Pressure Difference Analysis Across Face Masks

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Abstract

To test the effectiveness of daily use face masks, this study graphical and numerical analysis of the pressure differences across different mask types during various activities. Using quantitative data from the pressure, temperature, and humidity sensors of an Adafruit BME680 environmental sensor, this experiment determined the pressure, temperature, and humidity differences across four different mask types: a surgical mask, white cloth mask, black polyester mask, and an N95 mask. By performing four different activities while wearing the four types of masks, this study also analyzed the effect of activity type on pressure, temperature, and humidity differences across mask types. Additionally, the effect of respiration on patterns of pressure differences across masks over time was also studied.

1 Introduction

Face masks nowadays are considered an essential aspect of daily life. With nearly 140 million COVID-19 cases worldwide - 23% of them occurring in the United States - public health officials have urged the public to view face masks as a means of protection against infectious air droplets from this respiratory disease (Allen). In order to get the most use out of a face mask, it is important to have an idea of the effectiveness of different types of face masks, specifically how effective different face masks are in filtering out airborne particulates.

This study aims to provide research into the pressure differences across four different types of daily use, commercially available face masks. While a majority of data on the effectiveness of face masks comes from studies done *in vitro* through the use of a respiratory machine mimicking the effect of human breathing, or from studies measuring the particle count differences across face masks (Cary Hill), some research allude to mask airflow resistance, or the pressure difference across a face mask while breathing, as another aspect to consider when evaluating the effectiveness of a face mask (Skaria & Smaldone). This study measures the pressure difference between the environments inside and outside a face mask while being worn by a study participant, in order to study a correlation between the pressure differences of different masks and their materials.

Because face masks are capable of filtering out airborne particulates to some degree, this study looks into the pressure difference between the inside and outside environments across four different face masks.

2 Procedure

2.1 Apparatus

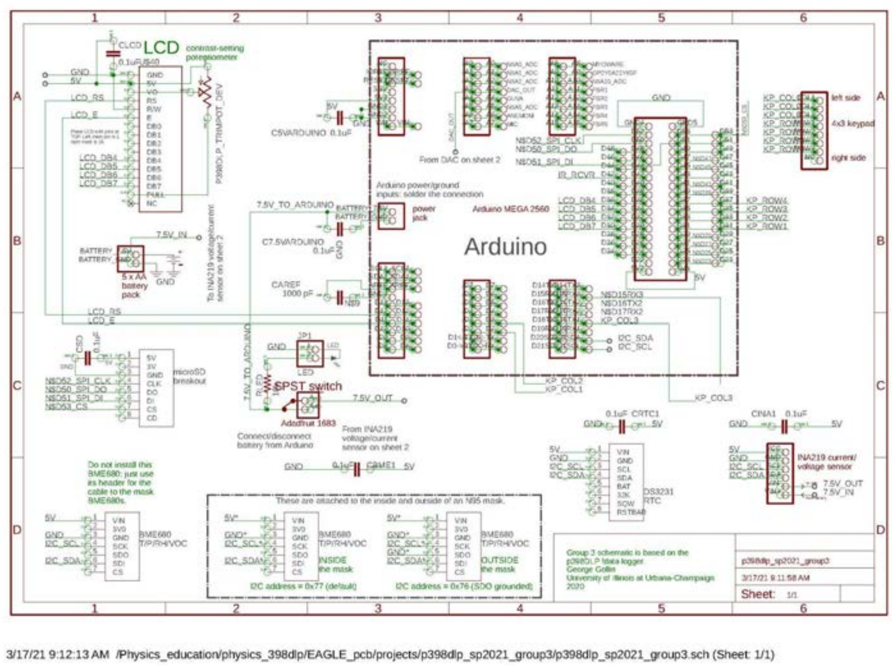


Figure 2.1: Schematic representation of the printed circuit board (PCB) used in this experimental setup

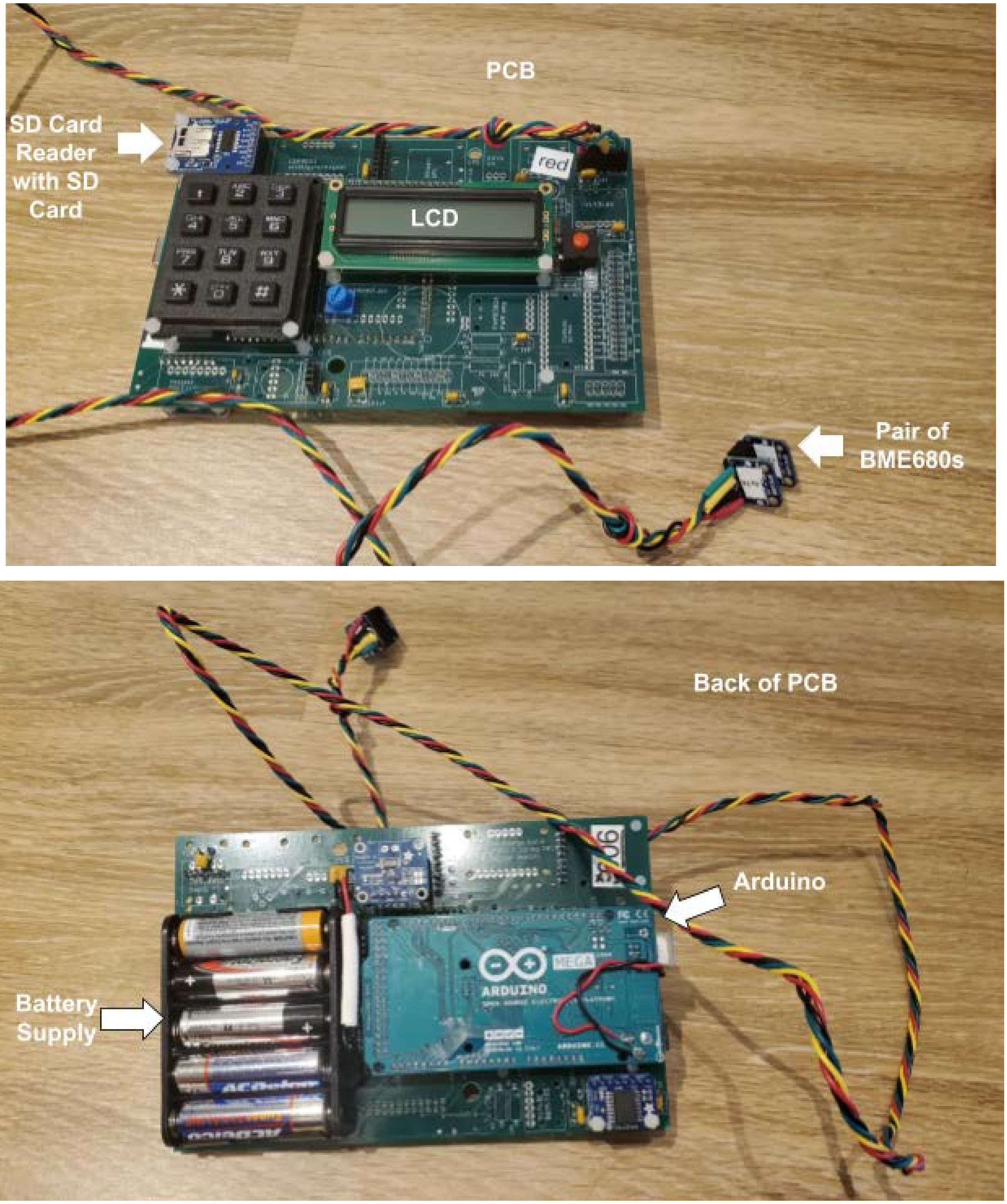


Figure 2.2: Front (top) and back (bottom) of the physical PCB. The BME680 sensors attached at the end of the long intertwined wires.

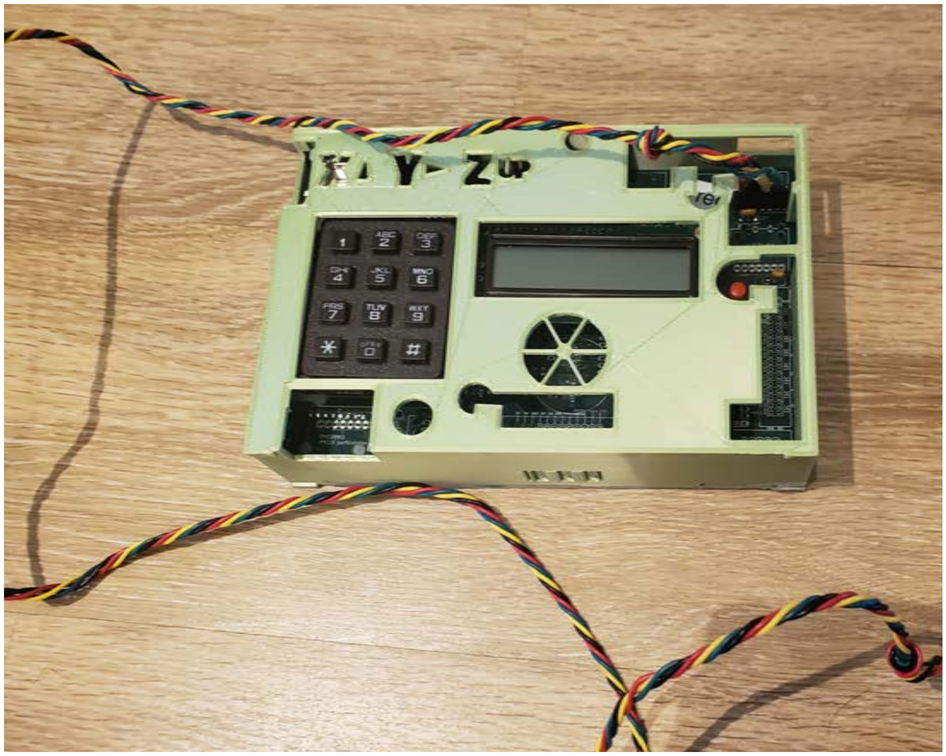


Figure 2.3: PCB board with the 3D printed plastic covering. This cover mainly serves as protection to prevent any potential shorts in the circuit.

This experiment used a schematic (Figure 2.1) drawn by Professor George Gollin. The PCB devices provided by Professor Gollin were manufactured by JLCPCB. Each of the circuit components are part of the Adafruit manufacturing lineup. An additional 3D printed covering was provided (Figure 2.3) to minimize probability of potential circuit shorts.

The major component of the hardware was the Adafruit BME680. A pair of BME680s, attached to the PCB by the multicolored wires, obtained data about pressure, temperature, and humidity. The pressure sensor within the BME680 uses micro-electro-mechanical system (MEMS) technology. This setup consists of one capacitive plate in contact with the sensor's environment, forming a diaphragm. This diaphragm can be deformed by the effects of atmospheric pressure. The higher the atmospheric pressure, the more deformed the diaphragm becomes, and the larger the pressure reading. Although the BME680 has a volatile organic compound (VOC) sensor as well, this experiment turned off this sensor to increase pulling rate of pressure, temperature, and humidity data.

The specifications of the operating range and accuracy of the pressure, temperature, and humidity sensors of the BME680 are described in Tables 2.1 and 2.2 below. BME680 sensors provide temperature data in degrees Celsius, pressure data in hectopascals (hPa), and humidity data in percent. A hectopascal (equivalent to 100 pascals) is a low value compared to other units of measuring pressure, and is therefore ideal for experiments regarding atmospheric or low gas pressure, such as this study.

Sensor	Operating Range
Temperature	-40 to 85 C (or -40 to 185 F)
Pressure	300 to 1100 hPa (sea level ~ 1013 hPa)
Humidity	0 to 100% humidity

Table 2.1: Specific Pressure, Temperature, and Humidity Operating Ranges for the BME680 sensors. The values of sea level atmospheric pressure in hectopascals (hPa) is provided for reference. The data collected within this experiment was well within the operating ranges for the BME680 sensors, so as not to interfere with the integrity of the BME680.

Sensor	Accuracy
Temperature	± 1 Celsius
Pressure	± 1 hPa
Humidity	± 3 %

Table 2.2: Specific Pressure, Temperature, and Humidity Accuracies for the BME680 sensors. These ranges help to ensure the pair of BME680s are within reasonable measuring range of each other, since the maximum baseline difference between measurements from the two BME680s should not exceed the doubled value of the accuracy range for the respective sensor.

The data acquisition software (DAQ) used to pull data from the pair of BME680s was written in the Arduino integrated development environment (IDE) through collaboration between the experimenters, Professor Gollin, and Ivan Velkovsky. The DAQ obtains data from the pressure, temperature and humidity sensors of both BME680s, and also turns off readings from the volatile compound gas sensor to increase the pulling rate. Data from the inside BME680 (0x77) is stored as Pressure 1, Temperature 1, Humidity 1, etc, and the data from the outside BME680 (0x76) is stored as Pressure 2, Temperature 2, Humidity 2, etc. The program also calculates the pressure, temperature, and humidity differences directly from the corresponding sensor data, allowing for easier offline analysis. The collected data is stored in a data file on the SD card, which can be specified by the user. Before running the DAQ, the user can also specify the length of the data file (i.e. how many data points to collect in one trial, before closing the data file). After the specified number of data points is collected, the data file is closed, and the SD card is able to be removed from the PCB so that the data file can be extracted for offline analysis.

The offline analysis code was done in Python using the Spyder application. After saving the data file as a .csv file within the Spyder application folder, the offline analysis code could extract pressure, temperature, and humidity data from the saved data file and graph the differences.

Four different mask types were used in this experiment. The first was a disposable, non-sterile, blue, 3-ply surgical mask, which is typically effective against large-particle airborne particulates that may serve as vectors for viruses and/or bacteria (FDA). The second was an ATA Reusable SILVADUR™ 930 FLEX anti-microbial white cloth face mask, with 3-ply cotton construction. The third was a black 3-ply 100% polyester face mask, with a non-woven liner. The fourth was a Kimberly-Clark N95 pouch respirator (53358) which is NIOSH-approved, meaning that it provides a filtration efficiency of at least 95% of 0.3 micron particles.

The pair of BME680s were fitted through the different types of masks so that pressure, temperature, and humidity data could be taken on both sides of the mask. Figures 2.4 and 2.5 below show images of the BME680s connected to both the inside and outside of a surgical mask, for reference. The BME680s are in fact removable, and can be placed through any of the four types of masks. Holes were made for the leads of the BME680 using a sharp needle.

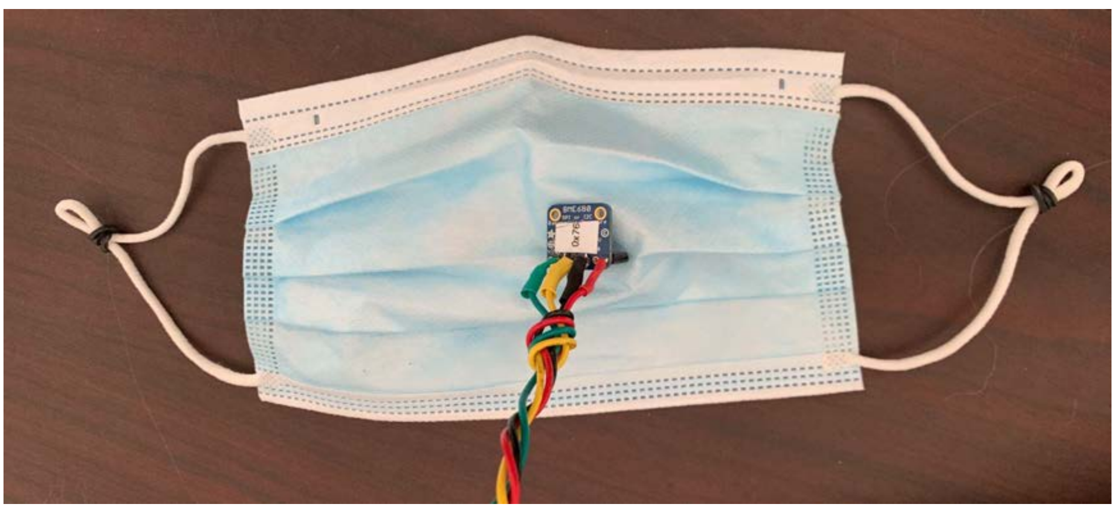


Figure 2.4: Outside of a surgical mask with the pair of BME680s attached. The "outside" BME680, labelled 0x76, is visible from the outside of the mask.

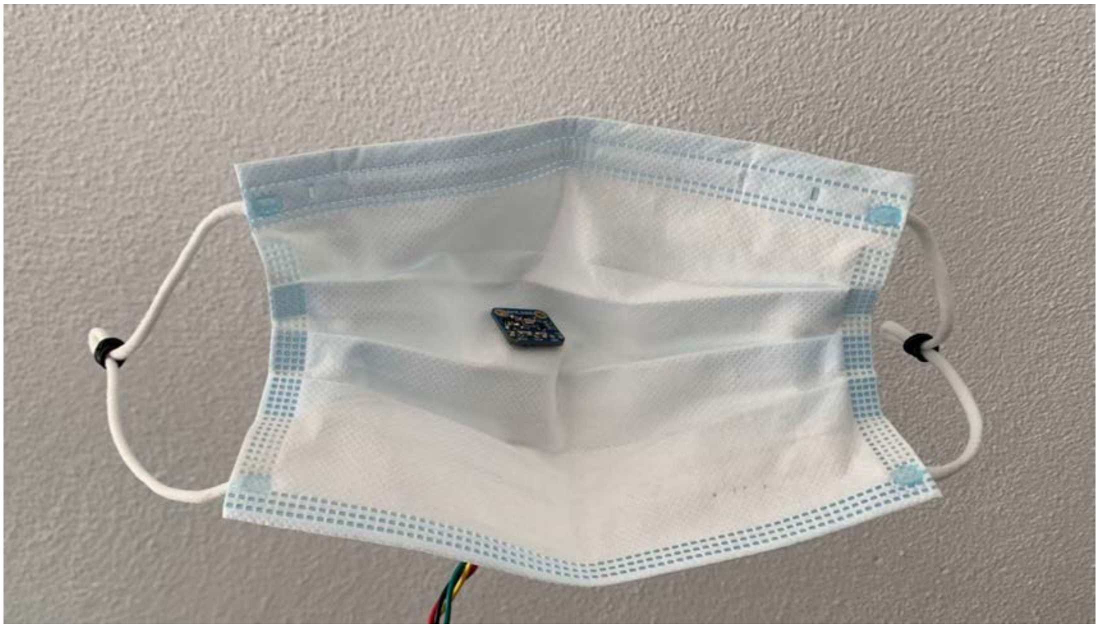


Figure 2.5: Inside of a surgical mask with the pair of BME680s attached. The "inside" BME680, labelled 0x77, is visible from the inside of the mask.

To ensure tightness of fit when wearing the masks, participants could also use black rubber bands to bind and shorten the ends of the ear loops, as shown in Figures 2.4 and 2.5. A visual example of how a participant wears a mask connected to the BME680s during experimental trials, as well as images on how different mask types look, are included in Figures 2.6-2.8 below.

Figure 2.6: Participant wearing a surgical mask with BME680s attached. The placement of the BME680s in the middle of the mask allows the sensors to be in the direct center of any environmental change between the inside and outside regions of the mask. To prevent mouth, nose, or skin interference with the sensors, the wire connecting the pair of BME680s was held during experimental trials to prevent the BME680s from pulling the mask down and having accidental contact with the skin.

Figure 2.7: Participant wearing a white cloth mask with BME680s attached through the center of the mask.

Figure 2.8: Participant wearing a black polyester mask with BME680s attached through the center of the mask.

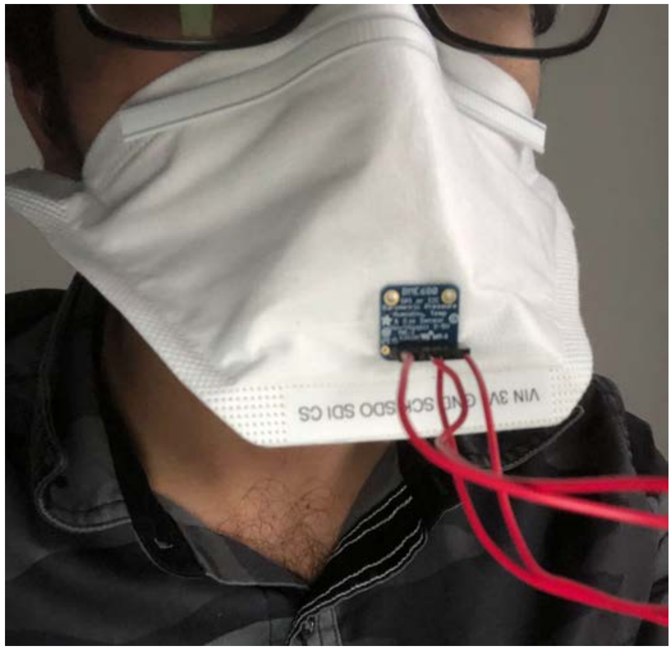


Figure 2.9: Participant wearing a N95 mask with BME680s attached through the center of the mask.

2.2 Methods

Before any experimental trials were performed, each participant determined their own normal respiration rate by wearing any mask attached to the BME680s, and recording their breathing over 1000 data points. From this data, wave-like patterns in the temperature difference graphs were correlated with respiration patterns.

By counting the number of respiration cycles found in the temperature difference graph, the respiration rate found in these trials is set as the normal breathing rate i.e. the number of breaths the participant usually takes in one minute. This number serves as a reference for deep breathing, which was defined in the experiment as approximately 50-75% the number of breaths in one minute as normal breathing.

After determining the respiration rate for each participant, experimental trials to determine the pressure difference across each mask type were conducted. Each experimental trial consists of a baseline data collection and an experimental data collection. During the baseline data collection, the BME680s is allowed to sit at rest in the same environment that the experimental data collection will take place. No mask is attached to the BME680s at this time. The PCB is connected to the participant's laptop, and the DAQ is run for 5 minutes (300000 milliseconds) to collect pressure, temperature, and humidity data for approximately 6667 data points.

After the baseline data is collected, the data file from the SD card is extracted for offline graphical analysis. The participant then connects the pair of BME680s through the mask, and puts on the mask as normal with no intentional gaps. After allowing the apparatus to calibrate for at least 5 minutes, the DAQ is run again for the same amount of time as the baseline data collection, in order to collect data about the pressure, temperature, and humidity differences across the mask during normal breathing for the experimental data collection part. This procedure, with the exact millisecond run times, was repeated for normal breathing performed with a surgical mask, white cloth mask, and black polyester mask. For the N95 pouch mask, the DAQ was run for 1 minute (60000 milliseconds) over a total of approximately 1000 data points.

Measuring the baseline pressure difference between the pair of BME680s before each trial allowed for calculations of the actual pressure difference across the BME680s for each trial, and provided a means of control for differences in environment or experimenter between each trial. Calibrating the parameter differences will also confirm if pressure differences are actually due to the action of breathing, and not due to random environmental conditions. Data from the baseline differences also provides information about the baseline temperature and humidity differences between the pair of BME680s at rest.

To determine the effect of activity on pressure, temperature, and humidity differences across different mask types, participants repeated the above procedure of taking baseline measurements before performing a specific activity while wearing a face mask attached to the BME680s. The four activities performed during this experiment were normal breathing (as defined by the participant's normal respiration rate), deep breathing (as defined by roughly half the number of breaths per minute as normal respiration rate for the participant), talking, and smiling. The talking activity included reading from a set of paragraphs in English while wearing the specific face mask attached to the pair of BME680s. The smiling activity consisted of contorting the participant's mouth upwards, thereby also inducing changes in the conformation of the facial skin and impacting the contact points of the face mask and the face itself. These activities were modeled off of qualitative mask fit tests conducted by mask manufacturers, and aim to mimic activities that mask-wearers might perform in their daily life while wearing a mask. Pressure, temperature, and humidity difference data was reported and compared across the four activity types, as well as across the four different mask types.

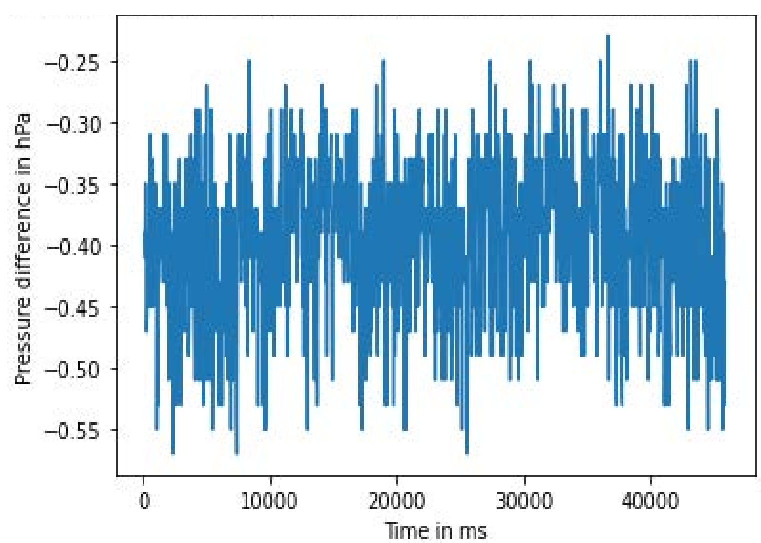
To analyze the effect of respiration on patterns of pressure difference across masks over time, pressure, temperature, and humidity differences were averaged over one inhalation/exhalation cycle to determine the average difference during the period of a cycle. The respiration cycles, deduced from the temperature difference graphs as was described earlier when determining the respiration rate of individual participants, were related to microscopic trends of pressure difference to study if there was any relationship between respiration rate and the pressure difference during inhalation vs exhalation.

Note that all “difference” values are defined as the difference between the inside and outside values as measured by the inside and outside BME680s, respectively. Specifically, each difference value was calculated by subtracting the outside value from the inside value (i.e. pressure difference in hPa = inside pressure value in hPa - outside pressure value in hPa).

3 Results and Discussion

3.1 Determining Respiration Rate for Normal Breathing

An example of the data taken to determine respiration rate of an individual participant is shown below in Table 3.1. The graphs take into account the baseline differences in pressure, temperature, and humidity between one pair of BME680s. Specifically, the data in Table 3.1 was taken using the pair of BME680s provided to Grace Chiou, and thus takes into account the baseline data from Grace’s BME680s. The process of determining the actual difference from baseline and experimental differences is described in more detail in Section 3.2.

Determining Respiration Rate for Normal Breathing	
Pressure Difference (hPa)	

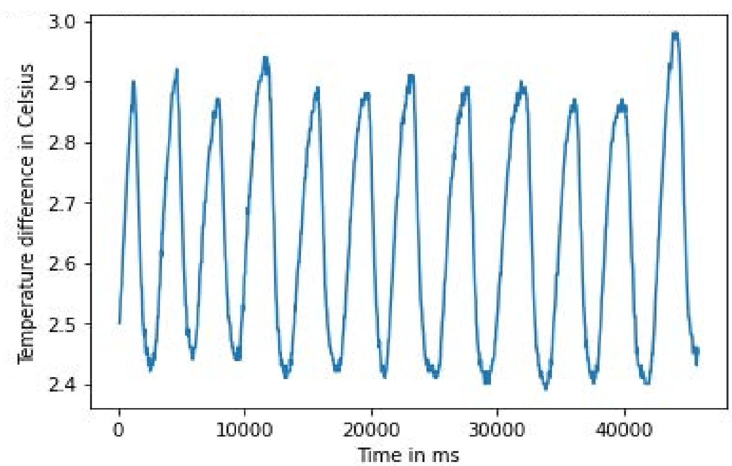
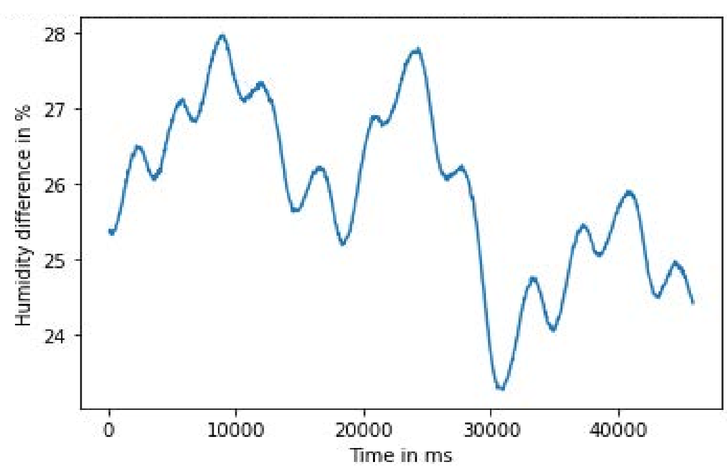
Temperature Difference (Celsius)	
Humidity Difference (%)	
Calculated Respiration Rate	12 breaths per 45 seconds = 16 breaths per 60 seconds

Table 3.1: Pressure, Temperature, and Humidity Difference Graphs for Normal Breathing performed while wearing a Surgical Mask. Any type of mask can be worn while determining the respiration rate. The number of cycles in the wave-like pattern found in the temperature difference graph was summed; each full wavelength represents one respiration cycle of inhalation and exhalation. This number of respiration cycles was averaged over the total amount of time it took to collect the data, and then scaled up to determine the amount of breaths normally taken for this participant in a minute.

As seen in the graphs above, the temperature difference graph clearly shows oscillations in the temperature difference over time. Correlating this wave-like pattern to the respiration pattern of the participant's normal breathing, it was determined that inhalation caused a decrease in the temperature difference and was seen as the relative minimas in the temperature difference graph, while exhalation caused an increase in the temperature difference and was seen as the relative maximas in the temperature difference graph.

Counting each full wavelength as a single breath in the temperature difference graph, the number of breaths per minute was able to be calculated for each participant. The graphs in Table 3.1 were produced for each participant's respiration rate. The calculated respiration rate was then used as a reference for how many breaths per minute should be expected in normal breathing activity trials. Deep breathing activity trials were expected to see roughly 50-75% the number of breaths per minute as the normal breathing rate.

3.2 Determining Actual Differences from Baseline Differences and Experimental Differences

Tables 3.2-3.4 below show example data of how actual pressure, temperature, and humidity differences were determined. Experimental differences are defined as the pressure, temperature, and humidity differences measured while the mask, attached to a pair of BME680s, is being worn by a participant. Baseline differences are defined as the pressure, temperature, and humidity differences measured while the same pair of BME680s is at rest with no mask attached in between them. Actual differences are then defined as the experimental difference with the baseline difference accounted for (i.e. actual difference = experimental difference - baseline difference).

The y-axis (parameter) scales between graphs of the same parameter type (i.e. pressure, temperature, humidity) were kept constant between the experimental difference graphs and their corresponding actual difference graphs, so the effect of accounting for the baseline difference can be easily seen. The x-axis (time) scale was kept constant throughout all graphs, regardless of parameter type, and was chosen to be 50000 milliseconds, or 50 seconds, so that the respiration patterns of the participant are clearly visible in the experimental difference graphs. There are no visible respiration patterns in any of the baseline difference graphs because no breathing occurs across the BME680s during baseline data collection; the pair of BME680s are simply allowed to rest with no breathing and no mask attached between them during baseline data collection.

Determining Actual Pressure Difference of Black Polyester Mask During Normal Breathing

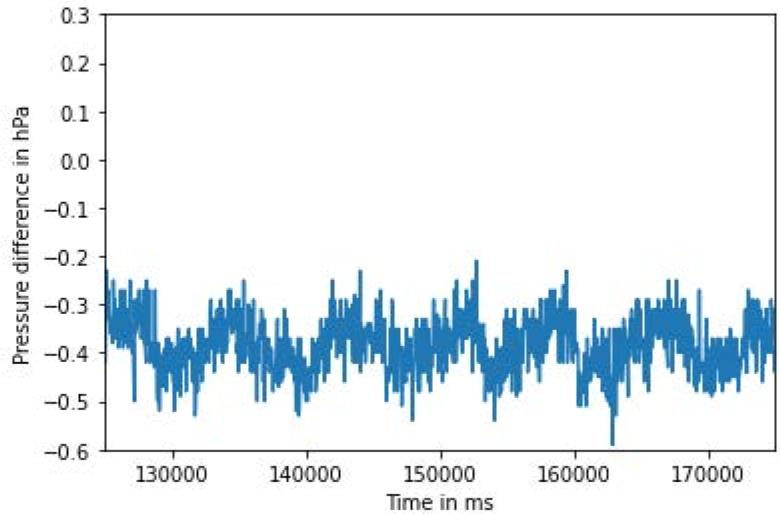
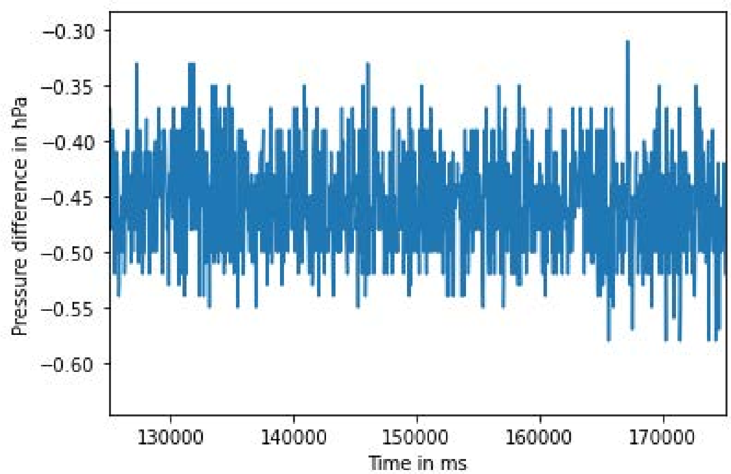
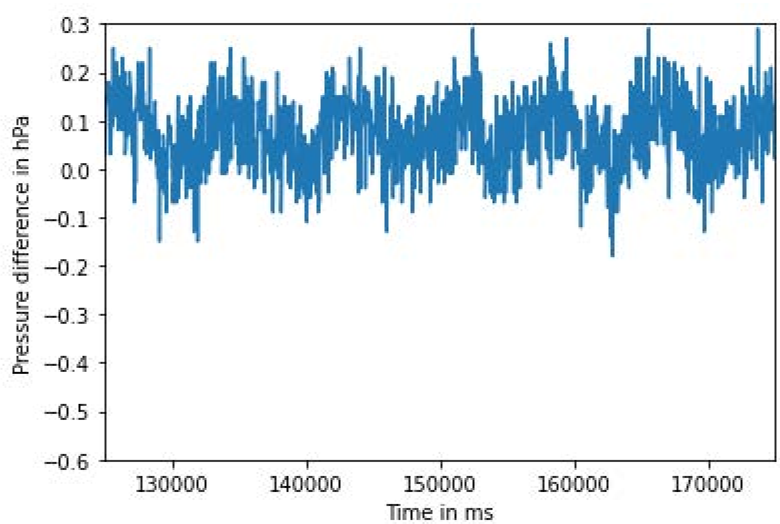
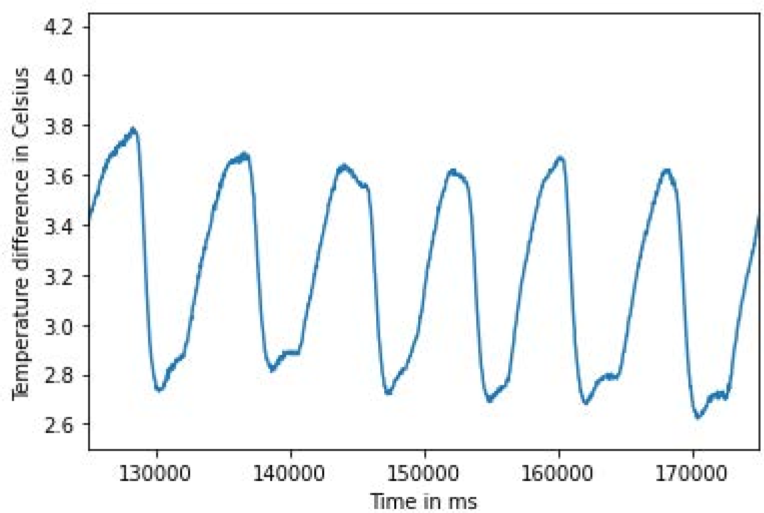
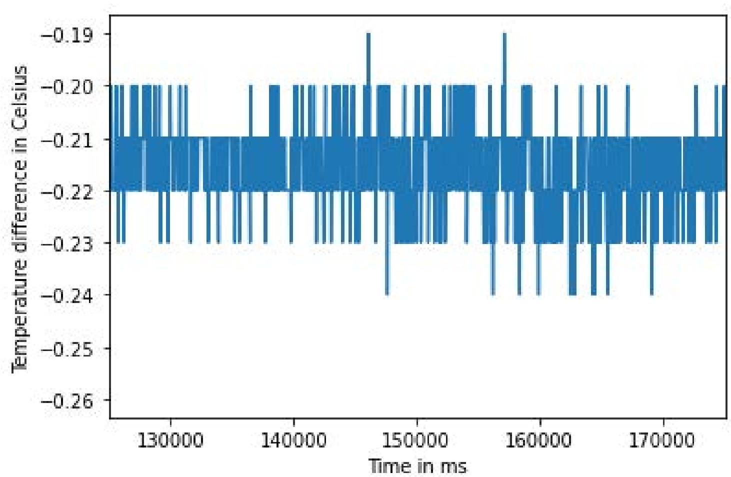
Experimental Pressure Difference	
Baseline Pressure Difference	
Actual Pressure Difference (Actual = Experimental - Baseline)	

Table 3.2: Actual Pressure Difference of Black Polyester Mask During Normal Breathing. The actual pressure difference graph was generated by subtracting the baseline pressure difference values from the experimental pressure difference values. Specifically, this pressure difference data was taken from Trial 1 of the Normal Breathing trials with a black polyester mask to determine the pressure difference across different mask types, using the pair of BME680s provided to Grace Chiou.

<table>
<tr><th colspan="2">Determining Actual Temperature Difference of Black Polyester Mask During Normal Breathing</th></tr>
<tr><td>Experimental Temperature Difference</td><td>
</td></tr>
<tr><td>Baseline Temperature Difference</td><td>
</td></tr>
</table>

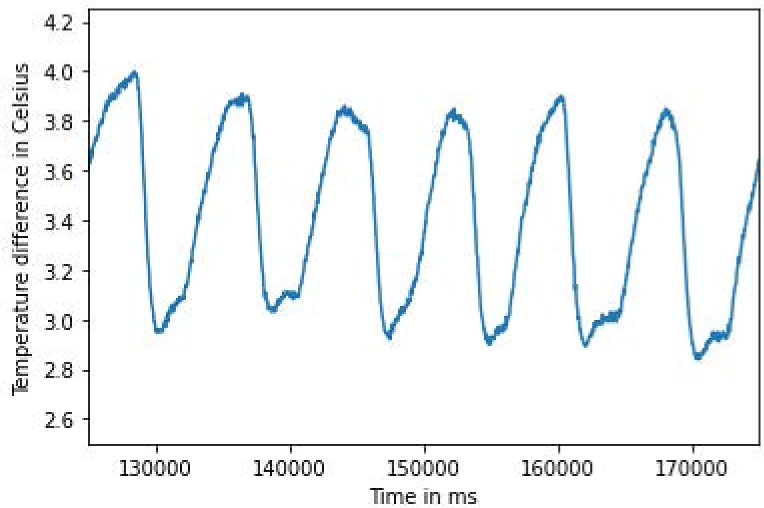
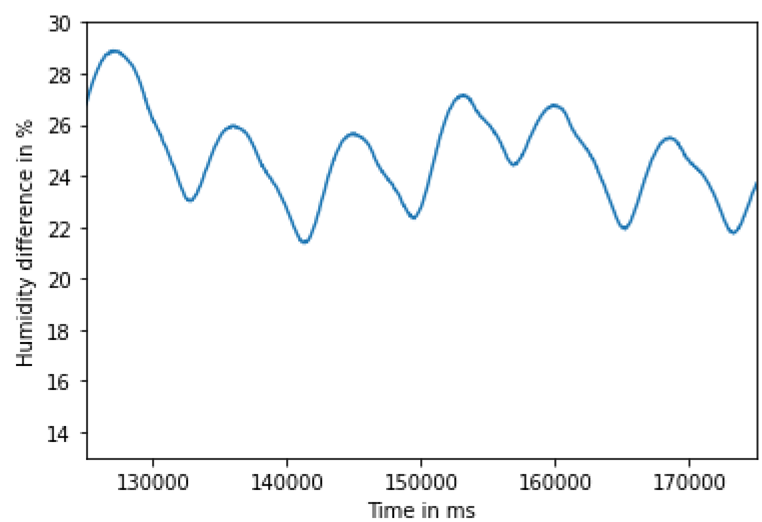
Actual Temperature Difference (Actual = Experimental - Baseline)	

Table 3.3: Actual Temperature Difference of Black Polyester Mask During Normal Breathing. The actual temperature difference graph was generated by subtracting the baseline temperature difference values from the experimental temperature difference values. Specifically, this temperature difference data was taken from Trial 1 of the Normal Breathing trials with a black polyester mask to determine the temperature difference across different mask types, using the pair of BME680s provided to Grace Chiou.

Determining Actual Humidity Difference of Black Polyester Mask During Normal Breathing	
Experimental Humidity Difference	

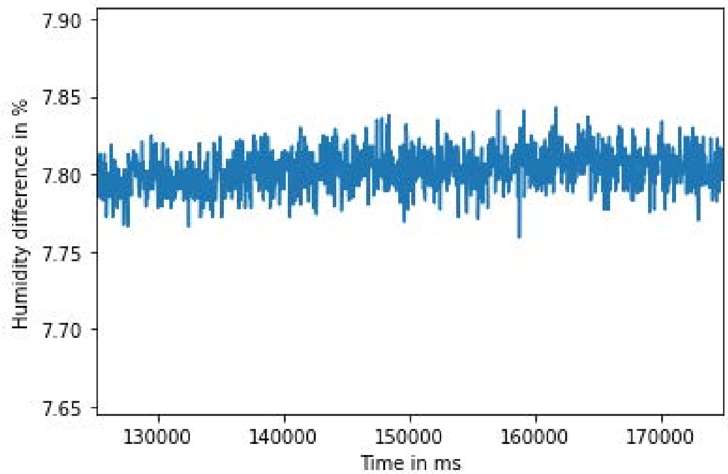
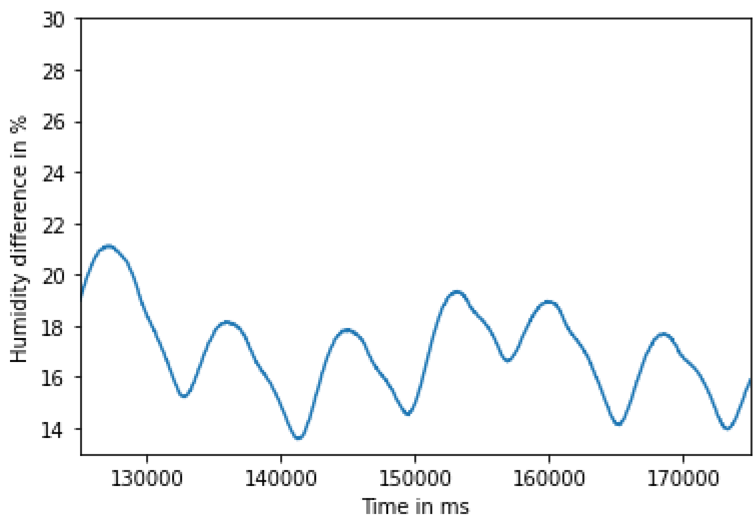
Baseline Humidity Difference	
Actual Humidity Difference (Actual = Experimental - Baseline)	

Table 3.4: Actual Humidity Difference of Black Polyester Mask During Normal Breathing. The actual humidity difference graph was generated by subtracting the baseline humidity difference values from the experimental humidity difference values. Specifically, this humidity difference data was taken from Trial 1 of the Normal Breathing trials with a black polyester mask to determine the humidity difference across different mask types, using the pair of BME680s provided to Grace Chiou.

As seen in Table 3.2, the experimental pressure difference is, on average, smaller than the baseline pressure difference. This phenomenon is explored in more detail in Section 3.4. For the calculations portrayed in Table 3.2, the actual pressure difference still displays the effect of normal breathing through a black polyester mask. For reference, the baseline pressure difference between the two BME680s (provided to Grace Chiou) at rest is around -0.45 hPa. However, with the presence of a black polyester mask and the act of normal breathing, the pressure difference between the same two BME680s has an average value of roughly -0.379861 hPa. Because it is known that there is some existing baseline pressure difference that already exists even in the absence of all masks and all breathing patterns, subtracting the baseline pressure difference values from the experimental pressure difference values will show the effect that normal breathing through a black polyester mask has on the pressure difference between the same pair of BME680s. The baseline pressure difference is a certain number; normal breathing through the black polyester mask makes the pressure difference appear closer to zero. Therefore, we can determine that the actual pressure difference is around -0.07 hPa.

Tables 3.3 and 3.4 are relatively more straightforward. Since the baseline temperature difference has a negative average value, it can be determined that the temperature measured by the “outside” BME680 is, on average, larger than the temperature measured by the “inside” BME680, when there is no mask attached between the two BME680s. When performing normal breathing through a black polyester mask with the same two BME680s attached, however, the temperature difference is, on average, a positive value, which agrees with the fact that when the mask is worn and the BME680s are placed in their respective environments, the temperature of the inside BME680 is expected to be, on average, larger than the the temperature of the outside BME680. Accounting for the baseline temperature difference, it can be determined that the actual temperature difference is actually larger than the experimental temperature difference, because act of normal breathing through a black polyester mask must “overcome” the negative baseline temperature difference between the pair of BME680s at rest in order to produce a positive temperature difference.

For the humidity difference calculations, both the baseline humidity difference and the experimental humidity difference are positive, meaning that the inside BME680 measures a larger humidity than the outside BME680 both when the pair of BME680s is at rest and when the pair of BME680s is being used while normal breathing through a black polyester mask. However, the humidity difference between the two BME680s is larger when performing normal breathing through a black polyester mask than it is when the pair of BME680s is just at rest with no mask attached between them. By subtracting the baseline humidity difference from the experimental humidity difference, it can be determined that the actual humidity difference is smaller than the experimental difference due to the offset of the baseline humidity difference.

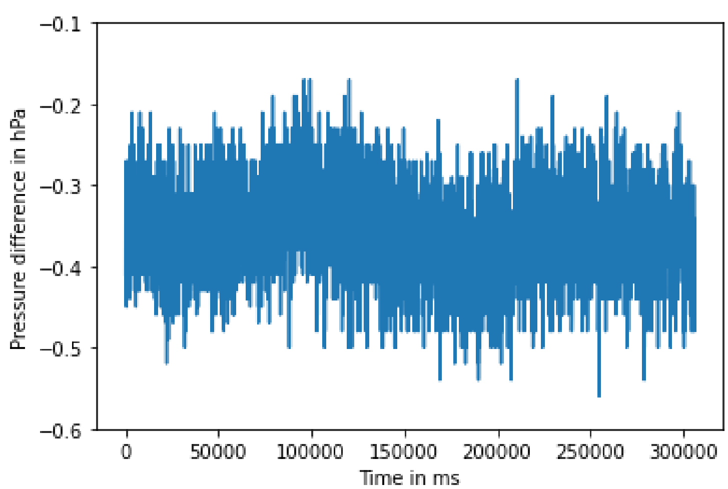
The calculations of subtracting the baseline difference from the experimental difference to determine the actual difference were repeated for each mask type trial (surgical, white cloth, black polyester, N95) and for each activity type (normal breathing, deep breathing, talking, smiling). Unless specified otherwise, further pressure, temperature, and humidity difference graphs display the actual pressure, temperature, and humidity differences, which means they display the experimental differences with the baseline differences accounted for.

3.3 Measuring the Average Pressure Difference Across One Breath Cycle

When trying to compare the pressure differences between difference mask types, it was found that the pressure difference graphs often appeared very noisy, even with the baseline pressure differences subtracted off and accounted for. However, by decreasing the range of the x-axis (time), patterns in pressure differences over time became more visible, and seemed to follow the wave-like pattern due to respiration, as was discovered in Section 3.1 when using the temperature difference graphs to determine respiration rate.

As a result, it was decided to average the pressure difference across one cycle of respiration rather than taking an average of the pressure difference across the entire time interval of data collection. The average pressure difference across one cycle of respiration could then be used as a point of comparison between different mask types.

Tables 3.5-3.16 below show the pressure, temperature, and humidity difference graphs of all four mask types during normal breathing, with increasingly smaller time ranges on the x-axis. Y-axis scales were kept constant as much as possible between decreases in the x-axis scale; the y-axis scale was only decreased to maintain the overall shape of the difference curves. The data for the surgical, white cloth, and black polyester masks were taken using the pair of BME680s provided to Grace Chiou, while the data for the N95 mask was taken using the pair of BME680s provided to Akash Prasad. Data from Tables 3.5-3.16 were taken from the first trials of the respective experimental trials for determining the pressure differences between mask types, shown in Section 3.4.

Surgical Mask with Normal Breathing: Trial 1		
Time Interval	Pressure Difference Graphs	Pressure Difference Values (hPa)
0 to 300 seconds 300 second time interval		Average Pressure Difference: -0.355029

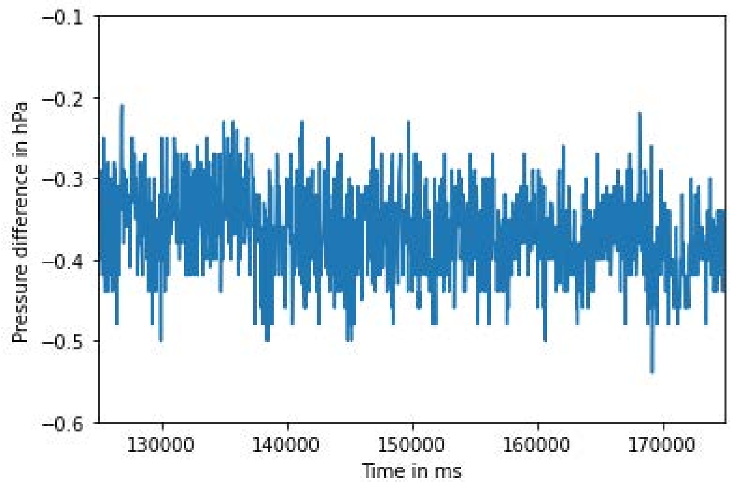
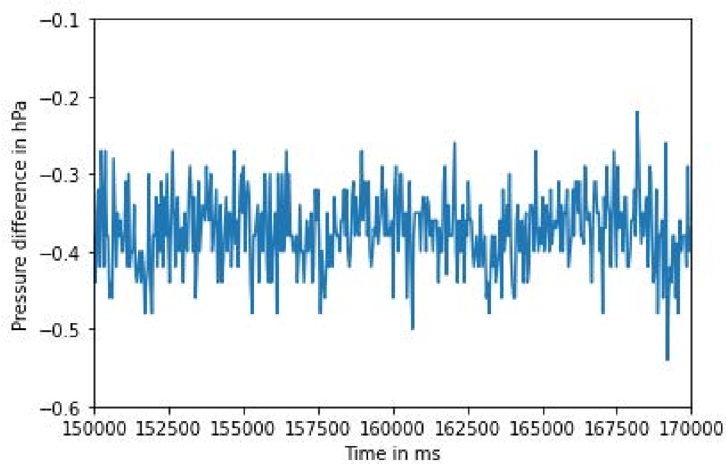
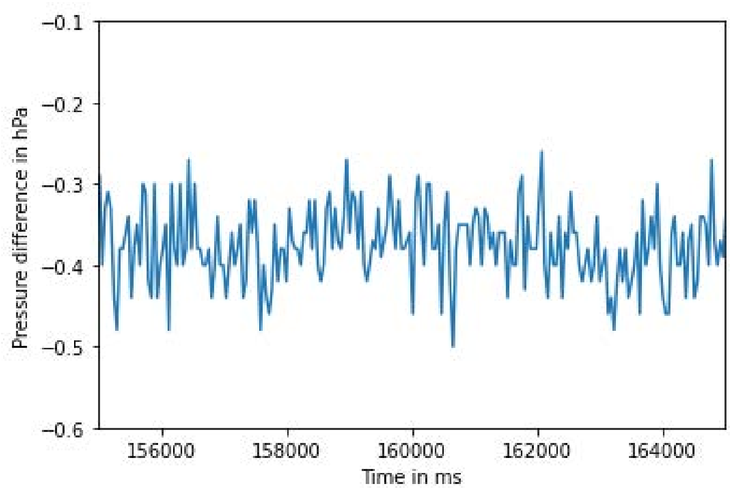
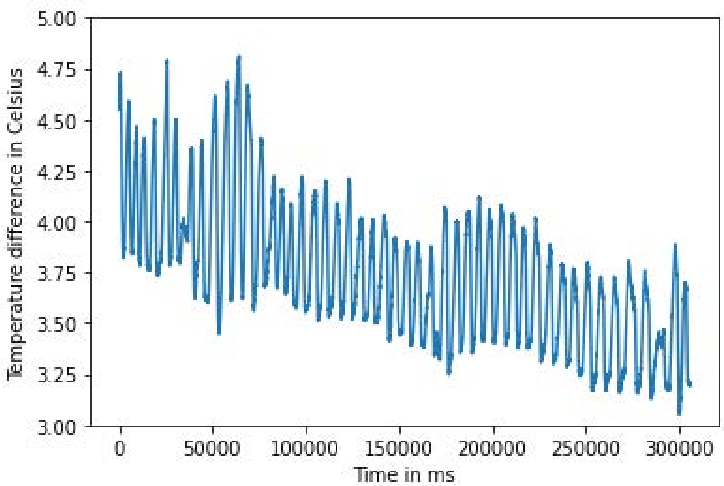
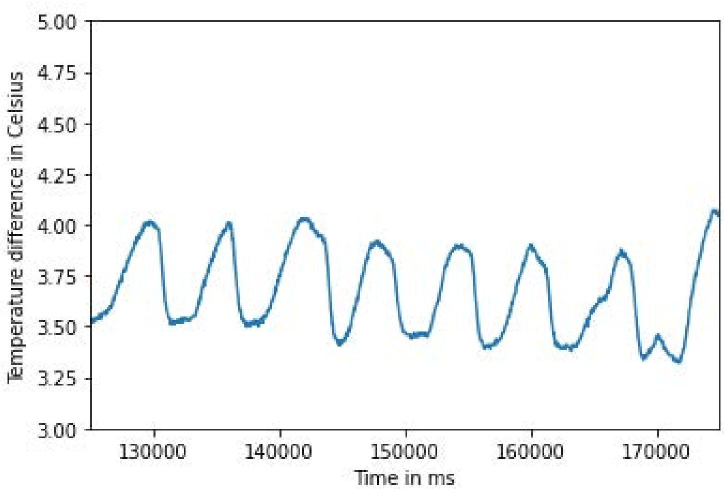
125 to 175 seconds 50 second time interval	 	Average Pressure Difference: -0.366547
150 to 170 seconds 20 second time interval	 	Average Pressure Difference: -0.36783
155 to 165 seconds 10 second time interval	 	Average Pressure Difference: -0.37827

Table 3.5: Pressure difference graphs for normal breathing with a surgical mask. Average pressure difference across each time interval was calculated. The average pressure difference

across the smallest time interval (10 seconds) was used as the point of comparison between mask types.

Surgical Mask with Normal Breathing: Trial 1		
Time Interval	Temperature Difference Graphs	Temperature Difference Values (Celsius)
0 to 300 seconds 300 second time interval		Average Temperature Difference: 3.753793
125 to 175 seconds 50 second time interval		Average Temperature Difference: 3.74156

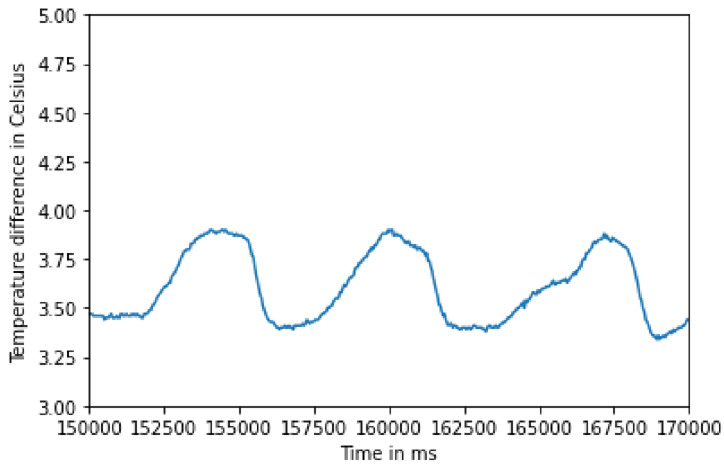
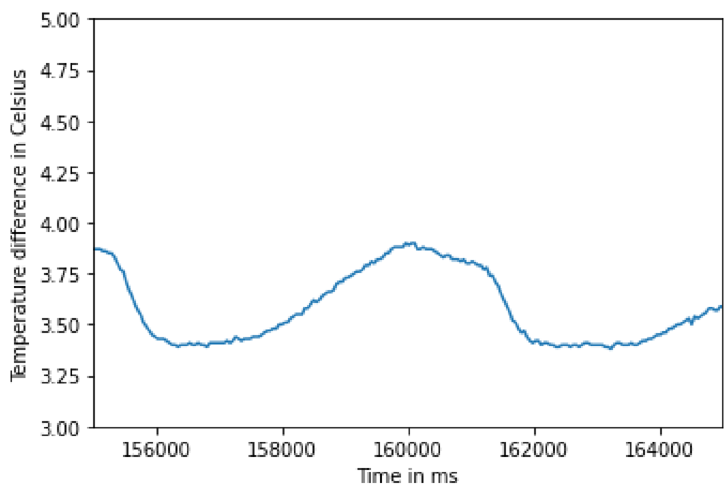
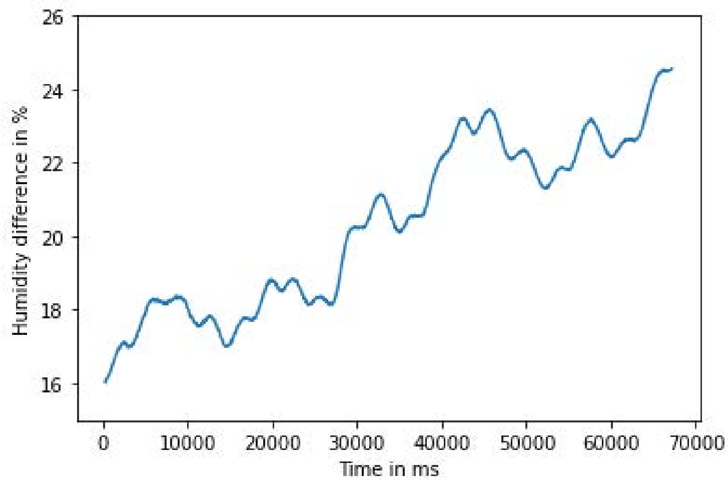
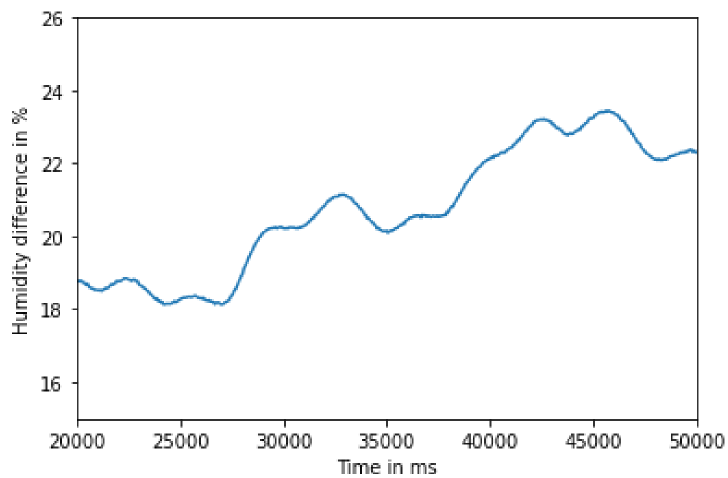
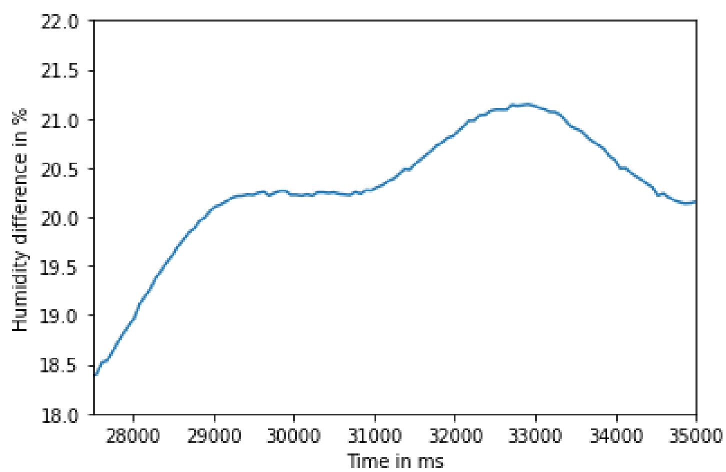
150 to 170 seconds 20 second time interval		Average Temperature Difference: 3.72342
155 to 165 seconds 10 second time interval		Average Temperature Difference: 3.68219

Table 3.6: Temperature difference graphs for normal breathing with a surgical mask. Average temperature difference across each time interval was calculated. The average temperature difference across the smallest time interval (10 seconds) was used as the point of comparison between mask types.

Time Interval	Humidity Difference Graphs	Humidity Difference Values (%)

0 to 300 seconds 300 second time interval		Average Humidity Difference: 20.32222
125 to 175 seconds 50 second time interval		Average Humidity Difference: 20.5493
150 to 170 seconds 20 second time interval		Average Humidity Difference: 19.7247

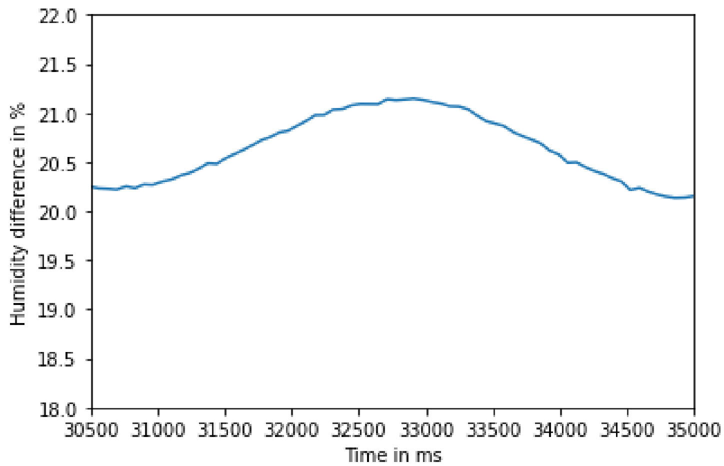
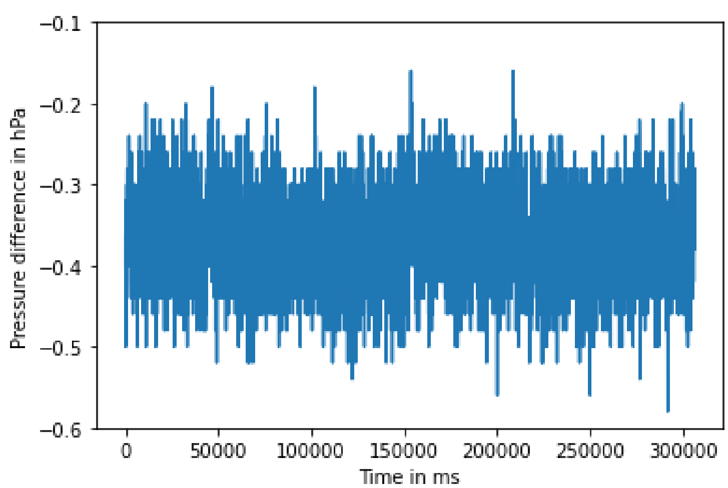
155 to 165 seconds 10 second time interval		Average Humidity Difference: 20.7814

Table 3.7: Humidity difference graphs for normal breathing with a surgical mask. Average humidity difference across each time interval was calculated. The average humidity difference across the smallest time interval (10 seconds) was used as the point of comparison between mask types.

White Cloth Mask with Normal Breathing: Trial 1		
Time Interval	Pressure Difference Graphs	Pressure Difference Values (hPa)
0 to 300 seconds 300 second time interval		Average Pressure Difference: -0.366548

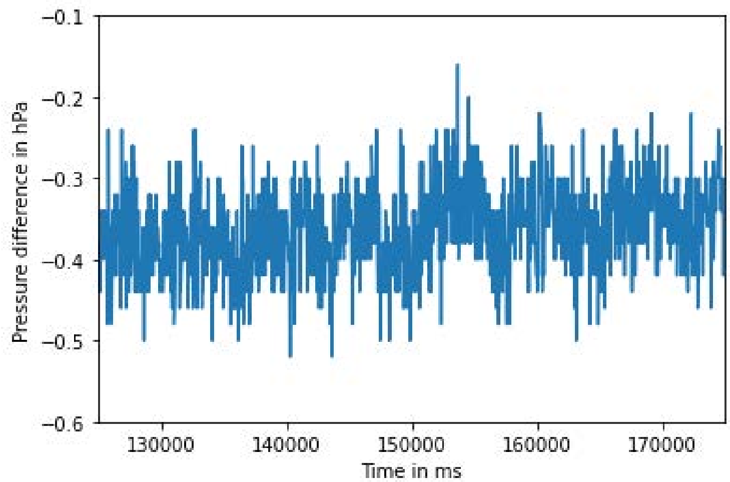
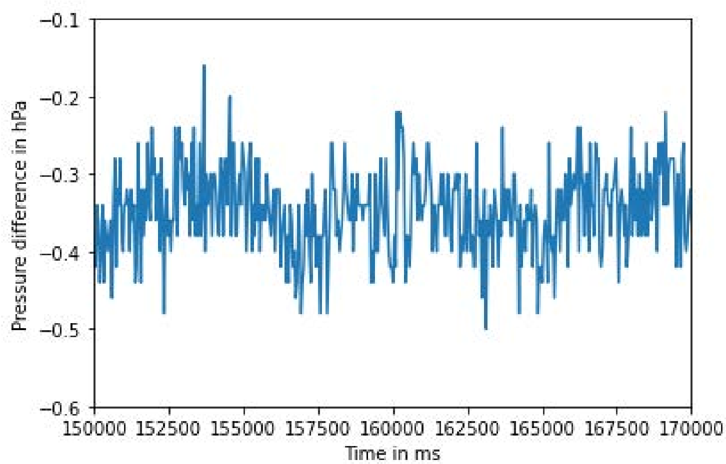
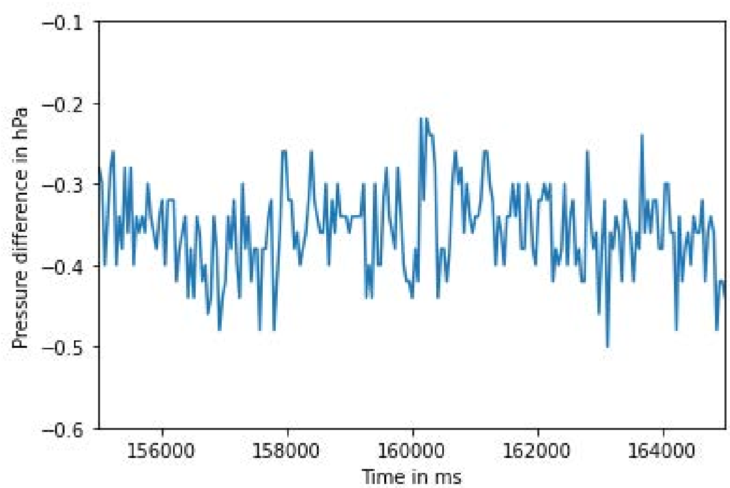
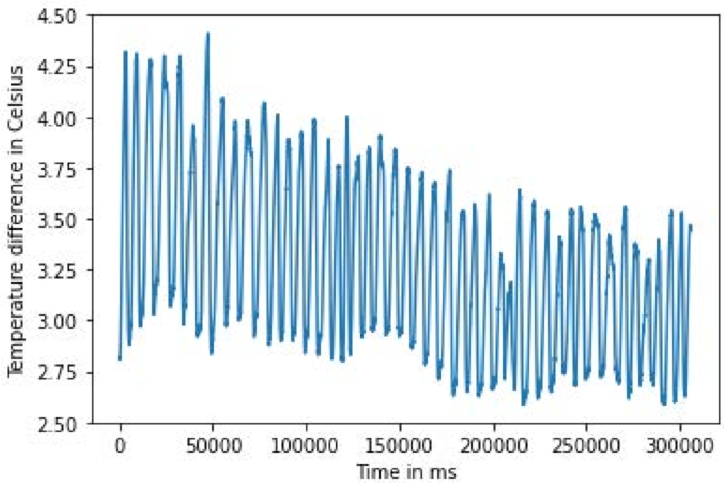
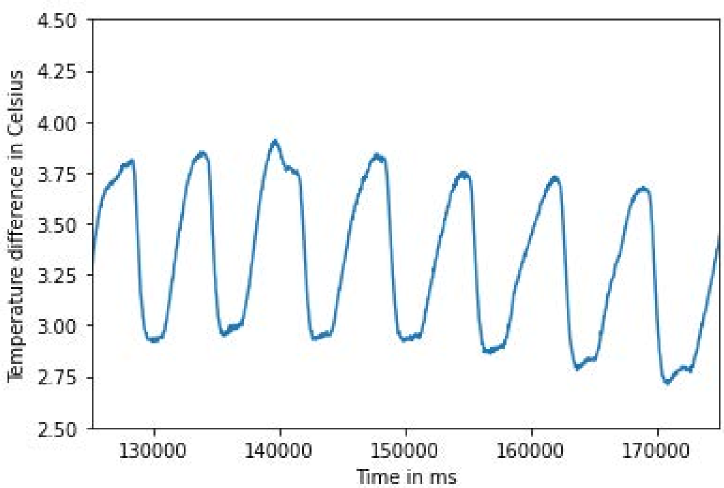
125 to 175 seconds 50 second time interval		Average Pressure Difference: -0.33495
150 to 170 seconds 20 second time interval		Average Pressure Difference: -0.32439
155 to 165 seconds 10 second time interval		Average Pressure Difference: -0.35688

Table 3.8: Pressure difference graphs for normal breathing with a white cloth mask. Average pressure difference across each time interval was calculated. The average pressure difference

across the smallest time interval (10 seconds) was used as the point of comparison between mask types.

White Cloth Mask with Normal Breathing: Trial 1		
Time Interval	Temperature Difference Graphs	Temperature Difference Values (Celsius)
0 to 300 seconds 300 second time interval		Average Temperature Difference: 3.271561
125 to 175 seconds 50 second time interval		Average Temperature Difference: 3.27093

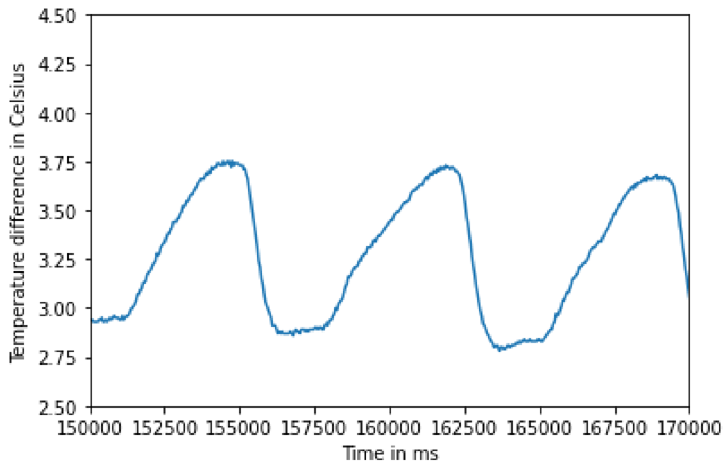
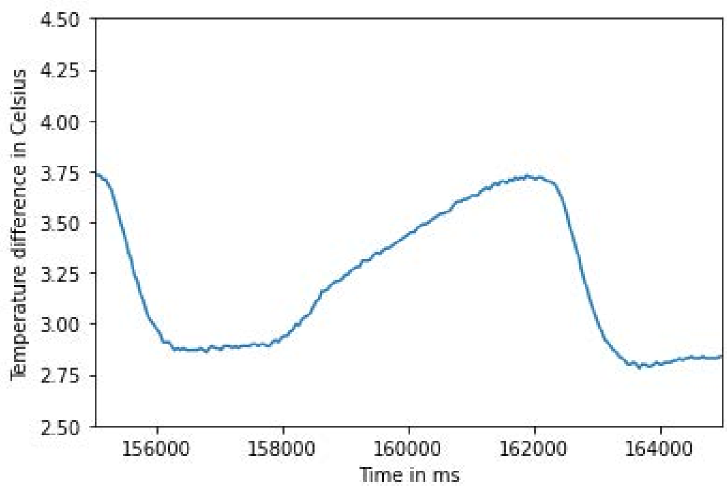
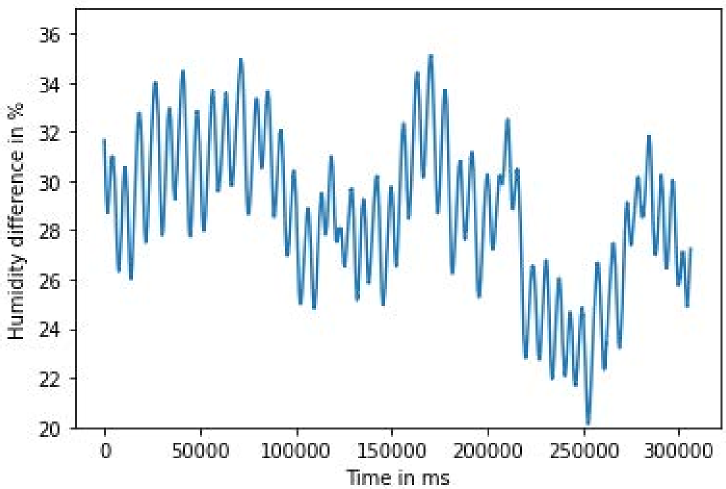
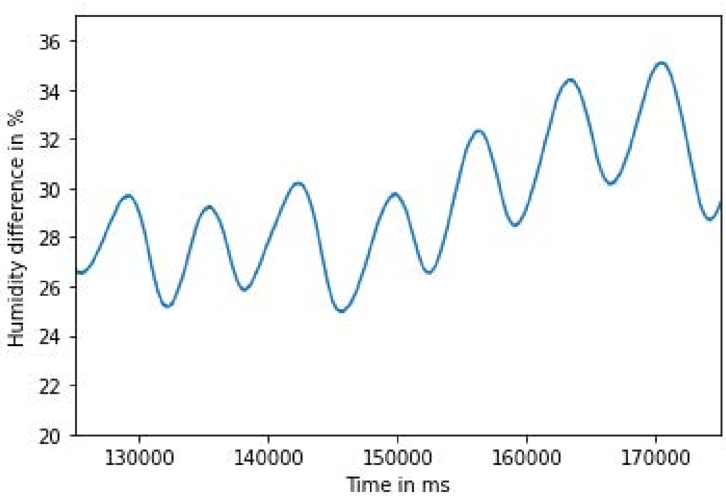
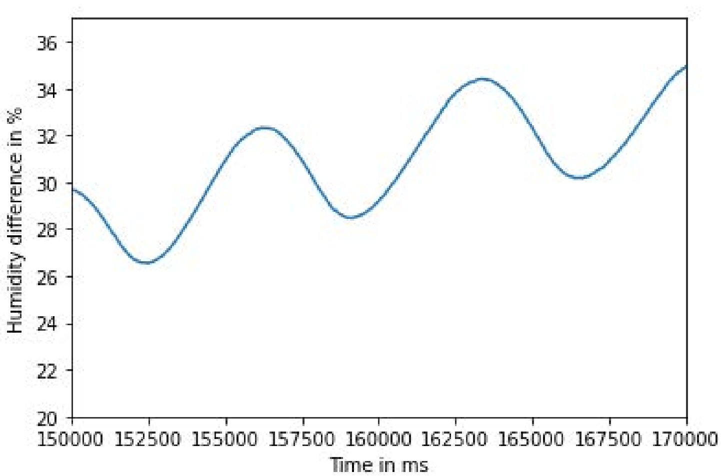
150 to 170 seconds 20 second time interval		Average Temperature Difference: 3.26186
155 to 165 seconds 10 second time interval		Average Temperature Difference: 3.26712

Table 3.9: Temperature difference graphs for normal breathing with a white cloth mask. Average temperature difference across each time interval was calculated. The average temperature difference across the smallest time interval (10 seconds) was used as the point of comparison between mask types.

White Cloth Mask with Normal Breathing: Trial 1		
Time Interval	Humidity Difference Graphs	Humidity Difference Values (%)

0 to 300 seconds 300 second time interval		Average Humidity Difference: 28.64332
125 to 175 seconds 50 second time interval		Average Humidity Difference: 29.1862
150 to 170 seconds 20 second time interval		Average Humidity Difference: 30.94653

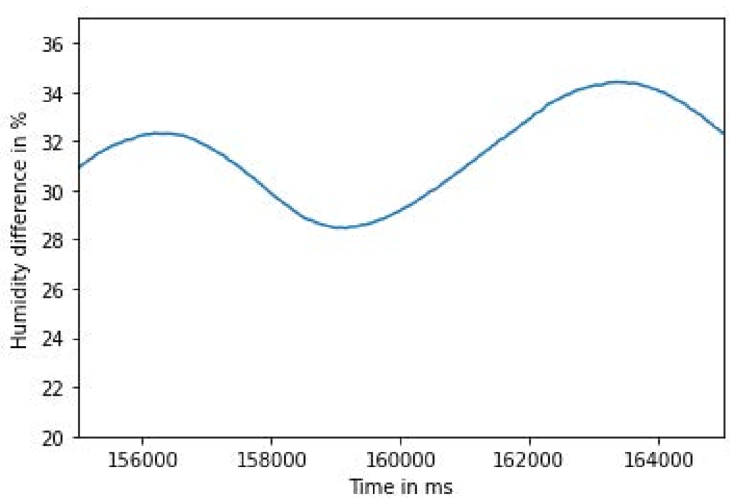
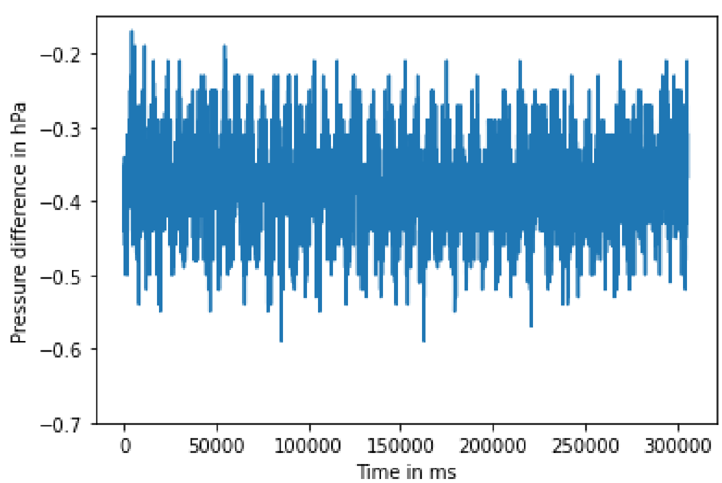
155 to 165 seconds 10 second time interval		Average Humidity Difference: 31.8719

Table 3.10: Humidity difference graphs for normal breathing with a white cloth mask. Average humidity difference across each time interval was calculated. The average humidity difference across the smallest time interval (10 seconds) was used as the point of comparison between mask types.

Black Polyester Mask with Normal Breathing: Trial 1		
Time Interval	Pressure Difference Graphs	Pressure Difference Values (hPa)
0 to 300 seconds 300 second time interval		Average Pressure Difference: -0.379861

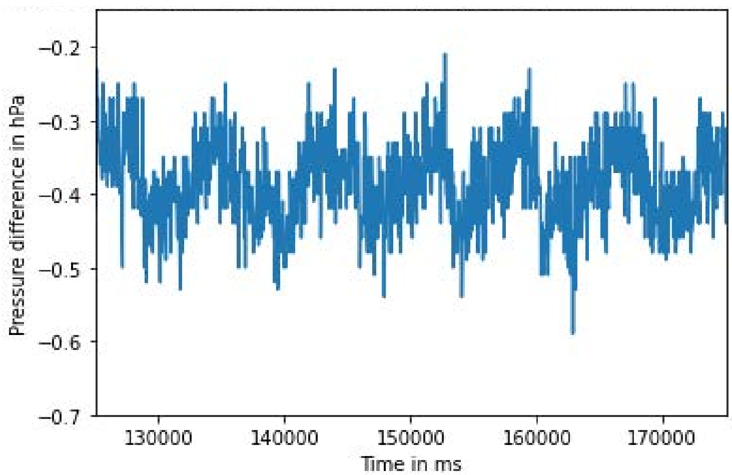
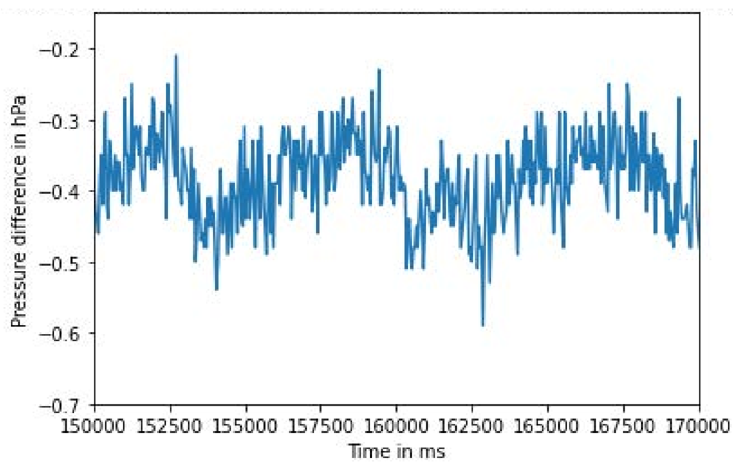
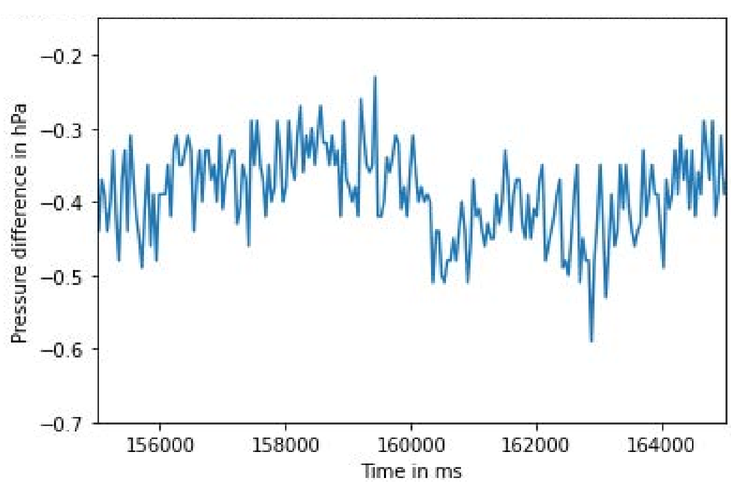
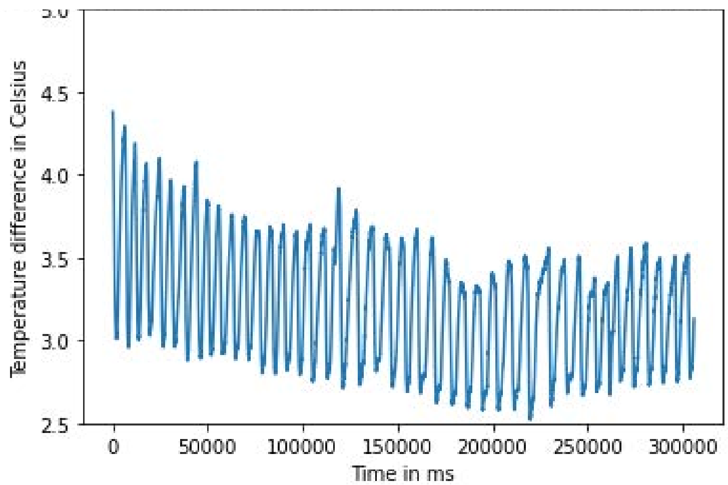
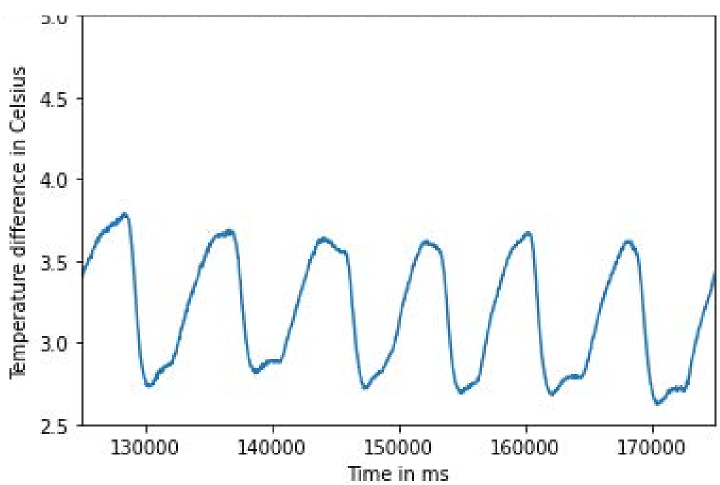
125 to 175 seconds 50 second time interval		Average Pressure Difference: -0.38157
150 to 170 seconds 20 second time interval		Average Pressure Difference: -0.382631
155 to 165 seconds 10 second time interval		Average Pressure Difference: -0.39214

Table 3.11: Pressure difference graphs for normal breathing with a black polyester mask. Average pressure difference across each time interval was calculated. The average pressure difference across the smallest time interval (10 seconds) was used as the point of comparison between mask types.

Black Polyester Mask with Normal Breathing: Trial 1		
Time Interval	Temperature Difference Graphs	Temperature Difference Values (Celsius)
0 to 300 seconds 300 second time interval	 	Average Temperature Difference: 3.217188
125 to 175 seconds 50 second time interval	 	Average Temperature Difference: 3.24834

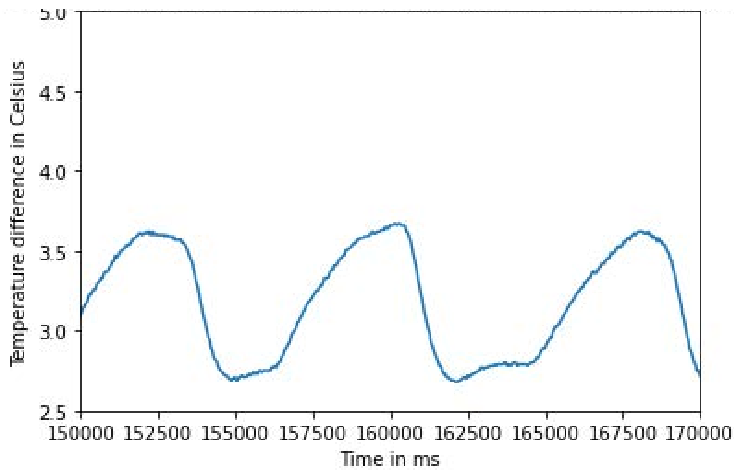
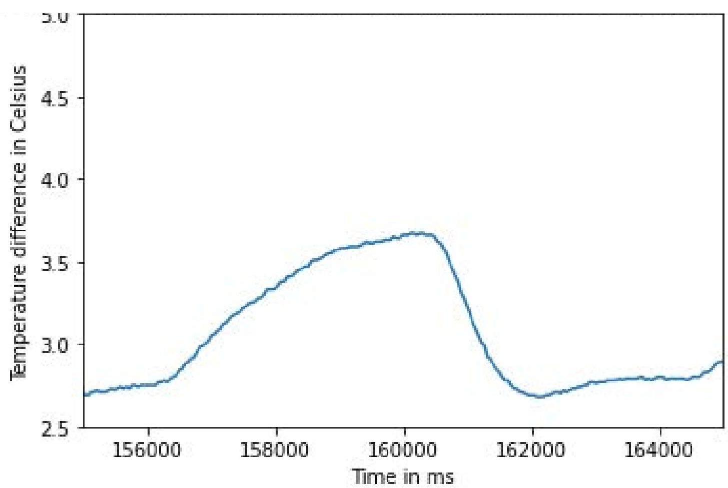
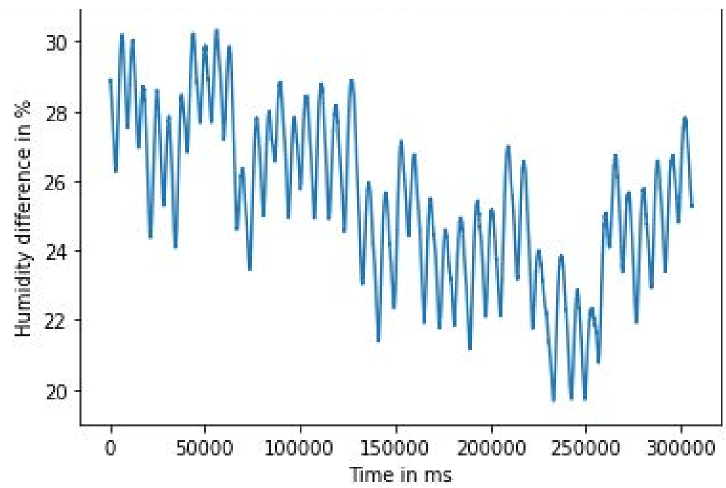
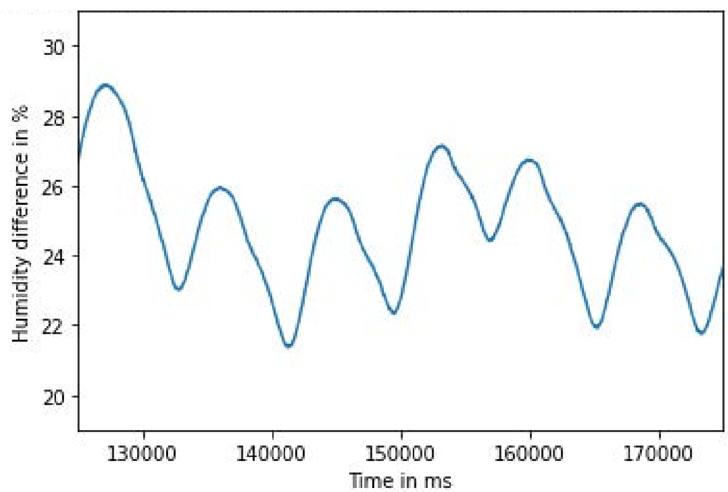
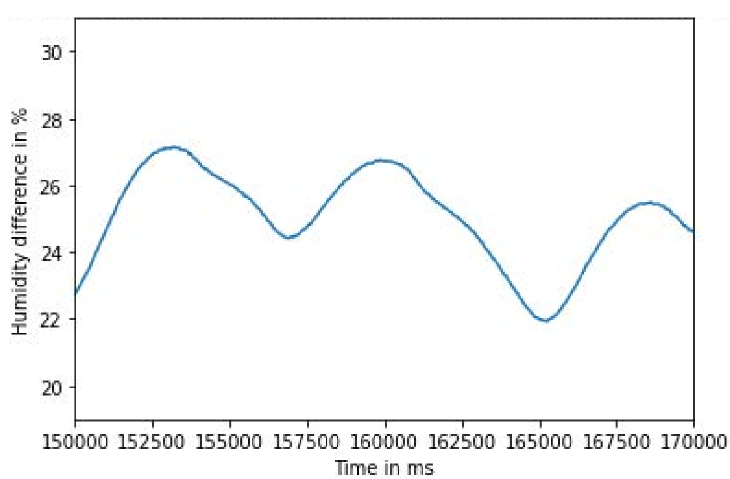
150 to 170 seconds 20 second time interval		Average Temperature Difference: 3.17947
155 to 165 seconds 10 second time interval		Average Temperature Difference: 3.23189

Table 3.12: Temperature difference graphs for normal breathing with a black polyester mask. Average temperature difference across each time interval was calculated. The average temperature difference across the smallest time interval (10 seconds) was used as the point of comparison between mask types.

Black Polyester Mask with Normal Breathing: Trial 1		
Time Interval	Humidity Difference Graphs	Humidity Difference Values (%)

0 to 300 seconds 300 second time interval		Average Humidity Difference: 25.42806
125 to 175 seconds 50 second time interval		Average Humidity Difference: 24.8348
150 to 170 seconds 20 second time interval		Average Humidity Difference: 24.7165

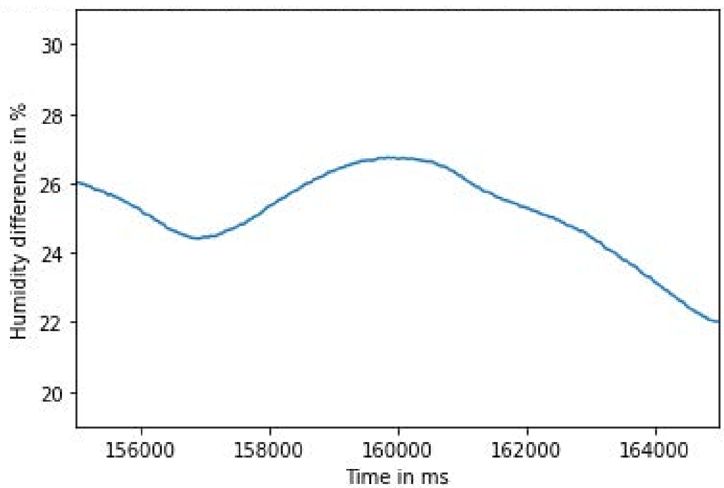
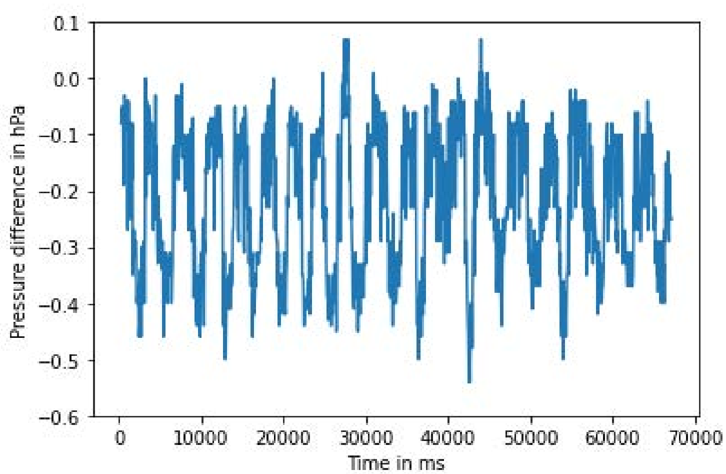
155 to 165 seconds 10 second time interval		Average Humidity Difference: 24.5839

Table 3.13: Humidity difference graphs for normal breathing with a black polyester mask. Average humidity difference across each time interval was calculated. The average humidity difference across the smallest time interval (10 seconds) was used as the point of comparison between mask types.

N95 Mask with Normal Breathing: Trial 1		
Time Interval	Pressure Difference Graphs	Pressure Difference Values (hPa)
0 to 300 seconds 300 second time interval		Average Pressure Difference: -0.220565

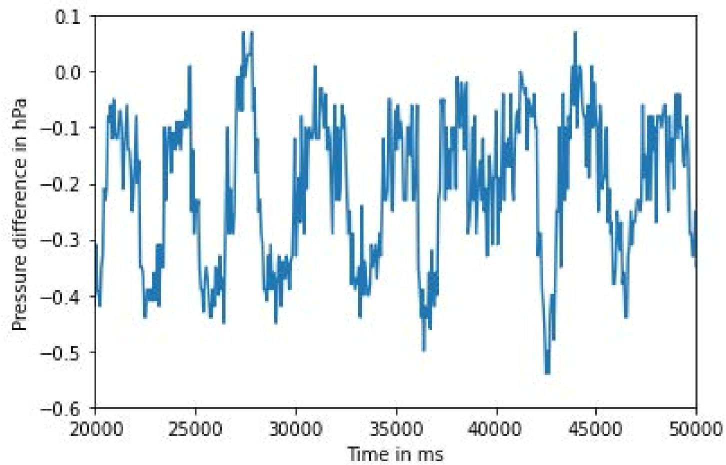
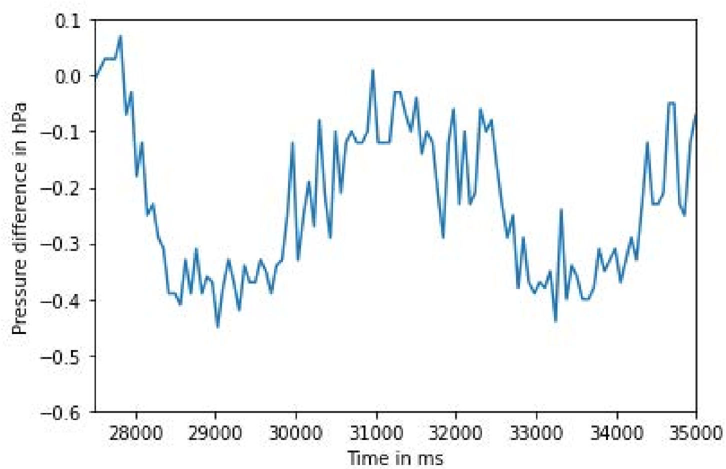
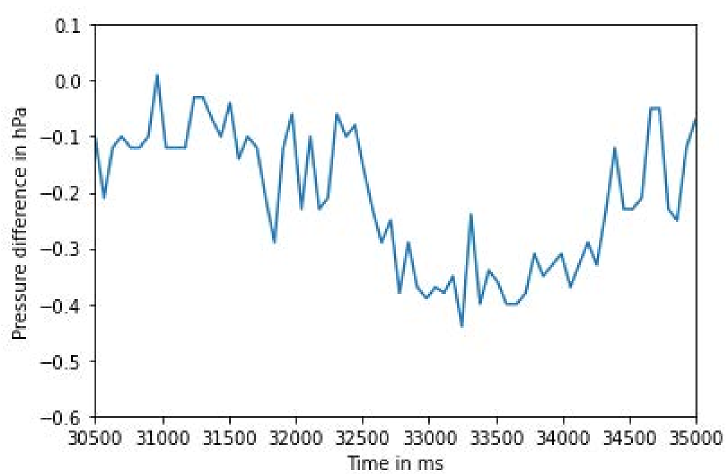
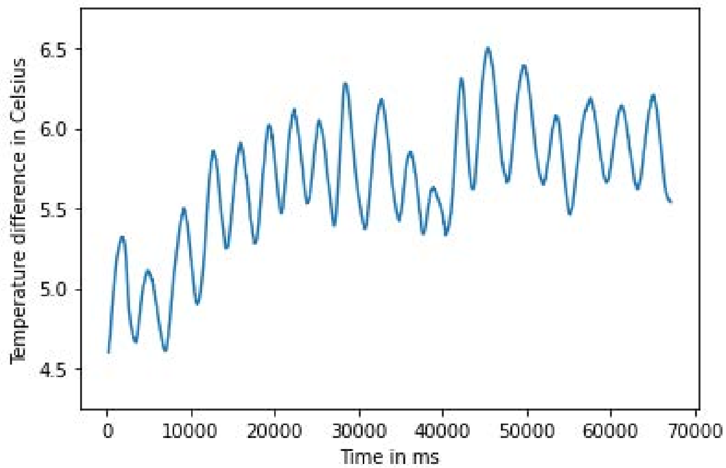
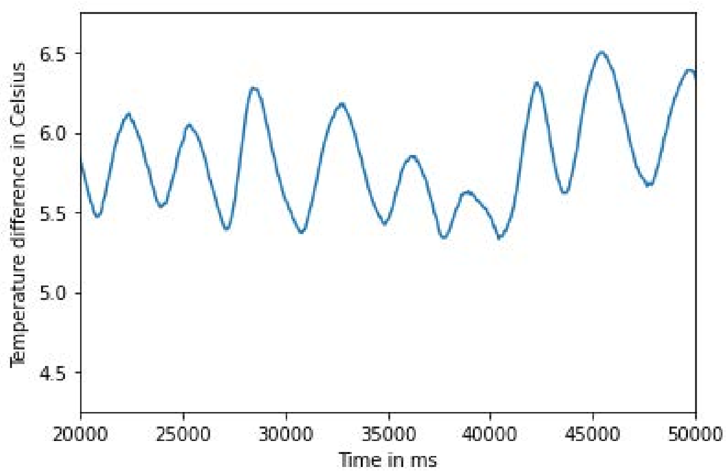
125 to 175 seconds 50 second time interval		Average Pressure Difference: -0.254237
150 to 170 seconds 20 second time interval		Average Pressure Difference: -0.246682
155 to 165 seconds 10 second time interval		Average Pressure Difference: -0.210247

Table 3.14: Pressure difference graphs for normal breathing with a N95 mask. Average pressure difference across each time interval was calculated. The average pressure difference across the smallest time interval (10 seconds) was used as the point of comparison between mask types.

N95 Mask with Normal Breathing: Trial 1		
Time Interval	Temperature Difference Graphs	Temperature Difference Values (Celsius)
0 to 300 seconds 300 second time interval		Average Temperature Difference: 5.673503
125 to 175 seconds 50 second time interval		Average Temperature Difference: 5.87896

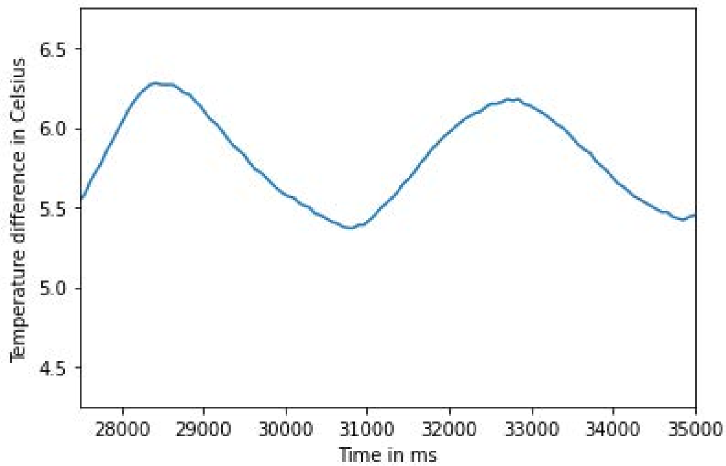
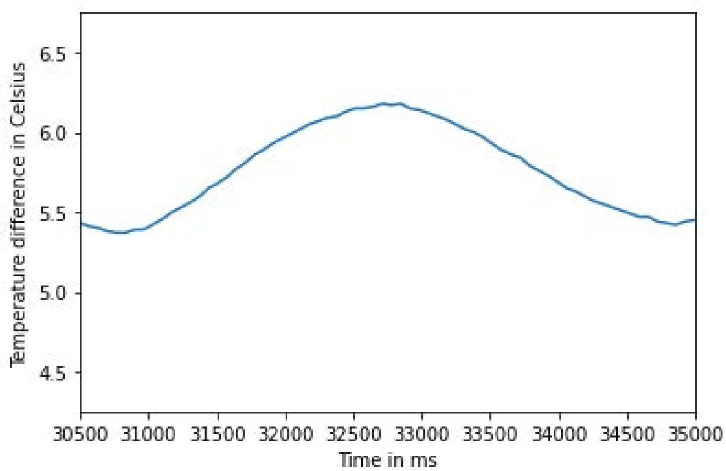
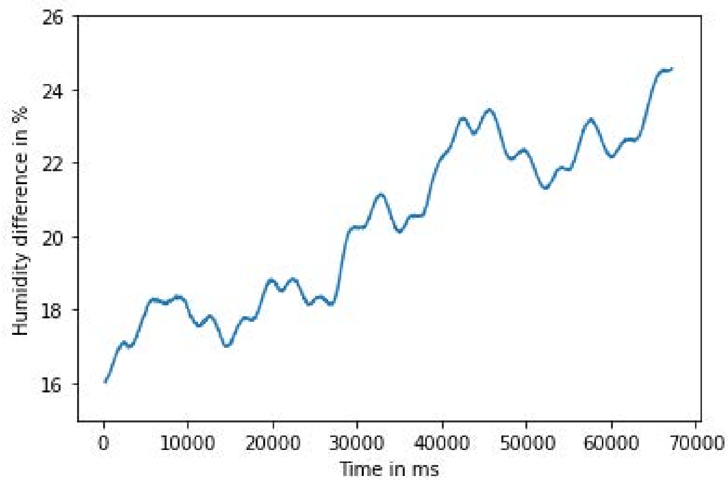
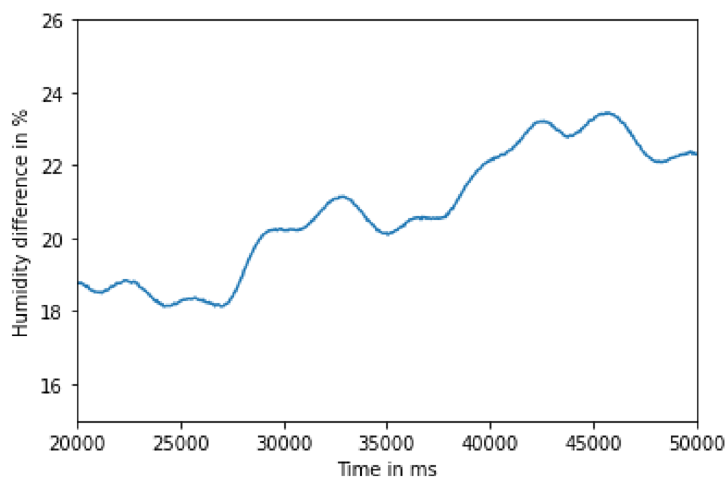
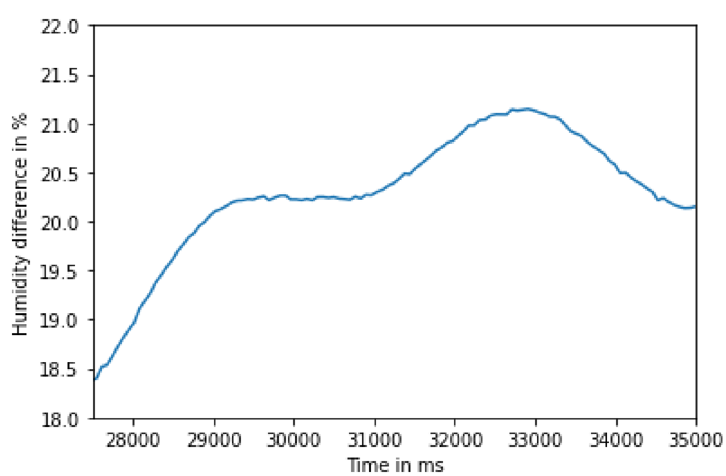
150 to 170 seconds 20 second time interval		Average Temperature Difference: 5.82721
155 to 165 seconds 10 second time interval		Average Temperature Difference: 5.76485

Table 3.15: Temperature difference graphs for normal breathing with a N95 mask. Average temperature difference across each time interval was calculated. The average temperature difference across the smallest time interval (10 seconds) was used as the point of comparison between mask types.

N95 Mask with Normal Breathing: Trial 1		
Time Interval	Humidity Difference Graphs	Humidity Difference Values (%)

0 to 300 seconds 300 second time interval		Average Humidity Difference: 20.32222
125 to 175 seconds 50 second time interval		Average Humidity Difference: 20.5493
150 to 170 seconds 20 second time interval		Average Humidity Difference: 19.7247

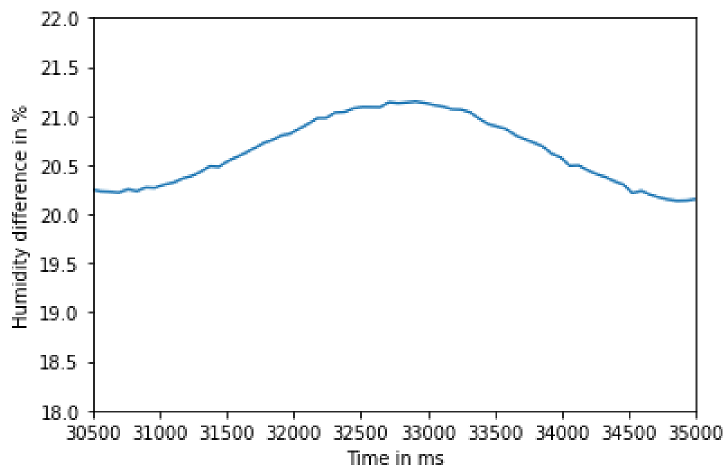
155 to 165 seconds 10 second time interval		Average Humidity Difference: 20.7814

Table 3.16: Humidity difference graphs for normal breathing with a N95 mask. Average humidity difference across each time interval was calculated. The average humidity difference across the smallest time interval (10 seconds) was used as the point of comparison between mask types.

Although data from only one trial is shown for each mask type, this analysis was repeated for each trial and each mask type to determine the average pressure differences across time intervals of 10 seconds. The pressure, temperature, and humidity difference graphs are separated into different tables for clearer resolution. However, the graphs of one mask type, focused during a specific time interval, match with graphs of the same mask type focused during the same time interval. For example, the pressure difference graph for normal breathing through a surgical mask, focused during the 155 to 165 second time interval, matches the temperature difference graph and humidity difference graph for normal breathing through a surgical mask, focused during the 155 to 165 second time interval. In other words, the data from those three aforementioned graphs were taken at the same time, and trends in the temperature difference graph can therefore be related to trends at the corresponding time in the pressure difference graph.

The length of one respiration cycle was determined by the temperature difference graph, and then the average pressure difference was averaged over that respiration cycle. The values from the analyses above are used for comparison in determining the pressure, temperature, and humidity differences across mask types, discussed in Sections 3.4 and 3.5.

3.4 Determining Pressure Differences Across Different Mask Types

To determine if there was a difference in the differential pressure, temperature, and humidity across different mask types, the average differences for each parameter were calculated for different mask types over a time interval delineated by one respiration cycle. These differences were determined by experiments consisting of five trials each for a surgical mask, white cloth mask, and a black polyester mask, and three trials for an N95 mask. The experimenter breathed normally, as determined by his/her own respiration rate, while wearing the mask with no intentional gaps around the mask edges. Table 3.17 below shows the results for the mean actual pressure, temperature, and humidity differences across a surgical mask, reported with standard error.

As described above in Section 3.2, the actual parameter differences were calculated by subtracting the baseline parameter difference (between the two BME680s at rest, no mask attached) from the parameter difference measured while the normal breathing activity was performed, and the mask was being worn by a participant. The baseline differences, as mentioned above, were measured right before the participant put on the mask apparatus and allowed the sensors to stabilize. Taking the baseline measurements before each activity allows a more accurate calculation for the actual pressure, temperature, and humidity differences.

Normal Breathing with Surgical Mask									
Trial	Baseline Pressure Difference (hPa)	Baseline Temp Difference (Celsius)	Baseline Humidity Difference (%)	Experimental Pressure Difference (hPa)	Experimental Temp Difference (Celsius)	Experimental Humidity Difference (%)	**Actual Pressure Difference (hPa)**	Actual Temp Difference (Celsius)	Actual Humidity Difference (%)
1	-0.496504	-0.222659	7.151872	-0.37827	3.68219	26.7335	**-0.141474**	3.976453	21.55315
2	-0.438813	-0.209802	7.988445	-0.339996	3.534579	30.67546	**-0.098817**	3.744382	22.68701
3	-0.426147	-0.203649	8.276091	-0.353563	3.514278	30.63533	**-0.072583**	3.717927	22.35924
4	-0.464736	-0.250670	7.966393	-0.372220	3.454923	27.42219	**-0.092516**	3.705594	19.45579
5	-0.482034	-0.269111	7.749826	-0.385783	3.193397	30.52514	**-0.096250**	3.462509	22.77532
Mean Actual Differences ± Standard Error							**-0.10032 ± 0.01009**	3.72137 ± 0.072902	21.7661 ± 0.55141

Table 3.17: Baseline, Experimental, and Actual Average Values for the Pressure, Temperature, and Humidity Differences during Normal Breathing with a Surgical Mask. The actual differences were calculated by subtracting the baseline difference from the experimental difference. Each trial consists of 6667 baseline data points (collected over a span of ~5 minutes), and 6667 experimental data points (also collected over a span of ~5 minutes, after the baseline data was

collected). Measurements were taken using the BME680s and hardware provided to Grace Chiou.

Tables 3.18-3.20 show the results for the mean actual pressure, temperature, and humidity differences across a white cloth mask, black polyester mask, and N95 mask, respectively.

Normal Breathing with White Cloth Mask									
Trial	Baseline Pressure Difference (hPa)	Baseline Temp Difference (Celsius)	Baseline Humidity Difference (%)	Experimental Pressure Difference (hPa)	Experimental Temp Difference (Celsius)	Experimental Humidity Difference (%)	**Actual Pressure Difference (hPa)**	Actual Temp Difference (Celsius)	Actual Humidity Difference (%)
1	-0.493737	-0.252404	7.368811	-0.35688	3.26712	31.8719	**-0.127189**	3.523965	21.27451
2	-0.499374	-0.223504	7.464074	-0.267345	4.354949	43.31764	**-0.232028**	4.578453	35.85357
3	-0.433917	-0.268963	8.371268	-0.293276	3.228207	36.90089	**-0.140641**	3.497170	28.52962
4	-0.432416	-0.304953	8.377553	-0.352825	3.340609	27.68339	**-0.079591**	3.645562	19.30584
5	-0.443981	-0.267283	8.314868	-0.294720	2.955391	39.66377	**-0.149261**	3.222675	31.34890
Mean Actual Differences ± Standard Error							**-0.145742 ± 0.02209**	3.693565 ± 0.2073	27.26249 ± 2.766

Table 3.18: Baseline, Experimental, and Actual Average Values for the Pressure, Temperature, and Humidity Differences during Normal Breathing with a White Cloth Mask. The actual differences were calculated by subtracting the baseline difference from the experimental difference. Each trial consists of 6667 baseline data points (collected over a span of ~5 minutes), and 6667 experimental data points (also collected over a span of ~5 minutes, after the baseline data was collected). Measurements were taken using the BME680s and hardware provided to Grace Chiou.

Normal Breathing with Black Polyester Mask									
Trial	Baseline Pressure Difference (hPa)	Baseline Temp Difference (Celsius)	Baseline Humidity Difference (%)	Experimental Pressure Difference (hPa)	Experimental Temp Difference (Celsius)	Experimental Humidity Difference (%)	**Actual Pressure Difference (hPa)**	Actual Temp Difference (Celsius)	Actual Humidity Difference (%)

1	-0.458146	-0.220624	7.788669	-0.39214	3.23189	24.5839	**-0.078285**	3.437812	17.63939
2	-0.441124	-0.254288	8.260146	-0.401860	3.725079	9.910724	**-0.039264**	3.979368	1.650578
3	-0.460673	-0.258441	8.090290	-0.400883	3.748025	12.88592	**-0.059790**	4.006467	4.795630
4	-0.530876	-0.230979	6.905744	-0.387903	3.359480	15.48950	**-0.142972**	3.590460	8.583757
5	-0.558430	-0.264586	7.483852	-0.413022	3.633100	16.56023	**-0.145407**	3.897686	9.076385
Mean Actual Differences ± Standard Error							**-0.093143 ± 0.01944**	3.782359 ± 0.1015	8.349148 ± 2.403

Table 3.19: Baseline, Experimental, and Actual Average Values for the Pressure, Temperature, and Humidity Differences during Normal Breathing with a Black Polyester Mask. The actual differences were calculated by subtracting the baseline difference from the experimental difference. Each trial consists of 6667 baseline data points (collected over a span of ~5 minutes), and 6667 experimental data points (also collected over a span of ~5 minutes, after the baseline data was collected). Measurements were taken using the BME680s and hardware provided to Grace Chiou.

Normal Breathing with N95 Mask									
Trial	Baseline Pressure Difference (hPa)	Baseline Temp Difference (Celsius)	Baseline Humidity Difference (%)	Experimental Pressure Difference (hPa)	Experimental Temp Difference (Celsius)	Experimental Humidity Difference (%)	**Actual Pressure Difference (hPa)**	Actual Temp Difference (Celsius)	Actual Humidity Difference (%)
1	-0.571987	1.087917	4.710465	-0.210247	5.76485	20.7814	**-0.351421**	4.585585	15.61175
2	-0.550934	1.033922	4.161658	-0.229619	4.571791	21.36970	**-0.321315**	3.537869	17.20804
3	-0.563391	1.136405	3.443482	-0.224713	4.322796	20.47303	**-0.338677**	3.186391	17.02955
Mean Actual Differences ± Standard Error							**-0.337138 ± 0.00712**	3.769949 ± 0.3431	16.61645 ± 0.4123

Table 3.20: Baseline, Experimental, and Actual Average Values for the Pressure, Temperature, and Humidity Differences during Normal Breathing with an N95 Mask. The actual differences

were calculated by subtracting the baseline difference from the experimental difference. Each trial consists of 1000 baseline data points (collected over a span of ~1 minute), and 1000 experimental data points (also collected over a span of ~1 minute, after the baseline data was collected). Measurements were taken using the BME680s and hardware provided to Grace Chiou.

From the calculated actual pressure differences (bolded in each table), normal respiration with an N95 mask caused the largest average pressure difference (-0.337138 ± 0.00712 hPa) between the two BME680s. Normal respiration with a white cloth mask caused the second largest pressure difference (-0.145742 ± 0.02209 hPa), followed by normal respiration with a surgical mask (-0.10032 ± 0.01009 hPa) and lastly, normal respiration with a black polyester mask (-0.093143 ± 0.01944 hPa).

Looking at the baseline and experimental pressure differences, it is clear that the experimental pressure differences are consistently closer to zero hPa than the baseline pressure differences for each trial. Table 3.21 below provides a closer analysis into the baseline and experimental average pressure values for both inside and outside the mask. The outside pressure value is subtracted from the inside pressure value to obtain the pressure difference value, so looking more closely at the pressure values resulting in an average experimental pressure difference that is closer to zero hPa than the average baseline pressure difference will provide information on the effect of normal respiration rate across a mask on the pressure difference across face masks.

Normal Breathing with Surgical Mask				
Trial	Baseline Average Inside Pressure (hPa)	Baseline Average Outside Pressure (hPa)	Experimental Average Inside Pressure (hPa)	Experimental Average Outside Pressure (hPa)
1	992.8582061 ± 0.00043597	993.3547107 ± 0.00045269	992.8393409	993.194371
2	992.587685 ± 0.000448276	993.0264989 ± 0.00044318	992.7137538	993.0537506
3	992.5987387 ± 0.00042972	993.0248863 ± 0.00047564	992.7697261	993.1232899
4	992.9220353 ± 0.00042838	993.386772 ± 0.00041442	993.1469824	993.5192031
5	992.7253276 ± 0.00043167	993.207362 ± 0.00042172	992.950861	993.3366441

Mean ± Standard Error	**992.7383985 ± 0.060155**	**993.20004598 ± 0.069178**	**992.8841328 ± 0.068605**	**993.2454517 ± 0.074172**
Mean Pressure Difference	**-0.46164748**		**-0.3613189**	

Table 3.21: Average pressure values from the inside and outside BME680s. Baseline averages were measured while there was no mask attached between the pair of BME680s, and experimental averages were measured while a participant wore a surgical mask attached between the pair of BME680s and had a normal respiration rate. The baseline average pressure values are reported with the standard errors of their corresponding data samples for reference on how small the standard error is compared to the mean value. Measurements were taken using the BME680s and hardware provided to Grace Chiou.

From Table 3.21, it can be seen that the average pressure measured by the outside BME680 is consistently larger than the average pressure measured by the inside BME680, regardless of whether or not a mask is present between the two BME680s. It is also evident that while there is an approximate 0.04540572 hPa increase from the average pressure measured by the outside BME680 between the baseline and experimental average pressures, there is also a simultaneous, larger increase of 0.1457343 hPa in the average pressure measured by the inside BME680 between the baseline and experimental average pressures. Because the average pressure measured by the inside BME680 increased more drastically with normal respiration across a surgical mask than the average pressure measured by the outside BME680 did, the mean pressure difference decreased in magnitude from -0.46164748 hPa to -0.3613189 hPa. The effect of normal respiration across a surgical mask, therefore, is not to make the average inside pressure larger and the average outside pressure smaller, as might be suggested from a smaller average pressure difference. Rather, the effect of normal respiration across a surgical mask is to increase both the average inside and outside pressures; however, the average inside pressure is increased by a greater amount than the average outside pressure is increased, resulting in a mean pressure difference that is smaller in magnitude.

Table 3.22 below demonstrates that this analysis also holds true for the effect of normal respiration across a white cloth mask.

Normal Breathing with Surgical Mask				
Trial	Baseline Average Inside Pressure (hPa)	Baseline Average Outside Pressure (hPa)	Experimental Average Inside Pressure (hPa)	Experimental Average Outside Pressure (hPa)
1	992.7907578	993.2844957	992.7062545	993.0728032

2	992.8606451	993.3600191	993.307181	993.5745262
3	993.1229699	993.5568874	993.3238971	993.6171729
4	993.2313289	993.6637458	993.4723205	993.8251462
5	993.2230573	993.6670388	993.2743089	993.5690293
Mean ± Standard Error	**993.0457518** ± 0.08273	993.50643736 ± 0.070365	993.2167924 ± 0.11813	993.53173556 ± 0.110857
Mean Pressure Difference	**-0.46068556**		**-0.31494316**	

Table 3.22: Average pressure values from the inside and outside BME680s. Baseline averages were measured while there was no mask attached between the pair of BME680s, and experimental averages were measured while a participant wore a white cloth mask attached between the pair of BME680s and had a normal respiration rate. Measurements were taken using the BME680s and hardware provided to Grace Chiou.

3.5 Determining Temperature and Humidity Differences Across Different Mask Types

Returning back to the average actual differences from Tables 3.17-3.20, there is a small but measurable difference in the average temperature differences between normal respiration across different mask types. Normal respiration with a black polyester mask caused the largest average temperature difference (3.7823591242 ± 0.10156 Celsius) between the two BME680s. Normal respiration with an N95 mask caused the second largest temperature difference (3.769948886 ± 0.34313 Celsius), followed by normal respiration with a surgical mask (3.7213734556 ± 0.072902 Celsius) and lastly, normal respiration with a white cloth mask (3.6935655222 ± 0.20731 Celsius).

The difference between the average actual humidity differences is more drastic: normal respiration with a white cloth mask resulted in the largest average humidity difference (27.262492424 ± 2.766 %), followed by normal respiration with a surgical mask (21.76610762 ± 0.55141 %) and normal respiration with an N95 mask (16.61645246 ± 0.41232 %). Finally, normal respiration with a black polyester mask had the smallest average humidity difference (8.3491486656 ± 2.4033 %).

While the average temperature and humidity differences do not follow the same trend as the average pressure differences when correlated with mask type, the temperature and humidity difference trends may offer some insight into the other characteristics of the mask types, and how these characteristics can play a role in protecting the wearer against airborne particulates. In terms of materials, polyester, as well as synthetic fibers in general, are known to have higher thermal conductivity values than cotton and other natural fibers (Abdel-Rehim *et al*). The higher thermal conductivity values can result in a higher rate of heat transfer, allowing polyester to hold and retain heat more effectively than cotton, which is often considered the more breathable fabric. The results of this experiment, which found that normal respiration with a black polyester mask caused the largest average temperature difference compared to all the other mask types and normal respiration with a white cloth mask caused the smallest average temperature difference, are therefore in agreement with the fabric analysis between cotton and polyester.

Regarding the trends found for the average humidity differences across mask types, research published by the National Institutes of Health (NIH) in February 2021 tested the effect of mask type on the change in humidity of the air directly surrounding the face mask (Wein *et al*). The experiment tested four masks of similar materials to this study: three-ply disposable surgical mask, two-ply cotton-polyester mask, heavy cotton mask, and an N95 mask. The results yielded the largest increase in humidity of inhaled air when wearing the thick cotton mask. These NIH findings, combined with the data from this experiment, suggest that cotton masks are most effective at retaining moisture in inhaled air, causing the largest average humidity difference between the inside and outside BME680 sensors.

3.6 Determining the Effect of Activity Type on Pressure, Temperature, and Humidity Differences Across Masks

This experiment also looked into the effect of activity on the average pressure, temperature, and humidity differences across masks, and whether there was a pattern in the way activity affected average parameter differences across mask types. Tables 3.23-3.26 below show average pressure, temperature, and humidity differences during four different activities for a surgical mask, white cloth mask, black polyester mask, and an N95 mask, respectively.

Effect of Activity Type on Average Actual Differences with Surgical Mask					
Average Difference	Exercise	Trial 1	Trial 2	Trial 3	Mean ± Standard Error
Average Actual	Normal Breathing	0.148691745	0.088015744	0.078851927	0.1051864 ± 0.01789

Pressure Difference	Deep Breathing	0.099963884	0.09375892	0.080473364	0.091398 ± 0.004694
	Talking	0.124244148	0.096599832	0.072510525	0.09778483 ± 0.0122
	Smiling	0.058641215	0.11475694	0.0963878	0.0899286 ± 0.01348
Average Actual Temperature Difference	Normal Breathing	1.566635985	3.972503135	3.666777095	3.06863873 ± 0.6174
	Deep Breathing	1.220620105	4.311160609	3.955946486	3.16257573 ± 0.7972
	Talking	1.56719708	4.392552519	4.26501502	3.4082548 ± 0.75221
	Smiling	1.38358338	3.985525179	3.671381212	3.01349659 ± 0.6695
Average Actual Humidity Difference	Normal Breathing	5.616843452	6.691638099	7.179905199	6.4961289 ± 0.37696
	Deep Breathing	3.801526012	9.575614929	8.988067279	7.4550694 ± 1.49796
	Talking	9.445829822	10.76832902	9.215079299	9.8097461 ± 0.3951
	Smiling	5.893990532	5.834384849	4.333860129	5.3540785 ± 0.41674

Table 3.23: Actual Average Differences for Pressure, Temperature, and Humidity during 4 different exercises performed while wearing a Surgical Mask. Although each baseline and experimental difference is not shown, the average actual differences in this table were calculated by subtracting the baseline parameter difference from the experimental parameter difference, as was demonstrated in Tables 3.18-3.20. Measurements were taken using the BME680s and hardware provided to Alex Huynh.

Effect of Activity Type on Average Actual Differences with White Cloth Mask					
Average Difference	Exercise	Trial 1	Trial 2	Trial 3	Mean ± Standard Error
Average Actual Pressure Difference	Normal Breathing	0.064411693	0.070898347	0.063129754	0.0661465 ± 0.00196
	Deep Breathing	0.023208405	0.065476928	0.053867594	0.0475176 ± 0.01029

	Talking	0.030440985	0.069484762	0.058473955	0.0527999 ± 0.00948
	Smiling	0.019270034	0.063387012	0.049293857	0.0439836 ± 0.01062
Average Actual Temperature Difference	Normal Breathing	2.172261572	3.27451689	2.86394839	2.7702422 ± 0.26261
	Deep Breathing	2.195054741	3.85357219	3.02947284	3.0260332 ± 0.39092
	Talking	2.210570122	4.52962674	3.89463398	3.5449436 ± 0.56494
	Smiling	2.007337121	2.3058406	2.16483754	2.15933842 ± 0.0704
Average Actual Humidity Difference	Normal Breathing	6.457716422	8.52920482	6.28942931	7.09211685 ± 0.5881
	Deep Breathing	6.467196602	8.84920393	6.40287071	7.23975708 ± 0.6572
	Talking	6.501927482	9.28493582	7.20498055	7.66394795 ± 0.6822
	Smiling	6.173970532	8.42093477	6.22848534	6.9411302 ± 0.60426

Table 3.24: Actual Average Differences for Pressure, Temperature, and Humidity during 4 different exercises performed while wearing a White Cloth Mask. Although each baseline and experimental difference is not shown, the average actual differences in this table were calculated by subtracting the baseline parameter difference from the experimental parameter difference, as was demonstrated in Tables 3.18-3.20. Measurements were taken using the BME680s and hardware provided to Alex Huynh.

Effect of Activity Type on Average Actual Differences with Black Polyester Mask					
Average Difference	Exercise	Trial 1	Trial 2	Trial 3	Mean ± Standard Error
Average Actual Pressure Difference	Normal Breathing	0.408884255	0.39053086	0.364813653	0.38807625 ± 0.0104
	Deep Breathing	0.339458415	0.404942448	0.411313672	0.38523818 ± 0.0187
	Talking	0.403325363	0.374780999	0.384274248	0.38746021 ± 0.0068

	Smiling	0.299129779	0.437107692	0.311221109	0.34915286 ± 0.0361
Average Actual Temperature Difference	Normal Breathing	7.889439577	7.012742609	3.113843754	6.00534198 ± 1.1983
	Deep Breathing	5.939229167	5.734534544	3.821431375	5.16506502 ± 0.5506
	Talking	8.376096415	8.283003358	6.181141124	7.61341363 ± 0.5851
	Smiling	6.169709647	6.369929772	3.608778788	5.38280607 ± 0.7257
Average Actual Humidity Difference	Normal Breathing	13.13439039	24.09192332	27.52446805	21.5835939 ± 3.5429
	Deep Breathing	15.54405128	19.34701292	27.21177554	20.7009465 ± 2.8051
	Talking	28.3639905	18.40386184	26.19947384	24.3224421 ± 2.4695
	Smiling	21.87594045	21.57613359	25.76761291	23.0732289 ± 1.1022

Table 3.25: Actual Average Differences for Pressure, Temperature, and Humidity during 4 different exercises performed while wearing a Black Polyester Mask. Although each baseline and experimental difference is not shown, the average actual differences in this table were calculated by subtracting the baseline parameter difference from the experimental parameter difference, as was demonstrated in Tables 3.18-3.20. Measurements were taken using the BME680s and hardware provided to Akash Prasad.

Effect of Activity Type on Average Actual Differences with N95 Mask					
Average Difference	Exercise	Trial 1	Trial 2	Trial 3	Mean ± Standard Error
Average Actual Pressure Difference	Normal Breathing	0.351421817	0.342367856	0.349781038	0.347856 ± 0.00227
	Deep Breathing	0.338874537	0.328231658	0.330032384	0.3323795 ± 0.00269
	Talking	0.33069631	0.307345864	0.314216248	0.3174194 ± 0.00566
	Smiling	0.302427378	0.316051863	0.306528703	0.3083359 ± 0.00329

Average Actual Temperature Difference	Normal Breathing	4.585585637	3.483873927	3.515116852	3.8615254 ± 0.2957
	Deep Breathing	4.741711763	3.578098305	4.609575275	4.309795 ± 0.300333
	Talking	4.593213225	4.884554539	4.770921284	4.749563 ± 0.069221
	Smiling	2.979399364	2.472822771	2.866223718	2.7728152 ± 0.12534
Average Actual Humidity Difference	Normal Breathing	20.94443506	11.3661363	15.65473642	15.988436 ± 2.26173
	Deep Breathing	15.61175749	16.65923998	16.22305389	16.164684 ± 0.24804
	Talking	22.62388847	22.62239483	23.40853061	22.884937 ± 0.37023
	Smiling	14.11683134	14.15118085	14.17518297	14.147732 ± 0.01382

Table 3.26: Actual Average Differences for Pressure, Temperature, and Humidity during 4 different exercises performed while wearing an N95 Mask. Although each baseline and experimental difference is not shown, the average actual differences in this table were calculated by subtracting the baseline parameter difference from the experimental parameter difference, as was demonstrated in Tables 3.18-3.20. Measurements were taken using the BME680s and hardware provided to Akash Prasad.

Comparing the average actual pressure differences across a surgical mask, it is evident in Table 3.23 that the largest average pressure difference occurs during normal breathing (0.1051864 ± 0.01789 hPa), followed by talking (0.09778483 ± 0.0122 hPa), and deep breathing (0.091398 ± 0.004694 hPa). Smiling while wearing a surgical mask resulted in the smallest average pressure difference (0.0899286 ± 0.01348 hPa). This trend is supported by the average pressure difference values across a white cloth mask (Table 3.24) and a black polyester mask (Table 3.25), but not by the average pressure differences across an N95 mask (Table 3.26), where the average pressure difference while deep breathing (0.3323795 ± 0.00269 hPa) is larger than the average pressure difference while talking (0.3174194 ± 0.00566 hPa).

The average pressure difference trend found across all mask types suggests that normal breathing creates the largest average pressure drop across the surface of the mask. Slowing down a wearer's breathing rate (i.e. deep breathing) results in a smaller average pressure drop across the mask as compared to normal breathing, which could suggest that airflow becomes easier when taking longer breaths with a smaller frequency. Smiling while wearing any type of mask causes an average pressure difference smaller than all other average pressure differences measured during any other type of activity. This could possibly be due to the fact that smiling and or frowning changes the conformation of the face structure, and therefore also impacts the edge seals of the face mask around the face. Smiling in such a way that creates more gaps or larger gaps between the face mask and the face itself may result in a smaller average pressure difference, by allowing air from inside the mask to escape to the outside environment via the side gaps on the mask.

Looking at the average temperature difference across a surgical mask in Table 3.23, the largest average temperature difference occurs during talking (3.4082548 ± 0.75221 Celsius). Deep breathing while wearing the surgical mask results in the second largest average temperature difference between the four activities (3.16257573 ± 0.7972 Celsius), followed by normal breathing (3.06863873 ± 0.6174 Celsius), and smiling (3.01349659 ± 0.6695 Celsius). The average temperature difference data across a white cloth mask (Table 3.24) and an N95 mask (Table 3.26) also agrees with this trend. While normal breathing while wearing a black polyester mask actually results in the second largest average temperature difference among the four activities performed while wearing the black polyester mask (Table 3.25), data across all four mask types support that talking while wearing any type of mask results in the largest average temperature difference as compared to performing any other type of activity while wearing the same mask.

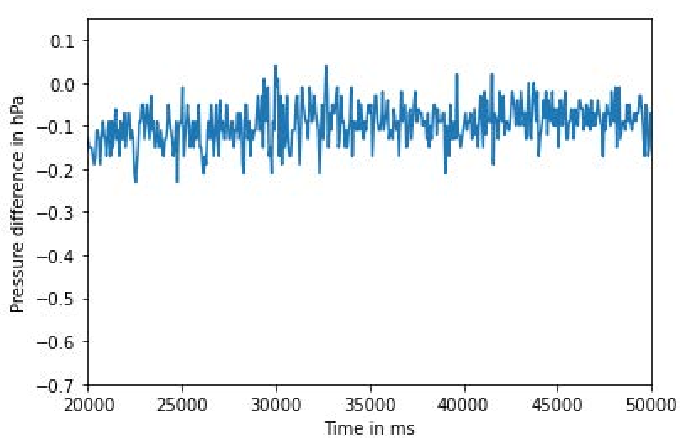
This conclusion in the average temperature difference could be related to the corresponding trend in average humidity differences across mask types for different activities. For a surgical mask, the largest average humidity difference occurs during talking (9.8097461 ± 0.3951 %). Deep breathing while wearing the surgical mask results in the second largest average humidity difference between the four activities (7.4550694 ± 1.49796 %), followed by normal breathing (6.4961289 ± 0.37696 %), and smiling (5.3540785 ± 0.41674 %). This trend is again supported by average humidity difference data from both a white cloth mask (Table 3.24) and an N95 mask (Table 3.26). Data from all 4 mask types support that the largest humidity difference occurs when talking, as compared to performing any other activity while wearing the same mask. There is a correlation between the largest average temperature and humidity differences both occurring when the mask wearer is talking; however, it is unclear as to whether an increase in humidity causes an increase in temperature and vice versa, or if there is simply no causal relationship between temperature and humidity regarding mask environments.

3.7 Comparing Baseline Pressure, Temperature, and Humidity Differences Between Three Pairs of BME680s

As mentioned before, there exists some intrinsic difference between the measured values of one BME680 and the next, due to variations in manufacturing. While the data in this experiment attempts to account for this intrinsic variation by subtracting the measured baseline differences from the experimental data, further analysis was done into how prominent the intrinsic variation can be between pairs of BME680s.

In this experiment, each of the three experimenters was given a pair of BME680s. Tables 3.27-3.29 below display baseline data taken from each pair of BME680, taken over at least 1 minute intervals but focused on 30 second time intervals for clearer pattern resolution. As mentioned before, baseline data is taken while the pair of BME680s sits at rest with no mask attached between them, so there is no need for mask or activity type specification in these graphs. Y-axis scales were kept constant between graphs where the values were relatively nearby in range, specifically in comparing the pressure and temperature differences. However, some baseline differences were too different from each other to keep on the same axis without compromising the reading resolution of the graphs. In the case of the humidity differences, Alex's pair of BME680s uses a different humidity difference scale than the other two pairs of BME680s.

Average pressure, temperature, and humidity differences were measured over the 30 second time interval for comparison among the three pairs of BM680s.

Comparing Baseline Pressure Difference Between Three Pairs of BME680s		
Baseline Pressure Difference of Akash's Pair of BME680s		Average Baseline Pressure Difference (hPa): -0.097245

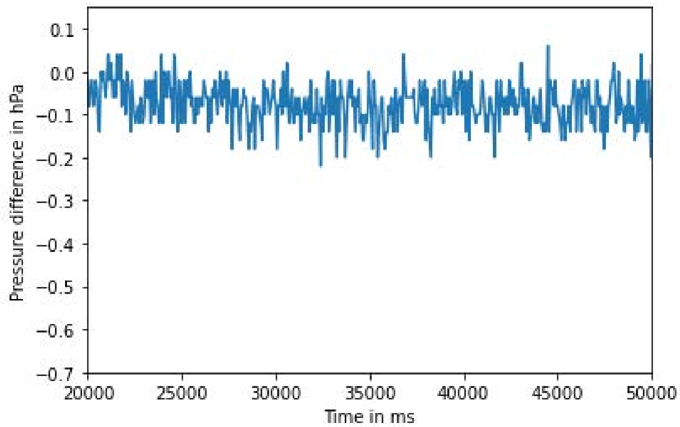
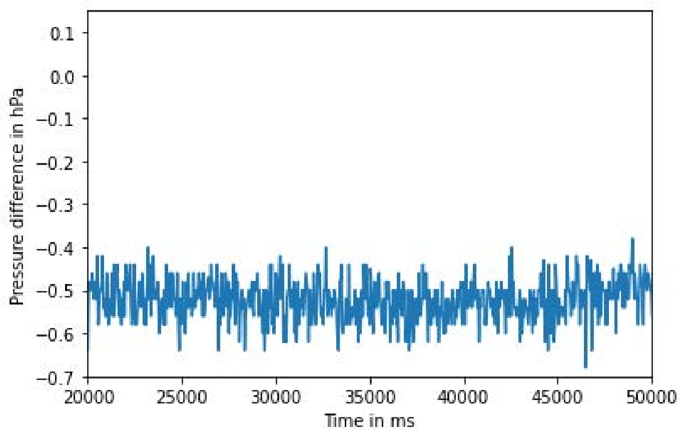
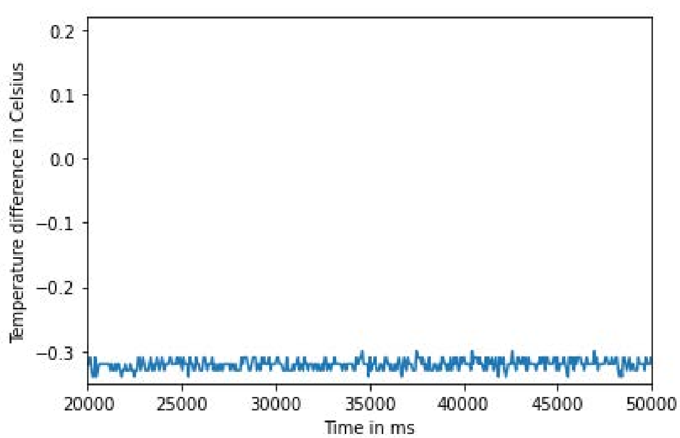
Baseline Pressure Difference of Alex's Pair of BME680s		Average Baseline Pressure Difference (hPa): -0.078132
Baseline Pressure Difference of Grace's Pair of BME680s		Average Baseline Pressure Difference (hPa): -0.51296

Table 3.27: Baseline pressure differences of three different pairs of BME680s, with averaged pressure differences for each pair. Data is presented over a 30 second time interval in order to more clearly see microscopic changes in the pressure difference over time.

Comparing Baseline Temperature Difference Between Three Pairs of BME680s		
Baseline Temperature Difference of Akash's Pair of BME680s		Average Baseline Temperature Difference (Celsius): -0.33719

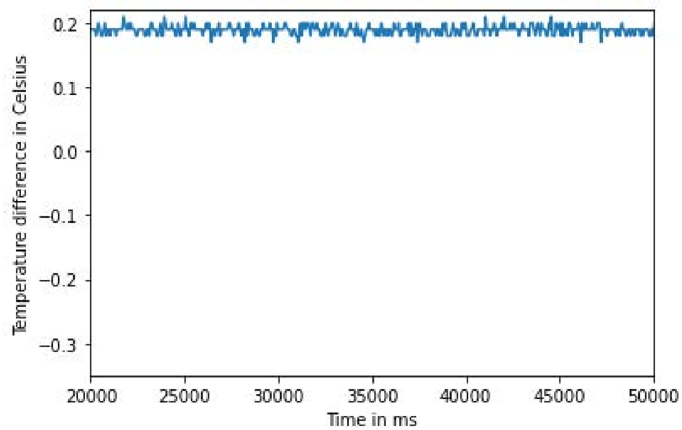
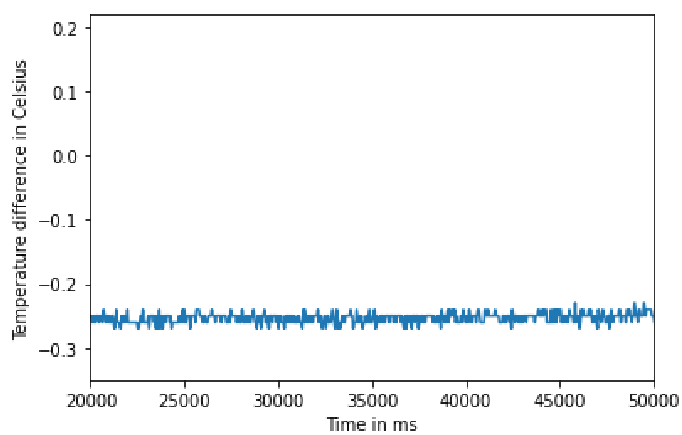
Baseline Temperature Difference of Alex's Pair of BME680s		Average Baseline Temperature Difference (Celsius): 0.19465
Baseline Temperature Difference of Grace's Pair of BME680s		Average Baseline Temperature Difference (Celsius): -0.26492

Table 3.28: Baseline temperature differences of three different pairs of BME680s, with averaged temperature differences for each pair. Data is presented over a 30 second time interval in order to more clearly see microscopic changes in the temperature difference over time.

Comparing Baseline Humidity Difference Between Three Pairs of BME680s

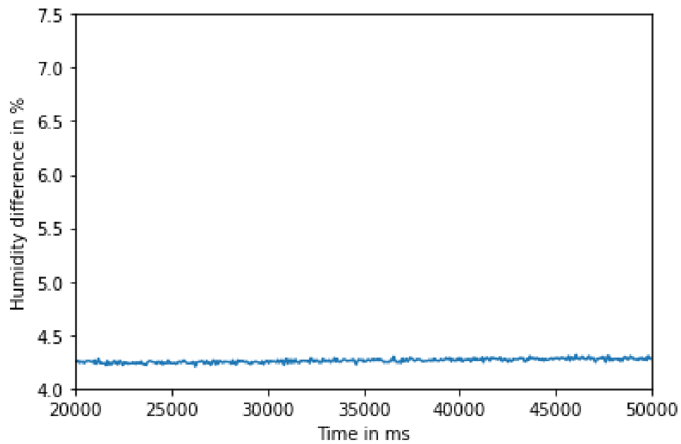
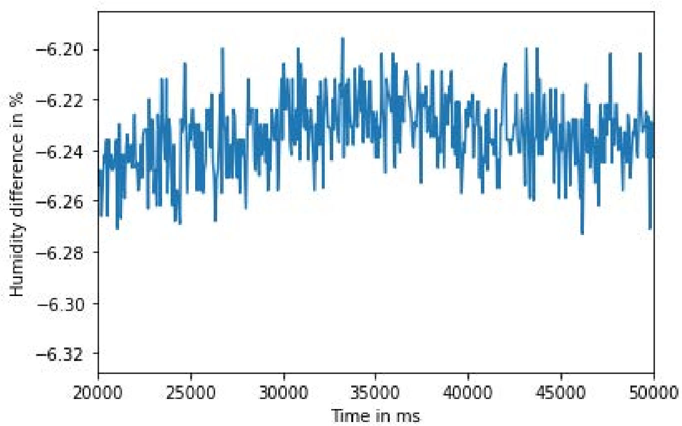
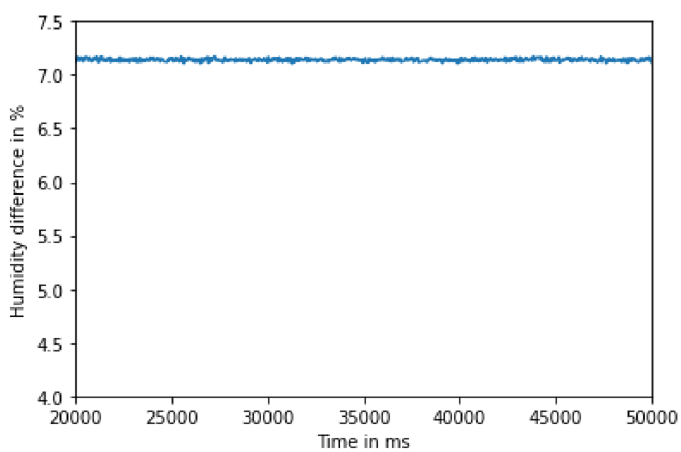
Baseline Humidity Difference of Akash's Pair of BME680s		Average Baseline Humidity Difference (%): 4.27361
Baseline Humidity Difference of Alex's Pair of BME680s		Average Baseline Humidity Difference (%): -6.23758
Baseline Humidity Difference of Grace's Pair of BME680s		Average Baseline Humidity Difference (%): 7.16544

Table 3.29: Baseline humidity differences of three different pairs of BME680s, with averaged humidity differences for each pair. Data is presented over a 30 second time interval in order to more clearly see microscopic changes in the humidity difference over time.

Among the three pairs of BME680s, Akash's and Alex's pairs have relatively similar average baseline pressure differences. Grace's pair of BME680s, however, has an average baseline pressure difference of around -0.51296 hPa. When considering the accuracy range specifications of the BME680s, as was listed above in Section 2.1, the combined pressure accuracy range of two BME680s should not exceed double the amount of the pressure accuracy range of one BME680. Therefore, since one BME680 has an accuracy range of +/- 1 hPa, it is reasonable for two BME680s to have ~0.5 hPa difference between them.

Looking at the baseline temperature differences of the three pairs of BME680s, a noticeable difference between the average baseline values is that Alex's BME680s measure a positive difference between the two BME680s, whereas the other two pairs measure a negative difference. A positive baseline temperature difference means that Alex's "inside" BME680, on average, measures a larger temperature value than the "outside" BME680, even when there is no mask attached between the two BME680s. A negative baseline temperature difference means that the "outside" BME680, on average, measures a larger temperature than the "inside" BME680, which appears to be the case for both Akash and Grace's pairs of BME680s.

Again considering the accuracy ranges of a single BME680, which notes that the temperature accuracy range for one BME680 is +/- 1 degree Celsius, it is reasonable to see that the baseline temperature differences between two BME680s are less than a 0.4 degree Celsius difference in magnitude.

Regarding the baseline humidity differences of the three BME680 pairs, the same difference in sign can be seen in Alex's pair of BME680s. While Akash and Grace's pairs of BME680s, on average, register a positive difference in humidity, Alex's pair of BME680s registers a negative difference in humidity. A negative baseline humidity difference means that Alex's "outside" BME680, on average, measures a larger humidity value than the "inside" BME680, even when there is no mask attached between the two BME680s. A positive baseline humidity difference means that the "inside" BME680, on average, measures a larger humidity than the "outside" BME680, which appears to be the case for both Akash and Grace's pairs of BME680s.

Considering the humidity accuracy range of +/- 3 % for one BME680, having a baseline humidity difference of 6-7% (as is seen in Alex and Grace's pairs of BME680s) is stretching the reasonable range of accuracy for two BME680s. However, the difference is not too drastic, and does not provide any reasonable evidence for the BME680s not working as expected.

4 Conclusion

People's everyday respiratory hygiene and etiquette have drastically been changed by the SARS-CoV-2, COVID-19, pandemic. With this, the mass public has adopted a new social norm of wearing face masks. These masks aim to protect both the wearer and those around them from potentially infectious compounds, through the filtration material in the masks. However, few studies have shown the effectiveness of different materials of masks without the use of an expensive device that distinctively measures the particulates through the filter materials. Also, there is little data regarding whether or not a person's breathing conditions affect the filtration ability of the mask material they are wearing.

Skaria and Smaldone (2014) suggested that the filtration power of a mask could be correlated with the pressure difference between the mask and its environment. Similar studies by Joshi *et al*. (2020) and Tcharkhtchi *et al.* (2021) also support this correlation. However, many of these studies were done *in vitro*, in a controlled lab setting with a mannequin as the basis for the mask. The breathing was simulated through a pump as respirator. This experiment aimed to reach similar conclusions *in vivo*, by having actual people breathe into the masks. Despite the human factor, the results from this experiment found similar conclusions to the studies done before.

Based on the experiments we have conducted, the material of the mask does have an effect on the pressure difference between the inside and outside of the mask. Interestingly, the results of the pressure difference show a similar trend to the filtration power measured in Joshi *et al*. (2020) and Tcharkhtchi *et al.* (2021). This reinforces the idea that the pressure difference has a correlation with the filtration power of the mask material. In addition, the mask material also had an effect on both the humidity and temperature of the inside of the mask, which was supported by the NIH, Abdel-Rehim *et al*, and Wein *et al*. However, this trend is not consistent with the filtration power found previously, so this suggests that there is either a weak or lack of correlation between these factors. Also, through analyzing the different activities, this data found suggests that there may be some causal relationship between the temperature and the humidity. However, this data trend was not consistent with the result of the pressure difference, and therefore has little or no correlation to the filtration power, as well. Finally, a quantitative analysis was conducted on two conditions, normal and deep breathing, to determine when the participant was exhaling or inhaling.

The study was limited by several components. First, while this study was *in vivo*, movement was still discouraged due to the rigidity of the wiring of the PCB. Even minute movements proved to be enough to disconnect some of the wires from the device. Mask effectiveness is most important when a person is moving around other people, and that data was not accounted for in this setup. Also, while the data suggests that pressure difference and filtration effectiveness are affected by mask's material, that is through extrapolated data. A more effective way to measure this would be to have both a mechanism to measure the pressure difference and the molecules that go through the mask. To promote further study from this experiment for more reliable results, the users should be asked more to avoid having the mouth touching the BME680 sensors wherever possible, as it does affect the parameter readings by a drastic amount. The trial experiments can be repeated with having the PCB to be more portable, or just have the both BME680 sensors to be wirelessly connected via bluetooth or wifi. That way, more breathing patterns can be performed for extra sets of data, such as when the user is walking or jogging, which can show more patterns of showing the pressure differences.

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