.3	3.8
NC-SC-KCL-009	B	Masked	Not_Used	16.87	15.881	16.762	1.7	4.3	4.3	3.8
NC-SC-KCL-010	B	None	Radial_2	182.779	25.048	27.723	NA	NA	NA	NA
NC-SC-KCL-011	B	None	Radial_2	168.028	76.006	79.999	NA	NA	NA	NA
NC-SC-KCL-012	B	None	Radial_2	203.394	69.343	71.562	NA	NA	NA	NA
NC-SC-KCL-013	B	None	Radial_2	103.021	93.817	77.817	NA	NA	NA	NA
NC-SC-KCL-014	B	Masked	Radial_2	6.026	3.185	3.001	1.9	3.5	4.8	4.5
NC-SC-KCL-015	B	Masked	Radial_2	3.227	2.992	2.917	3.0	3.5	4.8	4.5
NC-SC-KCL-016	B	Masked	Radial_2	2.478	2.925	2.581	3.0	3.5	4.8	4.5
NC-SC-KCL-017	B	Masked	Radial_2	4.055	3.011	3.336	1.5	3.5	4.8	4.5
NC-SC-KCL-018	B	None	Radial_1	105.279	29.44	69.483	NA	NA	NA	NA
NC-SC-KCL-019	B	None	Radial_1	162.515	32.385	63.852	NA	NA	NA	NA
NC-SC-KCL-020	B	None	Radial_1	182.205	33.762	60.773	NA	NA	NA	NA
NC-SC-KCL-021	B	None	Radial_1	168.962	31.141	54.801	NA	NA	NA	NA
NC-SC-KCL-022	B	Masked	Radial_1	13.219	10.811	13.921	1.4	3.6	3.9	3.8
NC-SC-KCL-023	B	Masked	Radial_1	11.579	8.627	13.386	1.4	3.6	3.9	3.8
NC-SC-KCL-024	B	Masked	Radial_1	16.592	7.971	15.655	1.4	3.6	3.9	3.8
NC-SC-KCL-025	B	Masked	Radial_1	10.69	8.575	11.362	1.4	3.6	3.9	3.8
NC-SC-KCL-026	G	Masked	Not_Used	18.831	17.214	16.188	1.4	3.6	3.9	3.8
NC-SC-KCL-027	G	Masked	Not_Used	15.716	14.405	11.287	1.4	2.7	2.8	2.5
NC-SC-KCL-028	G	Masked	Not_Used	14.032	16.496	13.928	1.4	2.7	2.8	2.5
NC-SC-KCL-029	G	Masked	Not_Used	11.692	13.147	11.011	1.4	2.7	2.8	2.5
NC-SC-KCL-030	G	None	Not_Used	95.649	74.341	86.497	NA	NA	NA	NA
NC-SC-KCL-031	G	None	Not_Used	87.031	62.761	114.41	NA	NA	NA	NA

NC-SC-KCL-032	G	None	Not_Used	96.458	72.963	78.695	NA	NA	NA	NA
NC-SC-KCL-033	G	None	Not_Used	88.009	71.412	84.2	NA	NA	NA	NA
NC-SC-KCL-034	G	None	Radial_1	29.234	36.628	54.727	NA	NA	NA	NA
NC-SC-KCL-035	G	None	Radial_1	30.818	38.374	82.565	NA	NA	NA	NA
NC-SC-KCL-036	G	None	Radial_1	24.071	30.123	62.312	NA	NA	NA	NA
NC-SC-KCL-037	G	None	Radial_1	26.567	34.022	70.958	NA	NA	NA	NA
NC-SC-KCL-038	G	Masked	Radial_1	6.87	8.968	16	1.9	4.0	2.5	3.8
NC-SC-KCL-039	G	Masked	Radial_1	5.824	8.107	14.669	1.9	4.0	2.5	3.8
NC-SC-KCL-040	G	Masked	Radial_1	5.351	8.132	13.731	2.0	4.0	2.5	3.8
NC-SC-KCL-041	G	Masked	Radial_1	3.094	5.555	9.205	2.0	4.0	2.5	3.8
NC-SC-KCL-042	G	None	Radial_2	17.76	18.696	21.539	NA	NA	NA	NA
NC-SC-KCL-043	G	None	Radial_2	15.906	19.881	22.835	NA	NA	NA	NA
NC-SC-KCL-044	G	None	Radial_2	16.813	20.907	24.973	NA	NA	NA	NA
NC-SC-KCL-045	G	None	Radial_2	17.766	21.483	28.104	NA	NA	NA	NA
NC-SC-KCL-046	G	Masked	Radial_2	1.405	2.329	2.095	1.3	2.7	2.4	2.0
NC-SC-KCL-047	G	Masked	Radial_2	1.468	2.312	2.001	1.3	2.7	2.4	2.0
NC-SC-KCL-048	G	Masked	Radial_2	2.675	4.811	4.289	1.5	2.7	2.4	2.0
NC-SC-KCL-049	G	Masked	Radial_2	2.096	3.388	2.565	1.5	2.7	2.4	2.0
NC-SC-KCL-050	H	None	Not_Used	225.845	102.341	79.778	NA	NA	NA	NA
NC-SC-KCL-051	H	None	Not_Used	200.623	80.638	112.258	NA	NA	NA	NA
NC-SC-KCL-052	H	None	Not_Used	196.618	108.763	68.719	NA	NA	NA	NA
NC-SC-KCL-053	H	None	Not_Used	121.421	82.559	75.72	NA	NA	NA	NA
NC-SC-KCL-054	H	Masked	Not_Used	31.069	20.533	18.187	1.3	3.1	2.7	2.3
NC-SC-KCL-055	H	Masked	Not_Used	29.804	18.171	18.051	1.3	3.1	2.7	2.3
NC-SC-KCL-056	H	Masked	Not_Used	32.898	21.639	20.318	1.4	3.1	2.7	2.3
NC-SC-KCL-057	H	Masked	Not_Used	25.102	16.12	16.396	1.4	3.1	2.7	2.3
NC-SC-KCL-058	H	Masked	Radial_2	5.341	11.284	3.517	1.8	3.9	4.5	2.3
NC-SC-KCL-059	H	Masked	Radial_2	6.248	9.303	2.855	1.8	3.9	4.5	2.3
NC-SC-KCL-060	H	Masked	Radial_2	4.223	10.338	3.016	1.5	3.9	4.5	2.3
NC-SC-KCL-061	H	Masked	Radial_2	3.846	7.763	2.426	1.5	3.9	4.5	2.3
NC-SC-KCL-062	H	None	Radial_2	22.265	26.619	11.201	NA	NA	NA	NA
NC-SC-KCL-063	H	None	Radial_2	24.575	28.858	11.909	NA	NA	NA	NA

NC-SC-KCL-064	H	None	Radial_2	19.62	34.073	12.406	NA	NA	NA	NA
NC-SC-KCL-065	H	None	Radial_2	20.786	28.306	11.592	NA	NA	NA	NA
NC-SC-KCL-066	H	None	Radial_1	37.63	33.757	28.239	NA	NA	NA	NA
NC-SC-KCL-067	H	None	Radial_1	43.962	34.641	29.89	NA	NA	NA	NA
NC-SC-KCL-068	H	None	Radial_1	41.824	36.405	30.324	NA	NA	NA	NA
NC-SC-KCL-069	H	None	Radial_1	29.713	36.784	25.679	NA	NA	NA	NA
NC-SC-KCL-070	H	Masked	Radial_1	10.062	12.601	6.764	1.3	2.8	2.3	2.6
NC-SC-KCL-071	H	Masked	Radial_1	11.079	11.353	6.437	1.3	2.8	2.3	2.6
NC-SC-KCL-072	H	Masked	Radial_1	7.438	10.266	5.853	1.3	2.8	2.3	2.6
NC-SC-KCL-073	H	Masked	Radial_1	8.097	8.937	5.718	1.3	2.8	2.3	2.6
NC-SC-KCL-074	H	None	Square_1	95.769	73.979	65.822	NA	NA	NA	NA
NC-SC-KCL-075	H	None	Square_1	100.684	73.31	67.907	NA	NA	NA	NA
NC-SC-KCL-076	H	None	Square_1	108.676	77.669	75.347	NA	NA	NA	NA
NC-SC-KCL-077	H	None	Square_1	72.954	53.295	49.502	NA	NA	NA	NA
NC-SC-KCL-078	H	Masked	Square_1	22.729	14.035	9.974	1.5	2.6	2.2	2.9
NC-SC-KCL-079	H	Masked	Square_1	21.16	13.471	9.557	1.5	2.6	2.2	2.9
NC-SC-KCL-080	H	Masked	Square_1	26.764	16.786	11.961	1.6	2.6	2.2	2.9
NC-SC-KCL-081	H	Masked	Square_1	23.646	14.34	10.1	1.6	2.6	2.2	2.9
NC-SC-KCL-083	H	Masked	2_Square	11.342	7.502	4.043	1.2	3.5	2.9	4.1
NC-SC-KCL-084	H	Masked	2_Square	9.376	5.741	3.096	1.2	3.5	2.9	4.1
NC-SC-KCL-085	H	Masked	2_Square	18.515	11.231	5.761	1.6	3.5	2.9	4.1
NC-SC-KCL-086	H	Masked	2_Square	17.889	10.864	5.547	1.6	3.5	2.9	4.1
NC-SC-KCL-087	H	None	2_Square	51.202	37.869	26.203	NA	NA	NA	NA
NC-SC-KCL-088	H	None	2_Square	58.964	39.488	26.123	NA	NA	NA	NA
NC-SC-KCL-089	H	None	2_Square	62.532	39.378	28.25	NA	NA	NA	NA
NC-SC-KCL-090	H	None	2_Square	67.106	42.2	29.791	NA	NA	NA	NA
NC-SC-KCL-091	G	None	2_Square	14.058	13.731	19.061	NA	NA	NA	NA
NC-SC-KCL-092	G	None	2_Square	14.673	16.103	20.238	NA	NA	NA	NA
NC-SC-KCL-093	G	None	2_Square	15.846	16.985	20.853	NA	NA	NA	NA
NC-SC-KCL-094	G	None	2_Square	16.73	17.144	23.557	NA	NA	NA	NA
NC-SC-KCL-095	G	Masked	2_Square	3.696	4.065	3.846	1.1	3.1	2.6	3.7
NC-SC-KCL-096	G	Masked	2_Square	3.209	3.549	3.102	1.1	3.1	2.6	3.7

NC-SC-KCL-097	G	Masked	2_Square	4.615	5.224	4.891	1.6	3.1	2.6	3.7
NC-SC-KCL-098	G	Masked	2_Square	3.957	4.395	4.428	1.6	3.1	2.6	3.7
NC-SC-KCL-099	G	Masked	Square_1	8.468	7.92	8.591	1.7	2.9	3.1	4.2
NC-SC-KCL-100	G	Masked	Square_1	7.716	6.776	5.524	1.7	2.9	3.1	4.2
NC-SC-KCL-101	G	Masked	Square_1	7.437	6.366	5.926	1.0	2.9	3.1	4.2
NC-SC-KCL-102	G	Masked	Square_1	6.042	5.089	4.65	1.0	2.9	3.1	4.2
NC-SC-KCL-103	G	None	Square_1	34.733	35.448	51.063	NA	NA	NA	NA
NC-SC-KCL-104	G	None	Square_1	36.903	36.003	50.458	NA	NA	NA	NA
NC-SC-KCL-105	G	None	Square_1	38.001	36.431	56.127	NA	NA	NA	NA
NC-SC-KCL-106	G	None	Square_1	38.868	36.204	51.607	NA	NA	NA	NA
NC-SC-KCL-115	B	None	Square_1	31.562	31.145	35.519	NA	NA	NA	NA
NC-SC-KCL-116	B	None	Square_1	31.293	29.592	37.46	NA	NA	NA	NA
NC-SC-KCL-117	B	None	Square_1	41.207	38.02	34.98	NA	NA	NA	NA
NC-SC-KCL-118	B	None	Square_1	36.647	38.301	34.536	NA	NA	NA	NA
NC-SC-KCL-119	B	Masked	Square_1	5.96	5.993	5.061	1.6	3.2	3.1	2.2
NC-SC-KCL-120	B	Masked	Square_1	4.921	4.974	4.223	1.6	3.2	3.1	2.2
NC-SC-KCL-121	B	Masked	Square_1	4.609	4.502	4.47	1.5	3.2	3.1	2.2
NC-SC-KCL-122	B	Masked	Square_1	5.349	5.415	4.636	1.5	3.2	3.1	2.2
NC-SC-KCL-123	B	Masked	2_Square	2.359	2.656	3.203	1.3	2.7	3.1	2.6
NC-SC-KCL-124	B	Masked	2_Square	2.307	2.711	3.161	1.3	2.7	3.1	2.6
NC-SC-KCL-125	B	Masked	2_Square	2.699	2.522	4.344	1.2	2.7	3.1	2.6
NC-SC-KCL-126	B	Masked	2_Square	2.177	2.42	3.182	1.2	2.7	3.1	2.6
NC-SC-KCL-127	B	None	2_Square	12.433	12.984	18.885	NA	NA	NA	NA
NC-SC-KCL-128	B	None	2_Square	12.966	14.282	20.255	NA	NA	NA	NA
NC-SC-KCL-129	B	None	2_Square	15.153	14.552	25.058	NA	NA	NA	NA
NC-SC-KCL-130	B	None	2_Square	11.875	11.946	18.985	NA	NA	NA	NA

Table S5: Overall p-values for statistical analysis. In all cases, Diffusers*Masking was significant, indicating that looking at pairwise comparisons is acceptable.

Simulator	Layout		Df	Sum Sq	Mean Sq	F value	Pr(>F)
Speaker	B	Diffusers	4	1717	429.25	58.14	1.056E-13
		Masking	1	3132.9	3132.90	424.32	2.951E-19
		Diffusers:Masking	4	258.6	64.65	8.76	8.293E-05
		Residuals	30	221.5	7.38		
	G	Diffusers	4	1457	364.25	65.83	2.029E-14
		Masking	1	3610	3610.00	652.41	6.532E-22
		Diffusers:Masking	4	97	24.25	4.38	6.567E-03
		Residuals	30	166	5.53		
	H	Diffusers	4	2288.25	572.06	144.83	3.697E-19
		Masking	1	2856.1	2856.10	723.06	1.487E-22
		Diffusers:Masking	4	67.15	16.79	4.25	7.643E-03
		Residuals	30	118.5	3.95		
Left participant	B	Diffusers	4	1575.25	393.81	68.89	1.103E-14
		Masking	1	3385.6	3385.60	592.23	2.614E-21
		Diffusers:Masking	4	197.65	49.41	8.64	9.155E-05
		Residuals	30	171.5	5.72		
	G	Diffusers	4	1357	339.25	62.44	4.105E-14
		Masking	1	3724.9	3724.90	685.56	3.203E-22
		Diffusers:Masking	4	85.1	21.28	3.92	1.127E-02
		Residuals	30	163	5.43		
	H	Diffusers	4	1065.25	266.31	46.59	1.877E-12
		Masking	1	4000	4000.00	699.71	2.387E-22
		Diffusers:Masking	4	93.25	23.31	4.08	9.324E-03
		Residuals	30	171.5	5.72		
Right participant	B	Diffusers	4	1130.75	282.69	46.98	1.683E-12
		Masking	1	3763.6	3763.60	625.53	1.195E-21
		Diffusers:Masking	4	255.15	63.79	10.60	1.781E-05
		Residuals	30	180.5	6.02		
	G	Diffusers	4	1142.25	285.56	63.93	2.997E-14
		Masking	1	4000	4000.00	895.52	6.722E-24
		Diffusers:Masking	4	53.75	13.44	3.01	3.363E-02
		Residuals	30	134	4.47		
	H	Diffusers	4	1873.25	468.31	114.69	9.973E-18
		Masking	1	3276.1	3276.10	802.31	3.310E-23
		Diffusers:Masking	4	58.15	14.54	3.56	1.718E-02
		Residuals	30	122.5	4.08		

Table S6: Pairwise comparisons of diffusers and masking for speaker.

Simulator	Layout	Diffuser 1	Mask 1	Diffuser 2	Mask 2	diff	lower bound	upper bound	adjusted p-value
Speaker	B	Radial_1	Masked	Not_used	Masked	-6.250	-12.804	0.304	0.071
Speaker	G	Radial_1	Masked	Not_used	Masked	-11.250	-16.924	-5.576	0.000
Speaker	H	Radial_1	Masked	Not_used	Masked	-16.000	-20.794	-11.206	0.000
Speaker	B	Radial_2	Masked	Not_used	Masked	-15.250	-21.804	-8.696	0.000
Speaker	G	Radial_2	Masked	Not_used	Masked	-18.500	-24.174	-12.826	0.000
Speaker	H	Radial_2	Masked	Not_used	Masked	-20.500	-25.294	-15.706	0.000
Speaker	B	Radial_2	Masked	Radial_1	Masked	-9.000	-15.554	-2.446	0.002
Speaker	G	Radial_2	Masked	Radial_1	Masked	-7.250	-12.924	-1.576	0.005
Speaker	H	Radial_2	Masked	Radial_1	Masked	-4.500	-9.294	0.294	0.080
Speaker	B	Radial_2	Masked	Square_1	Masked	-2.250	-8.804	4.304	0.971
Speaker	G	Radial_2	Masked	Square_1	Masked	-11.750	-17.424	-6.076	0.000
Speaker	H	Radial_2	Masked	Square_1	Masked	-15.250	-20.044	-10.456	0.000
Speaker	B	Square_1	Masked	Not_used	Masked	-13.000	-19.554	-6.446	0.000
Speaker	G	Square_1	Masked	Not_used	Masked	-6.750	-12.424	-1.076	0.010
Speaker	H	Square_1	Masked	Not_used	Masked	-5.250	-10.044	-0.456	0.023
Speaker	B	Square_1	Masked	Radial_1	Masked	-6.750	-13.304	-0.196	0.039
Speaker	G	Square_1	Masked	Radial_1	Masked	4.500	-1.174	10.174	0.217
Speaker	H	Square_1	Masked	Radial_1	Masked	10.750	5.956	15.544	0.000
Speaker	B	Square_2	Masked	Not_used	Masked	-19.750	-26.304	-13.196	0.000
Speaker	G	Square_2	Masked	Not_used	Masked	-13.500	-19.174	-7.826	0.000
Speaker	H	Square_2	Masked	Not_used	Masked	-13.000	-17.794	-8.206	0.000
Speaker	B	Square_2	Masked	Radial_1	Masked	-13.500	-20.054	-6.946	0.000
Speaker	G	Square_2	Masked	Radial_1	Masked	-2.250	-7.924	3.424	0.932
Speaker	H	Square_2	Masked	Radial_1	Masked	3.000	-1.794	7.794	0.519
Speaker	B	Square_2	Masked	Radial_2	Masked	-4.500	-11.054	2.054	0.393
Speaker	G	Square_2	Masked	Radial_2	Masked	5.000	-0.674	10.674	0.121
Speaker	H	Square_2	Masked	Radial_2	Masked	7.500	2.706	12.294	0.000
Speaker	B	Square_2	Masked	Square_1	Masked	-6.750	-13.304	-0.196	0.039
Speaker	G	Square_2	Masked	Square_1	Masked	-6.750	-12.424	-1.076	0.010
Speaker	H	Square_2	Masked	Square_1	Masked	-7.750	-12.544	-2.956	0.000
Speaker	B	Not_used	Masked	Not_used	NoMask	-13.500	-20.054	-6.946	0.000
Speaker	G	Not_used	Masked	Not_used	NoMask	-17.500	-23.174	-11.826	0.000
Speaker	H	Not_used	Masked	Not_used	NoMask	-15.500	-20.294	-10.706	0.000
Speaker	B	Not_used	Masked	Radial_1	NoMask	-10.250	-16.804	-3.696	0.000
Speaker	G	Not_used	Masked	Radial_1	NoMask	-9.500	-15.174	-3.826	0.000
Speaker	H	Not_used	Masked	Radial_1	NoMask	-2.750	-7.544	2.044	0.633
Speaker	B	Not_used	Masked	Radial_2	NoMask	-12.250	-18.804	-5.696	0.000
Speaker	G	Not_used	Masked	Radial_2	NoMask	-4.250	-9.924	1.424	0.281
Speaker	H	Not_used	Masked	Radial_2	NoMask	7.500	2.706	12.294	0.000
Speaker	B	Not_used	Masked	Square_1	NoMask	-4.000	-10.554	2.554	0.553
Speaker	G	Not_used	Masked	Square_1	NoMask	-13.500	-19.174	-7.826	0.000

Speaker	H	Not_used	Masked	Square_1	NoMask	-11.500	-16.294	-6.706	0.000
Speaker	B	Not_used	Masked	Square_2	NoMask	5.750	-0.804	12.304	0.124
Speaker	G	Not_used	Masked	Square_2	NoMask	-0.250	-5.924	5.424	1.000
Speaker	H	Not_used	Masked	Square_2	NoMask	-7.500	-12.294	-2.706	0.000
Speaker	B	Radial_1	Masked	Not_used	NoMask	-19.750	-26.304	-13.196	0.000
Speaker	G	Radial_1	Masked	Not_used	NoMask	-28.750	-34.424	-23.076	0.000
Speaker	H	Radial_1	Masked	Not_used	NoMask	-31.500	-36.294	-26.706	0.000
Speaker	B	Radial_1	Masked	Radial_1	NoMask	-16.500	-23.054	-9.946	0.000
Speaker	G	Radial_1	Masked	Radial_1	NoMask	-20.750	-26.424	-15.076	0.000
Speaker	H	Radial_1	Masked	Radial_1	NoMask	-18.750	-23.544	-13.956	0.000
Speaker	B	Radial_1	Masked	Radial_2	NoMask	-18.500	-25.054	-11.946	0.000
Speaker	G	Radial_1	Masked	Radial_2	NoMask	-15.500	-21.174	-9.826	0.000
Speaker	H	Radial_1	Masked	Radial_2	NoMask	-8.500	-13.294	-3.706	0.000
Speaker	B	Radial_1	Masked	Square_1	NoMask	-10.250	-16.804	-3.696	0.000
Speaker	G	Radial_1	Masked	Square_1	NoMask	-24.750	-30.424	-19.076	0.000
Speaker	H	Radial_1	Masked	Square_1	NoMask	-27.500	-32.294	-22.706	0.000
Speaker	B	Radial_1	Masked	Square_2	NoMask	-0.500	-7.054	6.054	1.000
Speaker	G	Radial_1	Masked	Square_2	NoMask	-11.500	-17.174	-5.826	0.000
Speaker	H	Radial_1	Masked	Square_2	NoMask	-23.500	-28.294	-18.706	0.000
Speaker	B	Radial_2	Masked	Not_used	NoMask	-28.750	-35.304	-22.196	0.000
Speaker	G	Radial_2	Masked	Not_used	NoMask	-36.000	-41.674	-30.326	0.000
Speaker	H	Radial_2	Masked	Not_used	NoMask	-36.000	-40.794	-31.206	0.000
Speaker	B	Radial_2	Masked	Radial_1	NoMask	-25.500	-32.054	-18.946	0.000
Speaker	G	Radial_2	Masked	Radial_1	NoMask	-28.000	-33.674	-22.326	0.000
Speaker	H	Radial_2	Masked	Radial_1	NoMask	-23.250	-28.044	-18.456	0.000
Speaker	B	Radial_2	Masked	Radial_2	NoMask	-27.500	-34.054	-20.946	0.000
Speaker	G	Radial_2	Masked	Radial_2	NoMask	-22.750	-28.424	-17.076	0.000
Speaker	H	Radial_2	Masked	Radial_2	NoMask	-13.000	-17.794	-8.206	0.000
Speaker	B	Radial_2	Masked	Square_1	NoMask	-19.250	-25.804	-12.696	0.000
Speaker	G	Radial_2	Masked	Square_1	NoMask	-32.000	-37.674	-26.326	0.000
Speaker	H	Radial_2	Masked	Square_1	NoMask	-32.000	-36.794	-27.206	0.000
Speaker	B	Radial_2	Masked	Square_2	NoMask	-9.500	-16.054	-2.946	0.001
Speaker	G	Radial_2	Masked	Square_2	NoMask	-18.750	-24.424	-13.076	0.000
Speaker	H	Radial_2	Masked	Square_2	NoMask	-28.000	-32.794	-23.206	0.000
Speaker	B	Square_1	Masked	Not_used	NoMask	-26.500	-33.054	-19.946	0.000
Speaker	G	Square_1	Masked	Not_used	NoMask	-24.250	-29.924	-18.576	0.000
Speaker	H	Square_1	Masked	Not_used	NoMask	-20.750	-25.544	-15.956	0.000
Speaker	B	Square_1	Masked	Radial_1	NoMask	-23.250	-29.804	-16.696	0.000
Speaker	G	Square_1	Masked	Radial_1	NoMask	-16.250	-21.924	-10.576	0.000
Speaker	H	Square_1	Masked	Radial_1	NoMask	-8.000	-12.794	-3.206	0.000
Speaker	B	Square_1	Masked	Radial_2	NoMask	-25.250	-31.804	-18.696	0.000
Speaker	G	Square_1	Masked	Radial_2	NoMask	-11.000	-16.674	-5.326	0.000
Speaker	H	Square_1	Masked	Radial_2	NoMask	2.250	-2.544	7.044	0.837
Speaker	B	Square_1	Masked	Square_1	NoMask	-17.000	-23.554	-10.446	0.000

Speaker	G	Square_1	Masked	Square_1	NoMask	-20.250	-25.924	-14.576	0.000
Speaker	H	Square_1	Masked	Square_1	NoMask	-16.750	-21.544	-11.956	0.000
Speaker	B	Square_1	Masked	Square_2	NoMask	-7.250	-13.804	-0.696	0.021
Speaker	G	Square_1	Masked	Square_2	NoMask	-7.000	-12.674	-1.326	0.007
Speaker	H	Square_1	Masked	Square_2	NoMask	-12.750	-17.544	-7.956	0.000
Speaker	B	Square_2	Masked	Not_used	NoMask	-33.250	-39.804	-26.696	0.000
Speaker	G	Square_2	Masked	Not_used	NoMask	-31.000	-36.674	-25.326	0.000
Speaker	H	Square_2	Masked	Not_used	NoMask	-28.500	-33.294	-23.706	0.000
Speaker	B	Square_2	Masked	Radial_1	NoMask	-30.000	-36.554	-23.446	0.000
Speaker	G	Square_2	Masked	Radial_1	NoMask	-23.000	-28.674	-17.326	0.000
Speaker	H	Square_2	Masked	Radial_1	NoMask	-15.750	-20.544	-10.956	0.000
Speaker	B	Square_2	Masked	Radial_2	NoMask	-32.000	-38.554	-25.446	0.000
Speaker	G	Square_2	Masked	Radial_2	NoMask	-17.750	-23.424	-12.076	0.000
Speaker	H	Square_2	Masked	Radial_2	NoMask	-5.500	-10.294	-0.706	0.015
Speaker	B	Square_2	Masked	Square_1	NoMask	-23.750	-30.304	-17.196	0.000
Speaker	G	Square_2	Masked	Square_1	NoMask	-27.000	-32.674	-21.326	0.000
Speaker	H	Square_2	Masked	Square_1	NoMask	-24.500	-29.294	-19.706	0.000
Speaker	B	Square_2	Masked	Square_2	NoMask	-14.000	-20.554	-7.446	0.000
Speaker	G	Square_2	Masked	Square_2	NoMask	-13.750	-19.424	-8.076	0.000
Speaker	H	Square_2	Masked	Square_2	NoMask	-20.500	-25.294	-15.706	0.000
Speaker	B	Radial_1	NoMask	Not_used	NoMask	-3.250	-9.804	3.304	0.791
Speaker	G	Radial_1	NoMask	Not_used	NoMask	-8.000	-13.674	-2.326	0.001
Speaker	H	Radial_1	NoMask	Not_used	NoMask	-12.750	-17.544	-7.956	0.000
Speaker	B	Radial_2	NoMask	Not_used	NoMask	-1.250	-7.804	5.304	1.000
Speaker	G	Radial_2	NoMask	Not_used	NoMask	-13.250	-18.924	-7.576	0.000
Speaker	H	Radial_2	NoMask	Not_used	NoMask	-23.000	-27.794	-18.206	0.000
Speaker	B	Radial_2	NoMask	Radial_1	NoMask	2.000	-4.554	8.554	0.987
Speaker	G	Radial_2	NoMask	Radial_1	NoMask	-5.250	-10.924	0.424	0.088
Speaker	H	Radial_2	NoMask	Radial_1	NoMask	-10.250	-15.044	-5.456	0.000
Speaker	B	Radial_2	NoMask	Square_1	NoMask	8.250	1.696	14.804	0.006
Speaker	G	Radial_2	NoMask	Square_1	NoMask	-9.250	-14.924	-3.576	0.000
Speaker	H	Radial_2	NoMask	Square_1	NoMask	-19.000	-23.794	-14.206	0.000
Speaker	B	Square_1	NoMask	Not_used	NoMask	-9.500	-16.054	-2.946	0.001
Speaker	G	Square_1	NoMask	Not_used	NoMask	-4.000	-9.674	1.674	0.358
Speaker	H	Square_1	NoMask	Not_used	NoMask	-4.000	-8.794	0.794	0.166
Speaker	B	Square_1	NoMask	Radial_1	NoMask	-6.250	-12.804	0.304	0.071
Speaker	G	Square_1	NoMask	Radial_1	NoMask	4.000	-1.674	9.674	0.358
Speaker	H	Square_1	NoMask	Radial_1	NoMask	8.750	3.956	13.544	0.000
Speaker	B	Square_2	NoMask	Not_used	NoMask	-19.250	-25.804	-12.696	0.000
Speaker	G	Square_2	NoMask	Not_used	NoMask	-17.250	-22.924	-11.576	0.000
Speaker	H	Square_2	NoMask	Not_used	NoMask	-8.000	-12.794	-3.206	0.000
Speaker	B	Square_2	NoMask	Radial_1	NoMask	-16.000	-22.554	-9.446	0.000
Speaker	G	Square_2	NoMask	Radial_1	NoMask	-9.250	-14.924	-3.576	0.000
Speaker	H	Square_2	NoMask	Radial_1	NoMask	4.750	-0.044	9.544	0.054

Speaker	B	Square_2	NoMask	Radial_2	NoMask	-18.000	-24.554	-11.446	0.000
Speaker	G	Square_2	NoMask	Radial_2	NoMask	-4.000	-9.674	1.674	0.358
Speaker	H	Square_2	NoMask	Radial_2	NoMask	15.000	10.206	19.794	0.000
Speaker	B	Square_2	NoMask	Square_1	NoMask	-9.750	-16.304	-3.196	0.001
Speaker	G	Square_2	NoMask	Square_1	NoMask	-13.250	-18.924	-7.576	0.000
Speaker	H	Square_2	NoMask	Square_1	NoMask	-4.000	-8.794	0.794	0.166

Table S7: Pairwise comparisons of diffusers and masking for left participant.

Simulator	Layout	Diffuser 1	Mask 1	Diffuser 2	Mask 2	diff	lwr	upr	p adj
Left participant	B	Radial_1	Masked	Not_used	Masked	-8	-13.767	-2.233	0.002
Left participant	G	Radial_1	Masked	Not_used	Masked	-6.5	-12.122	-0.878	0.014
Left participant	H	Radial_1	Masked	Not_used	Masked	-10	-15.767	-4.233	0.000
Left participant	B	Radial_2	Masked	Not_used	Masked	-16	-21.767	-10.233	0.000
Left participant	G	Radial_2	Masked	Not_used	Masked	-17	-22.622	-11.378	0.000
Left participant	H	Radial_2	Masked	Not_used	Masked	-12	-17.767	-6.233	0.000
Left participant	B	Radial_2	Masked	Radial_1	Masked	-8	-13.767	-2.233	0.002
Left participant	G	Radial_2	Masked	Radial_1	Masked	-10.5	-16.122	-4.878	0.000
Left participant	H	Radial_2	Masked	Radial_1	Masked	-2	-7.767	3.767	0.970
Left participant	B	Radial_2	Masked	Square_1	Masked	-4	-9.767	1.767	0.380
Left participant	G	Radial_2	Masked	Square_1	Masked	-7.75	-13.372	-2.128	0.002
Left participant	H	Radial_2	Masked	Square_1	Masked	-8.5	-14.267	-2.733	0.001
Left participant	B	Square_1	Masked	Not_used	Masked	-12	-17.767	-6.233	0.000
Left participant	G	Square_1	Masked	Not_used	Masked	-9.25	-14.872	-3.628	0.000
Left participant	H	Square_1	Masked	Not_used	Masked	-3.5	-9.267	2.267	0.560
Left participant	B	Square_1	Masked	Radial_1	Masked	-4	-9.767	1.767	0.380
Left participant	G	Square_1	Masked	Radial_1	Masked	-2.75	-8.372	2.872	0.804
Left participant	H	Square_1	Masked	Radial_1	Masked	6.5	0.733	12.267	0.018
Left participant	B	Square_2	Masked	Not_used	Masked	-20	-25.767	-14.233	0.000
Left participant	G	Square_2	Masked	Not_used	Masked	-14.25	-19.872	-8.628	0.000
Left participant	H	Square_2	Masked	Not_used	Masked	-13.25	-19.017	-7.483	0.000
Left participant	B	Square_2	Masked	Radial_1	Masked	-12	-17.767	-6.233	0.000
Left participant	G	Square_2	Masked	Radial_1	Masked	-7.75	-13.372	-2.128	0.002
Left participant	H	Square_2	Masked	Radial_1	Masked	-3.25	-9.017	2.517	0.655
Left participant	B	Square_2	Masked	Radial_2	Masked	-4	-9.767	1.767	0.380
Left participant	G	Square_2	Masked	Radial_2	Masked	2.75	-2.872	8.372	0.804
Left participant	H	Square_2	Masked	Radial_2	Masked	-1.25	-7.017	4.517	0.999
Left participant	B	Square_2	Masked	Square_1	Masked	-8	-13.767	-2.233	0.002
Left participant	G	Square_2	Masked	Square_1	Masked	-5	-10.622	0.622	0.114
Left participant	H	Square_2	Masked	Square_1	Masked	-9.75	-15.517	-3.983	0.000
Left participant	B	Not_used	Masked	Not_used	NoMask	-15.5	-21.267	-9.733	0.000
Left participant	G	Not_used	Masked	Not_used	NoMask	-18.25	-23.872	-12.628	0.000
Left participant	H	Not_used	Masked	Not_used	NoMask	-20.25	-26.017	-14.483	0.000
Left participant	B	Not_used	Masked	Radial_1	NoMask	-6.25	-12.017	-0.483	0.025

Left participant	G	Not_used	Masked	Radial_1	NoMask	-12.25	-17.872	-6.628	0.000
Left participant	H	Not_used	Masked	Radial_1	NoMask	-8	-13.767	-2.233	0.002
Left participant	B	Not_used	Masked	Radial_2	NoMask	-10.5	-16.267	-4.733	0.000
Left participant	G	Not_used	Masked	Radial_2	NoMask	-6.25	-11.872	-0.628	0.020
Left participant	H	Not_used	Masked	Radial_2	NoMask	-4.5	-10.267	1.267	0.234
Left participant	B	Not_used	Masked	Square_1	NoMask	-7.75	-13.517	-1.983	0.003
Left participant	G	Not_used	Masked	Square_1	NoMask	-12.25	-17.872	-6.628	0.000
Left participant	H	Not_used	Masked	Square_1	NoMask	-16.25	-22.017	-10.483	0.000
Left participant	B	Not_used	Masked	Square_2	NoMask	4	-1.767	9.767	0.380
Left participant	G	Not_used	Masked	Square_2	NoMask	-0.5	-6.122	5.122	1.000
Left participant	H	Not_used	Masked	Square_2	NoMask	-12.25	-18.017	-6.483	0.000
Left participant	B	Radial_1	Masked	Not_used	NoMask	-23.5	-29.267	-17.733	0.000
Left participant	G	Radial_1	Masked	Not_used	NoMask	-24.75	-30.372	-19.128	0.000
Left participant	H	Radial_1	Masked	Not_used	NoMask	-30.25	-36.017	-24.483	0.000
Left participant	B	Radial_1	Masked	Radial_1	NoMask	-14.25	-20.017	-8.483	0.000
Left participant	G	Radial_1	Masked	Radial_1	NoMask	-18.75	-24.372	-13.128	0.000
Left participant	H	Radial_1	Masked	Radial_1	NoMask	-18	-23.767	-12.233	0.000
Left participant	B	Radial_1	Masked	Radial_2	NoMask	-18.5	-24.267	-12.733	0.000
Left participant	G	Radial_1	Masked	Radial_2	NoMask	-12.75	-18.372	-7.128	0.000
Left participant	H	Radial_1	Masked	Radial_2	NoMask	-14.5	-20.267	-8.733	0.000
Left participant	B	Radial_1	Masked	Square_1	NoMask	-15.75	-21.517	-9.983	0.000
Left participant	G	Radial_1	Masked	Square_1	NoMask	-18.75	-24.372	-13.128	0.000
Left participant	H	Radial_1	Masked	Square_1	NoMask	-26.25	-32.017	-20.483	0.000
Left participant	B	Radial_1	Masked	Square_2	NoMask	-4	-9.767	1.767	0.380
Left participant	G	Radial_1	Masked	Square_2	NoMask	-7	-12.622	-1.378	0.006
Left participant	H	Radial_1	Masked	Square_2	NoMask	-22.25	-28.017	-16.483	0.000
Left participant	B	Radial_2	Masked	Not_used	NoMask	-31.5	-37.267	-25.733	0.000
Left participant	G	Radial_2	Masked	Not_used	NoMask	-35.25	-40.872	-29.628	0.000
Left participant	H	Radial_2	Masked	Not_used	NoMask	-32.25	-38.017	-26.483	0.000
Left participant	B	Radial_2	Masked	Radial_1	NoMask	-22.25	-28.017	-16.483	0.000
Left participant	G	Radial_2	Masked	Radial_1	NoMask	-29.25	-34.872	-23.628	0.000
Left participant	H	Radial_2	Masked	Radial_1	NoMask	-20	-25.767	-14.233	0.000
Left participant	B	Radial_2	Masked	Radial_2	NoMask	-26.5	-32.267	-20.733	0.000
Left participant	G	Radial_2	Masked	Radial_2	NoMask	-23.25	-28.872	-17.628	0.000
Left participant	H	Radial_2	Masked	Radial_2	NoMask	-16.5	-22.267	-10.733	0.000
Left participant	B	Radial_2	Masked	Square_1	NoMask	-23.75	-29.517	-17.983	0.000
Left participant	G	Radial_2	Masked	Square_1	NoMask	-29.25	-34.872	-23.628	0.000
Left participant	H	Radial_2	Masked	Square_1	NoMask	-28.25	-34.017	-22.483	0.000
Left participant	B	Radial_2	Masked	Square_2	NoMask	-12	-17.767	-6.233	0.000
Left participant	G	Radial_2	Masked	Square_2	NoMask	-17.5	-23.122	-11.878	0.000
Left participant	H	Radial_2	Masked	Square_2	NoMask	-24.25	-30.017	-18.483	0.000
Left participant	B	Square_1	Masked	Not_used	NoMask	-27.5	-33.267	-21.733	0.000
Left participant	G	Square_1	Masked	Not_used	NoMask	-27.5	-33.122	-21.878	0.000
Left participant	H	Square_1	Masked	Not_used	NoMask	-23.75	-29.517	-17.983	0.000

Left participant	B	Square_1	Masked	Radial_1	NoMask	-18.25	-24.017	-12.483	0.000
Left participant	G	Square_1	Masked	Radial_1	NoMask	-21.5	-27.122	-15.878	0.000
Left participant	H	Square_1	Masked	Radial_1	NoMask	-11.5	-17.267	-5.733	0.000
Left participant	B	Square_1	Masked	Radial_2	NoMask	-22.5	-28.267	-16.733	0.000
Left participant	G	Square_1	Masked	Radial_2	NoMask	-15.5	-21.122	-9.878	0.000
Left participant	H	Square_1	Masked	Radial_2	NoMask	-8	-13.767	-2.233	0.002
Left participant	B	Square_1	Masked	Square_1	NoMask	-19.75	-25.517	-13.983	0.000
Left participant	G	Square_1	Masked	Square_1	NoMask	-21.5	-27.122	-15.878	0.000
Left participant	H	Square_1	Masked	Square_1	NoMask	-19.75	-25.517	-13.983	0.000
Left participant	B	Square_1	Masked	Square_2	NoMask	-8	-13.767	-2.233	0.002
Left participant	G	Square_1	Masked	Square_2	NoMask	-9.75	-15.372	-4.128	0.000
Left participant	H	Square_1	Masked	Square_2	NoMask	-15.75	-21.517	-9.983	0.000
Left participant	B	Square_2	Masked	Not_used	NoMask	-35.5	-41.267	-29.733	0.000
Left participant	G	Square_2	Masked	Not_used	NoMask	-32.5	-38.122	-26.878	0.000
Left participant	H	Square_2	Masked	Not_used	NoMask	-33.5	-39.267	-27.733	0.000
Left participant	B	Square_2	Masked	Radial_1	NoMask	-26.25	-32.017	-20.483	0.000
Left participant	G	Square_2	Masked	Radial_1	NoMask	-26.5	-32.122	-20.878	0.000
Left participant	H	Square_2	Masked	Radial_1	NoMask	-21.25	-27.017	-15.483	0.000
Left participant	B	Square_2	Masked	Radial_2	NoMask	-30.5	-36.267	-24.733	0.000
Left participant	G	Square_2	Masked	Radial_2	NoMask	-20.5	-26.122	-14.878	0.000
Left participant	H	Square_2	Masked	Radial_2	NoMask	-17.75	-23.517	-11.983	0.000
Left participant	B	Square_2	Masked	Square_1	NoMask	-27.75	-33.517	-21.983	0.000
Left participant	G	Square_2	Masked	Square_1	NoMask	-26.5	-32.122	-20.878	0.000
Left participant	H	Square_2	Masked	Square_1	NoMask	-29.5	-35.267	-23.733	0.000
Left participant	B	Square_2	Masked	Square_2	NoMask	-16	-21.767	-10.233	0.000
Left participant	G	Square_2	Masked	Square_2	NoMask	-14.75	-20.372	-9.128	0.000
Left participant	H	Square_2	Masked	Square_2	NoMask	-25.5	-31.267	-19.733	0.000
Left participant	B	Radial_1	NoMask	Not_used	NoMask	-9.25	-15.017	-3.483	0.000
Left participant	G	Radial_1	NoMask	Not_used	NoMask	-6	-11.622	-0.378	0.029
Left participant	H	Radial_1	NoMask	Not_used	NoMask	-12.25	-18.017	-6.483	0.000
Left participant	B	Radial_2	NoMask	Not_used	NoMask	-5	-10.767	0.767	0.134
Left participant	G	Radial_2	NoMask	Not_used	NoMask	-12	-17.622	-6.378	0.000
Left participant	H	Radial_2	NoMask	Not_used	NoMask	-15.75	-21.517	-9.983	0.000
Left participant	B	Radial_2	NoMask	Radial_1	NoMask	4.25	-1.517	10.017	0.301
Left participant	G	Radial_2	NoMask	Radial_1	NoMask	-6	-11.622	-0.378	0.029
Left participant	H	Radial_2	NoMask	Radial_1	NoMask	-3.5	-9.267	2.267	0.560
Left participant	B	Radial_2	NoMask	Square_1	NoMask	2.75	-3.017	8.517	0.825
Left participant	G	Radial_2	NoMask	Square_1	NoMask	-6	-11.622	-0.378	0.029
Left participant	H	Radial_2	NoMask	Square_1	NoMask	-11.75	-17.517	-5.983	0.000
Left participant	B	Square_1	NoMask	Not_used	NoMask	-7.75	-13.517	-1.983	0.003
Left participant	G	Square_1	NoMask	Not_used	NoMask	-6	-11.622	-0.378	0.029
Left participant	H	Square_1	NoMask	Not_used	NoMask	-4	-9.767	1.767	0.380
Left participant	B	Square_1	NoMask	Radial_1	NoMask	1.5	-4.267	7.267	0.996
Left participant	G	Square_1	NoMask	Radial_1	NoMask	0	-5.622	5.622	1.000

Left participant	H	Square_1	NoMask	Radial_1	NoMask	8.25	2.483	14.017	0.001
Left participant	B	Square_2	NoMask	Not_used	NoMask	-19.5	-25.267	-13.733	0.000
Left participant	G	Square_2	NoMask	Not_used	NoMask	-17.75	-23.372	-12.128	0.000
Left participant	H	Square_2	NoMask	Not_used	NoMask	-8	-13.767	-2.233	0.002
Left participant	B	Square_2	NoMask	Radial_1	NoMask	-10.25	-16.017	-4.483	0.000
Left participant	G	Square_2	NoMask	Radial_1	NoMask	-11.75	-17.372	-6.128	0.000
Left participant	H	Square_2	NoMask	Radial_1	NoMask	4.25	-1.517	10.017	0.301
Left participant	B	Square_2	NoMask	Radial_2	NoMask	-14.5	-20.267	-8.733	0.000
Left participant	G	Square_2	NoMask	Radial_2	NoMask	-5.75	-11.372	-0.128	0.042
Left participant	H	Square_2	NoMask	Radial_2	NoMask	7.75	1.983	13.517	0.003
Left participant	B	Square_2	NoMask	Square_1	NoMask	-11.75	-17.517	-5.983	0.000
Left participant	G	Square_2	NoMask	Square_1	NoMask	-11.75	-17.372	-6.128	0.000
Left participant	H	Square_2	NoMask	Square_1	NoMask	-4	-9.767	1.767	0.380

Table S8: Pairwise comparisons of diffusers and masking for right participant.

Simulator	Layout	Diffuser 1	Mask 1	Diffuser 2	Mask 2	diff	lwr	upr	p adj
Right participant	B	Radial_1	Masked	Not_used	Masked	-5.5	-11.417	0.417	0.085
Right participant	G	Radial_1	Masked	Not_used	Masked	-7.10543E-15	-5.098	5.098	1.000
Right participant	H	Radial_1	Masked	Not_used	Masked	-12.25	-17.124	-7.376	0.000
Right participant	B	Radial_2	Masked	Not_used	Masked	-16.75	-22.667	-10.833	0.000
Right participant	G	Radial_2	Masked	Not_used	Masked	-13.5	-18.598	-8.402	0.000
Right participant	H	Radial_2	Masked	Not_used	Masked	-19.75	-24.624	-14.876	0.000
Right participant	B	Radial_2	Masked	Radial_1	Masked	-11.25	-17.167	-5.333	0.000
Right participant	G	Radial_2	Masked	Radial_1	Masked	-13.5	-18.598	-8.402	0.000
Right participant	H	Radial_2	Masked	Radial_1	Masked	-7.5	-12.374	-2.626	0.000
Right participant	B	Radial_2	Masked	Square_1	Masked	-7	-12.917	-1.083	0.011
Right participant	G	Radial_2	Masked	Square_1	Masked	-7.25	-12.348	-2.152	0.001
Right participant	H	Radial_2	Masked	Square_1	Masked	-12.5	-17.374	-7.626	0.000
Right participant	B	Square_1	Masked	Not_used	Masked	-9.75	-15.667	-3.833	0.000
Right participant	G	Square_1	Masked	Not_used	Masked	-6.25	-11.348	-1.152	0.007
Right participant	H	Square_1	Masked	Not_used	Masked	-7.25	-12.124	-2.376	0.001
Right participant	B	Square_1	Masked	Radial_1	Masked	-4.25	-10.167	1.667	0.334
Right participant	G	Square_1	Masked	Radial_1	Masked	-6.25	-11.348	-1.152	0.007
Right participant	H	Square_1	Masked	Radial_1	Masked	5	0.126	9.874	0.041
Right participant	B	Square_2	Masked	Not_used	Masked	-14	-19.917	-8.083	0.000
Right participant	G	Square_2	Masked	Not_used	Masked	-10.25	-15.348	-5.152	0.000
Right participant	H	Square_2	Masked	Not_used	Masked	-16	-20.874	-11.126	0.000
Right participant	B	Square_2	Masked	Radial_1	Masked	-8.5	-14.417	-2.583	0.001
Right participant	G	Square_2	Masked	Radial_1	Masked	-10.25	-15.348	-5.152	0.000
Right participant	H	Square_2	Masked	Radial_1	Masked	-3.75	-8.624	1.124	0.250
Right participant	B	Square_2	Masked	Radial_2	Masked	2.75	-3.167	8.667	0.845
Right participant	G	Square_2	Masked	Radial_2	Masked	3.25	-1.848	8.348	0.494

Right participant	H	Square_2	Masked	Radial_2	Masked	3.75	-1.124	8.624	0.250
Right participant	B	Square_2	Masked	Square_1	Masked	-4.25	-10.167	1.667	0.334
Right participant	G	Square_2	Masked	Square_1	Masked	-4	-9.098	1.098	0.228
Right participant	H	Square_2	Masked	Square_1	Masked	-8.75	-13.624	-3.876	0.000
Right participant	B	Not_used	Masked	Not_used	NoMask	-18.5	-24.417	-12.583	0.000
Right participant	G	Not_used	Masked	Not_used	NoMask	-21.75	-26.848	-16.652	0.000
Right participant	H	Not_used	Masked	Not_used	NoMask	-15.75	-20.624	-10.876	0.000
Right participant	B	Not_used	Masked	Radial_1	NoMask	-11.5	-17.417	-5.583	0.000
Right participant	G	Not_used	Masked	Radial_1	NoMask	-18	-23.098	-12.902	0.000
Right participant	H	Not_used	Masked	Radial_1	NoMask	-6.5	-11.374	-1.626	0.003
Right participant	B	Not_used	Masked	Radial_2	NoMask	-12.5	-18.417	-6.583	0.000
Right participant	G	Not_used	Masked	Radial_2	NoMask	-9.5	-14.598	-4.402	0.000
Right participant	H	Not_used	Masked	Radial_2	NoMask	4.75	-0.124	9.624	0.061
Right participant	B	Not_used	Masked	Square_1	NoMask	-7.5	-13.417	-1.583	0.005
Right participant	G	Not_used	Masked	Square_1	NoMask	-14.25	-19.348	-9.152	0.000
Right participant	H	Not_used	Masked	Square_1	NoMask	-12.25	-17.124	-7.376	0.000
Right participant	B	Not_used	Masked	Square_2	NoMask	-1	-6.917	4.917	1.000
Right participant	G	Not_used	Masked	Square_2	NoMask	-6.5	-11.598	-1.402	0.005
Right participant	H	Not_used	Masked	Square_2	NoMask	-5.5	-10.374	-0.626	0.017
Right participant	B	Radial_1	Masked	Not_used	NoMask	-24	-29.917	-18.083	0.000
Right participant	G	Radial_1	Masked	Not_used	NoMask	-21.75	-26.848	-16.652	0.000
Right participant	H	Radial_1	Masked	Not_used	NoMask	-28	-32.874	-23.126	0.000
Right participant	B	Radial_1	Masked	Radial_1	NoMask	-17	-22.917	-11.083	0.000
Right participant	G	Radial_1	Masked	Radial_1	NoMask	-18	-23.098	-12.902	0.000
Right participant	H	Radial_1	Masked	Radial_1	NoMask	-18.75	-23.624	-13.876	0.000
Right participant	B	Radial_1	Masked	Radial_2	NoMask	-18	-23.917	-12.083	0.000
Right participant	G	Radial_1	Masked	Radial_2	NoMask	-9.5	-14.598	-4.402	0.000
Right participant	H	Radial_1	Masked	Radial_2	NoMask	-7.5	-12.374	-2.626	0.000
Right participant	B	Radial_1	Masked	Square_1	NoMask	-13	-18.917	-7.083	0.000
Right participant	G	Radial_1	Masked	Square_1	NoMask	-14.25	-19.348	-9.152	0.000
Right participant	H	Radial_1	Masked	Square_1	NoMask	-24.5	-29.374	-19.626	0.000
Right participant	B	Radial_1	Masked	Square_2	NoMask	-6.5	-12.417	-0.583	0.022
Right participant	G	Radial_1	Masked	Square_2	NoMask	-6.5	-11.598	-1.402	0.005
Right participant	H	Radial_1	Masked	Square_2	NoMask	-17.75	-22.624	-12.876	0.000
Right participant	B	Radial_2	Masked	Not_used	NoMask	-35.25	-41.167	-29.333	0.000
Right participant	G	Radial_2	Masked	Not_used	NoMask	-35.25	-40.348	-30.152	0.000
Right participant	H	Radial_2	Masked	Not_used	NoMask	-35.5	-40.374	-30.626	0.000
Right participant	B	Radial_2	Masked	Radial_1	NoMask	-28.25	-34.167	-22.333	0.000
Right participant	G	Radial_2	Masked	Radial_1	NoMask	-31.5	-36.598	-26.402	0.000
Right participant	H	Radial_2	Masked	Radial_1	NoMask	-26.25	-31.124	-21.376	0.000
Right participant	B	Radial_2	Masked	Radial_2	NoMask	-29.25	-35.167	-23.333	0.000
Right participant	G	Radial_2	Masked	Radial_2	NoMask	-23	-28.098	-17.902	0.000
Right participant	H	Radial_2	Masked	Radial_2	NoMask	-15	-19.874	-10.126	0.000
Right participant	B	Radial_2	Masked	Square_1	NoMask	-24.25	-30.167	-18.333	0.000

Right participant	G	Radial_2	Masked	Square_1	NoMask	-27.75	-32.848	-22.652	0.000
Right participant	H	Radial_2	Masked	Square_1	NoMask	-32	-36.874	-27.126	0.000
Right participant	B	Radial_2	Masked	Square_2	NoMask	-17.75	-23.667	-11.833	0.000
Right participant	G	Radial_2	Masked	Square_2	NoMask	-20	-25.098	-14.902	0.000
Right participant	H	Radial_2	Masked	Square_2	NoMask	-25.25	-30.124	-20.376	0.000
Right participant	B	Square_1	Masked	Not_used	NoMask	-28.25	-34.167	-22.333	0.000
Right participant	G	Square_1	Masked	Not_used	NoMask	-28	-33.098	-22.902	0.000
Right participant	H	Square_1	Masked	Not_used	NoMask	-23	-27.874	-18.126	0.000
Right participant	B	Square_1	Masked	Radial_1	NoMask	-21.25	-27.167	-15.333	0.000
Right participant	G	Square_1	Masked	Radial_1	NoMask	-24.25	-29.348	-19.152	0.000
Right participant	H	Square_1	Masked	Radial_1	NoMask	-13.75	-18.624	-8.876	0.000
Right participant	B	Square_1	Masked	Radial_2	NoMask	-22.25	-28.167	-16.333	0.000
Right participant	G	Square_1	Masked	Radial_2	NoMask	-15.75	-20.848	-10.652	0.000
Right participant	H	Square_1	Masked	Radial_2	NoMask	-2.5	-7.374	2.374	0.759
Right participant	B	Square_1	Masked	Square_1	NoMask	-17.25	-23.167	-11.333	0.000
Right participant	G	Square_1	Masked	Square_1	NoMask	-20.5	-25.598	-15.402	0.000
Right participant	H	Square_1	Masked	Square_1	NoMask	-19.5	-24.374	-14.626	0.000
Right participant	B	Square_1	Masked	Square_2	NoMask	-10.75	-16.667	-4.833	0.000
Right participant	G	Square_1	Masked	Square_2	NoMask	-12.75	-17.848	-7.652	0.000
Right participant	H	Square_1	Masked	Square_2	NoMask	-12.75	-17.624	-7.876	0.000
Right participant	B	Square_2	Masked	Not_used	NoMask	-32.5	-38.417	-26.583	0.000
Right participant	G	Square_2	Masked	Not_used	NoMask	-32	-37.098	-26.902	0.000
Right participant	H	Square_2	Masked	Not_used	NoMask	-31.75	-36.624	-26.876	0.000
Right participant	B	Square_2	Masked	Radial_1	NoMask	-25.5	-31.417	-19.583	0.000
Right participant	G	Square_2	Masked	Radial_1	NoMask	-28.25	-33.348	-23.152	0.000
Right participant	H	Square_2	Masked	Radial_1	NoMask	-22.5	-27.374	-17.626	0.000
Right participant	B	Square_2	Masked	Radial_2	NoMask	-26.5	-32.417	-20.583	0.000
Right participant	G	Square_2	Masked	Radial_2	NoMask	-19.75	-24.848	-14.652	0.000
Right participant	H	Square_2	Masked	Radial_2	NoMask	-11.25	-16.124	-6.376	0.000
Right participant	B	Square_2	Masked	Square_1	NoMask	-21.5	-27.417	-15.583	0.000
Right participant	G	Square_2	Masked	Square_1	NoMask	-24.5	-29.598	-19.402	0.000
Right participant	H	Square_2	Masked	Square_1	NoMask	-28.25	-33.124	-23.376	0.000
Right participant	B	Square_2	Masked	Square_2	NoMask	-15	-20.917	-9.083	0.000
Right participant	G	Square_2	Masked	Square_2	NoMask	-16.75	-21.848	-11.652	0.000
Right participant	H	Square_2	Masked	Square_2	NoMask	-21.5	-26.374	-16.626	0.000
Right participant	B	Radial_1	NoMask	Not_used	NoMask	-7	-12.917	-1.083	0.011
Right participant	G	Radial_1	NoMask	Not_used	NoMask	-3.75	-8.848	1.348	0.304
Right participant	H	Radial_1	NoMask	Not_used	NoMask	-9.25	-14.124	-4.376	0.000
Right participant	B	Radial_2	NoMask	Not_used	NoMask	-6	-11.917	-0.083	0.045
Right participant	G	Radial_2	NoMask	Not_used	NoMask	-12.25	-17.348	-7.152	0.000
Right participant	H	Radial_2	NoMask	Not_used	NoMask	-20.5	-25.374	-15.626	0.000
Right participant	B	Radial_2	NoMask	Radial_1	NoMask	1	-4.917	6.917	1.000
Right participant	G	Radial_2	NoMask	Radial_1	NoMask	-8.5	-13.598	-3.402	0.000
Right participant	H	Radial_2	NoMask	Radial_1	NoMask	-11.25	-16.124	-6.376	0.000

Right participant	B	Radial_2	NoMask	Square_1	NoMask	5	-0.917	10.917	0.155
Right participant	G	Radial_2	NoMask	Square_1	NoMask	-4.75	-9.848	0.348	0.084
Right participant	H	Radial_2	NoMask	Square_1	NoMask	-17	-21.874	-12.126	0.000
Right participant	B	Square_1	NoMask	Not_used	NoMask	-11	-16.917	-5.083	0.000
Right participant	G	Square_1	NoMask	Not_used	NoMask	-7.5	-12.598	-2.402	0.001
Right participant	H	Square_1	NoMask	Not_used	NoMask	-3.5	-8.374	1.374	0.334
Right participant	B	Square_1	NoMask	Radial_1	NoMask	-4	-9.917	1.917	0.414
Right participant	G	Square_1	NoMask	Radial_1	NoMask	-3.75	-8.848	1.348	0.304
Right participant	H	Square_1	NoMask	Radial_1	NoMask	5.75	0.876	10.624	0.011
Right participant	B	Square_2	NoMask	Not_used	NoMask	-17.5	-23.417	-11.583	0.000
Right participant	G	Square_2	NoMask	Not_used	NoMask	-15.25	-20.348	-10.152	0.000
Right participant	H	Square_2	NoMask	Not_used	NoMask	-10.25	-15.124	-5.376	0.000
Right participant	B	Square_2	NoMask	Radial_1	NoMask	-10.5	-16.417	-4.583	0.000
Right participant	G	Square_2	NoMask	Radial_1	NoMask	-11.5	-16.598	-6.402	0.000
Right participant	H	Square_2	NoMask	Radial_1	NoMask	-1	-5.874	3.874	0.999
Right participant	B	Square_2	NoMask	Radial_2	NoMask	-11.5	-17.417	-5.583	0.000
Right participant	G	Square_2	NoMask	Radial_2	NoMask	-3	-8.098	2.098	0.601
Right participant	H	Square_2	NoMask	Radial_2	NoMask	10.25	5.376	15.124	0.000
Right participant	B	Square_2	NoMask	Square_1	NoMask	-6.5	-12.417	-0.583	0.022
Right participant	G	Square_2	NoMask	Square_1	NoMask	-7.75	-12.848	-2.652	0.001
Right participant	H	Square_2	NoMask	Square_1	NoMask	-6.75	-11.624	-1.876	0.002