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Performance of Valved Respirators to Reduce Emission of Respiratory Particles Generated by Speaking

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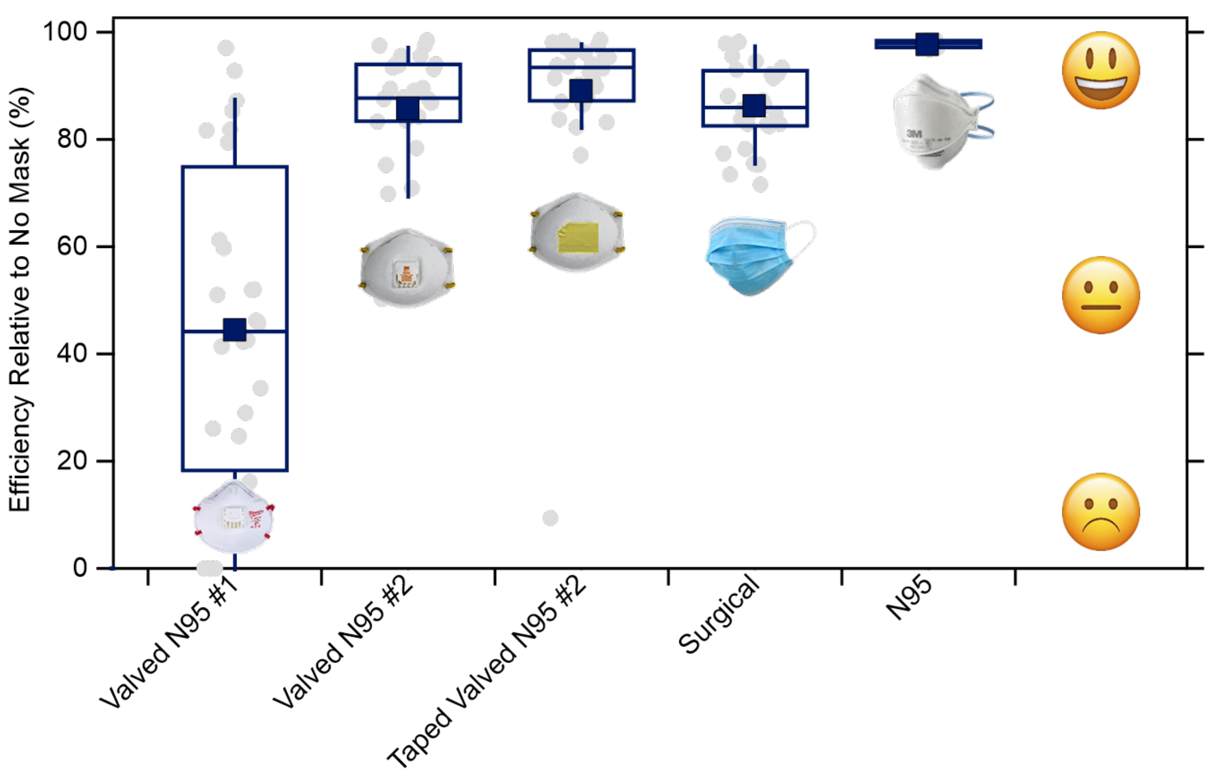
Keywords:

face coverings, masks, respiratory particles

ABSTRACT:

Wearing of face coverings serves two purposes: reducing the concentration of ambient particles inhaled and reducing the emission of respiratory particles generated by the wearer. The efficiency of different face coverings depends on the material, design, and fit. Face coverings such as N95 respirators, when worn properly, are highly efficient at filtering ambient particles during inhalation. Some N95 respirators, as well as other face covering types, include a one-way valve to allow easier exhalation while still maintaining high filtration efficiency towards inhaled ambient particles. The extent to which these valves decrease filtration of emitted respiratory particles is, however, not well established. Here, we show that different valved N95s exhibit highly variable filtration efficiencies for exhaled respiratory particles. As such, valved N95s may not provide reliable source control of respired particles and their use should be discouraged in situations where such source control is needed.

TOC ART:



Introduction:

Face coverings reduce the concentrations of both inhaled and exhaled particles and their efficiencies vary by design and type. In many settings, the primary purpose of face coverings, generically referred to as masks, is to protect the wearer from inhalation of ambient particles that might be toxic or otherwise unhealthy.[1] Generally, cloth masks and medical procedure masks do not provide the same level of protection as a well-fit respirator (e.g., N95 filtering facepiece respirators) for inhaled ambient particles.[2-5] Some N95 respirators, as well as other types of face coverings, include an exhalation valve, the purpose of which is to facilitate easier breathing and reduce humidity and temperature inside the mask interior volume while still providing protection to the wearer against inhalation of ambient particles.[6, 7] The inclusion of an exhalation valve makes sense if the primary purpose is to protect the wearer, so long as it does not affect the mask filtration efficiency towards inhaled ambient particles. However, as the ongoing COVID-19 pandemic has made clear, masks also provide an important other function, namely source control via reduction of the emission of potentially infectious respiratory particles[8, 9] that are produced during breathing, speaking, coughing, or sneezing.[10, 11]

In this context, it is critical to understand the extent to which an exhalation valve reduces mask efficiency towards exhaled respiratory particles and to compare their performance with other mask types. Staymates (2021) provides qualitative evidence that valved N95 respirators lead to excessive escape of respiratory particles and therefore a substantial reduction in their efficiency.[12] National Institute for Occupational Safety and Health (NIOSH) researchers performed experiments using test aerosol to challenge various valved respirators firmly sealed around their edges to a surface. In contrast to Staymates,[12] NIOSH found relatively high efficiencies (~70%), despite the presence of the valve, although it is possible that the valves in the respirators used may have remained mostly closed during testing leading to artificially high efficiencies.[13] Additionally, these measurements considered performance under ideal conditions (perfect sealing) and did not address performance when worn by people. Asadi et al. (2020) provided measurements of the effectiveness of a vented N95 respirator towards exhaled respiratory particles when worn by people, finding reasonably good performance.[14] However, their measurements were limited to two people only and one respirator type. Also, they only measured particle emissions in the forward direction and may have undersampled any particles that escaped through the valve.

To provide the public with clear guidance regarding appropriate mask wearing to reduce both inhaled and exhaled particle concentrations requires clear understanding of the reduction afforded by valved respirators when worn by actual people while speaking. Speaking is one of the most common respiratory particle generating processes that leads to emission of particles at about 10x the rate of breathing.[10] Here, we address this issue by making measurements of the reduction in respiratory particle concentrations generated by people when speaking afforded by wearing of different masks, including readily available (in the U.S.) valved N95 respirators.

MATERIALS AND METHODS:

Following from the methods used by Cappa et al. (2021) and associated other works,[10, 14-16] we measured the concentrations of respiratory particles emitted while speaking by 10 individuals ranging in age from 20-43 with four self-identified females and six self-identified males. The University of California Davis Institutional Review Board approved this study (IRB# 844,369–4), and all research was performed in accordance with relevant guidelines and regulations of the Institutional Review Board. The participants spoke the *Rainbow Passage* while either not wearing or wearing one of four face coverings: a surgical procedure mask (ValuMax, Model: 5130E-SB), a valved 3M N95 respirator (Model: 8511), the same 3M 8511 N95 but with the valve taped over in the mask interior, or a valved Milwaukee N95 respirator (Model: 48-73-4011). These particular valved respirators were selected as they are readily available to the public in the U.S. Participants were provided instructions for and guided towards proper wearing of the masks but no formal fit test was conducted; the intent here is to consider masks as they might be worn by the public. To reduce the potential for sticking of the N95 respirator valves the valve flaps were gently pushed out prior to the initial wearing.

A laminar flow hood (Air Science, PURAIR FLOW-48) housed the sampling funnel and provided HEPA filtered air such that background particle concentrations were negligible. **Figure S1** shows the experimental setup. Participants spoke with their face and the sides of the face coverings inside the outer circumference of a large (30 cm diameter) funnel from which an Aerodynamic Particle Sizer (APS; TSI, Inc, 5 lpm) and a Condensation Particle Counter (CPC; TSI, Inc., 0.3 lpm) continuously sampled along with an excess flow of 19.7 lpm, such that the total flow into the funnel was 25 lpm. The APS characterizes size distributions and concentrations of particles having diameters >0.5 microns while the CPC measures the concentration of all particles >0.01 microns. The stopping distance of 1 micron particles that escape from the mask edges is << 1 cm and thus these will be predominately entrained into the airflow passing into the funnel, although particles may be carried further by the jets of airflow out the mask edges. The extent to which such particles were not sampled by the APS was characterized by measuring CO_2 concentrations in the APS exhaust. Exhaled breath has [CO_2] much greater than ambient. The measured [CO_2] depends on how much of the 25 lpm total flow is made up of exhaled breath and will be lower if exhaled air is not sampled into the funnel. These CO_2 measurements were made separately from the speaking experiments and for one participant only but using the same experimental setup. Further details regarding the methods are available in the Supplemental Material.

Each participant performed two non-sequential replicates for each condition using the same mask and the order of tests was varied between participants. One participant repeated these tests using different masks (e.g., multiple readings wearing different 3M 8511 respirators) to help establish whether between-participant differences derive primarily from differences in how the individuals wore the masks and spoke versus from differences in the individual masks. This participant also performed the tasks wearing a non-valved N95 respirator (3M, Model Aura 9205+). The ratio (R_{mask}) between the particle concentration measured with wearing of a given mask and without provides a measure of the mask efficiency ($\eta_{mask} = 1 - R_{mask}$) for reducing emission of respiratory particles. In cases where the R_{mask} exceeded unity the η_{mask} were set to 0% as negative efficiencies are not allowed.

RESULTS AND DISCUSSION:

With no face covering, measured particle concentrations and size distributions were consistent with previous observations,[10, 11, 15-17] with the CPC measuring on average 24x as many particles as the APS, indicating that particles <0.5 microns dominate the overall number (**Figure S2** and **Figure S3**). Comparing the observations across all participants, the median (or geometric mean) η_{mask} for all particles varied substantially between face covering types, with η_{mask} = 45% (44%) for the Milwaukee, 86% (88%) for the 3M 8511, 89% (93%) for the taped 3M 8511, and 86% (85%) for the surgical masks (**Figure 1a**). The results for particles >0.5 microns were similar (**Figure 1b**). The multiple repeats by the one participant wearing different individual masks yielded similar results, included in **Figure 1a**, with example time-series of particle count rates shown in **Figure 1c**.

The magnitude of the decrease in particle emissions during speaking with surgical mask wearing is consistent with our previous findings,[15, 16] albeit with a somewhat higher overall efficiency. The η_{mask} for the 3M 8511 was similar to that observed by Asadi et al. (2020)[14] for a different valved N95 respirator and in line with the range observed by NIOSH (73%-82% at a flowrate of 25 lpm),[13] while that for the Milwaukee was significantly lower. Taping over the valve in the mask interior for the 3M 8511 reduced the respiratory particle emissions by about a factor of two. The observed surgical mask efficiency was similar to the 3M 8511 mask and significantly better than the Milwaukee mask (based on paired t-tests; **Table S1**). The trials by the participant who repeated the speaking tasks multiple times additionally indicate that wearing of the non-valved 3M Aura N95 mask provided excellent reduction in exhaled particle concentrations, with the median η_{mask} = 98% (**Figure 1a**).

The CO_2 measurements indicate that imperfect sampling of particles that escape out the mask edges may have led to some underestimate of the total particle emission rates with mask wearing, resulting in an overestimate of mask efficiency. Specifically, the CO_2 measurements (**Figure 2**) suggest a potential low bias in the particle emission rates of 4% (surgical), 17% (3M Aura), 23% (3M 8511), and 21% (Milwaukee). The between-participant variability may exceed that observed here for one participant, and we cannot rule out the possibility that this contributed to some of the variability in η_{mask}. The somewhat low value of the non-valved 3M Aura could indicate that some filtered air is also undersampled, implying the actual impact on measured particle emission rates is smaller than the CO_2 measurements suggest. The similarity of the three N95 respirators indicates the particle reduction efficiencies can be quantitatively compared in a relative sense, even if the absolute efficiencies are biased slightly low.

For a few participants, the particle concentrations with mask wearing exceeded that with no mask, which can occur when e.g., skin-mask rubbing releases non-respiratory particles (**Figure 1b**).[16, 17] Alternatively, this could reflect natural variability in the emission of respiratory particles by individuals; for the participant who repeated the tasks multiple times the ratio between the maximum and minimum observed particle emission rates equaled 1.6. The potential for non-respiratory particle contributions means that the actual reduction afforded by the masks could be greater than the observations suggest. However, we have no reason to think that the Milwaukee mask led to significantly greater production of such non-respiratory particles than the other masks as the fit and material were generally similar to that 3M 8511.

The individual η_{mask} for a given mask type varied widely between participants for all mask types but most notably for the Milwaukee mask. In general, the variability in both the absolute concentrations (**Figure S3**) and the η_{mask} (**Figure 1a**) between participants greatly exceeded the difference in the replicates for an individual participant, consistent with previous observations for surgical mask wearing.[15, 16] The greater variability between individuals could indicate greater consistency in either how the masks were worn or in the speaking activity performed by one participant than between participants.

The Milwaukee and 3M 8511 respirators both have their valve similarly positioned in the center. As such, the very different performance of these two valved respirators likely results from a difference in the ease with which the valve opens during speaking. This indicates that highly variable performance of different valved respirators, if worn by the public, is expected and with some models providing almost no reduction in exhaled respiratory particles produced when speaking. The NIOSH results for test particles indicate that the η_{mask} values for valved respirators decrease as flowrate increases, suggesting that efficiencies for coughing would be even lower than those observed here for speaking.[13] Thus, although valved respirators can provide protection to the wearer against inhalation of ambient particles, the use of valved masks when source control of respiratory particles is also desired should be avoided in favor of masks with higher efficiency towards exhaled particles, as is the case when the aim is reduction of respiratory disease transmission.

ASSOCIATED CONTENT

Supporting Information: The supporting information is available free of charge at https:

Additional experimental details (particle background, participant demographics, experiments with CO_2), table of statistical comparison between mask types, and figures showing average particle size distributions, absolute particle emission rates, impact of the particle background.

An earlier version of this work was submitted to a pre-print server.[18]

AUTHOR CONTRIBUTIONS:

J.M.H. and C.D.C. conducted the experiments. C.D.C. conceived the research, analyzed the data, and wrote the paper with contributions from J.M.H.

ACKNOWLEDGEMENTS:

We thank all of the participants for their time and Prof. Bill Ristenpart (UC Davis) for use of the laminar flow hood.

CONFLICT OF INTEREST:

The authors declare no competing financial interest.

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FIGURES

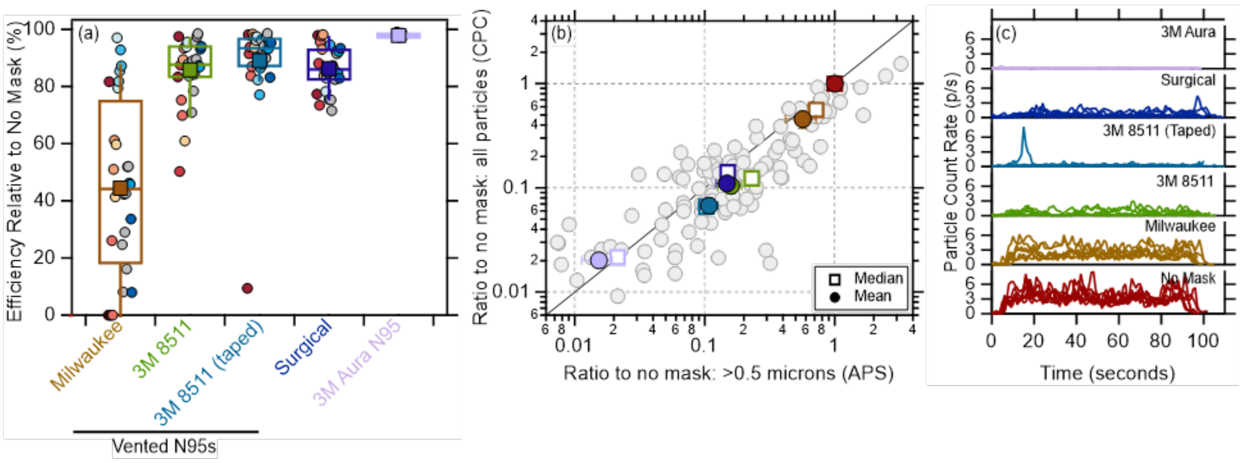

Figure 1: Observations of the reduction in respiratory particles emitted during speaking with wearing of various mask types. (a) Mask efficiency results for all participants, with colored points corresponding to different individuals. Results for one individual repeating the task many times are shown as gray. The box and whisker plots show the median (horizontal line), 25th/75th percentile (boxes), and 10th/90th percentiles (whiskers), along with the geometric mean (square). (b) Relationship between the particle reduction ratio determined from the CPC and the APS, with all results shown as gray, geometric mean values as colored circles, and medians as colored squares. (c) The observed time-series of CPC-measured respiratory particle emission rates from speaking associated with the gray data from (a). Note that these have not been corrected for dilution.

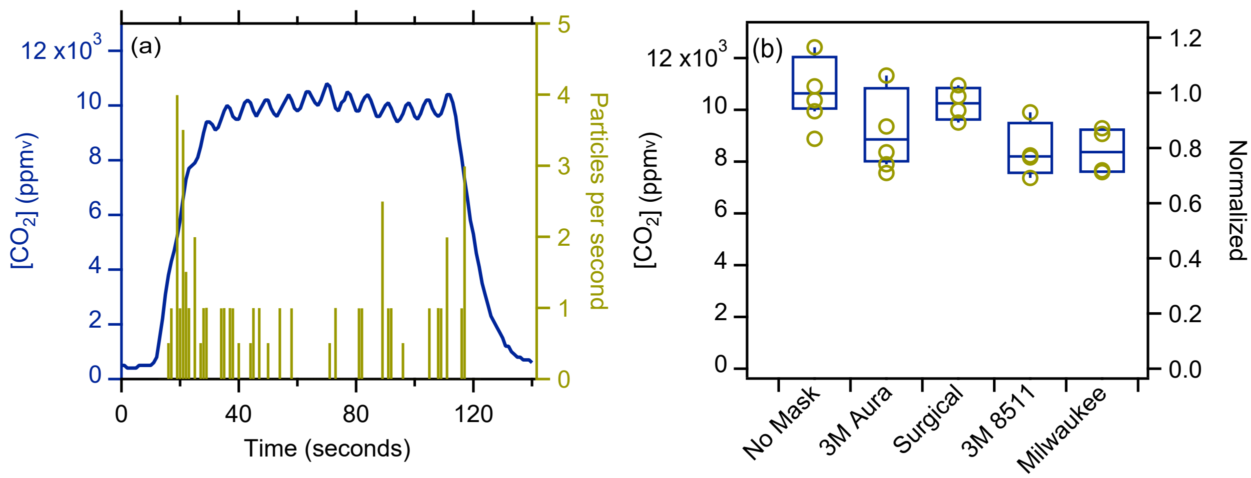

Figure 2: (a) Example time-series of CO_2 measured (blue) and particle counts (yellow) for ~100 seconds of breathing with no mask wearing. The oscillations in the CO_2 result from cycles of inhalation and exhalation. (b) The average [CO_2] measured for each trial for wearing of different face coverings. Individual results are shown as yellow circles and the overall behavior summarized with the box and whisker plot. Absolute CO_2 concentrations are shown on the left axis and the corresponding values normalized to the median from no mask wearing on the right axis.

Supplementary Material for "Performance of Valved Respirators to Reduce Respiratory Particles Generated by Speaking"

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Methods – Additional Details:

Particle Background

A photograph of the experimental setup is shown in Fig. S1. Background particle concentrations were characterized by measuring with the laminar flow hood on but without a participant present carrying out expiratory activities. Typically, for the APS no particles were measured over an ~2 min period, but occasionally 1-2 particles were measured, corresponding to average particle count rates of 0.008 or 0.016 p/s. The background for the CPC was higher, ~0.25 p/s. This compares to a CPC-measured average particle count rate during speaking of 9 p/s (no mask), 1.1 p/s (surgical), 1.1 p/s (3M 8511), 4.4 p/s (Milwaukee) and 0.85 p/s (3M 8511 that is taped). For comparison, typical count rates for sampling of room air are ~5000 p/s. No correction for background counts were applied for results presented in the main text. This will have a larger impact on the masks with higher efficiency. The influence of subtracting the background counts is illustrated in **Figure S4**. Consideration of the background values influences the specific values, especially for the APS, but does not change the general conclusions.

Importantly, the participants were breathing the clean, HEPA filtered air in the laminar flow hood throughout the experiments. When this is not the case, participants will inhale ambient room particles, only some of which will deposit in the respiratory system. The room particles that do not deposit will be subsequently exhaled. The concentration of particles in the room substantially exceeds that in exhaled breath. Therefore, if participants are breathing room air the majority of the particles exhaled can be these non-deposited room particles that were inhaled. This appears as an excessively high particle emission rate and confounds determination of the impact of wearing face coverings on emitted respiratory particles. By having participants breathe the clean air in the laminar flow hood we can ensure that the measured particles are only generated from the respiratory activity, although this can include particles that shed from the mask.

Participant demographics

Participants ranged in age from 20 to 43 years. Six self-identified as male and four as female. None had any substantial facial hair. Three wore glasses. About half commented about the various N95s having an overly tight fit.

Experiments with CO_2

The CO_2 concentration in the total airflow sampled into the funnel was characterized using an ExplorIR-W 100% CO_2 sensor from CO2meter.com. The CO_2 sensor was attached to the exhaust flow of the APS. The APS exhaust combines the sample and sheath flow, and thus provides a measure of the [CO_2] in the sampled air. CO_2 concentrations were measured at 1 Hz. The CO_2 sensor was referenced to room air, assuming that the room air [CO_2] = 419 ppm_v. This may slightly underestimate the actual CO_2

concentration in room air, but as we subtract the background value this will not have a material impact on the results.

Experiments with CO_2 were performed with one participant only, as the CO_2 sensor was only obtained after the particle emission experiments were conducted. The participant was positioned in the same manner as the speaking experiments, with their face inside the sampling cone. They breathed in through their nose and out through their mouth while listening to a metronome on 4/4 time at 70 beats per minute for 100 seconds. The person would breathe in for four counts and out for four counts, corresponding to 8.75 breaths per minute. These breathing cycles are apparent in the observed $[CO_2]$ as oscillations in the CO_2 at a nominally steady state value (**Figure 2**a). At the start of an experiment the CO_2 concentration rises over about 8 seconds to reach a steady state value. At the end of the experiment the CO_2 concentration falls with a similar time constant. Breathing was considered here rather than speaking to enhance reproducibility, as variability in speaking volume can lead to variations in particle emissions.

The participant carried out the breathing exercise in the following order: (i) no mask and with wearing of the (ii) 3M Aura, (iii) a surgical mask, (iv) the 3M 8511 with the valve not taped, and the (v) Milwaukee. This series of activities was repeated four times for (iii)-(v) and five times for the no mask and 3M Aura cases. The average CO_2 concentration during the steady state period was determined for teach trial.

Statistical Analysis

The average values of $\log_{10}(R_{\text{mask}})$ and $\log_{10}(\overline{N}_p)$ were determined for each participant. Paired t-tests were performed for each pair of masks in Igor Pro (8.0.4.2, Wavemetrics) using the command "StatsTTest/ALPH=0.05 /CI /PAIR" and the p values determined. In general, when $p < 0.05$ the difference between masks is considered "significant" and the null hypothesis can be rejected, although caution should be taken in overinterpreting the significance of the differences (or lack thereof) for p values that are very close to the $p = 0.05$ threshold.

The p values comparing the Milwaukee valved masks to all other masks are $\leq 4.04 \times 10^{-4}$, indicating the difference is unlikely to be due to chance. Comparing the particle emission rates with no mask wearing to with mask wearing, in all cases—including the Milwaukee valved respirator—the difference is significant, with the largest p value = 5.24×10^{-3}. The particle reduction with wearing the un-taped 3M 8511 is indistinguishable from the surgical mask ($p = 0.831$).

There are a number of comparisons that are very close to the $p < 0.05$ level of significance. For example, $p = 0.033$ comparing the 3M 8511 to the taped 3M 8511. It may be that a larger effect of taping would have occurred for the Milwaukee respirator for which the intrinsic reduction (without taping) was smaller to begin with. The 3M Aura leads to a significant reduction compared to the Milwaukee and surgical masks, but has p values slightly greater than 0.05 when compared with the 3M 8511 ($p = 0.084$) and taped 3M 8511 ($p = 0.059$).

Supplemental Figures & Tables:

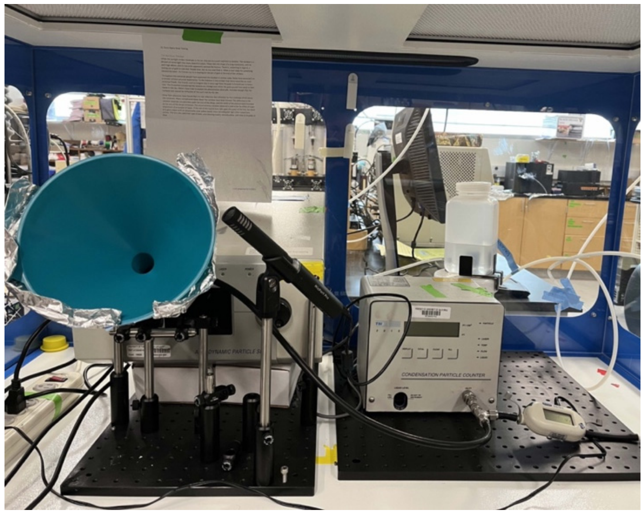

Figure S1: Experimental setup to measure the concentration of respiratory particles emitted while speaking.

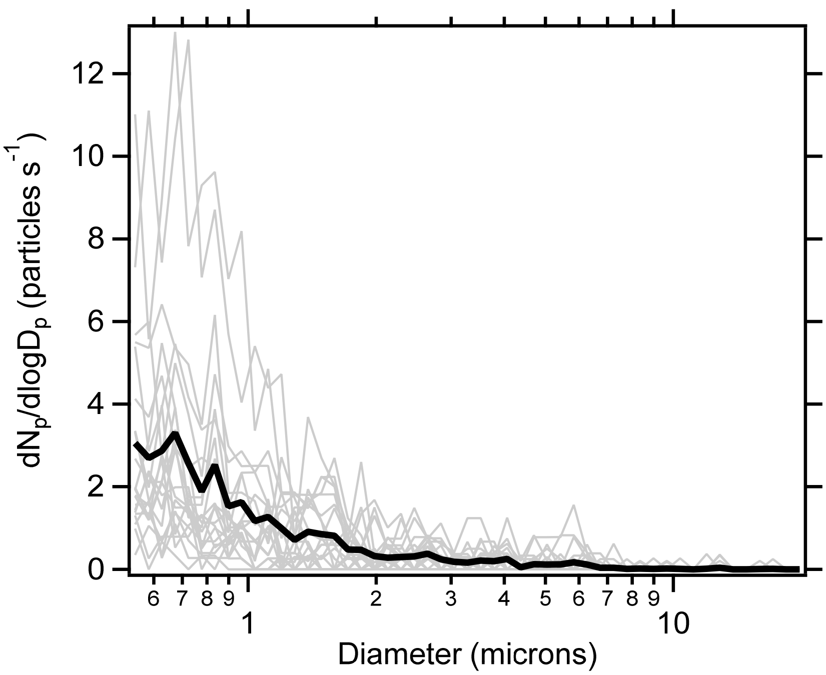

Figure S2: Observed average particle size distribution for speaking with no mask.

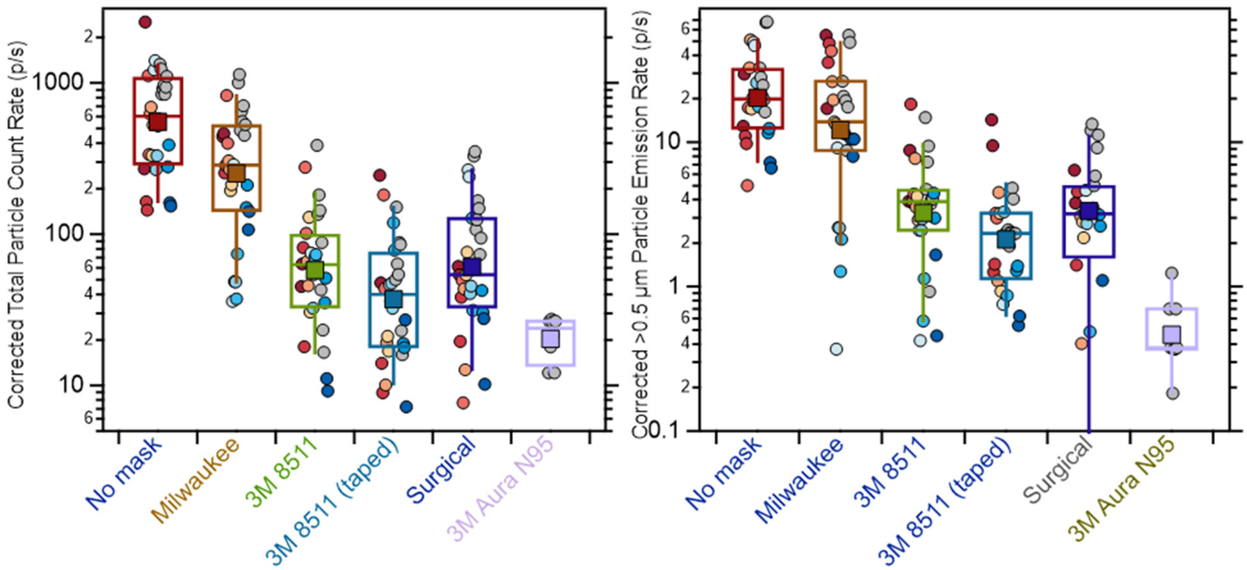

Figure S3: Particle emission rates from speaking with various face coverings measured with the (left) CPC for all particles > 10 nm and (right) with the APS for particles > 0.5 microns. Point colors correspond to different participants. The box and whisker plots show the median (horizontal line), 25th/75th percentile (boxes), and 10th/90th percentiles (whiskers), along with the geometric mean (square). The observed particle count rates were adjusted upwards to account for the fraction of time spent speaking (averaging 75%) and for the total exhaled breath during speaking, which we assume to have a flowrate of 13 lpm, following the approach in Cappa et al. (2021).

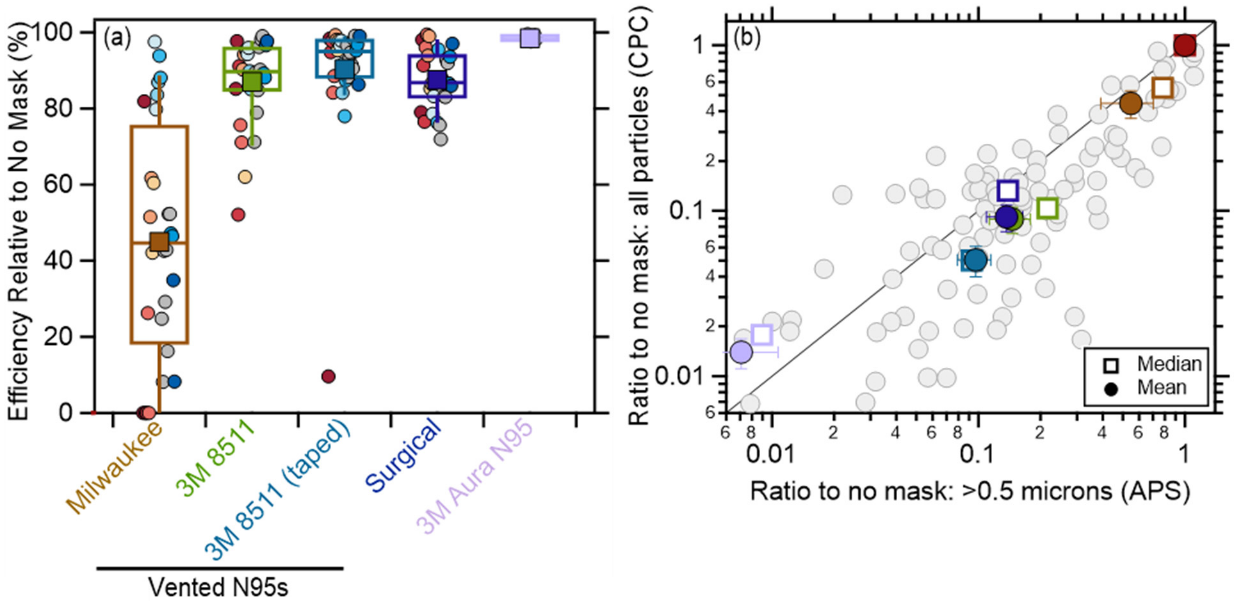

Figure S4: Same as Figure 1a,b but after subtracting the background values from the CPC and APS measurements.

Table S1: Tables of p values calculated using a paired t-test for (top-to-bottom) $\log_{10}(R_{\text{mask}})$ and $\log_{10}(\overline{N}_p)$, where the $\overline{N}_p$ is the observed particle count rate from the CPC. The individual p values are highlighted with color depending on their range, with gold ($p \leq 10^{-4}$), yellow ($10^{-4} < p \leq 0.05$), light blue ($0.05 < p \leq 0.2$) and dark blue ($p > 0.2$).

log(Ratio)	Milwaukee	3M 8511	3M 8511 (taped)	Surgical	3M Aura
Milwaukee		6.34E-05	2.12E-05	4.04E-04	8.20E-05
3M 8511			0.033	0.831	0.089
3M 8511 (taped)				0.062	0.070
Surgical					4.12E-03
3M Aura					

log(Particle Counts)	No Mask	Milwaukee	3M 8511	3M 8511 (taped)	Surgical	3M Aura
No Mask		5.24E-03	2.52E-08	2.22E-09	5.02E-09	1.27E-04
Milwaukee			6.34E-05	2.12E-05	4.04E-04	4.45E-04
3M 8511				0.033	0.831	0.084
3M 8511 (taped)					0.062	0.059
Surgical						8.32E-03
3M Aura						