A Measure of the Effectiveness of Social Distancing and Face Coverings for the Prevention of the Spread of the SARS-CoV-2 Virus by Simulation

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Contents

Declaration

I hereby certify that this material, which I now submit for assessment on the program of study as part of computer science qualification, is *entirely* my own work and has not been taken from the work of others - save and to the extent that such work has been cited and acknowledged within the text of my work.

I hereby acknowledge and accept that this thesis may be distributed to future final year students, as an example of the standard expected of final year projects.

Signed: 

Date: 29/03/2021

Acknowledgements

I would like to express my deepest appreciation to my supervisor Charles Markham for providing unwavering guidance and constructive advice. I would also like to extend my gratitude to my peers who provided helpful discussion throughout the course of the project.

Abstract

The aim of the project was to investigate the effectiveness of face coverings and physical distancing between people as a means of reducing the spread of the SARS-CoV-2 virus (COVID-19). The technique by which this was achieved was a dynamic physical simulation of droplets expelled by a cough for which the motion was governed by differential equations that represented forces incident on the droplets. The simulation consisted of an infected subject facing a healthy subject while coughing. The number of droplets that landed on the healthy person was recorded for different conditions. The mask was deemed effective at filtering many droplets so that the total number expelled was on average 74% less for two metre separation. The number of droplets that contacted the face as a percentage went from 8.9% with a mask down to 5.1% without. The increase in separation resulted in a linear decrease in droplets which contacted the healthy subject. A significant decrease in droplets which contacted the face was observed when increasing separation of the subjects from one metre to two metres: just over 30% of the number at one metre. Considerable evaluation of the results was conducted to support the accuracy of the simulation and the results obtained from it. A combined use of masks and social distancing was deemed to be the most effective method of lowering the probability of infection.

Chapter one: Introduction

Summary

1.1 Topic addressed in this project

The topic addressed by this project was an investigation into the effectiveness of wearing masks and physical distancing of people for reducing the spread of COVID-19 and to present it in such a way that it would be an effective educational tool. It was decided that a dynamic, physical model of the motion of droplets using well established physical phenomena would be a good way to gather data for how these droplets travel.

1.2 Motivation

It is evident that ejected saliva droplets are at least a significant form of respiratory based viral spread, if not the most influential; therefore, it is essential to understand how particles ejected into the air travel so that the correct measures can be taken to limit the spread of such a virus [1] (Coronavirus disease (COVID-19): How is it transmitted?, 2020). The use of such knowledge to come to conclusions is shown by Das when outlining correct social distancing measures [2] (Das, Alam, Plumari and Greco, 2020). The droplets ejected cause spread of the virus directly by means of uninfected people inhaling them but also indirectly. If droplets land on peoples clothes it cannot be ruled out that the viruses contained in these are transferred inside the body of the person by contact with hands, then nose or mouth.

Although knowledge of this droplet dispersion is of the utmost importance to members of academia and this project aims to provide a visual demonstration of the effectiveness of masks and social distancing in the spread of disease to strengthen the knowledge of this. For any measures taken to be effective, everyone must follow them. So, it stands to reason that if everyone understands the problem, then the likelihood that people are willing to follow the guidelines based on academic studies rather than blindly following rules they do not understand [3] (Wang et al., 2018).

1.3 Problem statement

Building a simulation involved using a suitable IDE and coding language, which allowed implementation of a physical model and a graphical front end to display the representation of a cough. A lot of coding languages suited the numerical methods used for the model. There are many ways to add a graphical front end in those languages, so one would be distinguished as more suitable.

The position of a droplet in space is solely subject to forces exerted on them. Each of these forces had to be identified and accounted for—this involved building mathematical formulas to sum up the forces on each particle advancing in time.

The different real-life situations which the project was going to model had to be decided upon, such as distances and wearing of masks. It had to reflect the situations in which people may interact accurately. It had to show evidence to support a suitable distance people can safely stand from a potentially infected person and what effect wearing a mask will have on such a circumstance.

1.4 Approach

The language and IDE chosen was Processing. It is software based on Java and is suitable for simulating physical systems. It allows for shapes to be drawn and updated in a graphical window. Given the correct mathematical model, it fitted the problem well.

The forces that act on a moving droplet were identified as gravity, drag and diffusion. Gravity depended only on the mass of a droplet in the earth's gravitational field. Although liquid does not form a perfect spherical droplet, the relatively small sizes of respiratory particles can be accurately approximated to small spheres as surface tension is strong enough to effectively negate other forces which might distort the shape. From this, Stoke's law (drag force exerted on a sphere in a viscous fluid, i.e. air) can be used to calculate the drag force exerted on a droplet.

It was decided that modelling an infected and healthy person facing each other would be a valuable situation to simulate. The infected person would cough, and the number of droplets that reach a healthy person could be counted. This situation would be evaluated at different distances from one metre up to 4 metres. The effect of masks on the behaviour and number of droplets expelled was also investigated.

A 2-D model was chosen as it was going to be represented on a screen. It was determined that a two-dimensional simulation would be an adequate representation as the same results could be extrapolated in two people facing each other directly.

1.5 Metrics

The radial spread of the droplets was expected to fit an inverse relationship (Figure 1.1) close to the source (mouth) with distance in the two dimensions of this simulation. The data collected was analysed to see if this was the case.

The work was evaluated by comparing results with academic papers. Each aspect was collated with peer-reviewed work and outlines the simulation's accuracy, along with testing of the software. One such study which produces results which are comparable to the results which this project aims to put together is a simulation carried out by Li [4] (Li et al., 2020). This is particularly useful in evaluating the accuracy in the distance particles travel as it outlines the number of particles that land on a person facing an infected, coughing person at one and two metres of separation.

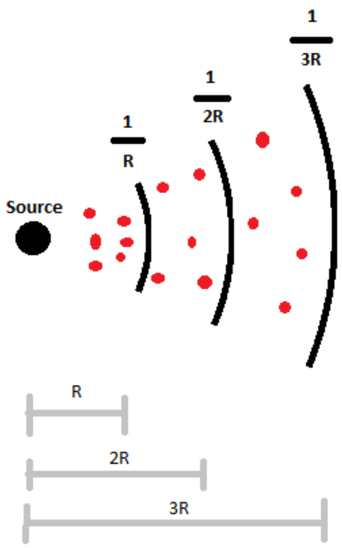

Figure 1.1- Visual representation of expected inverse relationship.

1.6 Project

The project successfully corroborates other studies done in the area. It models the motion of cough droplets to an acceptable degree of accuracy. Also, it would be a great educational aid in explaining the importance of social distancing and the wearing of masks during a pandemic. This is all presented in an aesthetically pleasing user interface (Figure 1.2) which presents the information in a way that a person with minimal scientific background could understand.

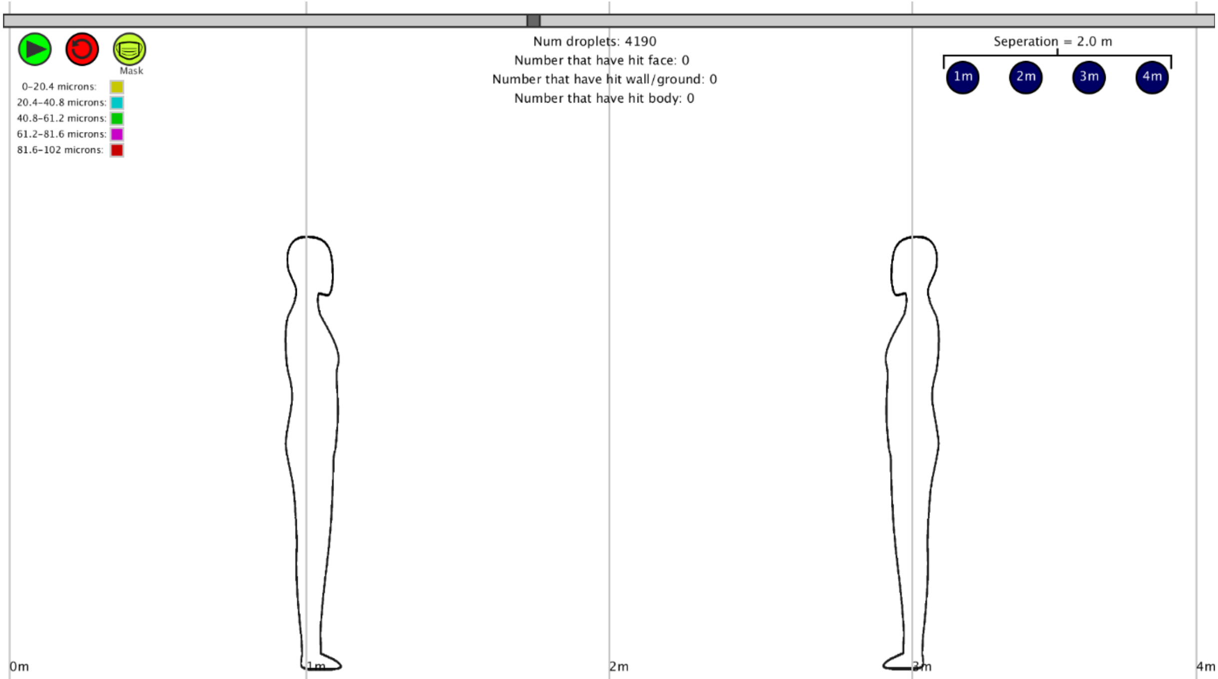

Figure 1.2 - Graphical interface for cough simulation

Chapter two: Theoretical foundations

2.1. Identification of constants and physical parameters required for modelling

2.1.1. Droplet size

Duguid investigated the size of respiratory particles in detail by catching droplets on glass slides, measuring the droplets' size on the glass, and then extrapolating the original airborne droplet size. He concludes that 95% of expelled respiratory droplets lie in the range of 2 µm-100 µm [5] (Duguid, 1946). From this information, a gaussian distribution with a mean of 51 µm and standard deviation of 24.5 µm was calculated using the fact that 95% of a sample lies within two standard deviations of the mean. This was used as the size parameter of the particles for the simulation.

2.1.2. Velocity

In her study of human cough velocity, VanSciver found from a sample of 29 people, their coughs' velocities ranged from 1.5 m/s to 28.8 m/s. In this study, a mean velocity of 10.2 m/s with a standard deviation of 6.7 m/s was established for the sample group's average cough [6] (VanSciver, Miller and Hertzberg, 2011). This gaussian distribution of velocity was used to assign velocity to the particles for this project.

2.1.3. Masks

The simulation included masks on both the infected and healthy individual. These masks' efficacy would need to be known to accurately model their effects on particles' emission due to a cough from the sick person. In a study lead by Asadi, this was studied by experimental means. They found that, on average, the number of droplets that were expelled during a cough was 74% less while using either surgical masks or unvented KN95 respirators than without a face covering. Also, the particles that made it past the face coverings tended to be those of size less than 5 μm in diameter [7](Asadi et al., 2020).

2.1.4. Viral load of droplets

The number of viruses varies in general but especially with the size of the droplets, this is shown by To in a study of the viral load in infected people's saliva. In the study it was concluded that there is a median of $3 \times 10^6 units\ per\ millilitre\ (U/mL)$ in human saliva, meaning there are 3 million copies of the 2019-nCoV present per millilitre of saliva [8](To et al., 2020). This is of course relevant to the spread of the virus but for this study the focus will be on the effect of masks and distance on reducing the number of droplets that make physical contact with a healthy person.

The viral load which is required to infect a person is not known exactly and therefore the number of droplets required is not known exactly. Additionally, the size of each droplet plays a part in the infectivity of the particles due to varying viral load contained within them and smaller particles can be drawn deeper into the lungs when inhaling. The exact number of droplets inhaled which causes infection is unknown but Vuorinen provides an order of magnitude estimate of this number, calculated from a few events where numerous people were infected. The result of this estimate was in the order of 100 droplets inhaled [9](Vuorinen et al., 2020). This study will assume a critical does of 100 droplets but the uncertainty in this will be kept in mind.

2.2 Code generation

2.2.1. Processing

Processing allows for code to be developed in Java. It consists of two main methods – setup() and draw(). The setup method is run only once at the start of the program and it initialises the draw method. The draw method is run in a loop to create animated displays. The code developed in Processing can be used to create standalone executables on Windows, Linux, and Android platforms. For this project Processing 3.1.1 was used to create a standalone application in Windows 10 by making use of the draw method to update the droplet positions in a cough.

2.2.2 2D model

A 2-dimensional model is used in this project. The use of 2D modelling is justified for a few reasons. The study concerns an infected person who has coughed facing a healthy individual. This means the most relevant droplets will be the ones travelling in the x-y plane; the droplets in the z-dimension would be relevant to a study which is concerned with the movement of particles throughout a space where there are many people. The relative effectiveness of a mask and distance can be evaluated without this third dimension. There were many particles being modelled for this project so including a third dimension would have increased the computation needed to calculate each particles velocity and position even further.

2.2.3 Standard deviation and error

The standard deviation was calculated for each set of data gathered and from this the standard error was calculated to show the accuracy of the self-contained simulation as shown in equations (1), (2). Equation (1) has a divisor of $\sqrt{n-1}$ because the sample sized used in this project is relatively small and this gives a more accurate value for standard deviation in these cases.

$$\sigma = \sqrt{\frac{\sum_{i=1}^{n}(x_i - \bar{x})^2}{n-1}} \qquad [10](\text{Taylor}, 1982) \tag{1}$$

$$\delta x = \frac{\sigma}{\sqrt{n}} \qquad [10](\text{Taylor}, 1982) \tag{2}$$

2.3 Mathematical foundations

2.3.1. Analytical interpretation of the problem - Inverse relationship

The relationship expected for radial movement from a point source is an inverse square in 3 dimensions (*equation (3)*), neglecting any influencing factors such as gravity and drag force as in this project. This is equivalent to the particles falling on a unit area of the sphere at increasing distance. This project is based on a two-dimensional model so the relationship would instead be expected to be an inverse relationship (*equation (4)*) instead of inverse square.

$$Inverse\ square\ law: n = \frac{1}{r^2} \tag{3}$$

$$Inverse\ law: n = \frac{1}{r} \tag{4}$$

2.4. Building the differential equations describing droplet motion

To accurately model each particle's motion, differential equations had to be built for each force in each dimension. These were then combined to give expressions for how each particle moved in each time step (*dt*).

2.4.1 Gravity

Gravity only acts towards the centre of the earth, so only the y-direction must be accounted for in this part. Defining the direction moving towards the ground as negative in the y-direction, the velocity due to gravity in terms of time is derived in equations (3)-(5) taking the acceleration due to gravity on earth to two decimal places [11](The NIST Reference on Constants, Units, and Uncertainty, 2018).

$$F = -mg \tag{5}$$

$$F = ma = m\frac{dv}{dt} = -mg \tag{6}$$

$$dv = -g\ dt = -9.81\ dt \tag{7}$$

F is the force due to gravity, *m* is the mass of an object, *g* is the gravitational acceleration on earth.

2.4.2. Stokes' law/drag force

Stokes' law relates the opposing force on a sphere of radius *r* to the dynamic viscosity of a fluid it is travelling through as in equation (6).

$$F_{drag} = -(6\pi r\eta)v = -kv \tag{8}$$

Where *r* is the radius of a sphere, η is the viscosity of the air, and *v* is the velocity of the droplet. The force is negative as drag opposes the motion of the droplet. The drag force will always directly oppose the movement, so if a sphere is travelling in a positive direction, the force will be in the negative direction. Velocity added to each particle due to drag force is derived in equations (9), (10)

$$F = ma = m\frac{dv}{dt} = -kv \tag{9}$$

$$dv = -\frac{k}{m}v\,dt \tag{10}$$

2.4.3. Diffusion

Diffusion could be modelled as an additional random velocity added to a droplet, but this force's magnitude is far smaller than gravitational and drag forces. The force exerted on the particles is solely from the collision of droplets into each other and collision with air molecules. The former is very unlikely for each drop due to their relatively low concentration and small size, and the latter is a minimal force due to the small mass of air molecules [12](Yang, 1949). From this reasoning it was deemed that the modelling of diffusion and collisions was beyond the scope of this project.

2.4.4. Euler-Cromer method for numerical integration

Numerical integration is used in this project to approximate the velocity and position of particles over a set interval of time (*dt*). The droplets initial velocity was set along with their radius and mass at their creation to fit a gaussian distribution. This velocity was then updated by a Euler-Cromer method of integration and the position of each was updated based on the velocity by the same method.

The mathematical model of droplet velocity used in the project is described in equations (11)-(14). Positions of the particles then update according to equations (15), (16).

$$F_x = -F_{drag} \tag{11}$$

$$dv_x = -\frac{k}{m}v\,dt \tag{12}$$

$$F_y = -F_{grav} - F_{drag} \tag{13}$$

$$dv_y = -9.81 - \frac{k}{m}v\ \ dt \tag{14}$$

$$x = x + vx\ dt \tag{15}$$

$$y = y + vy\ dt \tag{16}$$

Chapter 3: Implementation and Code Development

3.1. Data structures

3.1.1 Droplets

Due to the project involving many droplets, a class for them works very efficiently. It simplifies each droplet's creation and management as they will move based on the same set of differential equations. The main class attributes were x and y positions, x and y velocities, radius, and mass. Each droplet was created by a general constructor method of the class (Figure 2.1 left). Each was assigned a random radius with gaussian distribution with a mean of 51 microns and a standard deviation of 24.5 microns calculated from Duguid's experimental conclusions [5](Duguid, 1946). They were also assigned random initial x velocities with gaussian distribution with a mean of 100 and a standard deviation of 67 [6](VanSciver, Miller and Hertzberg, 2011).

The droplet class also contained an 'advance' method (Figure 2.1 right) to update each droplets velocity according to the differential equations derived previously and then update the position based on these velocities. This advance happened continuously due to the draw method in processing calling the advance function each frame. The differential equations are a model of the change in velocity over a time step *dt*, so a time step had to be included, which would set over what time frame each update was taking place. A value for *dt* was chosen to be 0.01 s. This allowed for an adequate resolution of movement while not making the computation of thousands of moving droplets very complex. Every time the advance function was called, the droplet moved the equivalent of how far it would move in a hundredth of a second in reality.

In addition to droplet motion, they should stop when they hit a surface, person, or mask. In the case of surfaces, the droplets velocity was set to zero if its position was at the simulation's boundaries. If the background directly behind the droplet was black (colour of face image), the droplet's motion went to zero. When a droplet passes over a mask, there is a chance that it will stop based on the number of particles that statistically pass through a face covering; this should block 74% of droplets from infected individuals [7](Asadi et al., 2020).

To achieve a 74% filtration rate by stopping the particles when the colour behind them was that of the mask some calibration was required. When moving the droplets sometimes moved more than one pixel at a time depending on their speed. This meant that using a mask one pixel wide, a lot of particles moved from one side to the other without passing over the mask. Instead a mask of three pixels wide was used. This meant that some particles may have passed over more than one pixel of the mask. To account for this some tests were carried out to calibrate the probability that a droplet will stop while occupying one pixel where the mask is so that of all the droplets, on average 74% where filtered. This probability was calculated to be 50%. Once a droplet stopped, a Boolean attribute called 'stopped' was set to true, allowing to save some computation by simply not calling the advance function on any droplet that has stopped.

```
//General constructor
Droplet(){
  //Small deviation in starting positions to represent mouth
  x=(width-60/2)-(((width-60))*seperation)+160;
  y=(float)randNo.nextGaussian()*0.001 + height+500;
  //Velocity distribution(VanSciver, Miller and Hertzberg, 2011).
  vx=(float)randNo.nextGaussian()*67 + 100;
  //Small vertical spread in velocity
  vy=(float)randNo.nextGaussian()*10;

  //Sets random radius and then mass based off of radius
  //95% of droplets lie in 2micrometers - 100micrometers (Duguid, 1946)
  //Calculated standard deviation from this.
  radius=(float)randNo.nextGaussian()*(2.45E-2/2) +(5.1E-2/2); //
  m = ((4/3)*PI*pow(radius,3));

  //Sets droplet colour to represent radius range
  if(radius < (10.2E-2/2) *1/5){c=color(200, 200, 0);}
  else if(radius < (10.2E-2/2) *2/5){c=color(0, 200, 200);}
  else if(radius < (10.2E-2/2) *3/5){c=color(0, 200, 0);}
  else if(radius < (10.2E-2/2) *4/5){c=color(200, 0, 200);}
  else{c=color(200, 0, 0);}
}
```

```
void advance(){
  if(stopped==false){
    //------------Differential Equations-------------//
    vx=vx-(6*PI*radius*k*vx)*dt;
    x=x+(vx*dt);

    vy=vy-(m*g)-(6*PI*radius*k*vy)*dt;
    y=y+(vy*dt);
    //Advance time
    t += dt;
    //---------------------------------------------//
```

Figure 2.1 - Code snippet showing class constructor and advance method for droplet. Droplet class (left) creates the droplets and sets their size and velocity from a theoretical distribution and mass is proportional to radius. Position is slightly randomised to represent particles from whole area of mouth. Colour of droplets are set for size ranges. Advance class (right) is the implementation of differential equations which update the velocity and position of the droplets by a Euler-Cromer method

This motion was all set up in a space four meters long and 3 meters high. To represent this graphically on any size screen, the distances had to be scaled and mapped to the correct size. This was possible by writing a custom draw method (Figure 2.2) within the droplet class which would be called by the main draw method to sketch the droplets to the screen. Although the area on the screen represented 3x4 meters, the units used for this were millimetres, as processing runs into problems when using very small values in the calculation, limited by the floating-point precision. It would be working with small values if the droplets' size were represented in meters instead of millimetres. The draw function mapped the droplet positions from 0 – 4000 mm and 0 – 3000 mm to their scaled positions along the screen's length and height, 0 - width and height - 0. To add to visual representation, a colour code was introduced to assign five different colours to five size ranges of droplets, divided evenly. The circles' size was set depending on their size range to further represent the different sizes.

```
void drawDrop(){
   float sx= map(x,0,4000,0,width); //maps x position to screen
   float sy= map(y,0,3000,height,0); //maps y position to screen
   fill(c);  //sets droplet to size range colour
   stroke(c);
   //Sets size of droplet based on discrete range of radius values
   if(radius < (10.2E-2/2) *1/5){circle(sx,sy,2);}
   else if(radius < (10.2E-2/2) *2/5){circle(sx,sy,4);}
   else if(radius < (10.2E-2/2) *3/5){circle(sx,sy,6);}
   else if(radius < (10.2E-2/2) *4/5){circle(sx,sy,8);}
   else{circle(sx,sy,10);}
}
```

Figure 2.2- Code which maps the droplets position to the screen. Maps the droplet size to discrete ranges to represent as five different size ranges on the screen.

3.1.2. Masks

Having the droplet motion represented the masks could be implemented. The masks were represented as grey lines, 3 pixels wide, and, as mentioned, had a chance of stopping each particle. There was a button included for putting the masks on/off the infected and healthy people. This was especially important for gathering information about the effectiveness of face coverings versus no covering.

3.1.3. Adjusting separation of infected and uninfected subjects

The distance between the subjects needed to be variable so, four buttons were included to set the separation to 1, 2, 3 and 4 meters. This would give a good range to show the effect distance has on limiting the number of droplets that land on a person's face. The buttons changed a separation variable that governed where the faces' images were positioned and then reset the sketch. The Interface included a distance scale to show the distance scale of the simulation.

3.2 UI/Information display

The user interface is vital in this project as it should represent the actual physical situation in a way that anybody understands. The following information had to be displayed and updated during the simulation - the number of droplets being simulated, the number that had landed on the healthy person's face and body, and the number blocked by each mask. This information was displayed as text, with the numbers changing as the droplets progressed. A legend was included to show the size ranges of the droplets along with their corresponding colours. A slider was chosen to change the number of droplets that would be simulated. The option to change the separation, number of particles, and masks being put on and off was disabled during simulation, see figure 3.1. These were normally controlled by the buttons which were implemented using a custom button class.

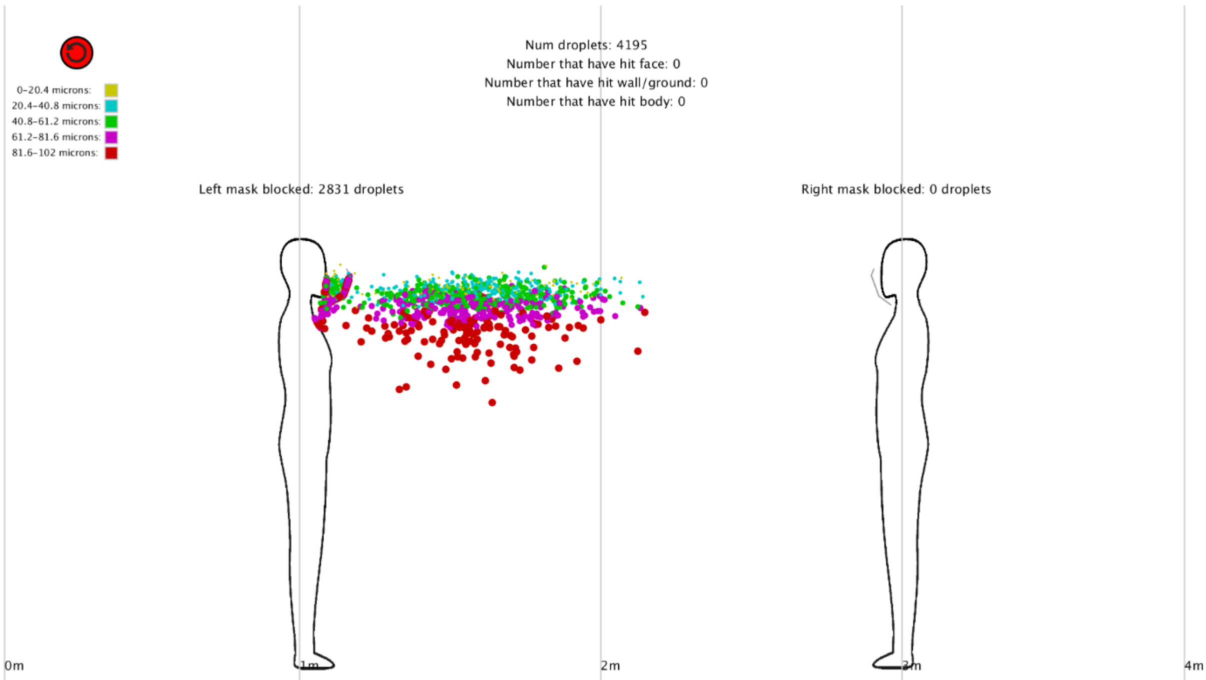

Figure 3.1- Simulation graphical interface with options for separation, number of particles and masks disabled during simulation.

3.3. Collecting data for analysis

When building the simulation was completed results had to be gathered which outlined the effectiveness of masks and social distancing.

3.3.1. Masks

The effectiveness of masks was tested at a two-metre separation as this is the widely advised separation to limit the spread of the virus and this is a common situation in which masks are in use (shops etc). The simulation was run with 5000 droplets 10 times both with and without masks. The simulation run until the rate of collision with the subject fell below 1 per 10 seconds so the results were taken at a consistent point each time. The number of droplets on each surface was then recorded for analysis.

3.3.2. Distance

When testing the effectiveness of varying distance on the spread of the virus, the simulation was carried out 5 times each for 1, 2, 3, and 4 metres separation. The number of droplets was again set to 5000 for each simulation and ran until the number of droplets per second hitting the healthy person slowed to below 0.1. The number of droplets that landed on each surface was again recorded. These tests were carried out without masks to keep results for masks and distancing independent of one another.

Chapter 4: Results, and discussion

4.1 General comments

When a simulation starts, the droplets remain close together. As it progresses, they become separated either because of deviation in initial velocity, the different gravitational force due to distinct mass or varying radius and therefore drag force. The more massive a droplet, the quicker it falls. Some of the smaller particles appear to become suspended in the air as the simulation progresses. This is due to the drag force on them, which can eventually slow their velocity in the x-direction close to zero if their initial speed was low enough. If their mass was small, their small gravitational force does not quickly

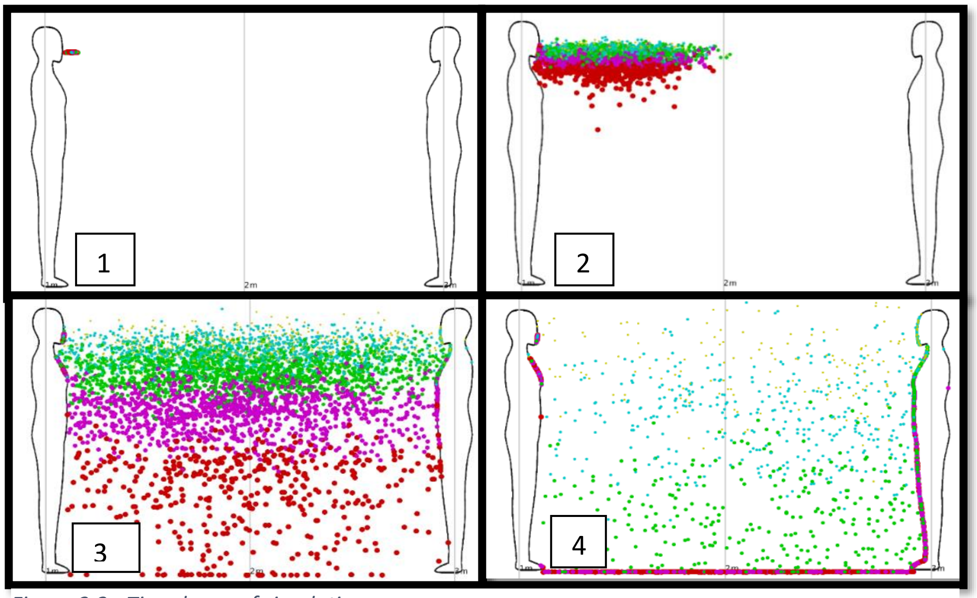

Figure 3.2 - Time-lapse of simulation

draw them to the ground as the drag resists this motion. These particles are relevant to the study as there is a risk that others can pass through the area and either inhale the particles or gather them on their person. Time-lapse of simulation running displayed in figure 3.2.

4.2. Analysis of mask performance

4.2.1 Control group

Simulations done without masks showed a significant percentage of the droplets expelled landing on the healthy individual. There was 2770 out of 5000 average total droplets landing on the person. Furthermore, the mean number of droplets to land on the healthy subject's face was 247.1 ± 5.1, which is approximately 8.9% of the total that landed on the person. The complete data used to derive these values is displayed in Figure 4.1 (left), along with an image of one such simulation in Figure 4.2.

4.2.2. Masks

There was a significant decrease in the number of droplets landing on the person for the tests using masks. Out of 5000 droplets, an average of 914.3 contacted them, and of this, 46.9 droplets or 5.1% of these reached the face. The infected persons mask blocked significantly more particles than the healthy persons mask, comparing the mean of 3383.9 and 61.1, respectively. These average values were calculated from data in Figure 4.1 (right), and Figure 4.3 shows an image of one of the tests done to collect it. The observation that the mask on the infected subject is more effective than on the uninfected subject as a means of stopping spread of disease is supported by the literature [13](Wang, Deng, and Shi, 2020).

4.2.3. Findings

Comparing the total number of particles that contacted the healthy individual, there is a 66% decrease when wearing a mask. This reduction correlates with the number of particles filtered by the mask (74%) with a slight alteration. The particles close to 100 microns were much less likely to hit the person, particularly ones in the range of 82.6-102 microns (coloured red Figure 4.2) as the gravitational force on them is enough to drag most to the ground. These particles are filtered with the

Simulation	Face	Body	Total
1	235	2528	2763
2	271	2450	2721
3	249	2506	2755
4	262	2451	2713
5	242	2507	2749
6	248	2575	2823
7	236	2588	2824
8	224	2503	2727
9	234	2600	2834
10	270	2521	2791
Mean	247.1	2522.9	2770
Standard Deviation	16.1	52.0	45.3
Percentage hits on face	8.9		

Simulation	Face	Body	Mask Left	Mask Right	Total on person
1	46	884	3367	64	930
2	50	825	3393	60	875
3	49	884	3413	47	933
4	44	876	3402	61	920
5	37	834	3344	62	871
6	47	856	3368	59	903
7	56	871	3374	70	927
8	53	875	3398	61	928
9	45	869	3413	61	914
10	42	900	3367	66	942
Mean	46.9	867.4	3383.9	61.1	914.3
Standard Deviation	5.5	23.1	23.1	5.9	24.2
Percentage hits on face	5.1				

Figure 4.1 – Data collected for subjects not wearing masks (left) and wearing masks (right). Outlines the number of particles that collided with different parts of the simulation of 5000 initial particles.

same frequency as all other droplet sizes, so the number of particles which land on the person is not reduced by exactly the amount they are filtered by the infected person's mask.

The percentage decrease in particles colliding with the healthy person's body is almost identical to the whole person with a 66% reduction also. The percentage of all the particles which hit the person's face was 3.8% less. This small decrease is likely partially due the mask on the healthy persons face filtering some particles. Although the mask filters the particles there is a danger that the act of the person breathing may draw them through the mask or there may be contamination when removing the mask which must be considered.

Assuming all droplets on the face were drawn into the lungs when inhaling; the simulation with masks does not meet the order of magnitude estimate of critical dose of 100 droplets. This does not guarantee that this person would not be infected but it is estimated that on average under these conditions a cough would not cause infection.

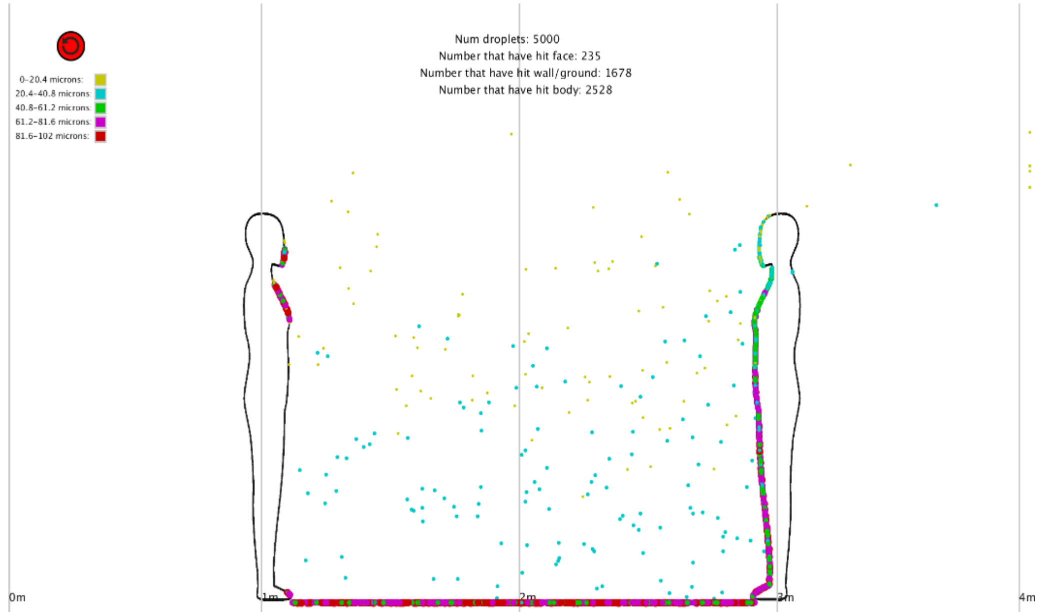

Figure 4.2 - One iteration of simulation without masks. 5000 particles where expelled. Significant droplet contacted uninfected subject

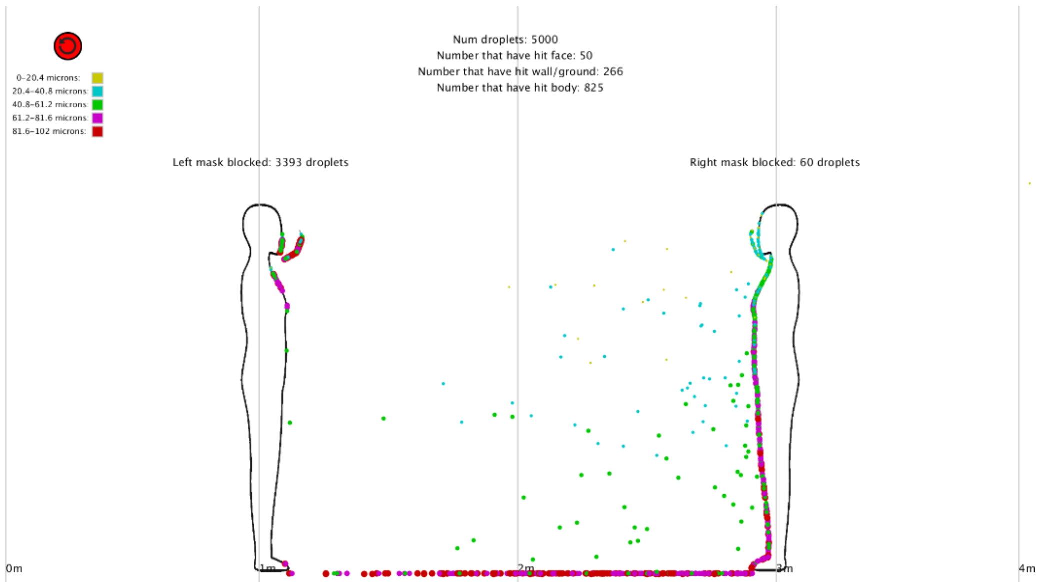

Figure 4.3 - One iteration of simulation with masks. 5000 particles were expelled. Largely reduced droplet contact with uninfected subject compared with no masks.

4.3. Distance

The data recorded (Figure 4.4) when altering the separation between the infected and healthy subjects shows a decrease in the number of collisions with an increase in distance. Looking at the number of droplets that land on the face, there is a rapid decrease near the source, and this begins to level out further out, as shown in Figure 4.5. This suggests that if the distance was increased further that the number of hits would not change dramatically. However, most droplets had very low velocity when they reached the person at four metres of separation. They would eventually fall lower than the face or to the ground. It is unclear at what separation this effect may become apparent as the slower a particle travels, the lower the drag force becomes as it is proportional to the droplet's velocity. The decline in droplets reaching the person before this is primarily due to the larger droplets being influenced strongly by gravity until they reach the ground, but this effect reduces with a decrease in size as the drag force begins to dominate the movement in the y-direction.

Although the number of particles that hit the body are less likely to infect an individual, they cannot be ignored. The high R^2 value for the linear fit for hits to the body vs distance in Figure 4.6 suggests that the relationship between distance and number of collisions within these distance bounds is linearly proportional. According to this relationship, the separation between the people must be 10.3 metres before no droplets are landing on the healthy individual. As mentioned before, the drag force may alter this as the distance is increased and more particles stop moving in the x-direction altogether. More research into this would have to be done to confirm that this is the case.

This data lends some weight to the widely advised two metre separation. The decrease in droplets landing on the person when moving from one metre to two is important but not hugely significant for doubling of separation. More importantly the decrease in particles landing on the face where they could potentially be inhaled is decreased to just over 30% of the number at one metre. Assuming all these particles were inhaled by the person and comparing this to the 100-droplet critical dose this distance is not sufficient. However, all these particles are likely not inhaled as this number encompasses all particles on the face. Continuing to increase distance does not provide the same level of reduction. When increasing to three metres the number of droplets contacting the face is decreased by approximately half. Of course, any increase in separation would be beneficial in preventing the spread of disease it is certainly worth enforcing a social distancing of two metres due to the disproportionate benefits it provides without a large hindrance to everyday activities. Subjects spaced by one and four metres are shown in Figures 4.7 and 4.8 respectively.

	1		2		3		4	
Simulation	Face	Body	Face	Body	Face	Body	Face	Body
1	800	3060	241	2522	107	1794	70	1160
2	803	3129	263	2516	125	1758	66	1070
3	814	3075	231	2566	133	1695	82	1061
4	823	3073	231	2516	117	1788	84	1117
5	754	3162	252	2510	143	1783	87	1158
Mean	798.8	3099.8	243.6	2526	125	1763.6	77.8	1113.2
Standard error	11.9	19.5	6.2	10.2	6.2	18.2	4.1	21.0
Percentage hits on face	20.5		8.8		6.6		6.5	

Figure 4.4 - Data collected for varying separation of subjects. Shows number of droplets that hit each part of the simulation.

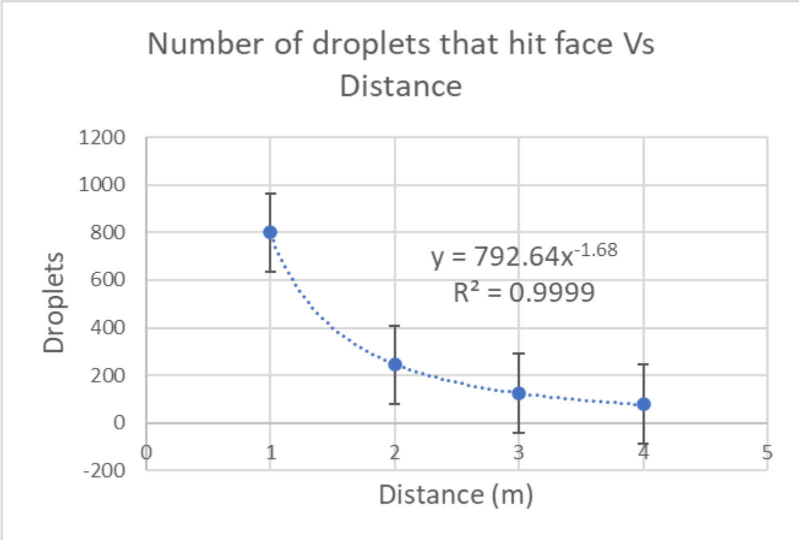

Figure 4.5 - Number of droplets which collided with healthy persons face plotted against separation distance. Power relationship line is overlaid.

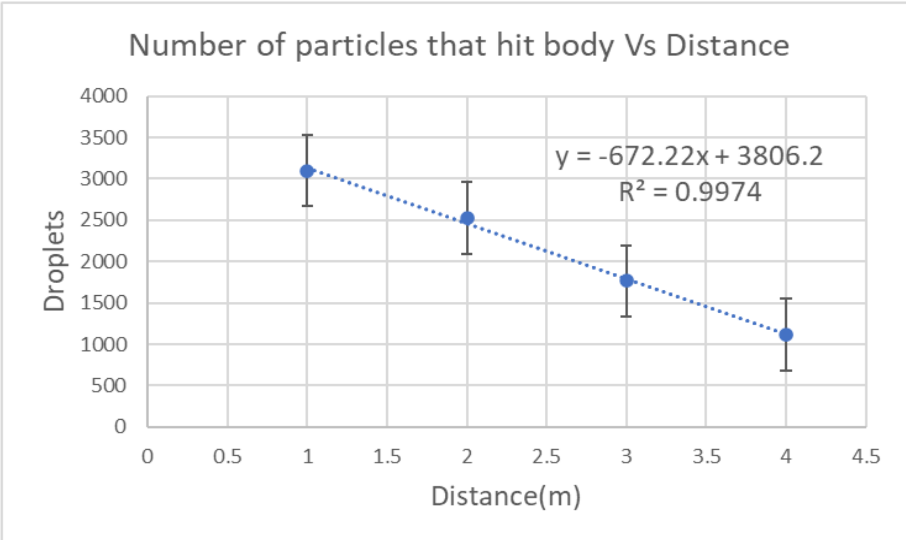

Figure 4.6 - Number of droplets which collided with healthy persons face plotted against separation distance. Linear relationship line overlaid.

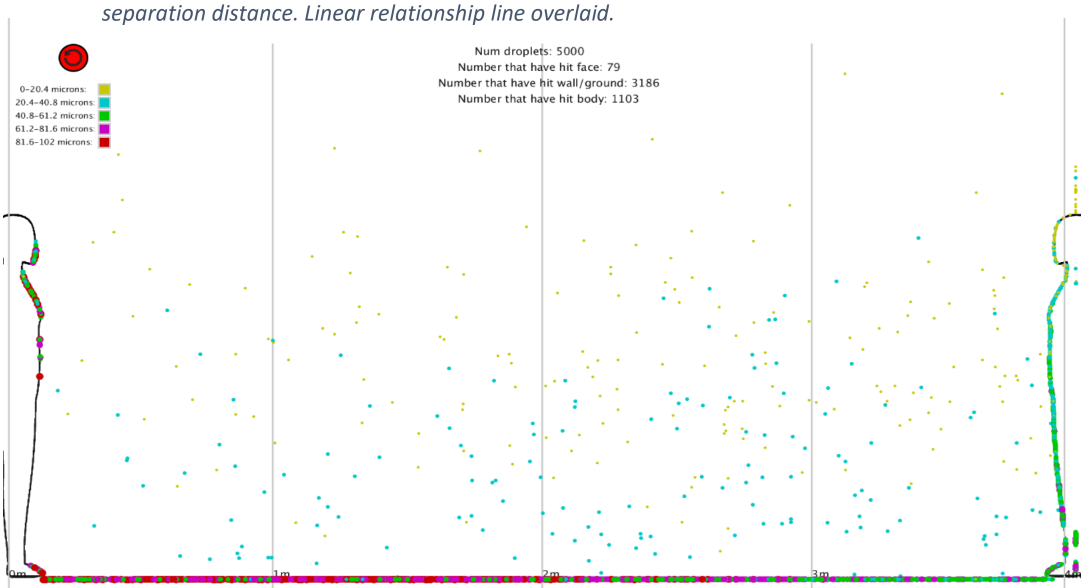

Figure 4.7 - Simulation with subjects separated by 4m. Showing one extreme of the distancing in the simulation.

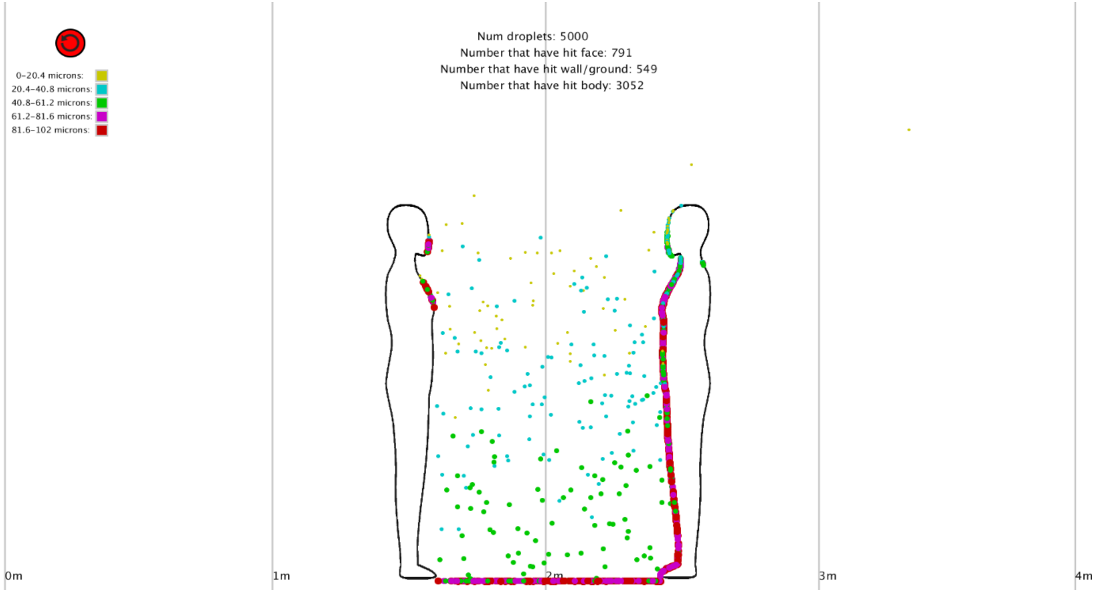

Figure 4.8 - Simulation with subjects separated by 1m. Showing one extreme of the distancing in the simulation.

Chapter 5: Evaluation

5.1. Verification

An incremental model was used to develop the code. This approach ensured that the simulation was operational at each stage of its development. Each aspect of the simulation was developed section by section starting with a rudimentary projectile motion model all the way up to a fully functioning simulation of the cough. Any bugs in the software were identified and eliminated before moving onto subsequent operations of the project. For example, the physics which governed the particles was first tested on a single particle simulation without any randomness or other factors in order to verify the accuracy of the differential equations before extending this to numerous droplets and eventually including random velocities and sizes. Also, when incremental tests were being run the random number generators were not seeded the same for each test.

Version control was made use of to ensure that if any bugs which were undetected in earlier stages of development, there were earlier versions which could be rolled back to. This was very useful in keeping track of when something went wrong. Each version of the code was stored in local filed storage and backed up to cloud storage.

Additionally, when tracking down bugs the very useful debugger in processing was used. This was especially useful when ensuring the physics of the particles where moving how they would be expected to in real life.

5.2. Validation

5.2.1. Demonstration of the inverse relationship between contamination and separation

The relationship between the number of droplets which landed on the persons face as a percentage of all droplets that landed on them and the separation between the people was expected to be an inverse relationship. For the hypothesis that there is an inverse relationship to be proven a graph of $Ln(N)\ vs\ Ln(d)$ can be plotted and the resulting slope outlines the relationship as shown in equations (3)-(7), where *N* is the number of droplets, *c* is the y-intercept of the line of fit, *d* is the distance from the source and *p* is the power *d* is raised to. A value of -1 for *p* would suggest evidence that the simulation mimics the physical laws that it is based on to a certain level of accuracy.

$$N = \frac{c}{d} = cd^{-1}\ expected\ relationship \tag{17}$$

$$N = cd^{p} \tag{18}$$

$$Ln(N) = Ln(c) + Ln(d^{p}) \tag{19}$$

$$\{Ln(N) = Ln(c) + pln(d)\} = \{y = c + mx\} \tag{20}$$

$$p = m \tag{21}$$

Although there should be alterations to this relationship in this instance, for short distances it should not deviate much as the forces exerted on the particles will not have strongly affected the droplets trajectory i.e. initial velocity is much more influential at this point. The natural log of the data was plotted (Figure 5.1) for the full range of separation and a value of -0.8618 with a standard error of 0.168814. This is relatively close to the expected slope of -1 obtained, this shows some evidence for the inverse relationship but as mentioned before the inverse relationship is affected by the forces on the particles at further distances. The same information was plotted (Figure 5.2) again for separation up to 3 metres and a value of -1.05 with a standard error of 0.136367 was obtained for the slope. This fits the expected model for droplets over distance for a 2D analytical model within experimental error. This value with the error on the calculation fits the expected relationship as shown in equation (20) therefore supporting the accuracy of the simulation.

$$N = 2.988d^{-1} = \frac{2.988}{d} \tag{22}$$

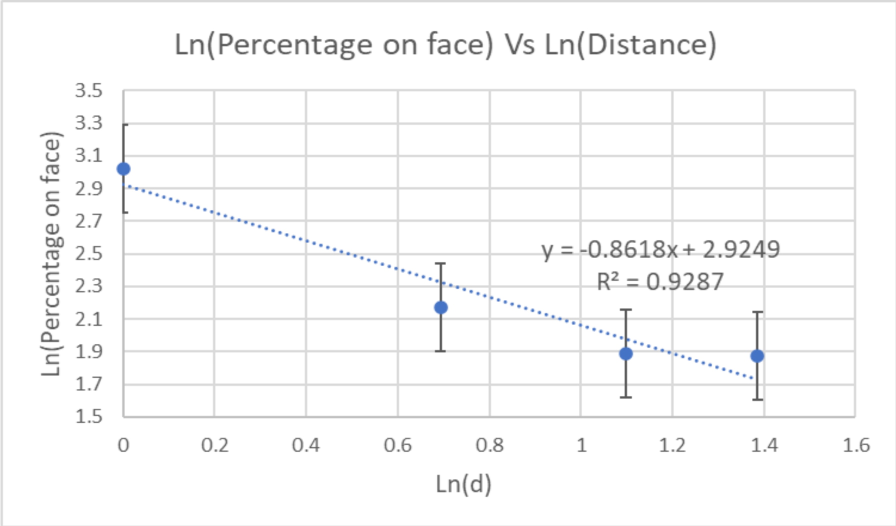

Figure 5.1 - Natural log of percentage of droplets that land on the face as a percentage of the whole person plotted against natural log of separation up to four metres.

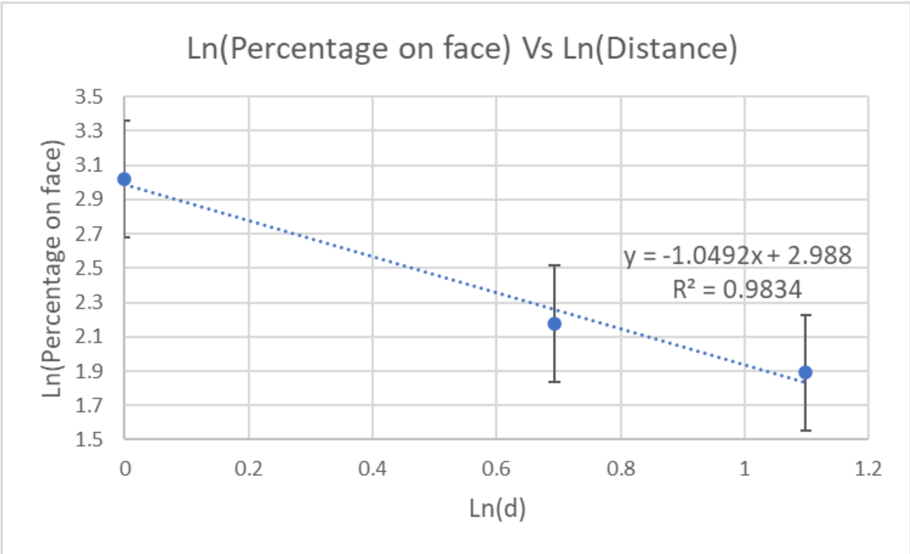

Figure 5.2 - Natural log of percentage of droplets that land on face as a percentage of whole person plotted against natural log of separation up to three metres.

Size distribution

The size distribution of the particles on the face, body and ground were analysed to ensure it was as expected. Results are displayed in Figure 5.3. According to the central limit theorem, when taking a sufficiently large sample from a population the distribution of the sample means will be approximately normal. The mechanism by which the droplets arrived at the places outline were solely random within bounds meaning these droplets plotted on the histograms can be taken as a large sample of a population – all possible droplets that could land in these places. Each histogram gives an approximate normal distribution and so the theorem holds for this data.

The distribution on the face seems to be a right skewed distribution due to the mean of the data being close to zero and of course there are no negative sized droplets. The distribution on the body is highly normal which would be expected. The size distribution on the ground is slightly right skewed which is due to the discrete boundary between the ground and the person's body. Overall a decrease in droplet size is witness as height increase. The size of the particles on the body are smaller than the ground and the size of the particles on the face are smaller than the body which is a reasonable result. The larger the particle the larger the gravitational force so this was an expected outcome.

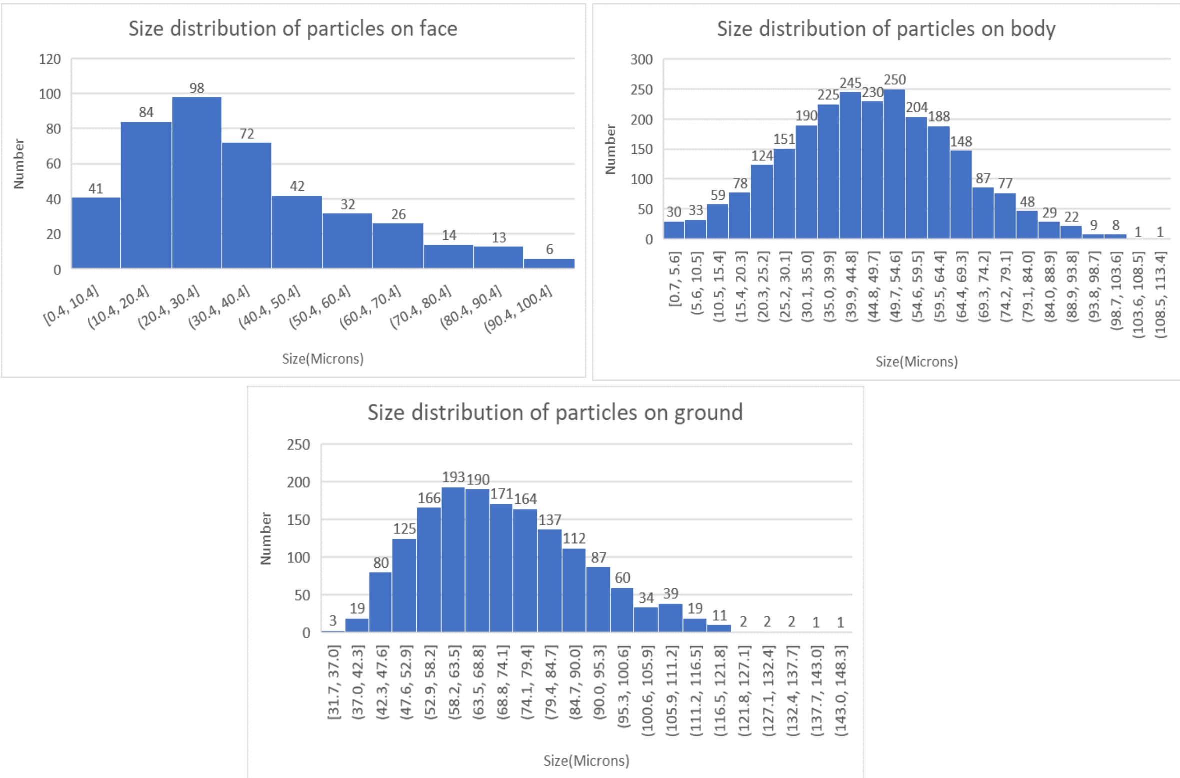

Figure 5.3 - Histograms of the size distribution across different parts of the simulation. Shows normal distribution of particles as expected.

5.3. Comparison with previous work

One study which obtained results comparable to the results of this project is outlined in a paper by Li [4](Li et al., 2020). This study investigated the dispersion of coughed droplets in a tropical environment. It was found that at one metre of separation more than 65% of the expelled droplets was deposited on the person facing the source. This is comparable to the over 75% found during this study. The disparity in these values could be due to the study done by Li including a wind speed of 2 m/s and as seen in the paper this carried some particles over the head. The simulation also differed from this one as it modelled a cough in three dimensions, so droplets also had a chance of travelling left or right of the person. Considering this, the percentage of droplets deposited would be quite similar for both simulations.

Another study which provides good support for the accuracy of this project is by Vuorinen [9](Vuorinen et al., 2020). The study states that small droplets (< 20 microns) tended to become suspended in the air between the subjects, with some remaining there for between 20 minutes to 1hr. A similar observation was made during this project in which droplets of this size stayed airborne for over 20 minutes of in simulation time.

Chapter 6: Conclusions

6.1. Achievements

- A processing program was developed to model droplet motion to investigate the effectiveness of face coverings and social distancing to lower the spread of the SARS-CoV-2 virus.
- The variables used in the code were based on data obtained in the literature by experimental means.
- Differential equations were built to accurately model the motion of droplets moving in the air by a Euler-Cromer method.
- The code developed included a GUI to show the processes in real time. This allowed a good understanding of what happens during a cough.
- Data was collected from the simulations and analysed to draw conclusions on the effectiveness of masks and social distancing.
- The data was analysed to verify the accuracy of the simulation along with comparison with the literature.

6.2. Final review of the mask study

Face masks certainly reduce the number of droplets expelled by a coughing person and by a highly significant amount. The filtering effect of masks is clear; they can reduce the overall number of droplets by over 70% and due to this the number of particles contacting an uninfected person can be decreased by 66%. This alone is a compelling reason but a further reduction in droplets landing on a person’s face is an even more compelling reason for the use of face coverings. The decline in particles landing on the face was even steeper than that of the body due to the size of particle which was likely to be at face height, two metres from the source being a more typical size for the distribution and were filtered by the same frequency. This is especially important as these are the particles which are likely to be inhaled and due to their small size are more likely to be drawn deeper into the lungs. The conservative estimate that all particles on the face have a chance to be inhaled shows that without the use of a mask the assumed critical dose is exceeded by well over double while with masks it is just under half the dose. This suggests a likely infection without - and a good probability of infection prevention.

6.3. Final review of the distance study

There is a definite decrease in droplets with an increase in separation between the infected person who coughed and the healthy person who is being coughed on. The particles incident on the person’s body falls in a linear fashion with separation which is important, but the more important effect is that of the inverse relationship of droplets falling on the face. The large drop of 20.5% on the face of all droplet’s incident on the person to 8.8% when moving from one to two metres separation, coupled with a total reduction in contact is not an unreasonable argument for practicing social distancing of two metres. This is further bolstered by the fact that the diminishing effectiveness of further separation has while simultaneously considering the feasibility of further separation being possible to distance people further in certain spaces. Having said this, when at all possible a maximum distancing should be considered as the data suggests a possibility of droplets travelling up to 10 metres over time.

The best course of action during a pandemic seems to be a combined use of masks and social distancing. Using a mask and social distancing of two metres seems to be a sufficient measure to on average prevent a person becoming infected if facing someone who coughs once.

6.4. Educational tool

In a non-pandemic time, it would have been interesting to show the simulations to people and then ask them to comment on the relative risks to them of wearing masks, other people wearing masks and separation. This would have given an indication of the effectiveness of the program in increasing peoples understanding of the topic and how the simulation could have possibly increased their awareness on the spread of the virus. The code developed provided an effective visualisation of the process involved. It does this by amplifying the size of the particles so they can be seen but keeping their motion and behaviour physically correct

6.5. Limitations

- The evaporation of cough droplets was outside the bounds of this project and therefore each droplet's size is assumed to be constant throughout the simulation.
- Particles were assumed to be filtered by masks in the same frequency regardless of size. If the project was to be extended this is a factor which should be considered.
- The constants used in the simulation were taken as average values based on previous physical experiments and outliers in specific variables should be considered in further work. One instance may include the possibility of a 'super-spreader' [14](Wong and Collins, 2020), which is the idea that a person can spread the disease at an abnormally high rate.

6.6. Future work

- Extending the simulation to three dimensions would be a good way to further the findings of this project. This would allow for greater accuracy and would especially improve the capability of the simulation to investigate the propagation of particles for further distances. The probability of infection could be studied in a more dynamic way as the movement of people in an area could be studied along with the particles.
- Including the effect of air motion on the particles would further increase the findings of the project for the same reasons that a three-dimensional model would and because air is never entirely still in life. An indoor environment would still be subject to some turbulence due to people moving and the motion of the cough itself.
- The evaporative effect on droplets should be considered in future work to advance the simulations accuracy.

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