Title: An improved and highly efficient geometry for facemasks

Authors: Christopher D. Cappa[1,*], The San Francisco Opera Costume Department[2,†], William D. Ristenpart,[3] Santiago Barreda,[4] Nicole M. Bouvier,[5] Anthony S. Wexler,[6] Sanziana A. Roman[7,*]

Affiliations:

[1] Dept. of Civil and Environmental Engineering, Univ. of California Davis; 1 Shields Ave., Davis, CA 95616 USA

[2] Costume Department, San Francisco Opera; 301 Van Ness Ave, San Francisco, CA 94102, USA

[3] Dept. of Chemical Engineering, Univ. of California Davis; 1 Shields Ave., Davis, CA 95616 USA.

[4] Dept. of Linguistics, Univ. of California Davis; 1 Shields Ave., Davis, CA 95616 USA.

[5] Department of Medicine, Division of Infectious Diseases, Icahn School of Medicine at Mount Sinai, 1 Gustave L. Levy Place, New York, NY 10029, USA

[6] Dept. of Mechanical Engineering, Univ. of California Davis; 1 Shields Ave., Davis, CA 95616 USA.

[7] Department of Surgery, Univ. of California, San Francisco; 1660 Divisadero St., San Francisco, CA 94143 USA

[†] Includes: Amy Ashton-Keller, Daniele McCartan, Galen Till, Jai Alltizer

*Corresponding authors: cdcappa@ucdavis.edu or Sanziana.Roman@ucsf.edu

Abstract

Wearing masks and face coverings helps reduce transmission of respiratory diseases. Various mask designs exist that target different populations, occupations, and environments. Here, we present evidence that a new facemask design, originally made for professional singers, offers advantages that will strongly benefit the public. Specifically, we show that with proper fitting the reusable cloth singing mask achieves overall filtering efficiencies for both exhaled expiratory aerosols and for inhaled ambient aerosols of >93%, better than surgical masks and approaching N95 respirators. We attribute the high efficiency largely to the mask design, rather than material. The mask design also provides for less inhibited mouth and jaw movement and overall lower humidity within the mask, suggesting it may provide a more palatable, high-efficiency alternative to medical-grade masks for the public.

1 Main

Respirators, face masks, and coverings play important roles in protecting wearers in various occupational settings and are important public health tools for reducing transmission of respiratory disease (*1, 2*). Masks differ in style, features, materials, and fit—including their overall level of protection—to account for different exposure conditions and wearer requirements. Often the most high-efficiency masks, such as N95 respirators, are those in the least supply, especially in times of critical need such as during the COVID-19 pandemic (*3*). When particularly transmissible variants of respiratory diseases arise, as is currently the case with the SARS-CoV-2 virus,(*4*) the need grows for masks for the public having high efficiency, but that have distinct supply chains from medical-grade masks and respirators.

Willingness to wear facemasks depends on real and perceived psychological and physiological drawbacks of mask wearing, which includes increased skin temperature, elevated humidity, difficulty breathing, and discomfort when speaking (*5, 6*). New mask designs that help to mitigate these drawbacks may precipitate greater willingness of people to wear masks, especially if such masks have high overall filtration efficiencies. Not all occupations benefit equally from current mask designs owing to the particular nature of their work. One community notably underserved by standard masks is that of performers, singers. Singing and theater performing require mask designs that generally allow for much more jaw movement compared to other professions as well as increased space between the face and the mask material. Thus, any mask appropriate for singing will also be more comfortable for speech, generally. Finally, group singing presents a particular challenge for community transmission of respiratory disease owing to multiple people vocalizing consistently and at the same time (*7*) (compared to speaking, where people typically take turns) and the loudness of singing compared to normal speech, as the production of potentially virus-laden aerosols increases with volume (*8, 9*). As such, masks used in conjunction with singing necessarily require relatively high efficiency.

Here, we characterize the aerosol-reduction efficacy of a mask designed originally for singing, but that we find has general benefits for wearing by the public. Developed by a surgeon who is a former opera singer (co-author S. A. R.) in partnership with the San Francisco Opera, the singing mask here (Figure 1a,b; see *Methods*) uniquely allows for facile jaw movement yet maintains overall high efficiency towards emission of expiratory aerosols, even after accounting for leakage flows. Some other masks targeting singers have been introduced during the COVID-19 pandemic. However, while the singing mask here shares some similarities it differs from these others in terms of fit, material, adjustability, and comfort. Importantly, we explicitly characterize the mask efficacy, which is the key factor. In addition, the mask allows the wearer to drink through a straw if needed without removing the mask, which lowers the risk of exposure over removing the mask and could provide benefits for rehearsals or in other situations where drinking occurs (e.g., schools, cafes, bars). The mask also efficiently filters ambient particles, demonstrating substantial protection to the infection-naive wearer as well. Although designed to accommodate singers, the high overall mask efficiency (>93%) suggests that the singing mask can provide a useful alternative to existing high-efficiency masks (e.g., N95's) for the public.

Following experimental methods desscribed in previous studies (*9, 10, 11; see Supplemental Material*), and consistent with previous findings (*8*), the observed particle emission rates for singing ($\langle \dot{N}_{p,sing} \rangle$ = 11.9 p/s) exceeded those for talking ($\langle \dot{N}_{p,talk} \rangle$ = 3.3 p/s by about a factor of three when no mask was used (Figure S1). The particle size distributions generally resembled each other for speaking and singing, although singing led to a slight enhancement in the number of particles between about 1 μm and 5 μm (Figure S2). Singing and talking differ somewhat in their physiological underpinnings. Singing and 'projecting' the voice typically involve a more rapid closing phase of the vocal folds, resulting in more high-frequency energy in the voice-source spectrum and a louder output sound (*12*). The higher vocal fold velocities, and the higher degree of vocal fold tension required to produce these higher velocities, could both influence the particle sizes and numbers produced by singers. Singing also requires different valving strategies at the larynx to keep subglottal pressure (and loudness) constant throughout a single 'phrase,' which could also result in different particle size distributions between speaking and singing (*13*). Regardless of the physiological origin, this small variability in the inherent particle size distribution between singing and speaking will have little influence on the efficiency with which the mask reduces emission of particles from expiration to the surrounding environment.

Representative aerosol emission data from one individual singing Ludwig van Beethoven's *Ode to Joy* with no mask or while wearing various facemasks, including the singing mask, demonstrate that the efficacy of expiratory particle filtration for airflow passing through the mask material varies with mask type (Figure 1c; Figure S3). Notably, the through-mask efficiency for the singing mask is as high as for an N95 and higher than that for two different types of surgical masks, as well as for various cloth masks including two made of the same cloth as the singing mask (see *Supplemental Materials*). Considering multiple participants, the through-mask reduction efficacy for expiratory aerosols while speaking the *Rainbow Passage* (*14*), singing *Ode to Joy*, and singing other user-selected songs was very high for the singing mask, with >99.5% average reduction observed for all activities and the lowest efficiency for a single individual of only 96.5% (Figure 2a). This high efficiency exceeds that observed for medical-grade surgical masks (Figure 2b) and for KN95 masks during speaking maneuvers (*10*) but is similar to that for an N95 as noted above (Figure 1c). With respect to sound, the mask effectively acts as a low-pass filter (Figure S4), consistent with previous findings on speech and mask wearing (*15*). The good aerosol filtering differs notably from a homemade cloth masks made from t-shirts—these had particle emission rates higher than observed without the mask owing to shedding of mask fibers, which may act as aerosolized fomites (*10*). The high filtering efficiency of the singing mask occurs despite considerable shedding when participants intentionally rubbed the mask against itself, (such as might occur with opening/closing the bottom for potential water sipping), with a shedding rate greater than for the homemade cloth masks (*10*) (geometric mean = 20 p/s for the singing mask vs. 1 p/s for the homemade mask; Figure S5). Most likely, this distinct lack of shedding during use for the singing mask results from separation of the mask material and the wearers face, thus eliminating contact abrasion of the mask material.

Additionally, the mask-face separation also likely contributes to the filtering ability for air that passes through the mask (Figure 1b). By creating distance between the mouth and nose and the mask material, the airstream will expand (*16*) and interact with a greater area of the mask while decreasing the air velocity (*17*), which will increase filtering capacity (Figure S6). For example, a single-fiber filtering efficiency of 90% at 0.5 cm separation will increase to over 99% at the singing mask separation of 6 cm assuming jet expansion. We tested this sampling from one participant while singing *Ode to Joy* who wore a two-layer and three-layer mask made of the same cloth but having a pleated surgical-mask style, as well as wearing a variation of the singing mask that eliminates the opening for drinking (see *Methods*; Figure S7). The pleated masks reduced the through-mask particle emission by a substantial, but comparably small, factor of ~14 compared to a >500 fold reduction for the singing masks (Figure 1b). This provides evidence of the key role that the separation of the mask material from the face plays in reducing through-mask expiratory particle emission.

The overall mask performance additionally depends on the extent to which particles escape from the edges of the mask; the above discussion only addresses air that passes through the mask material. Any leakage that results from imperfect sealing between the mask and wearers' face reduces all overall mask efficiencies (*11, 18, 19*). For high-quality filtering materials, the extent of leakage is the primary determinant of mask efficiency (*19*). Following from our previous study on surgical mask leakage during speaking (*11*), we determined the emission rates of particles from the top, bottom, and side quadrants of the singing mask while participants sang *Ode to Joy* (Figure

S3). The observed particle emission rates from these quadrants exceeded those for the forward, through-the-mask material direction (Figure 3a). Nonetheless, wearing a mask substantially decreases the observed particle emission rates from the no-mask condition in all directions.

The greatest between-participant variability in the absolute emission rate occurs for sampling from the mask top quadrant, near the nose (geometric standard deviation = 0.85). This suggests a greater sensitivity of emissions in this direction to how well the mask seals around the nose, which can result from individuals wearing the masks with different tightness. We confirmed this by having one participant sing *Ode to Joy* while securing the mask with (i) only the ear loops snug, but not tight, (ii) only the ear loops tight, and (iii) the ear loops tight plus the two head straps (Figure S8). With the snug ear loops-only, the observed particle emission rate from the mask top decreased by only a factor of three over no mask. However, with the tight ear loops-only the particle emission rate from the top decreased by a factor of 38 over no mask and with the tight ear loops and the head straps by a factor of 80 over no mask.

Sampling from the bottom quadrant yielded the largest with-mask particle emission rates. While this could indicate the greatest leakage flow in this quadrant, the associated particle size distribution differs notably from those observed in the other quadrants (Figure S9). In particular, a large-diameter mode between ~3-10 microns was observed, which strongly indicates a non-expiratory source. Owing to the extended volume of the singing mask, most participants could not avoid having the mask rub against the sampling funnel while sampling from the bottom quadrant. This strongly implicates shed fibers as a contributing particle source; consequently, the particle emission rate from the bottom quadrant provides an upper limit to leakage of expired particles.

We obtain the overall mask efficiency (η) for reduction of expiratory aerosol emission for each individual while singing by combining the observed particle emission rates without a mask to emission from the various quadrants plus through-mask (Figure 3b; see Methods). The median is 98% and the mean 97 $\pm$ 3%. (If the measurements from the participant who repeated the activities are combined into a single value the median is 97% and the mean 96 $\pm$ 4%.) Mask efficiencies of greater than 93% were determined for all but two participants wearing the singing mask. One of these individuals (η = 88%) had the highest normalized emission rate for the top quadrant, indicating that leakage around the nose contributed to this low, but still very good, efficiency. The other individual (η = 91%) produced a somewhat high normalized emission rate from the mask top and the second highest from the mask bottom, suggesting that both leakage and, likely, shed mask fibers contributed. Regardless, the observed high overall efficiencies indicate that with proper fit, in particular ensuring a good seal around the nose, the singing mask provides substantial reduction expiratory particle emission even while singing. Also, no visible spittle (i.e., droplets much larger than those measured here) was observed with wearing the singing mask, suggesting efficient elimination of very large droplets.

The overall efficiency determined here for the singing mask greatly exceeds that found for surgical masks, and further there is substantially less individual variation between participants (Figure 3b,c). The singing mask design provides a tighter fit that reduces, but does not eliminate, variability in the fit quality. This, together with the greater efficiency for air passing through the mask, leads to the overall improved performance compared to a surgical mask. Notably, the overall efficiency of the singing mask including leakage exceeds the efficiency of the surgical mask even if we assume zero leakage flow. While some tools exist to help improve sealing of cloth and surgical masks (*20, 21*) their use during singing is infeasible. Similarly, so-called double masking has been suggested, including by the U.S. Centers for Disease Control (*22*), as a way to improve both filtering ability and fit, and thus overall efficiency (*23*), but this too would not be appropriate for singing. Even so, outside of singing contexts (e.g., public adoption), double masking does not ensure one obtains a good seal and thus the actual benefit is difficult to know—especially given the wide range of cloth masks available. Also, while qualitative, the participants generally indicated that greater breathing comfort with the singing mask compared to the mask(s) each individual typically wore, most likely owing to the increased mask-face separation. We speculate that the more open design of the singing mask could increase mask wearing compliance.

While mask wearing plays an important role in reducing emission of expiratory particles, masks can also reduce inhaled particles concentrations. To address this, we measured for one participant the time-varying concentration of particles inside the singing mask during breathing (Figure 4). When leaving the mask neck seal intentionally somewhat loose the peak particle concentrations inside the mask upon inhalation approximately equaled the room air aerosol concentration. Upon exhalation the concentration fell to very low values, indicative of the lower aerosol concentration in exhaled breath compared to most ambient environments. However, when the mask was worn as designed, with the neck seal tight, the inside-mask concentration upon inhalation rose only to about 6% of the room air concentration, indicative of an effective efficiency of 94% for inhalation, similar to that found for expiratory particle emission. Distinct from expiratory aerosols, the room air aerosols were primarily smaller than 0.5 microns, with only ~10% of the particles larger. Filtration efficiency typically increases with particle size above this range (*24*) and thus we expect the efficiency of the singing mask towards expiratory aerosols emitted by others will be even greater than found here. Similar to exhalation, the singing mask geometry likely contributes to the high filtration efficiency towards ambient particles during inhalation. The greater mask-face separation will lead to air being drawn through nearly the entirety of the mask surface area, with a consequently lower face velocity and increased filtration efficiency compared to conventional designs. Overall, this demonstrates that wearing of the singing mask provides major benefits to both the wearer and others.

In summary, the overall efficiency of the singing mask when fit properly compares favorably to that expected for N95 respirators. As the materials comprising the singing mask and N95s differ, the singing mask, or similarly designed masks, could provide a viable alternative to N95s outside of healthcare or other specialized occupational settings for situations when greater mask efficiency is necessary or desired. For singers and other performers, in particular, the singing mask, when fit properly, has sufficiently high efficiency—maintained throughout the act of singing—that its adoption could facilitate in-person rehearsals with multiple people as long as other best practices (e.g., good ventilation) are also adopted.

2 Methods

Mask Design

The singing mask, shown in Figure 1, uses a two-bone structure to separate the mask material from the main area of the face by about 6 cm, while still allowing for a good seal. A 0.6 cm wide, 10 cm long thin aluminum strip is used around the nose, which the wearer can mold to their face. A felt strip on the inside runs across the nose area to help with sealing. The sides of the mask extend over the cheeks, nearly to the ears. Adjustable elastic ear loops keep the sides of the mask in place and two additional ties fasten the mask around the wearer's head to further seal the mask against the face. The mask completely envelops the wearer's jaw and chin, with an adjustable elastic band below the jaw that keeps the mask tight against the neck while allowing for free jaw movement. The mask has two main regions: the upper, boned structure that holds the filtering fabric in front of but away from the mouth and nose, and an unstructured, expanded volume below the chin. The upper region is composed of three layers in a cloth-liner-cloth arrangement, with 200 thread count cloth outer layers and and Pellon® 50 inner layer attached to the cotton with a fusible webbing material. The Pellon® 50 inner layer helps to stiffen the mask material but likely provides little filtering. The length of the top region is about 12 cm. The lower expanded volume is made of two cloth layers and opens at the bottom to allow for drinking by straw during rehearsals. The opening is sealed by folding the mask twice and then securing with embedded Velcro strips. Negligible particle emissions from this area were observed after closing. When closed, the length of the expanded region is about 10 cm. A modified version of the singing mask was also constructed. The difference from the standard singing mask is that there is no bottom opening; the modified mask is otherwise identical. During use, the cloth material comprising both the singing and modified singing masks was observed to deflect inward (for inhalation) and outward (for exhalation). However, the boning provides support that limits the amount of cloth deflection associated with inhalation and exhalation. With intentionally loose wearing, the deflection magnitude decreased. Hence, deflection provides a qualitative indication of good fit. The mask internal volume is about 0.5 L. This is similar to the tidal volume associated with normal breathing (*25*), but about half that for singing (*26*). Given the limited deflection of the mask material this implies substantial exchange of air, which will help to alleviate any depletion of oxygen or buildup of CO_2.

Proper wearing of the singing masks includes: first securing the mask using the ear loops, molding the aluminum strip around the nose, tightening the ear loops, tightening the neck strap elastic band, tying the top strap around the users head near the parietal eminence, and then tying the bottom strap around the users neck while sitting or standing up straight. With proper wearing, one should see no obvious gaps, especially around the nose; this can be qualitatively assessed by having the wearer look down towards their nose moving only their eyes. If they can see their nose below the mask then there is a gap and the mask should be better secured.

Two additional masks were constructed using the same materials as the singing mask. One was constructed having only two cloth layers and one having three layers (cloth-liner-cloth). Both used a general pleated surgical mask design, based on the design initially promoted by the U. S. Centers for Disease Control; the directions and instructional video originally made available by the CDC are no longer available online. Both used the same ear loops as with the singing mask and included two head straps. Additional tests for the through-mask efficiency were performed by one participant using an N95 respirator (3M, Model 8210), two different surgical masks (a medical-grade ValuMax 5130E-SB and an unknown model), and a non-medical 'Fashion Dust Preventive Mask' (30% cotton, 70% polyester) from YiWu Xuefeng Mask Factory, both without (FDPM) and with (FDPM(N95)) an N95 insert.

Human subjects

We recruited 12 volunteers (4 self-identified male and 8 self-identified female), ranging in age from 18 to 65 years old. The Institutional Review Board of the University of California, Davis approved this work (IRB# 844369-4), and all research performed followed the Institutional Review Board guidelines and regulations. Prior to the tests, written informed consent was obtained from all participants. Information collected from participants included their age and singing range (e.g., soprano, alto, baritone). Only self-reported healthy non-smokers were included in the study. All participants had to take the UC Davis Daily Symptom Survey (https://campusready.ucdavis.edu/symptom-survey) prior to accessing campus. Participants were encouraged to obtain a negative COVID-19 test just prior to their participation, although this was not required or tracked. Informed consent for publication of identifying information was obtained from the participant shown in Figure 1.

Expiratory Aerosol Experimental Description

We used an experimental setup similar to that in previous work (*9, 10, 27*). In brief, participants were asked to breath, speak, or sing in front of a stainless steel funnel connected by nonconductive tubing to both an aerodynamic particle sizer (APS, TSI Model 3321, 5 L/min) and a condensation particle counter (CPC, TSI Model 3775, 0.3 lpm) that were located in a HEPA-filtered laminar flow hood. The APS characterizes particles from 0.3 to 20 microns in aerodynamic diameter, with a decreased detection efficiency for particles <0.5 microns. The CPC characterizes the number concentration of all particles sampled, although with a reduced efficiency for particles larger than about 1 micron owing to impaction losses.

Participants donned the singing mask without direct assistance. They were asked to tighten the ear loops and the neck closure, pinch closed the metal bar in the singing mask around their nose, and to tie the neck and head straps. They were asked to "tighten everything as much as possible, but such that you are still comfortable."

Respiratory emissions with or without a mask were tested with the participant's head oriented in one of four positions, relative to the sampling funnel. These orientations were the same as those described in Cappa et al. (*11*) and are shown in Figure S3. These were as follows.

(i) *Forward/Through*: The participants sat directly facing the APS funnel. This was the orientation examined in prior studies (*9, 10, 27*). In this orientation, the APS samples air that has passed through the mask material.

(ii) *Top*: The participants tilted their heads downward to have the bridge of the nose approximately centered on the APS funnel, allowing for sampling of particles that leak from the mask nose area.

(iii) *Side*: The participants turned their head 90 degrees to face perpendicular to the APS funnel, with the side singing mask approximately centered on the funnel

(iv) *Bottom*: The participants positioned their chin just above the APS funnel with the mask material from the expanded volume over the top of the funnel. This allowed for sampling of particles that leak from the mask neck area.

Participants performed the speaking and singing activities while either wearing or not wearing the singing singing mask. Breathing was performed only with no mask. For speaking, participants were asked to read the "Rainbow Passage," both with no mask and while wearing the mask while oriented in the "forward" direction (Figure S3). Participants also performed two singing activities. First, they sang in English Beethoven's *Ode to Joy* from his Ninth Symphony, both wearing and not wearing the mask in each of four head orientations described above (Figure S3). Second, participants sang a song of their choosing of about two minutes in length. They performed this second activity both without a mask and with the mask in the forward orientation only.

For all speaking and singing activities, participants were asked to carry out the activity at a comfortable volume; no effort was made to control for volume differences between participants. While loudness can influence the emission rate of expiratory aerosols (*9*), we focus on the reduction achieved by wearing the mask, and thus loudness differences will have little effect. All particle emission rates were adjusted to units of particles per second by accounting for the actual duration of vocalization (t_{voc}), which excludes pauses between words or phrases as determined from microphone recordings. One participant repeated the *Ode to Joy* activities multiple times on different days.

The directly observed particle emission rates ($\dot{N}_p^{obs}$) does not necessarily equate to the total particle emission rate owing to differences between the APS total airflow rate (5 lpm) and the airflow rate of the expiratory activity ($Q_{\text{exp,tot}}$), as discussed in Cappa et al. (*Submitted*).(*11*) This raises certain challenges when combining the measurements from the different orientations to estimate the overall mask efficiency. Typical airflow rates associated with talking range from ca. 8-15 lpm (*16*). For singing, airflow rates are in the same general range although skewed perhaps a little higher, especially for louder singing, and females tend to exhibit slightly smaller values than males (*28, 29*). Consequently, the actual particle emission rates associated with talking and singing without a mask are about a factor of 8-15 times higher than the observed values. We present the unadjusted (observed) absolute values to remain consistent with previous studies.

With mask wearing the airflow during expiration can be split in multiple directions, with the amount of air in a given direction not known *a priori*. We previously accounted for this split for surgical masks while talking or coughing using a Monte Carlo method to determine probability distributions of the overall mask efficiency based on the median values across the population of participants (*11*). Overall, relatively narrow probability distributions resulted with only moderate sensitivity to the assumed split between the air that passed through the mask versus escaped out the top, sides, or bottom and the greatest deviations found for very low total expiratory airflow rates. We used a similar approach here, but applied the approach to the observations from each individual, rather than using the medians across participants. Over 10,000 iterations, we determined the fraction (f_x) of air that goes in a particular direction from a random distribution. We further assumed a log-normal distribution of expiratory airflow rates centered at 13 lpm with a width of 1.3. The $\dot{N}_{p,i}^{obs}$ in each orientation (i) for each individual are adjusted to actual particle emission rates ($\dot{N}_{p,i}$) based on the above assumptions. While we present the unadjusted (observed) absolute values to remain consistent with previous studies, when reporting particle emission rates normalized to the no-mask condition we use the airflow-adjusted values, which are also used to calculate the overall mask efficiency. The overall mask efficiency, η, is:

$$\eta = 1 - \frac{\sum \dot{N}_{p,i}}{\dot{N}_{p,nomask}}$$

The average value and standard deviation for each individual were determined from the distribution of η values from the simulations.

In the "bottom" orientation, the participants positioned their chin just above the APS funnel, with the mask material from the expanded volume draped over the top of the funnel. Some participants could not completely avoid contact between the mask material and the funnel in this position; consequently, mask fibers shed by friction between mask and funnel may have contributed to the particle counts from participants in this orientation.(*10, 30, 31*) Such non-expiratory particles confound the respiratory emission measurements, but they may still carry pathogens as aerosolized fomites (*32*). Based on the observed particle size distributions, a few participants appeared to generate a significant amount of mask-fiber particles. For these participants, when assessing the overall mask efficiency, we used the median value from the other participants in place of the value measured for the individual.

One participant sang *Ode to Joy* wearing a variety of mask types (see *Mask Design*) in the forward (through-mask) position, with three replicates for each mask type.

All data processing analyses were carried out using Igor Pro (v. 8.0.4.2, Wavemetrics). Differences between the $\dot{N}_{p,i}$ values are calculated after log-transformation using a single factor ANOVA test.

Inhalation Experimental Description

The concentration of particles inside the singing mask was measured for one participant while breathing. Here, a tube composed of conductive silicon was inserted below the mask at the neck area and the sampling end of the tube was positioned to sit in the main mask area in front of the face. The tube was attached to a condensation particle counter, which sampled at 0.3 lpm and measured the total concentration of particles every 1 second. Two experiments were conducted. In both, the participant was asked to breathe deeply in and out through their nose 10 times at a rate of about five breaths per minute while the particle concentration inside the mask was continually monitored. In one experiment, the neck strap was fully tightened, as appropriate for correct fit of the singing mask. For the second, the neck strap was left slightly loose to intentionally introduce a leak. Prior to starting the measurement, the participant was asked to breathe three times after the sampling tube was inserted. The concentration of particles in the room air was measured just prior to the measurements of particle concentrations inside the mask.

Influence of face-mask separation distance on filtration efficiency

For an expiratory jet, the air velocity, u, decreases with distance as $1/(\alpha \cdot x)$, where α is the divergence angle (~20°) and x is distance (*17*). Single-fiber filtration efficiencies (η_f) increase as velocity decreases, with $\eta_f \sim 1 - \exp\left(K \cdot u^{-\frac{2}{3}}\right)$, and where K is a scaling factor (*33*). Thus, for an aerosols carried in an expanding jet the single-fiber filtration efficiency will scale with the mouth-mask material separation distance as $\eta_f \sim 1 - \exp\left(K^* \cdot x^{\frac{2}{3}}\right)$, where K^* is a scaling factor. For a mask-face separation distance of ~6 cm for the singing mask, compared to ~0.5 cm for a conventional cloth mask, the air velocity through the singers mask is reduced by about 73%, leading to an increase in the single-fiber filtering efficiency (Figure S6). For an inspiratory flow, the airflow may pass through a greater proportion of the overall mask surface area when the mask surface is sufficiently separated from the face to avoid mask-face contact and when leakage is negligible. The face velocity for the singing mask relative to a conventional cloth mask that makes contact with the face will scale as the mask area through which the air passes. The total mask area is about 550 cm^2. For a conventional mask, we assume that the airflow passes through a circular area around the nose and the mouth, and we estimate a typical diameter will be ~7 cm, corresponding to an area of 38 cm^2. Thus, the face velocity through the singers mask during inspiration is ~14 times as large as through a conventional cloth mask, which engenders a large increase in the single-fiber filtration efficiency (Figure S6).

3 Reference

1. J. Howard *et al.*, An evidence review of face masks against COVID-19. *Proceedings of the National Academy of Sciences* **118**, e2014564118 (2021).
2. J. T. Brooks, J. C. Butler, Effectiveness of Mask Wearing to Control Community Spread of SARS-CoV-2. *JAMA*, (2021).
3. T. Dai, G. Bai, G. F. Anderson, PPE Supply Chain Needs Data Transparency and Stress Testing. *Journal of General Internal Medicine* **35**, 2748-2749 (2020).
4. Public Health England, *Investigation of novel SARS-CoV-2 variant, Variant of Concern 202012/01; Technical briefing 2* (2021 https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/948152/Technical_Briefing_VOC202012-2_Briefing_2_FINAL.pdf).
5. J. L. Scheid, S. P. Lupien, G. S. Ford, S. L. West, Commentary: Physiological and Psychological Impact of Face Mask Usage during the COVID-19 Pandemic. *International Journal of Environmental Research and Public Health* **17**, 6655 (2020).
6. S. Taylor, G. J. G. Asmundson, Negative attitudes about facemasks during the COVID-19 pandemic: The dual importance of perceived ineffectiveness and psychological reactance. *medRxiv*, 2020.2011.2017.20233585 (2020).
7. S. L. Miller *et al.*, Transmission of SARS-CoV-2 by inhalation of respiratory aerosol in the Skagit Valley Chorale superspreading event. *Indoor Air* **31**, 314-323 (2021).
8. M. Alsved *et al.*, Exhaled respiratory particles during singing and talking. *Aerosol Science and Technology* **54**, 1245-1248 (2020).
9. S. Asadi *et al.*, Aerosol emission and superemission during human speech increase with voice loudness. *Scientific Reports* **9**, 2348 (2019).
10. S. Asadi *et al.*, Efficacy of masks and face coverings in controlling aerosol particle emission from expiratory activities. *Scientific Reports* **10**, 15665 (2020).
11. C. D. Cappa *et al.*, Expiratory aerosol particle escape from surgical masks due to imperfect sealing. *Scientific Reports*, (Submitted).
12. B. Lindblom, J. Sundberg, in *Springer Handbook of Acoustics,* T. Rossing, Ed. (Springer, New York, NY, 2007).
13. H. J. Rubin, M. LeCover, W. Vennard, Vocal Intensity, Subglottic Pressure and Air Flow Relationships in Singers. *Folia Phoniatrica et Logopaedica* **19**, 393-413 (1967).
14. G. Fairbanks, *Voice and Articulation Drillbook*. (Harper and Row, New York, ed. 2nd, 1960), pp. 234.
15. R. Saeidi, I. Huhtakallio, P. Alku, in *INTERSPEECH 2016*. (International Speech Communication Association, San Francisco, 2016), pp. 1800-1804.
16. J. K. Gupta, C.-H. Lin, Q. Chen, Characterizing exhaled airflow from breathing and talking. *Indoor Air* **20**, 31-39 (2010).

17. M. Abkarian, S. Mendez, N. Xue, F. Yang, H. A. Stone, Speech can produce jet-like transport relevant to asymptomatic spreading of virus. *Proceedings of the National Academy of Sciences* **117**, 25237-25245 (2020).

18. T. Oberg, L. M. Brosseau, Surgical mask filter and fit performance. *American Journal of Infection Control* **36**, 276-282 (2008).

19. S. A. Grinshpun *et al.*, Performance of an N95 Filtering Facepiece Particulate Respirator and a Surgical Mask During Human Breathing: Two Pathways for Particle Penetration. *Journal of Occupational and Environmental Hygiene* **6**, 593-603 (2009).

20. D. A. Rothamer, S. Sanders, D. Reindl, T. H. Bertram, Strategies to minimize SARS-CoV-2 transmission in classroom settings: Combined impacts of ventilation and mask effective filtration efficiency. *medRxiv*, 2020.2012.2031.20249101 (2021).

21. P. W. Clapp *et al.*, Evaluation of Cloth Masks and Modified Procedure Masks as Personal Protective Equipment for the Public During the COVID-19 Pandemic. *JAMA Internal Medicine*, (2020).

22. J. T. Brooks *et al.*, Maximizing Fit for Cloth and Medical Procedure Masks to Improve Performance and Reduce SARS-CoV-2 Transmission and Exposure. *MMWR Morb Mortal Wkly Rep*, (2021).

23. M. Gandhi, L. C. Marr, Uniting Infectious Disease and Physical Science Principles on the Importance of Face Masks for COVID-19. *Med* **2**, 29-32 (2021).

24. F. Drewnick *et al.*, Aerosol filtration efficiency of household materials for homemade face masks: Influence of material properties, particle size, particle electrical charge, face velocity, and leaks. *Aerosol Science and Technology* **55**, 63-79 (2021).

25. S. Hallett, F. Toro, J. V. Ashurst, Physiology, Tidal Volume, in *StatPearls [Internet]* (StatPearls Publishing, Treasure Island, FL, 2020), Accessed on: 2 February 2021, https://www.ncbi.nlm.nih.gov/books/NBK482502/.

26. B. Binazzi *et al.*, Breathing pattern and kinematics in normal subjects during speech, singing and loud whispering. *Acta Physiologica* **186**, 233-246 (2006).

27. S. Asadi *et al.*, Effect of voicing and articulation manner on aerosol particle emission during human speech. *PLoS One* **15**, e0227699 (2020).

28. J. J. Jiang, R. B. Hanna, M. V. Willey, A. Rieves, The Measurement of Airflow Using Singing Helmet That Allows Free Movement of the Jaw. *Journal of Voice* **30**, 641-648 (2016).

29. E. B. Holmberg, R. E. Hillman, J. S. Perkell, Glottal airflow and transglottal air pressure measurements for male and female speakers in soft, normal, and loud voice. *The Journal of the Acoustical Society of America* **84**, 511-529 (1988).

30. D. Hospodsky *et al.*, Human Occupancy as a Source of Indoor Airborne Bacteria. *PLoS One* **7**, e34867 (2012).

31. R. P. Clark, S. G. Shirley, Identification of Skin in Airborne Particulate Matter. *Nature* **246**, 39-40 (1973).

32. S. Asadi *et al.*, Influenza A virus is transmissible via aerosolized fomites. *Nature Communications* **11**, 4062 (2020).

33. K. W. Lee, B. Y. H. Liu, Theoretical Study of Aerosol Filtration by Fibrous Filters. *Aerosol Science and Technology* **1**, 147-161 (1982).

4 Acknowledgements

The authors greatly appreciate the participation of the various professional and amateur singers who volunteered their time. **Author contributions:** C. D. C. led the measurements and analysis. S. A. R. and A. A-K.. of the San Francisco Opera, SFO) designed the mask. SFO constructed the masks and SFO and C. D. C provided design suggestions. W. D. R. contributed to experimental design and interpretation. A. S. W., S. B., and N. M. B. contributed to interpretation. C. D. C, and S. A. R. led the manuscript writing. All authors reviewed and revised the manuscript for accuracy and intellectual content. **Competing interests:** S. A. R. and A. A-K., have filed a patent application for the singing mask. All other authors declare no competing interests. **Data and materials availability:** All data needed to evaluate the conclusions in the paper are present in the paper and/or the Methods. Additional data and files related to this paper will be made publicly available at doi:10.25338/B8GD1B and are available for review at https://bit.ly/3qUJpiy.

5 Figures and Captions

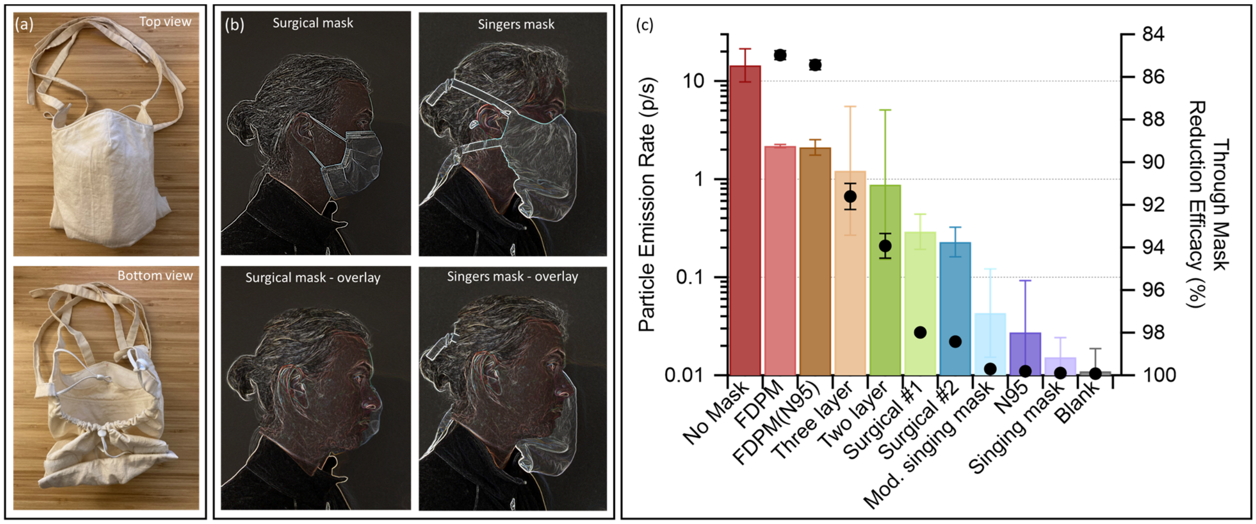

Figure 1. (a) Top and bottom view of the singing mask. (b) (top row) Images of one participant wearing a surgical mask and wearing the singing mask. (bottom row) Overlaid images of the participant with the surgical mask and with a singing mask to illustrate the increased mask-face material separation in the singing mask. The images in (b) were modified from the originals using the "glow edges" artistic effect in Microsoft PowerPoint to accentuate the mask edges and to overlay an image of the participant with no mask. Informed consent was obtained. (c) Observed particle emission rate for one participant singing *Ode to Joy* with no mask, or a homemade cloth two-layer or three-layer pleated mask made of the same material as the singing mask, a modified singing mask having no bottom opening, the standard singing mask (purple), a commercial cloth mask either without (FDPM) or with (FDPM(N95)) an N95 insert, either of two different surgical masks, or an N95 respirator (3M), as measured in the forward (through-mask) position. Note that jaw movement was substantially restricted with the non-singing masks, especially the N95 respirator. Three repeats were performed and error bars are 1σ geometric standard deviations. The right axis gives the associated reduction efficiency for the forward direction (black points).

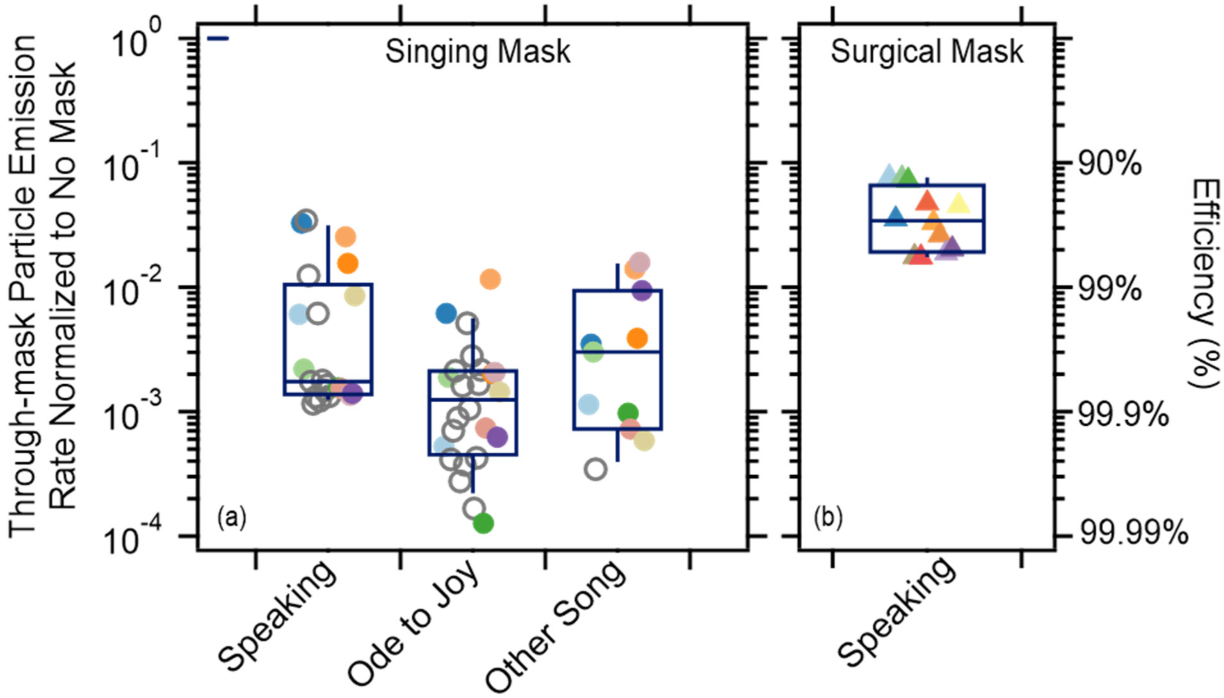

Figure 2. (a) The through-mask (forward) particle emission rates normalized to no mask (left axis) or the corresponding reduction efficiency (right axis) observed for participants while wearing the singing mask for speaking or singing either the *Ode to Joy* or a song chosen by the participant. Closed colored circles in (a) indicate unique individuals while open gray circles indicate repeats by one individual. (b) Normalized particle emission rates for participants speaking while wearing a surgical mask (data from Cappa et al. (*11*)). Note that the participants in (a) differ from those in (b). Box and whisker plots show the median, $25^{th}/75^{th}$ percentile, and $10^{th}/90^{th}$ percentile.

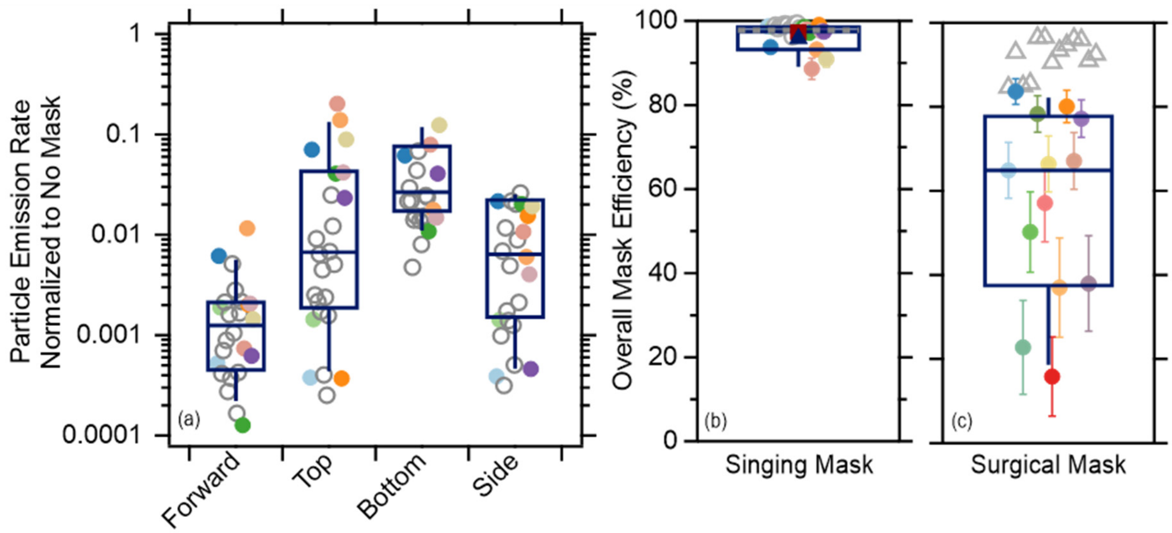

Figure 3. (a) Particle emission rates normalized to no mask wearing for singing *Ode to Joy* for the different orientations while wearing the singing mask. (b) The overall mask efficiency while singing *Ode to Joy* with the singing mask, accounting for leakage flows, colored by participant (circles). Uncertainty bars on individual points indicate 1σ determined from Monte Carlo simulations. The red square is the average across all measurements and the blue triangle the average after combining replicate measurements from one participant. (c) Overall efficiency for speaking with a surgical mask including leakage flows (solid points) or assuming all flow passes through the mask, i.e. zero leakage flows and perfect sealing (open points). Closed circles in (b) and (c) indicate unique individuals while open circles indicate repeats by one individual. Note that the participants in (a,b) differ from those in (c). Box and whisker plots show the median, $25^{th}/75^{th}$ percentile, and $10^{th}/90^{th}$ percentile.

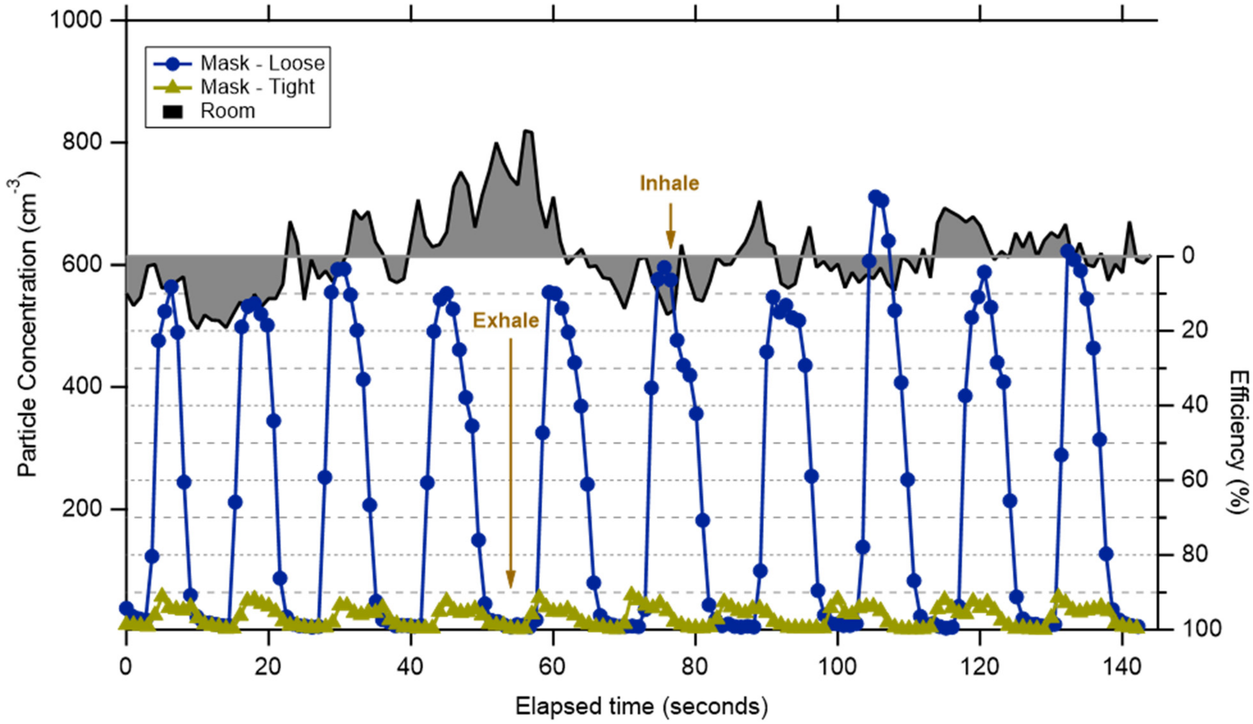

Figure 4. Time-series of particle concentrations measured for room air (solid black line), sampled inside the singing mask worn intentionally loose around the neck (blue circles), and when sampled inside the mask when worn tightly as designed (gold triangles). The right axis shows the approximate mask efficiency based on comparison with the mean room air concentration.

6 Extended Data Figures

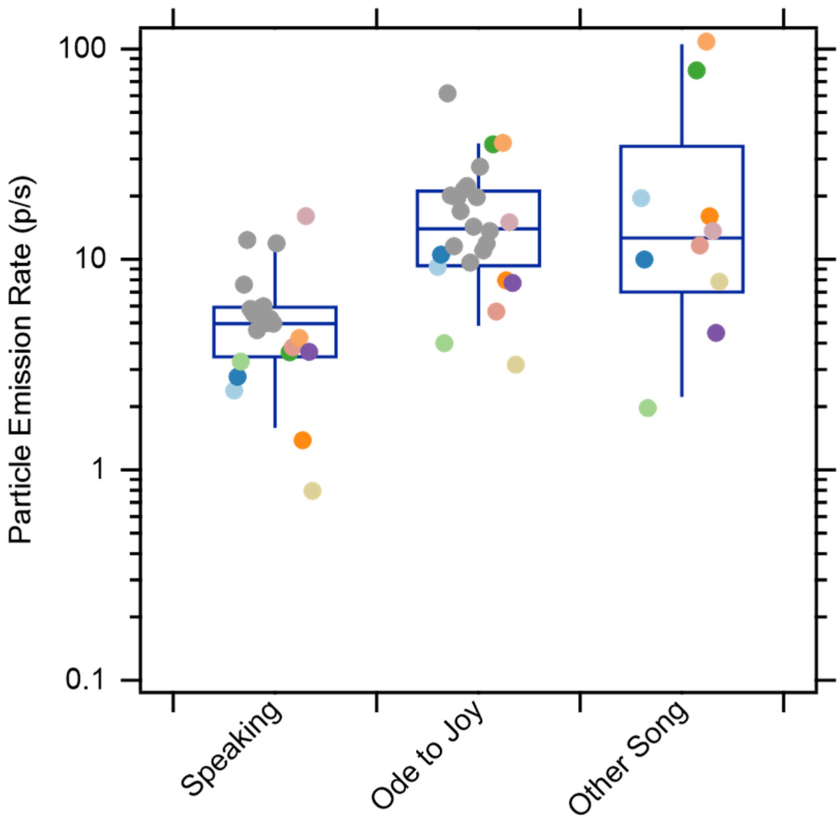

Figure S1. Observed particle emission rates (p/s) for the individual participants without mask wearing. These have not been corrected for undersampling by the APS (see methods). Emissions from the singing activities are three times greater than for speaking; the difference is statistically significant ($p = 0.002$). Points are colored by participant, with the gray dots indicating repeats from one individual.

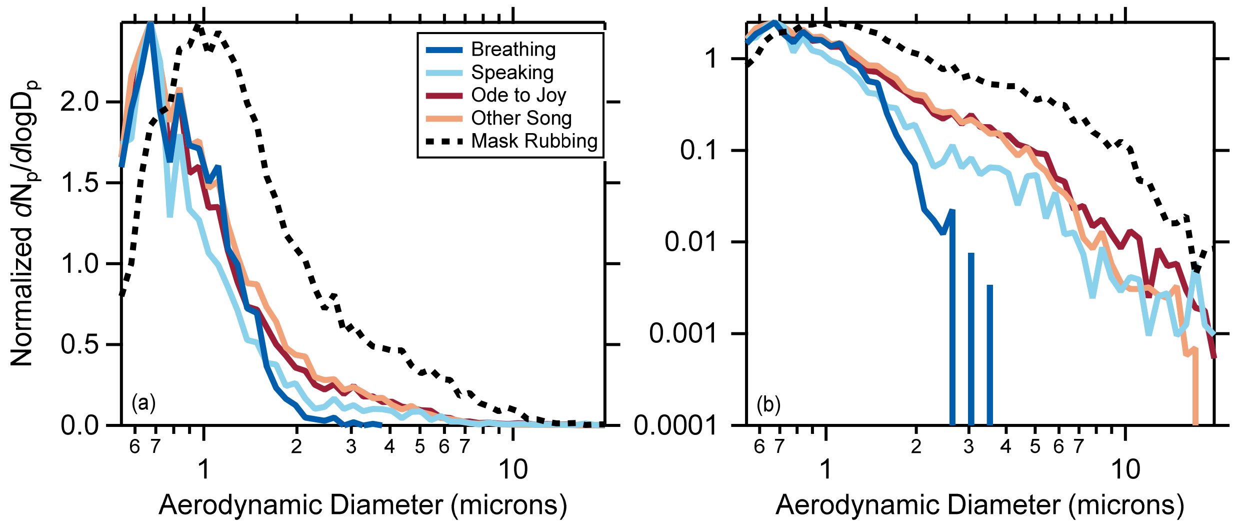

Figure S2. Particle emission rate size distributions for various expiratory activities (solid lines), i.e., breathing, speaking, and singing either the *Ode to Joy* or a song of the participants choice, and the size distribution resulting from physical rubbing of the mask material against itself (dashed line). All distributions are averages across the participants. The distributions are shown on (a) linear or (b) logarithmic y-axes.

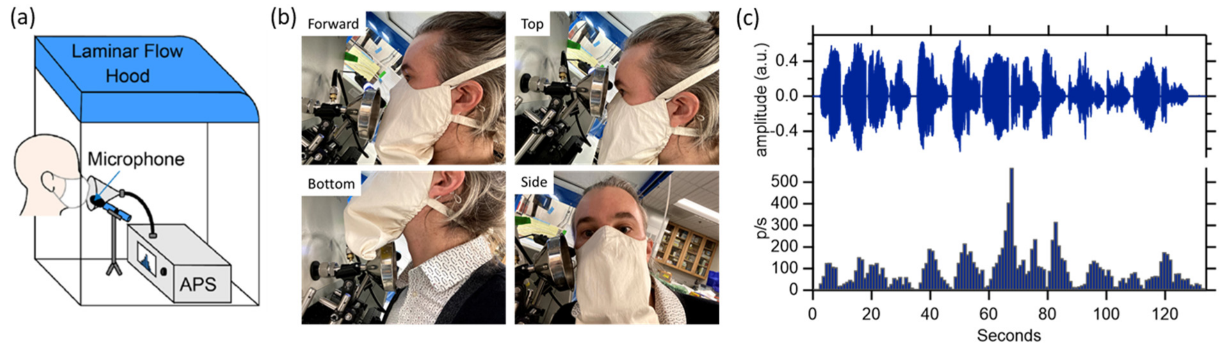

Figure S3. (a) Schematic of the experimental setup showing a participant wearing a mask in the forward orientation. (b) Photographs showing a participant in each of the four sampling orientations: forward, top, side, and bottom sampling. (c) Example microphone recording for a participant singing a song of the participants' choice without a mask and the associated particle counts by the APS.

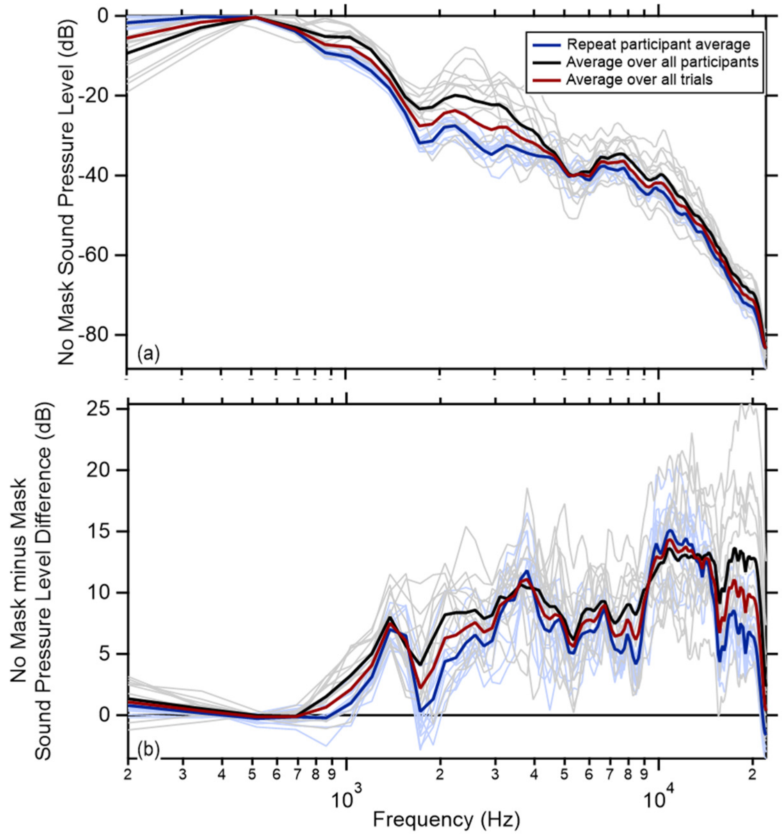

Figure S4. (a) Average power spectrum with no mask, set to full scale, and (b) difference between no mask and mask for participants singing *Ode to Joy*. Thin lines are individual measurements, with blue lines for the participant who performed replicate trials. The solid lines are averages across participants for (red) all individual trials, (blue) the repeat performer, and (black) over all participants using the average from the repeat performer.

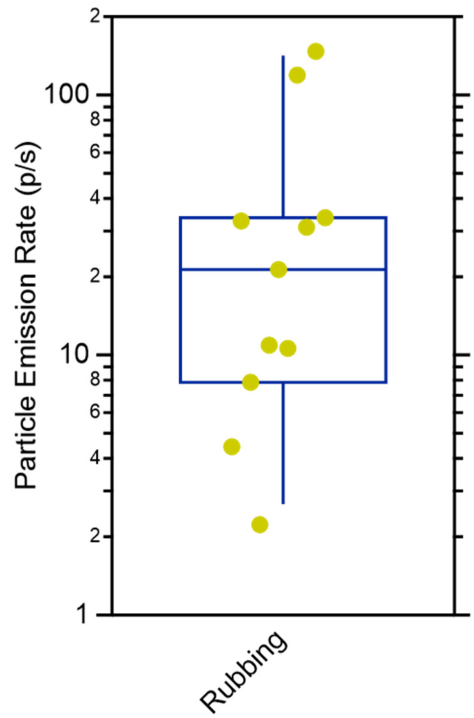

Figure S5. Observed particle emission rates (p/s) for rubbing the singing mask material together.

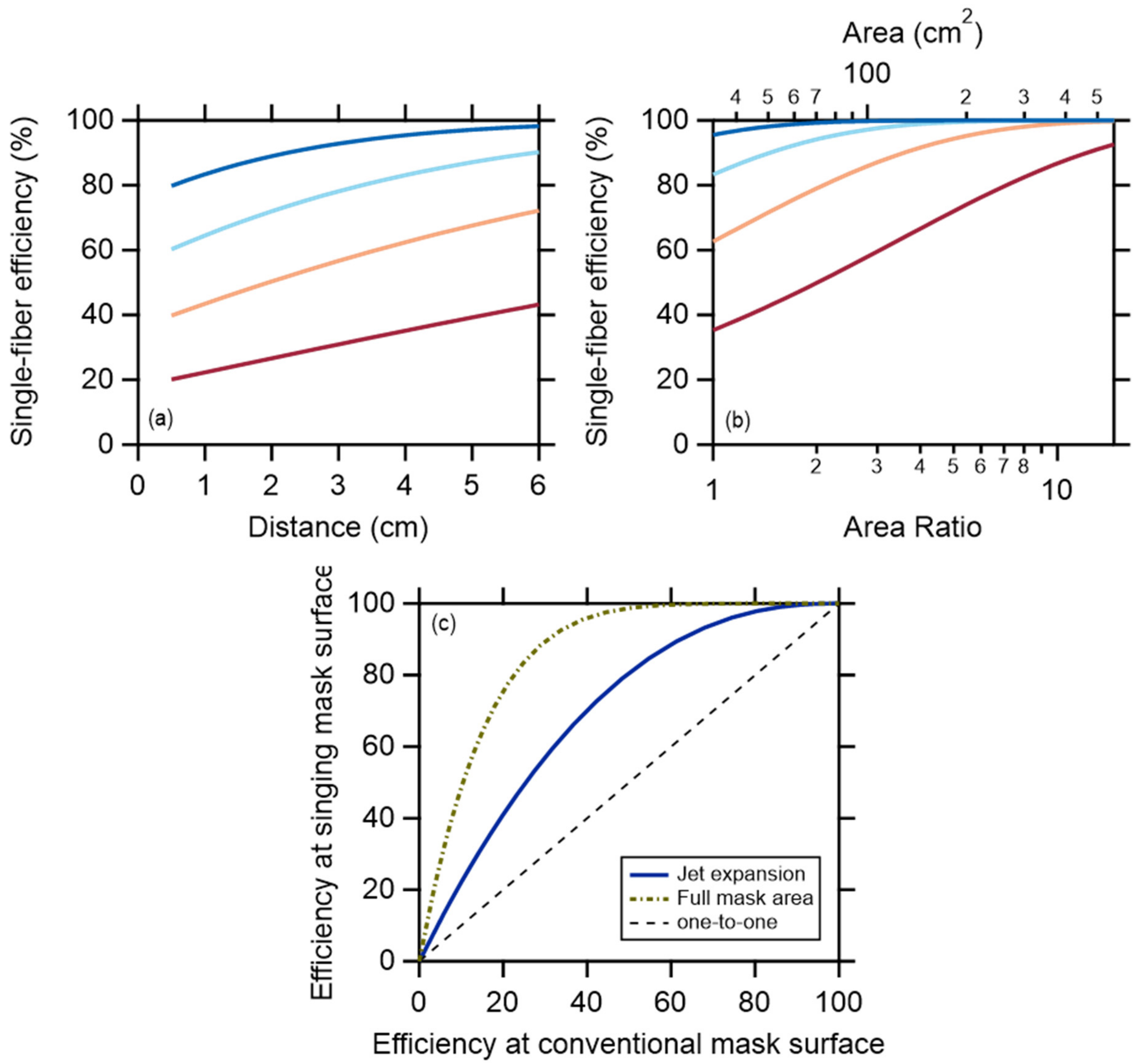

Figure S6. Effect of increasing the distance between the mouth and the mask material on single-fiber filtration efficiency. (a) Relationship between single-fiber efficiency and distance assuming an expanding conical jet that diverges at an angle of 20° with a radius of 2 cm at a distance of 0.5, which approximates expansion of an expiratory airflow. (b) Relationship between single-fiber efficiency and the mask surface area ratioed to the area of a circular area around the mouth and nose with a radius of 3.5 cm. Four curves are shown to illustrate how efficiency varies depending on the assumed efficiency at the reference distance or area. (c) The relationship between the efficiency at the singing mask surface and the expected efficiency at the surface of a conventional mask assuming an expanding conical jet (as in (a); blue line) or for the total mask area (as in (b); gold line). The black dashed line is the one-to-one line. The decreased air velocity at the mask surface engenders a large increase in the single-fiber filtering efficiency.

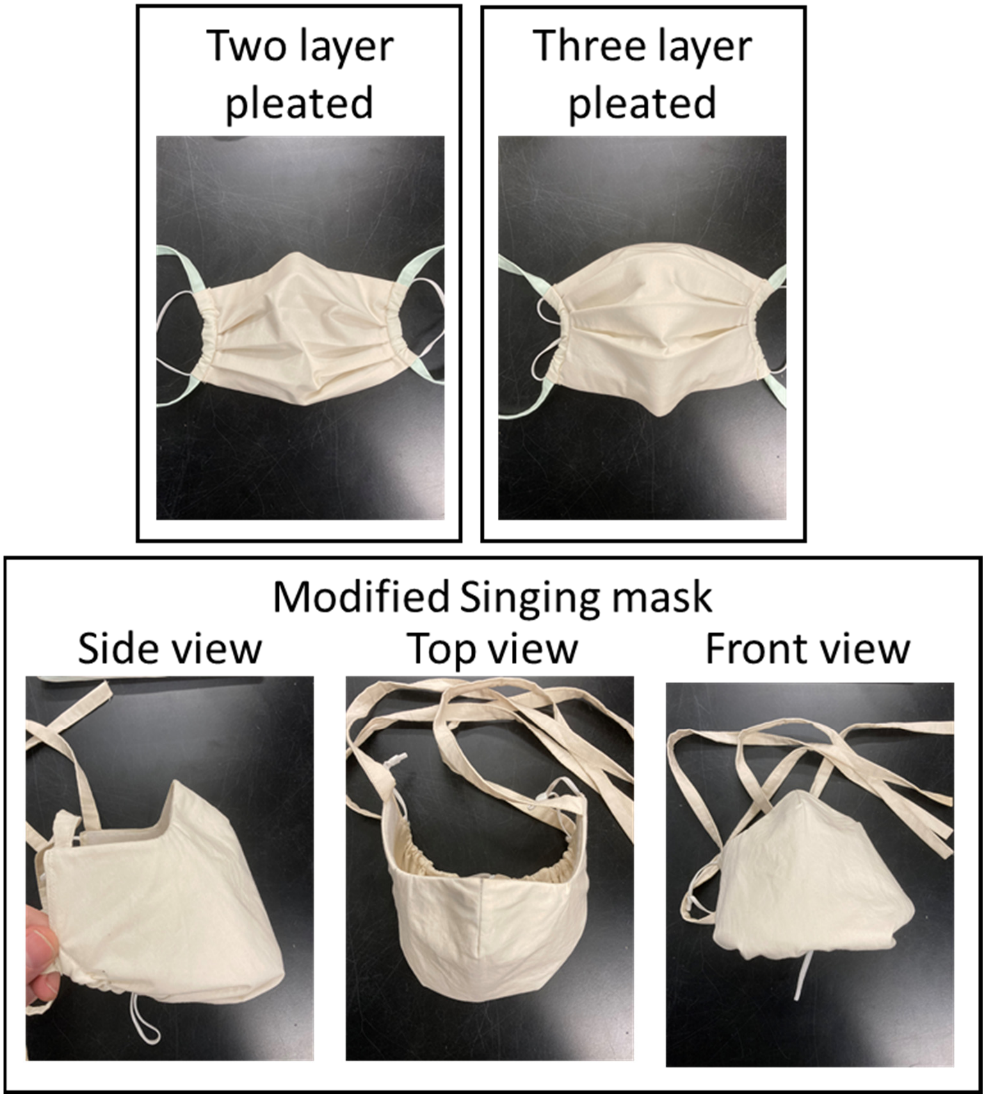

Figure S7. Photographs of the two-layer and three-layer pleated masks and the modified singing mask.

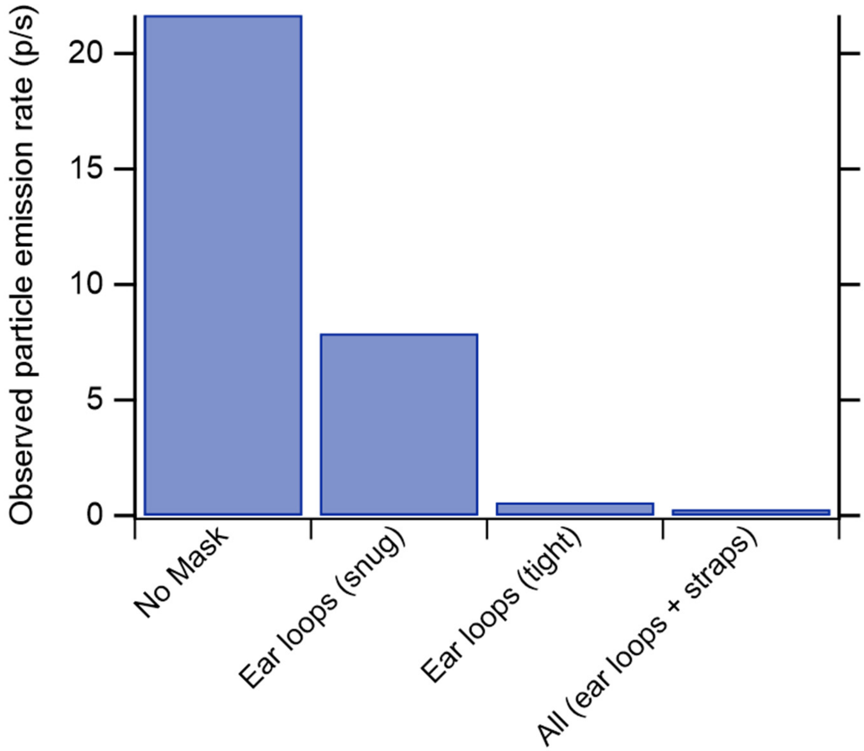

Figure S8. Observed particle emission rates (p/s) without a mask or for sampling from the top quadrant with the singing mask worn with snug ear loops only, tight ear loops-only, or tight ear loops plus the head straps.

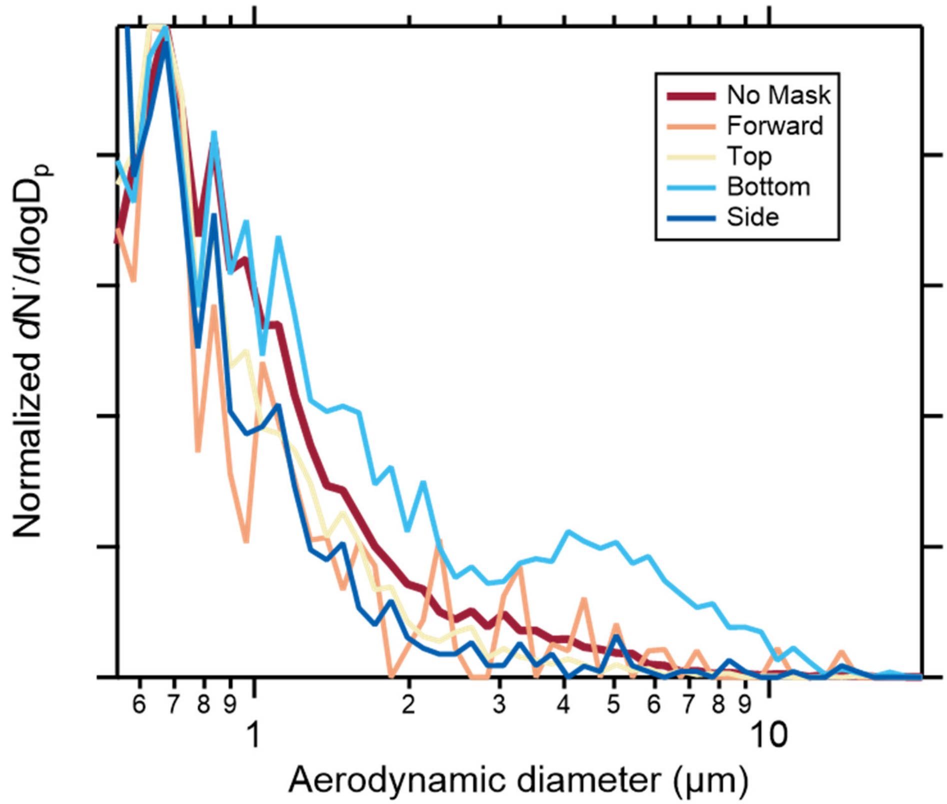

Figure S9. Normalized average particle emission rate size distributions for sampling with no mask or with the singing mask from different quadrants. Note the enhanced contribution of large particles (3-9 microns) when sampling from the bottom quadrant, indicative of fiber shedding.