On Covid-19 Transmission Mitigation Approaches in a Classroom Environment

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Summary:

While shields are effective at protecting the wearer from direct spray from a cough or sneeze, they provide no protection to the wearer from particles that are suspended in the air as an aerosol.

Likewise, a shield will deflect the spray from a cough or sneeze, outward and downward, thus providing some protection for a person within ~3 m who is directly in line. However, the aerosol particles from this event will escape into the room and still be a threat to people nearby.

In contrast, while a mask will not stop droplets from a close, direct cough or sneeze from impinging on a person's face and potentially getting into the eyes, it would greatly reduce the droplets released by a cough or sneeze including at least some of the aerosol sized drops. We find below, in agreement with many previous studies, that a face mask will greatly reduce the total load of emitted particles that could be a threat to others. Further, a mask would protect the wearer from the larger particles and at least some of the aerosol particles.

Thus in a classroom setting, a full face shield provides effectively no protection for either the wearer or the other people in the room. With expected distance and ventilation, a face mask will provide a significant reduction in emission and reduce the aerosol viral load of the room air as well as the amount which deposits on surfaces. A clear plastic face mask was found to be effective in preventing emission, however only if tightly fitted to the face to avoid leakage near the mouth.

It could be open for discussion that with adequate ventilation and distancing, that the lecturer could simply wear no face covering (provided all students wear face masks), however this would not provide any protection for students from the lecturer. This is problematic if the lecturer happens to be expressing a high viral load.

Introduction:

With the impending reopening of the University for students on August 10, it is imperative that the University quickly determine the most effective strategies for mitigating the transmission in our classrooms of the coronavirus SARS-CoV-2 leading to Covid-19. This involves means to prevent student to student transmission, faculty to student transmission, and most importantly transmission from students to faculty. This latter is most significant because 1) faculty as a group are far more likely to have a negative outcome from the Covid-19 disease than the much younger student population, and 2) with only moderate care and planning of a classroom environment, student to student transmission is much more likely to occur elsewhere on campus (e.g., dorms, group study, athletic activities, and other extracurricular activities in student life). The bulk of this analysis will therefore focus on mitigation of student to faculty transmission in the classroom, although faculty to student transmission will also be considered.

Many modes of transmission of the SARS-CoV-2 virus have been identified, including direct and indirect contact between individuals and contaminated surfaces, ingestion, etc. A recent article on the progress of the pandemic (Zhang, et al., PNAS 2020, www.pnas.org/cgi/doi/10.1073/pnas.2009637117) has demonstrated from an epidemiological perspective that the dominant mode of transmission is via airborne aerosols in an indoor environment. This is consistent with identified case studies such as the South Korean call center case (https://wwwnc.cdc.gov/eid/article/26/8/20-1274_article), the Washington church choir practice (https://www.cdc.gov/mmwr/volumes/69/wr/mm6919e6.htm), and the current example linking 128 confirmed primary cases to one East Lansing bar in Michigan in just two weeks after reopening (https://www.cnn.com/2020/07/02/us/michigan-bar-coronavirus-cases/index.html). The key question is how we can avoid such transmission in our classrooms.

In order to understand how classroom transmission can occur, it is necessary to understand the fluid mechanics of droplet generation, aerosol convection, dispersion, and deposition, and the processes by which this can lead to inhalation and infection. An excellent review of what is currently known of the fluid flow physics of Covid-19 transmission is provided by Mittal, et al. (doi:10.1017/jfm.2020.330). In general, oral activity such as breathing, speaking, singing, coughing, and sneezing results in the emission of droplets which have the potential to contain infectious viral particles. Once emitted, the droplets are subject to the fluid flow of the surrounding air as well as sedimentation due to gravity. In addition, depending on the relative humidity of the air droplets can dry out quite rapidly, reducing their volume by about 99% and thus affecting their fate: whether to deposit on a surface, or to remain a suspended aerosol in the environment.

The risk of transmission via oral droplet emissions is critically dependent on the size of the droplet and the competition between drying out (thus reducing their size and allowing them to stay airborne) and gravity causing them to fall to the floor or other surface. Droplets which do make it to surfaces (clothing, tables, etc.) are still capable of infection, but only by the fomite route where an individual will touch a contaminated surface and then rub their eyes or touch their mouth. The rate at which a drop dries out depends on its size, the temperature, and the relative humidity of the air. The rate with which it falls to the ground depends on its size and gravity. This competition has been extensively studied, and a useful summary for clean water drops and typical room air conditions is provided by Barrow and Pope (J Ap Energy, 2006, doi:10.1016/j.apenergy.2006.09.007):

Table 1
Evaporation time and distance travelled by a droplet in free-fall

Droplet diameter (μm)	Time (s)	Distance (m)
25	0.66	0.006
50	2.54	0.097
75	5.39	0.457
100	9.00	1.337
125	13.17	3.0
150	17.84	5.79
200	28.00	15.70

Terminal temperature = 291.1 K.
Initial temperature = 288.5 K.
Environment temperature = 301 K.
Environment relative humidity = 40%.

From this table it is apparent that drops with diameter greater than ~100μm will fall to the floor or other surface before drying out, while drops smaller than this will evaporate. A 25μm drop will evaporate in room air in less than a second, and before it falls 6mm. Because an oral droplet contains other materials (including possibly viral particles) comprising approximately 1% of the original mass, there will be a droplet residue with diameter 1/4.6 the original diameter. For a 100μm drop, this residue would be approximately 22μm in diameter, and have a settling velocity of 1.4 cm/s, small enough that it would be easily suspended in room air currents. While larger drops will fall to surfaces before drying, if they are emitted with sufficient velocity they will travel laterally a significant distance before this occurs and potentially be inhaled. It is the competition between this lateral motion and the settling velocity, plus the fact that even small aerosols will have a higher concentration in the vicinity of an emitter prior to mixing with room air which is the basis of the "six feet" rule for social distancing.

The infectious potential of the aerosol residue of oral droplets depends on the viral load of the saliva, the droplet volume, and the infectious dose. Unfortunately, none of these quantities are well determined and have an extraordinary amount of variability between individuals. A recent study (not yet peer reviewed) from Yale (Wyllie et al., doi: https://doi.org/10.1101/2020.04.16.20067835) shows both a very high viral load of SARS-CoV-2 from saliva (median patient between 10^6 and 10^7 copies per ml), as well as an extremely large variability between patients. One patient (out of 46 tested) had a count in excess of 10^{10} copies per ml and three (6.5%) had a titer greater than 10^9. This is quite significant, as the infectious capacity of droplets emitted by this individual would be over 1000 times greater than the average patient, and 10^6 times that of the infected patients with the smallest titer. It is likely that this sort of variability is what leads to "superspreading events" in which one individual with a high viral load is the equivalent to 1000 or more individuals.

The infectious dose of virus has not yet been determined for SARS-CoV-2. In a review of influenza-A transmission (Nikitin, et al., Adv. Virology 2014, http://dx.doi.org/10.1155/2014/859090) the authors found that approximately 2000-3000 viral particles were required for infection when administered as an aerosol in a controlled manner. Because Covid-19 is believed to be more infectious than influenza, the required number of viral particles may be lower for this disease, however the results for influenza-A provide a baseline estimate. Interestingly, studies cited by this paper have shown that for influenza-A the bulk of infection occurs through particles with diameter of 4μm or less (which would correspond to a hydrated droplet diameter of 20μm). Particles of this size could be particularly problematic because they are small enough to be drawn into the alveolar region of the lungs upon inhalation.

The droplet size distribution and total volume produced by oral activities has a very wide variability based on the nature of the activity and from individual to individual. In general, quiet breathing produces a small quantity of the smallest particles. Because the probability of a droplet containing one or more viral particles is proportional to the volume (which is proportional to the cube of the diameter), larger particles are potentially more infectious. A 100μm droplet could contain 1000 times more viral copies than a 10μm droplet, for example. Apart from a sneeze or cough, the largest source of emission in the classroom is through speech. In general, vowel sounds emit fewer and smaller droplets than consonants. In a recent study

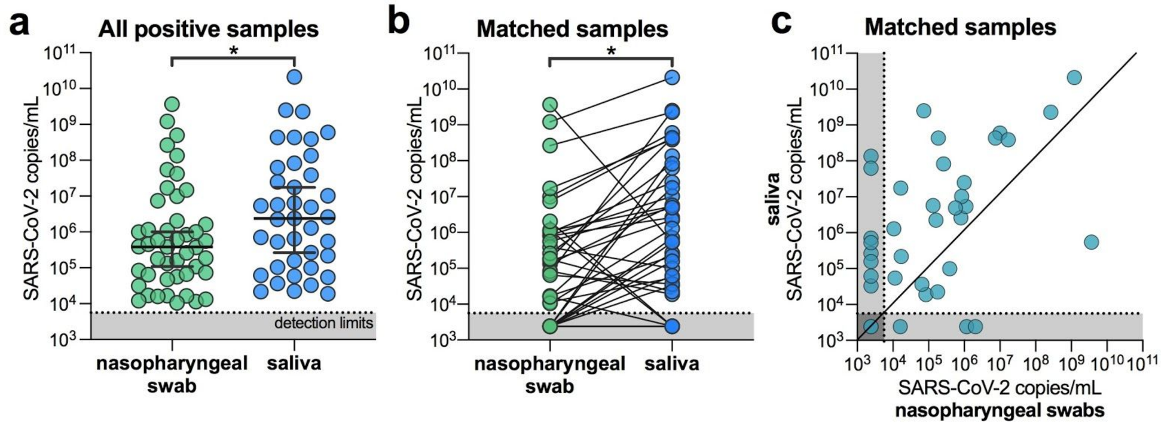


Figure 1. SARS-CoV-2 titers are higher in the saliva than nasopharyngeal swabs from hospital inpatients. (**a**) All positive nasopharyngeal swabs (n = 46) and saliva samples (n = 39) were compared by a Mann-Whitney test ($p < 0.05$). Bars represent the median and 95% CI. Our assay detection limits for SARS-CoV-2 using the US CDC "N1" assay is at cycle threshold 38, which corresponds to 5,610 virus copies/mL of sample (shown as dotted line and grey area). (**b**) Patient matched samples (n = 38), represented by the connecting lines, were compared by a Wilcoxon test test ($p < 0.05$). (**c**) Patient matched samples (n = 38) are also represented on a scatter plot. All of the data used to generate this figure, including the raw cycle thresholds, can be found in **Supplementary Data 1**. **Extended Data Fig. 1** shows the correlation between US CDC assay "N1" and "N2" results.

(Stadnytskyi, et al., PNAS 2020, www.pnas.org/cgi/doi/10.1073/pnas.2006874117) found that the "st" sound was particularly effective in emitting droplets of 25μm hydrated diameter, at a rate of thousands per second. The combination of high viral load of saliva in an infected individual plus the efficient emission of droplets which rapidly evaporate to aerosol nuclei suggest that such sounds in speaking are the most significant source for transmission in the classroom.

Putting these effects together we can determine a *very* rough estimate of the probability of a student or faculty member receiving an infectious dose of SARS-CoV-2 during a typical class. If an infected individual with virus titer of 10^7 copies/ml emits 25μm droplets, these drops would contain on average 0.08 copies per drop. Picking a 50-seat DeBartolo classroom as an example, the dimensions are approximately 10m X 10m X 3m, (volume = 300 m^3). The nominal ventilation rate will be 2 room volumes per hour or 0.17 m^3/s. If the speaking emission rate is 1000 drops/s then the long time (steady-state) concentration of drops in the air is (1000 drop/s)/(0.17 m^3/s) = ~6000 drop/m^3. A person sitting in a room with a typical breathing rate of 8 liter/min (= .000133 m^3/s) for 1 hour would thus breathe in about 3000 particles. If each particle contained on average 0.08 copies/particle then under this scenario, students or faculty would be expected to inhale on the order of 230 viral copies/hour which is probably below an infective dose. If the room were initially free of viral laden aerosol particles, the concentration of particles would increase over time, taking somewhat more than an hour to reach the maximum concentration. With this scenario a person would likely get about 150 virus copies. However, if the infected speaker is a "superspreader" with a higher saliva virus titer, then the number of viral copies inhaled could be several orders of magnitude greater than this, easily leading to an infective dose without mitigation in place.

Mitigation Approaches

1) Face Shields

In response to a JAMA opinion article suggesting the possibility of the use of face shields as an effective alternative to face masks (Perencevich, et al. doi:10.1001/jama.2020.7477) the University charged us with evaluating this suggestion. Many faculty would prefer to use a face shield as opposed to a face mask when lecturing in the classroom. The Perencevich article was based on an experimental study (Lindsley, et al., Journal of Occupational and Environmental Hygiene, 11: 509–518, 2014) of the effectiveness of face shields in preventing transmission of influenza virus between a coughing patient and a health care provider. In this study, a simulated cougher emitted coughs directly at a simulated breather, both with and without a face shield in place. The separation was either 46cm (18 inches) or 183cm (6 feet), and tests were done with either large (8.5μm volume mean diameter) or small (3.4μm) diameter droplets. The particles were detected both in the first minute (e.g., directly from the cough plume) or from 1-30 minutes (corresponding to particles more distributed through room air). The citation from the Perencevich article is:

> Most important, face shields appear to significantly reduce the amount of inhalation exposure to influenza virus, another droplet-spread respiratory virus. In a simulation study, face shields were shown to reduce immediate viral exposure by 96% when worn by a simulated health care worker within 18 inches of a cough.[10] Even after 30 minutes, the protective effect exceeded 80% and face shields blocked 68% of small particle aerosols,[10] which are not thought to be a dominant mode of transmission of SARS-CoV-2. When the study was repeated at the currently recommended physical distancing distance of 6 feet, face shields reduced inhaled virus by 92%,[10] similar to distancing alone, which reinforces the importance of physical distancing in preventing viral respiratory infections.

This description of the Lindsley article is a bit misleading, and is not directly relevant to the classroom environment in any case. The face shield was found to be effective in mitigating transmission from the cough plume, in which the simulated cough was directed at the detector and the cough and initial inhalation were synchronized. This was the basis of the 96% and 92% protection cited in the JAMA article. The 80% protective effect after 30 minutes was derived from 90% of the inhaled drops occurring in the first minute (e.g., the protective effect was principally in the first minute after the cough before the cloud had dispersed). In contrast, however, the subsequent protection provided by the face shield was much more modest. From the Lindsley article:

> The exposure measurements immediately after the cough were made while the cough aerosol particles were moving rapidly (the air velocity at the mouth of the coughing simulator peaks at about 32 m/sec). This aerosol included particles up to 100 µm in diameter, many of which would be expected to settle quickly after leaving the mouth (a 50-µm particle with a density

of 1 g/cm^2 will fall 1 m in about 13 sec). On the other hand, the long-term exposure measurements were made during the period from 1 min to 30 min after the cough, when the cough airflow had dissipated and the aerosol included mainly smaller particles that were able to remain airborne for an extended time and could flow more easily around a face shield. Consequently, using the face shield only caused a modest decrease in the inhalation of airborne particles over the long term (Figure 6).

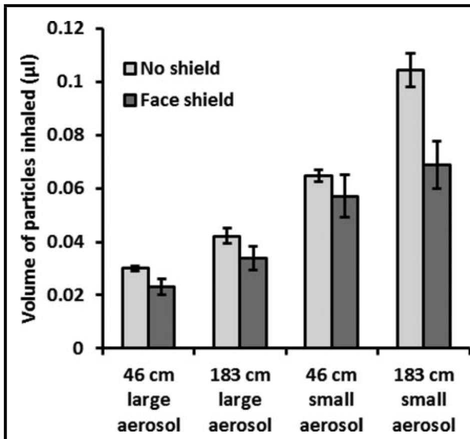


FIGURE 6. Volume of aerosol particles inhaled by the breathing simulator from 1 min to 30 min after a single cough. Each bar is the average ±SD of 3 experiments.

Why would face shields be so effective initially, and ineffective after particles have mixed into the room air? The answer lies in the fluid dynamics of the air flow and the effect of the face shield. A cough emerged from the simulator as a plume at a reported peak velocity of 32m/s. The total cough volume was 4.2 liters, and the peak flow rate was 11.4 l/s, thus the cough duration was less than a second. This plume would spread out and reduce its velocity as it traveled to the simulated breather, however the transit time (even with 2m separation) was much less than the duration of the cough. The breathing machine was set to draw air in an oscillatory manner at 32 l/min. The rate and tidal volume were not explicitly stated, however the paper did report that the inhalation period was 1.4s, which would correspond to a breathing rate of 21 breaths/min and a tidal volume of 1.5 liters. The inhalation was synchronized with the cough. Thus, during the second the plume was traveling past, approximately 1 liter of air was inhaled, comprising 2/3 of the total breath. For the 46cm separation, approximately 1% of the total number of emitted particles were breathed in on the first breath in the absence of a face shield.

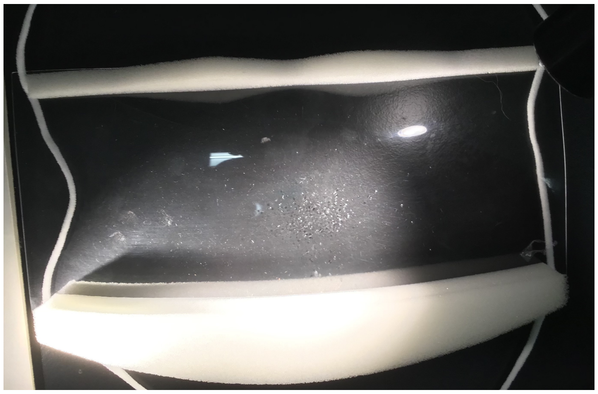
The effect of the face shield on this process is two-fold. In order for air to enter during a breath, the air would have to flow around the edges of the face shield and into the sampler. The droplets in the cough plume were traveling at a very high velocity tangential to the edges of the shield, and because of significant inertia the larger drops would not follow the curved fluid path to the collector. Second, the space between the face shield and the face has a finite volume. The surface area of the face shield was reported to be 548cm^2. If the average separation between the face shield and the face is 3cm (e.g., the stand off projection of a typical nose), then the stagnant volume between shield and face is approximately equal to the tidal volume of the breath. In effect, the cough plume is drawn into this dead volume in an oscillatory manner, and only a portion of the particles in the plume are mixed into this region and eventually inhaled. Most would be displaced back out of the dead volume during exhalation, and mix with the room air. Thus, the number of particles inhaled during the first minute would be greatly reduced by a face shield. If, instead, aerosol particles are well-mixed throughout the room, then the dead volume air between the face shield and the face would have the same concentration as the surrounding air. This was substantially borne out by the Lindsley paper (e.g., figure 4). The face shield would have minimal effect on aerosol inhalation under these conditions.

We have also been tasked with determining the effectiveness of face shields as protection for others (e.g., to determine the effect on droplet emission). Unlike a face mask, a face shield does not provide filtration, per se. Instead, the effect on emission is two-fold. First, it redirects the emitted droplets: rather than, say, a cough plume which can travel many meters as an expanding jet through a room, the emissions are redirected and spread out in the vicinity of the individual wearing the face shield. Second, at least some of the droplets are, in effect, filtered out via inertial impaction on the inner surface of the face shield. Whether a droplet is filtered out in this manner depends on the droplet size (e.g., inertia), the air flow velocity, and the separation distance between the mouth and the mask. A simple balance between inertia and Stokes[1] drag suggests that the critical drop diameter d is given by:

$$d \approx \left(18\frac{\mu \Delta x}{\rho U}\right)^{1/2}$$

where Δx is the face shield separation distance, μ is the air viscosity, ρ is the droplet density, and U is the air velocity exiting the mouth. This must be regarded as a rough estimate, as smaller drops could also impact the face shield depending on their originating streamline, and larger drops could escape if they were emitted during portions of the breath at lower velocities. For a typical breath velocity of 1.3m/s and a face shield separation of 3cm, this formula yields a critical droplet diameter of 86μm. This is much larger than the majority of the droplets produced by typical speech, thus it would not be expected to filter out a significant number of emitted droplets for these conditions. A cough, on the other hand, has a velocity approximately an order of magnitude greater. This would yield a critical droplet diameter of 27μm which would capture at least a portion of the drops emitted during a cough. In either case, droplets smaller than the critical size (which comprise the bulk of the emissions even for a cough) would largely follow the air flow into the room and be dispersed as an aerosol. Thus, while there would be some benefit in emission to wearing a face shield, the effect would be modest.

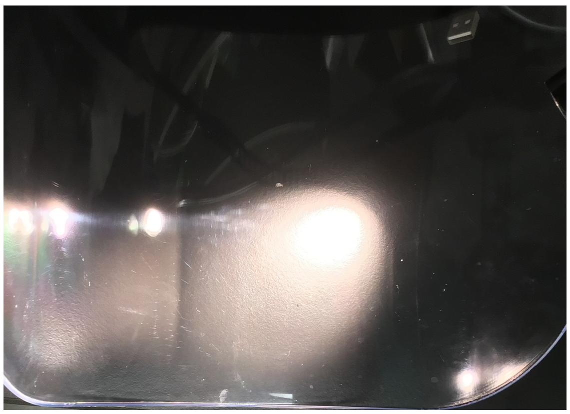
In order to provide experimental confirmation of this scaling analysis, we conducted a simple

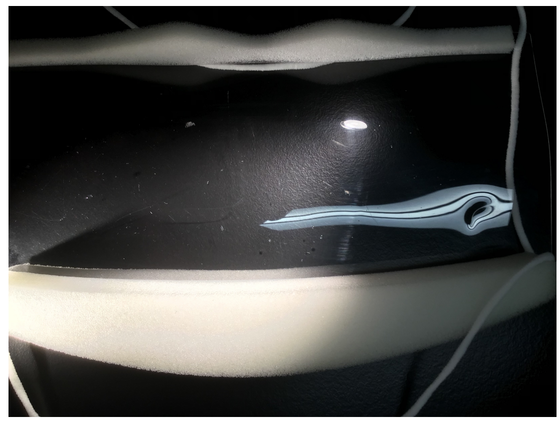


experiment comparing a plastic face mask to a standard face shield. The plastic face mask (theclearmask.com), purchased by the College of Engineering, covers the nose and mouth and has a molded foam filter over the nose bridge and a foam filter around the chin. When fitted tightly the separation between the mouth and clear plastic mask is only a few mm. In this test the subject (DTL) “hissed” while wearing the mask for 30s, and the mask was removed and

[1] https://en.wikipedia.org/wiki/Stokes%27_law

photographed. As can be seen from the image on the right, the inside of the mask was liberally speckled with the droplets emitted during the vocalization. The largest droplets and density are concentrated on the portion of the mask over the mouth, while smaller droplets at lower density were scattered further away, consistent with the inertial impaction mechanism. We repeated this experiment with both a standard face shield (held so that it was touching the nose, normally the projection of such a face shield is further off) as well as the same plastic face mask, but where it was not tightened to the face leaving an approximately 2cm gap between the mouth and plastic. This resulted in the images below:





As can be seen, there were virtually no droplets deposited on the face shield, and very few on the loosely fitted plastic face mask, again consistent with the inertial impaction scaling. Because there is no filtration provided by a face shield, any emitted droplets which do not inertially impact onto the shield escape into the room to deposit on surfaces or become aerosols. As a simple observation, if the interior of the face shield or mask is not coated with liquid during vocalization, then it is not effective in reducing emission of the droplets produced.

In addition to the face shields considered by Lindsley which are open at the bottom, some faculty have proposed a more complete full face shield which is closed at the bottom and only open at the back sides. Such a face shield is not sealed, of course, as air exchange is required. The inertial impaction filtration of such a face shield would be similar to that of one open at the bottom, however there is also the possibility of the removal of larger aerosols due to sedimentation. The idea here is that the tidal volume of the breath is much smaller than the volume enclosed by the shield, thus the volume between the face and the shield may be regarded as a well-mixed reservoir. Any droplet either emitted by the person wearing the shield or inhaled into this volume from the outside experiences a competition between exchange with the surroundings and sedimentation to the sealed bottom of the shield. The ratio of these two mechanisms determines the critical diameter of a drop for which the shield affects inhalation and emission. This balance yields an expression analogous to inertial impaction:

$$d \approx \left(18 \frac{Q\mu}{A\rho g} \right)^{1/2}$$

where Q is the breathing volumetric flow rate (typically 12 l/min for light activity) and A is the projected area at the bottom (about $100cm^2$). This yields a critical droplet diameter of $26\mu m$, which is much larger than typical aerosols which could be inhaled, and somewhat larger than droplets emitted during speech. Thus, while a full face shield is better than a partial shield, it does not significantly affect emission or inhalation of aerosols below about $20\mu m$ in diameter. This effect also relies on the breath tidal volume being much less than the dead volume of the face shield. While this is true for ordinary breathing, if a large breath is indrawn prior to speaking (up to about 3 liters for a typical adult), then this would exceed the shield dead volume (approximately 1.5 liters) and the volume would be completely cleared, resulting in no reduction in emission by this mechanism for any size particle.

Face shields play a very important role in protecting health care workers who are in close proximity to infected patients who are often coughing, sneezing, or expressing other symptoms. Proper protective equipment for such an individual would include a face shield to block direct transmission (protecting the eyes and face from direct contact as well as inhalation), and an N95 respirator or surgical mask to deal with the aerosols present in the room air from previous coughs and sneezes. In a classroom environment, the situation and hazards are far different. Students will be required to wear masks thus mitigating the release of large droplets and decreasing the velocity at emission. The conditions described in these papers would be replicated in the classroom only if the students were to remove their masks and then directly cough or sneeze at an unprotected fellow student or faculty member. *We believe that we can rely on our students not to allow this to occur*. As a result, the primary concern would be the aerosols mixed into the classroom air due to infected students breathing and talking over an extended period, or an occasional unexpected cough or sneeze into a mask or elbow. For this scenario a face shield would clearly be inadequate, providing little benefit to a faculty member and minimal protection to the students in the classroom. This is also consistent with observations in the last week, where a Swiss hotel found a dramatic difference in infection rates between employees wearing masks and those wearing face shields (https://techthelead.com/swiss-government-finds-plastic-visors-useless-against-coronavirus/). The Swiss government is currently evaluating whether to exclude face shields from satisfying their mandatory mask orders.

2) Face Masks

The CDC now recognizes that face masks play an important role in reducing the spread of Covid-19. In fact, a meta-analysis (Zhang, et al., PNAS 2020, www.pnas.org/cgi/doi/10.1073/pnas.2009637117) demonstrated that the transmission curve "flattened" only after mask wearing regulations were put into place: that social distancing (while important) was insufficient to control the pandemic. In an editorial published last week in JAMA (https://jamanetwork.com/journals/jama/fullarticle/2768532) the director of the CDC reiterates the importance of mask wearing by the general public. It also cites a Goldman Sachs research article (https://www.goldmansachs.com/insights/pages/face-masks-and-gdp.html) suggesting that increasing usage of masks can avoid an additional $1T hit to the GDP.

The effect of face masks is two-fold: it protects the wearer (to some degree) by filtering out a portion of the potentially contaminated aerosols in the environment, and it protects others by reducing the amount of viral particles released into the environment through oral activity by infected individuals. This latter is particularly important due to the high percentage of infected individuals who are not expressing symptoms (asymptomatic or presymptomatic).

The performance of mask material against aerosols depends very strongly on the filtration media, and for cloth masks on the thread count. For example, one study (Konda, et al., ACS Nano 2020, 14, 6339−6347, https://dx.doi.org/10.1021/acsnano.0c03252) showed that a two-layer cotton (600 TPI thread count) mask was able to filter out up to 99.5% of aerosols greater than 0.3μm, while a two-layer quilter's cotton (80 TPI, somewhat higher than a typical T-shirt) mask filtered out only 49% of aerosols in this size range. In contrast, N95 mask material filtered out 99.9% of aerosols greater than 0.3μm. This is in-line with other studies (e.g., Rengasamy et al., Ann. Occup. Hyg., Vol. 54, No. 7, pp. 789–798, 2010, doi:10.1093/annhyg/meq044) which demonstrated that T-shirt type material essentially offered no protection against micron sized aerosols.

The performance of an actual mask made of N95 material depends critically on the fit as leakage has a dramatic effect on protection. In the study by Konda, the authors simulated leakage by having a bypass with area of only 1% of the total mask area. Because of the resistance to flow caused by the filtration material, a much larger fraction of the air flow bypasses the mask. The authors found that an N95 mask tested in this way removed only 12% of the aerosols. Other mask materials fared slightly better in this bypass test, but all were below 50%. The conclusion to be drawn from these studies is that the protection offered by a mask depends on filtration material and seal. A two-layer cloth mask of high thread count, in which the mask seals to the mouth during inhalation, can offer significant protection against even small aerosols. Inhalation through the nose, in contrast, would inevitably cause significant leakage, and thus protection would be more limited.

Even if infection is not prevented by a mask, reduction of the amount of virus inhaled may reduce the severity of the resulting disease. A nice review of this effect is provided in a USA Today article (https://www.usatoday.com/story/news/health/2020/07/15/wearing-mask-may-offer-protection-against-catching-severe-covid-19/5431323002/), which cites the different outcome of passengers on two cruise ships (the Diamond Princess and the Shackleton). In the Diamond Princess case few passengers wore masks and only 18% of those infected were asymptomatic. In the case of the Shackleton all passengers were issued disposable masks and, while the number of infections was high, 85% of those infected were asymptomatic. This kind of dose-response has been observed in other respiratory illnesses. An interesting study has suggested that this (rather than mutation of the virus) was the reason for the increased mortality of the second wave of the Spanish Flu pandemic of 1918 (Paolo, et al, PLoS ONE 5(7): e11655. doi: 10.1371/journal.pone.0011655).

The performance of a face mask against droplet emission is likewise complex, depending on both mask material and fit, however it is much stronger due to the larger size of the emitted, hydrated droplets. The effect on droplet emission is much less studied than inward aerosol penetration, and is particularly complicated by the change in the fit of a cloth mask to the face during exhalation. Qualitative studies have shown that two layer masks substantially decrease the emission of 1-10μm drops (Verma, et al., Phys. Fluids **32**, 061708 (2020); doi: 10.1063/5.0016018). A two layer 80TPI cloth mask yielded the images below:

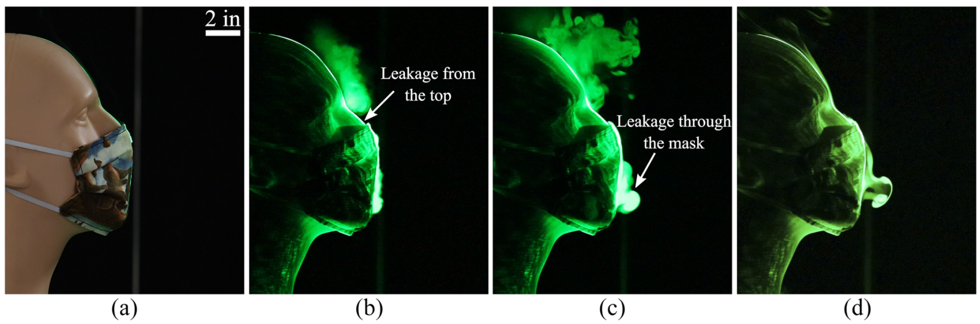
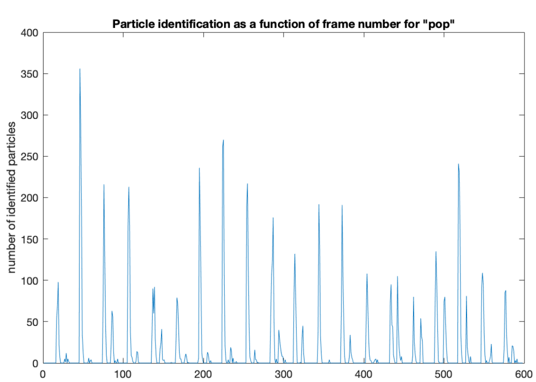
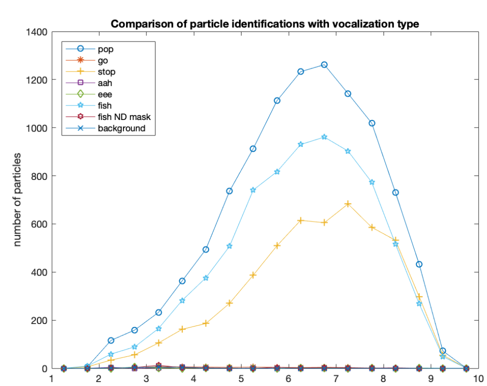


FIG. 4. (a) A homemade face mask stitched using two-layers of cotton quilting fabric. Images taken at (b) 0.2 s, (c) 0.47 s, and (d) 1.68 s after the initiation of the emulated cough.

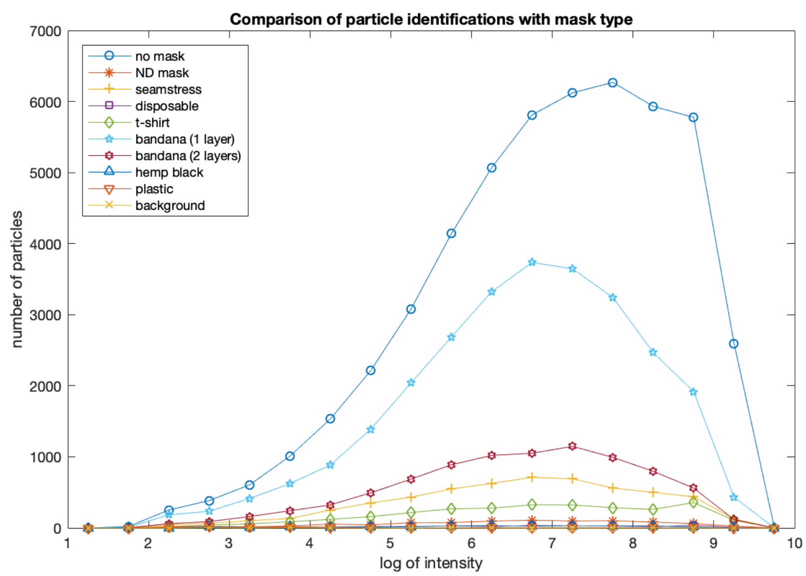
In contrast, in the absence of a mask, the simulated cough plume projected 8 ft from the source. Note that the authors also found that a single layer "bandana" type mask only slightly attenuated the plume, where particles projected some 3 ft from the source.

In order to determine the effectiveness of ND masks on droplet emission during speech we conducted a laser sheet imaging study, counting the droplets detectable passing through a laser sheet during different vocalizations both with and without a mask. These experiments are described in more detail in a companion paper, however a key limitation is that the set up is only capable of imaging droplets greater than about 10μm in diameter. Because of the relationship between volume and diameter detectable particles would comprise the majority of the volume emitted during speech. These droplets are primarily associated with consonants produced at the front of the mouth such as "p", "st", "f", etc. A plot of detected droplets for different vocalizations is given below. The intensity of the identified particles is associated with size. Based on calibration with 50μm glass spheres scattered through the laser sheet under the same conditions, the peak corresponds to droplets approximately 25μm in diameter, consistent with the recent work of Stadnytskyi et al., (www.pnas.org/cgi/doi/10.1073/pnas.2006874117). Droplets significantly smaller than this would evaporate to even smaller droplet nuclei prior to passing the laser sheet, and thus would be undetectable. This is why no drops were detected for the vowel sounds such as "eee" or "aah", as work by Asadi, et al. (https://www.nature.com/articles/s41598-019-38808-z) suggests that these have a droplet diameter of around 5μm at emission, and would evaporate to nuclei of 1μm prior to reaching the laser sheet. Droplet detection was also weak for consonants such as "g" in "go" which are produced further back in the mouth.





Focusing on the vocalization "pop" which produced the largest rate of detectable droplet emission, we compared a variety of masks to evaluate their effectiveness in capturing the emitted volume. This produced the result depicted below. It was apparent that, consistent with other research available in the literature, filtration depends significantly on the type of material used. A single layer cotton bandana removed only a small fraction of the droplets, somewhat improved by folding it over into a two-layer mask. This two-layer bandana was comparable to the performance of the masks made by the ND seamstresses at the beginning of this summer. The "t-shirt" was a very tight weave elastic polyester, and did somewhat better than the loose weave cotton bandana. In contrast, all of the commercial masks removed the vast majority of the detectable droplets. We may roughly quantify the removal by making the assumption that the intensity is approximately proportional to the square of the droplet size (Mie scattering), and summing the volume of each droplet to get the total release. Note that this is not precise as small drops likely escape the mask (e.g., as observed from the work of Verma, et al.) both through the material and via bypass and are not detectable in the laser sheet. Because of the volume/diameter ratio, however, it is anticipated that the contribution of these droplets to the total volume and corresponding viral release is small. Although effort was taken to direct the air in the vicinity of the subject through the laser sheet by means of a fan, detection of drops escaping via bypass is uncertain. For masks which are tightly fitted to the face, however, inertial impaction should prevent large droplets from escape via this mechanism and smaller drops are not detectable in any event. It should also be noted that while the plastic face mask performed well in this test, it was tightly fitted to the face and no droplets projected forwards. If loosely fitted to the face, however, large droplets escaped out the bottom, and they would not be reliably detected using the laser sheet technique.



Mask Type	Detected Droplet Volume Ratio for "pop"
Bandana (1 layer, loose weave)	0.33
Bandana (2 layer)	0.098
ND Seamstress Mask	0.072
Polyester T-shirt (tight weave)	0.050

Mask Type	Detected Droplet Volume Ratio for “pop”
ND Mask (polyester/bamboo cotton)	0.012
Disposable Face Mask	0.0046
Ananda Health Hemp Black	0.0025
Plastic Face Mask	3.4E-04
Background	4.5E-05

In conclusion, a face mask provides only limited protection against inhalation of virus containing aerosols, with the exception of properly fitted N95 masks (currently reserved for health care providers due to their scarcity). In contrast, however, ordinary cloth masks if worn by all participants will substantially reduce the potential viral load in the classroom, and thus likely mitigate the potential for SARS-CoV-2 transmission in a classroom environment. Based on review of the literature and these measurements it is recommended that all students and faculty wear the ND provided commercial face mask or the equivalent disposable face mask in the classroom, and in all buildings on campus with the exception of when alone in an individual office or in their dorm room. Masks should also be worn outdoors when the group density is high (e.g., when social distancing is not possible). A face shield is not recommended.