Human Behavior Simulations to Determine Best Strategies for Reducing COVID-19 Risk in Schools

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Abstract. The dynamics of COVID-19 spread have been studied from an epidemiological perspective, at city, country, and global scales (Rabajante, 2020, Ma, 2020, and Giuliani et al., 2020), although after two years of the pandemic we know that viruses spread mostly through built environments. This study is part of the Spatiotemporal Modeling of COVID-19 spread in buildings research (Gomez, Hadi, and Kemenova et al., 2020 and 2021), which proposes a multidimensional model that integrates spatial configurations, temporal use of spaces, and virus characteristics into one multidimensional model. This paper presents a specific branch of this model that analyzes the behavioral parameters, such as vaccination, masking, and mRNA booster rates, and compares them to reducing room occupancy. We focused on human behavior, specifically human interactions within six feet. We utilized the multipurpose simulation software, AnyLogic, to quantify individual exposure to the virus, in the high school building by Perkins and Will. The results show how the most effective solution, reducing the occupancy rates or redesigning layouts, being the most impractical one, is as effective as 80% of the population getting a third boost.

Keywords: Spatiotemporal Modeling, Behavior Analytics, COVID-19 Spread, Agent-Based Simulation, COVID-19 Prevention

1 Introduction

Beyond social distancing, and especially for countries or states where policies are loose or non-existent, the question is: What parameters of the space configuration and the organizational schedule can be modified to reach similar levels of protection or reduction of risk for our students? Even countries with previous virus prevention policies are adapting to life with the virus, and as of April 19th, 2022, U.S airlines have officially ended the mask travel mandate (Chokshi, Murphy 2022). This change in national policy highlights this shift in society's perception of COVID-19. It is important to continue research of virus spread in enclosed spaces in order to modify prevention techniques relative to the risk exposure.

Furthermore, Lippi and Mattiuzzi's (2022) assessment of mRNA booster dose efficacy highlights that there is an ongoing debate as to whether or not a booster dose restores, increases, or does not affect COVID-19 immunity six months after receiving two doses of a vaccine. Astoundingly, six months after vaccination, individuals are only 59% protected against COVID-19 infection. However, receiving a booster dose increases this protection to 65% or more.

To restore immunity, it is essential that people who have received the vaccine greater than six months ago obtain a booster shot, especially since 100% of the current March 2022 shares of SARS-CoV-2 sequences are the Omicron variant, which is one of the most infectious (Yale Medicine). Additionally, a greater number of boosted individuals helps impede the spread of the pandemic, as booster-vaccinated individuals have a lower viral load when infected with COVID-19 (Lippi, Mattiuzzi 2022).

Past research has evaluated the role of masking in conjunction with vaccines on the spread of COVID-19 in a school environment, to make the return to in-person school as safe as possible. The data shows that if 95% of the community is vaccinated and nobody wears a mask, then there will be only 2 excess COVID-19 cases per 100 students (Head, et al. 2022). However, since the CDC states that only 65% of Americans are fully vaccinated, this is not representative of the community and alternative vaccine and mask wearing combinations must be considered. Additionally, the U.S Census Bureau states that 6% of Americans are under 5 years old, which is the minimum age to get vaccinated. Thus, it was currently impossible to reach a 95% vaccination rate.

Another important aspect of the research is the question - who is wearing a mask, what type of mask are they wearing, and how often? Knowing the percentage of people wearing masks is crucial for running agent based simulations with masking parameters. In a 2020 study, it was noted that overall, young people were 20% less likely to wear a mask than their older counterparts (Haischer, Michael H., et al., 2020). Since 18 – 24 year olds are the least likely to wear a mask out of all the age groups, it is important to study masking and vaccination effects in this age group in order to determine the worst-case scenario of spread.

The overall research goal is to study how individual human interaction within six-feet, without maintaining social distance, can impact the overall COVID-19 exposure of a population, while taking into account the booster dose efficacy, mask-wearing behavior, and mask use behavior. The following research questions are investigated: What COVID-19 prevention policy is most effective and practical to implement in a built environment? Is increased societal masking as effective as if 80% of the population were to get boosted? What is the relationship between increasing virus prevention measures or decreasing the number of people present? For example, if the objective is to decrease individual exposure by 50%, can this also be achieved by decreasing the room occupancy by 50%?

2 Methodology

2.0 Experiment Design

The research design is based on the layout of the second floor of school, modeled as 30.6 meters wide and 93.2 meters long. AnyLogic Software was utilized for agent-based modeling, which simulated 100 students as agents arriving from the staircase on the left corner, entering one of the classrooms, and exiting, in a 50 second interval simulating one 50-minute class period. The school layout has five classrooms, and 20% of students entered each classroom to evenly distribute the agents. This spatial distribution does not significantly influence infection, and avoids agent congregation, to focus solely on how masking and vaccination rates affect the spread of COVID-19. While 20% of the student agents will leave through another staircase, the rest of them will enter the open-space library area (top of Figure 1) and spend some time there before leaving.

Further spatial analysis was conducted using Rhinoceros 3D, which outputs the total exposure count per classroom. The output from the AnyLogic model was inputted into Rhino, to study the model from a spatial perspective considering the total area of the room, number of agents in the room, and total time spent in the room. Figure 2 displays the space configuration for the school. The agents begin walking past classroom 4, with their path ending in classroom 0.

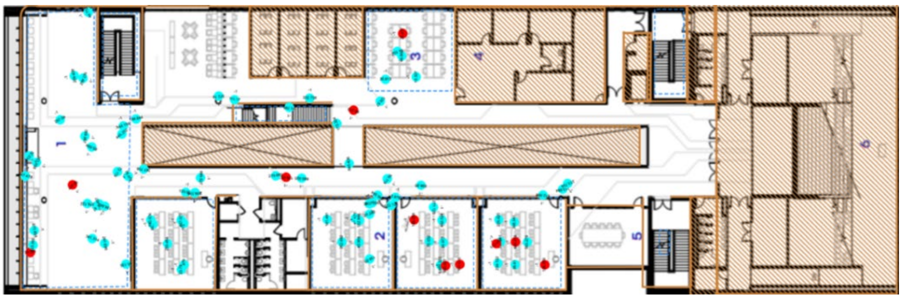

Figure 1. Agent-based modeling on the high school 2nd floor

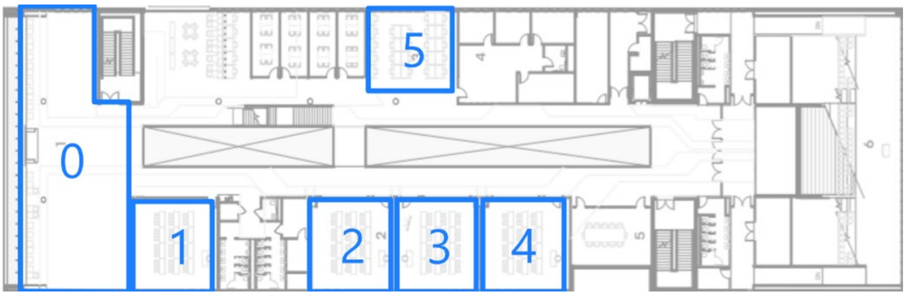

Figure 2. Spatial modeling of high school 2nd floor

2.1 Parameters Identified for Simulation in AnyLogic

2.1.1 Building Parameters:

The project, provided by Perkins & Will Design Process Lab, is a high school in Alabama, and it was the specific layout we used for the case study is of the second floor of school library, consisting of five classrooms, a hallway, and a stairwell.

2.1.2 Agent parameters:

The agent parameters include the following:

Occupancy: 100 agents
Number of Known Cases in Building: **10%**

Vaccination Status:

- Not fully vaccinated: Someone who is either not vaccinated at all against COVID-19 or has been vaccinated only once.
- Fully vaccinated without booster: A person who will have been fully vaccinated but not have received a booster shot.
- Fully vaccinated with booster: One who has been fully vaccinated in addition to receiving at least one booster shot.

PPE (Personal Protective Equipment) level:

- No mask: The person never wears a mask, neither indoors nor outdoors
- Fabric mask: Three-to-five layers of tightly woven fabric
- Surgical mask: A mask with three layers of filtration and fluid resistance
- N-95 respirator: Fit-tested, with five layers of filtration (and fluid resistance)

Health Status:

- Healthy, not sick with COVID-19 (Omicron variant)
- Symptomatic and actively contagious with COVID-19 (Omicron variant)

2.1.3 Scenarios:

Below is an outline of four different scenarios, which combine parameters in unique ways. Table 1 shows the parameters for each scenario, and the percentage of agents assigned to each parameter.

Scenario A: The current United States situation. It serves as a control group relative to Scenarios B and C. It is modeled off of the case rates, vaccination rates, and policies in United States in the spring of 2022. For example, as of March 28, 2022, 11% of people were not fully vaccinated, while 62.3% of people were vaccinated but not boosted (CDC: Our World in Data 2022). Additionally, the mask wearing data assumed that individuals follow CDC guidelines, which as of February 25th, 2022, state that 70% of Americans can stop wearing masks (Mandavilli 2022). However, for the remaining 30% of Americans that may continue to wear a mask, it was arbitrarily chosen that an equal majority of agents would wear either a fabric or surgical mask due to relative ease of purchase, with the remaining 1% of Americans wearing an N-95.

Scenario B: Increase number of boosted and vaccinated agents. It aims to improve the vaccination and booster situation of Scenario A by increasing the number of agents who are boosted and/or vaccinated. The mask wearing data remains the same as in Scenario A. To evaluate the effectiveness of the booster shot in decreasing the exposure risk, the number of agents with a booster shot was increased to 80%. To focus the insights on the effect of increasing the number of boosted individuals alone, this scenario assumed that every individual was vaccinated. The mask wearing assumptions remained the same as in Scenario A. Table 1 shows the vaccination parameters for Scenario B, with the percentage of agents assigned to each parameter.

The purpose of this scenario was to (1) evaluate how an increase in the number of boosted agents affects the total exposure count and (2) compare Scenario B with Scenario C, to determine whether changing vaccination status or mask-wearing is more effective in decreasing exposure count. If mask-wearing largely declines or ceases in the real-world, as seen through the recent U.S. airline policy change (Chokshi, Murphy 2022), the efficacy of the vaccine and/or booster alone must be evaluated.

Scenario C: Increase number of agents wearing a mask. It improves the mask wearing behavior of individuals, by increasing the number of agents wearing a mask, especially surgical and N-95 masks, while keeping the vaccination status the same as in Scenario A. To evaluate the effectiveness of masks in decreasing exposure count, the number of agents wearing a mask, especially a surgical or N-95 mask, was increased. To focus solely on improving masking-behavior and mask type, the vaccination status parameters remained the same as in Scenario A. Table 1 shows the masking parameters for Scenario C, with the percentage of agents assigned to each parameter.

The percentage of agents wearing masks was chosen based on research that was done during the peak of the pandemic in the US according to which 83% of Americans reported wearing a mask to mitigate risk (Hearne, Nino 2021). We adjusted this rate in our model to 90% to account for the increase in booster shots and vaccination from Scenario B. Thus, since we are assuming that everyone is vaccinated in Scenario B, we are assuming that a higher percentage of agents are wearing masks than during the peak of the pandemic.

Scenario D: Decrease the number of agents by 50%. This scenario keeps the same parameters as Scenario A, while decreasing the number of agents by 50%. This serves as a comparison to the measures implemented in Scenario B and Scenario C. Scenario D implements the same parameters as Scenario A, only decreasing the number of agents from 100 to 50. The purpose of decreasing the agents by 50% is to display the effectiveness of booster shots and masks. For example, if decreasing the overall exposure by 50% is obtained by either extensive masking and boosting or decreasing the agents by 50%, then the results may generate societal motivation to mask and get boosted to prevent having to implement lower occupancy restriction policies with social distancing measures. Thus, Scenario D aims to show the relative effectiveness of COVID-19 prevention measures versus decreasing human interaction.

Table 1. Percentage of agents assigned to each parameter for Scenario A, B, C, D

Parameter	Scenario A (100 agents)	Scenario B (100 agents)	Scenario C (100 agents)	Scenario D (50 agents)
Not fully vaccinated	11%	0%	11%	11%
Fully vaccinated without booster shot	62.3%	20%	62.3%	62.3%
Fully vaccinated with booster shot	26.7%	80%	26.7%	26.7%
Not wearing a mask	70%	70%	10%	70%
Wearing a fabric mask	14.5%	14.5%	30%	14.5%
Wearing a surgical mask	14.5%	14.5%	55%	14.%
Wearing an N-95 mask	1%	1%	5%	1%

2.2 Software and Metrics

The four scenarios were modeled in AnyLogic (version 8.7.10) for agent-based simulation. The software utilizes Java, and boolean logic was applied to assign agents to the specified parameters per scenario. The reference path of agents and results from AnyLogic were input into Rhinoceros 3D (version 7).

To evaluate the outputs, we introduce two variables: epidemiological status, which is quantified through infection amount, and exposure count. Each agent has an epidemiological status of either sick or healthy. Healthy means that the agent is not currently sick, but they have a low amount of virus particles from the vaccine, resulting in an initial infection amount of 0.1. If an agent is currently sick, they have an initial infection amount of 0.9. Each scenario randomly assigned 10% of the agents to be sick.

Exposure count is used to evaluate how exposure to COVID-19 increases as the agents interact in each scenario. Each time two agents are within six feet of each other, the exposure count of an individual agent increases based on the parameters in each scenario. For example, if an agent with a booster shot interacts with a sick agent, they receive less exposure than a non-boosted agent that interacts with a sick agent. Table 2 below shows how exposure count is affected by the various parameters. The decrease in exposure count with those vaccinated with a booster shot based on research showing that a person vaccinated with two doses is 80% protected from COVID-19 death, and a booster shot restores an individual to its original immunity (Lippi, Mattiuzzi 2022). The decrease in exposure count for those without a booster is based on data showing that after 25 weeks, vaccine effectiveness against the Omicron variant decreases to less than 20% (Sidik, S. M, 2022). The decrease in exposure count for fabric masks, surgical masks, and N-95 masks models real-world mask efficacy (Gurbaxani, Brian M).

Table 2. How each parameter decreases exposure count for an agent.

Parameter	% decrease in exposure count
Not fully vaccinated	0
Fully vaccinated with no booster	20
Fully vaccinated with booster	80
No mask	0
Fabric mask	33
Surgical mask	56
N-95 mask	96

3 Results

For each scenario, five trials were conducted to account for the randomized agent movement in each scenario. Preliminary data analysis involved averaging the exposure count for each trial, which was calculated as the sum of the exposure count per agent divided by the number of agents. This was again averaged over five trials to obtain an overall average. Further data analysis included calculating the standard deviation of each scenario. Figure 3 is a box plot that displays the mean, standard deviation, and range of each scenario.

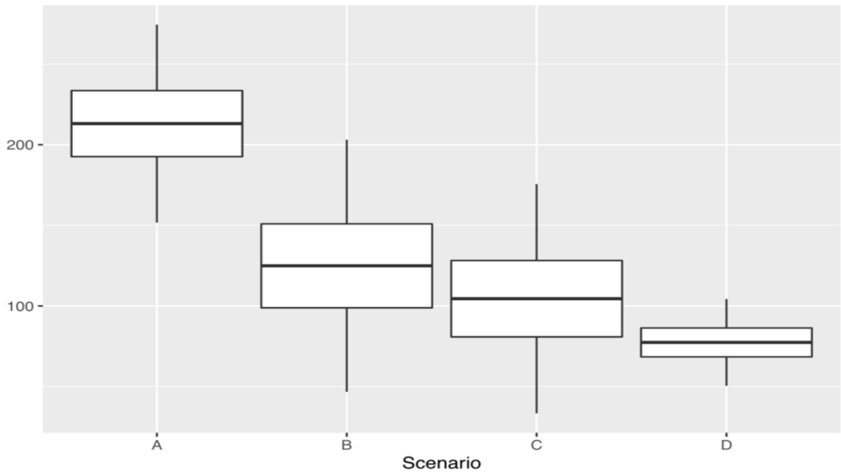

Figure 3. Box plot of exposure output's mean by scenario. Description below.

Scenario A, B, and C all have a population of 100 agents, while scenario D has a population of 50 agents. By using a 95% confidence interval, confidence interval ranges for each scenario are calculated: Scenario A has range [209.0747, 217.0933] for its mean with 20.456 standard deviation; Scenario B has range [119.804, 130.014] with standard deviation 26.044; Scenario C has [99.868, 109.1536] with standard deviation 23.69; Scenario D has [74.912, 79.876] with standard deviation 9.954.

Scenario B had the highest standard deviation, indicating that there is more uncertainty in the data due to outliers. Clearly, the outputs of Scenario D has the least uncertainty as it has the lowest standard deviation. Additionally, relative to Scenario A (control), which had an average overall exposure count of 213, Scenario D decreased the overall exposure count most significantly, by 63.6%. Scenario B decreased the overall exposure count by approximately 41.3%, while Scenario C decreased the overall exposure by approximately 50.9%.

3.1 Results Compared

The most novel aspect of this study was introducing booster variables into an agent-based simulation and studying the efficacy of booster doses in conjunction with mask-wearing behavior. Introducing spatial variables beyond social distancing reveals that schools should consider implementing mask mandates or require booster doses to reduce overall agent exposure count by at least 50%. One limitation of our study is that we are unable to directly compare vaccination and masking. Because of this, we only compare the output of Scenario B, C, and D directly to Scenario A. While Scenario D reduces occupancy by 50% and is the most effective in terms of decreasing overall agent exposure, it would be the least practical solution for schools to implement as it would require every building to either reduce room capacity or be physically modified. Scenario B and C both reduce the agent exposure by similar amounts (around 50%) with Scenario C, increased masking, being the more effective of the two. This shows that increased masking can be just as if not more effective than 80% of the population getting boosted.

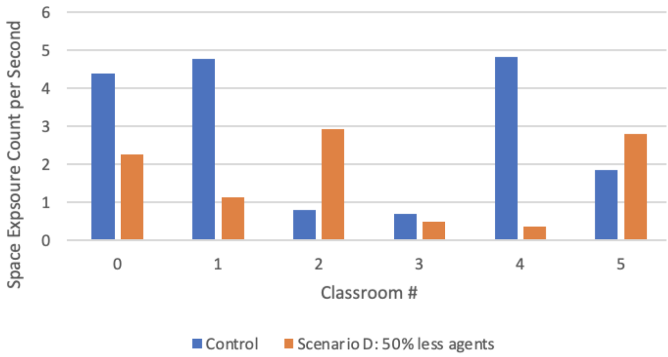

Figure 4. Space Exposure Count per second in each Classroom: Control, Scenario D

Thus, Scenario C, increasing the number of agents wearing a mask to 90% without changing the current March 2022 percent of vaccinated and boosted individuals, shows to be effective, and likely the most practical method to implement in a school environment. Therefore, the policy that would be most beneficial to implement in schools would be to increase masking and require masks with a higher filtration level such as replacing cloth masks and bandanas with surgical masks and N-95 masks.

Further spatial analysis shows that classrooms closer to the entrance result in a larger space exposure count per unit of time, which is measured as the exposure count per second, occurring when agents are less than 6 ft from one another. Room 4 (Figure 2) is of particular interest, as it is the closest room to where agents enter. When the total number of agents decreased by 50%, the exposure count per time decreased by a magnitude of 12 in room 4.

Furthermore, room 0 contained all the agents by the end of the simulation. Agents spent over 8000 seconds in room 0, while only spending an average of 1000 seconds in each classroom. The lower exposure count in room 0 versus room 4 shows that allowing agents to aggregate in a larger space was effective in decreasing the exposure count over time, as room 0 was over three times larger than the classrooms.

4 Discussion

Spatiotemporal modeling continues to be an effective way to model COVID-19 spread through individuals as it allows in-depth analysis of behavioral parameters, such as vaccination, masking, and mRNA booster rates in a controlled, simulated environment. The insights provided through this study furthers current research on the impact of human interactions on COVID-19 spread. The insights from this study will only be effective if schools implement the advised policies; this model emphasizes the fact that COVID-19 spread occurs even in ideal scenarios where every individual is vaccinated, and thus policies to prevent the spread of the disease are still necessary.

In the short-term, future research will involve expanding the current parameters and adding additional variables. For example, the epidemiological status of an individual was simplified down to just two possible cases - sick or healthy - but this could be expanded to include sick individuals who are symptomatic versus asymptomatic, as well as sick individuals who are vaccinated versus unvaccinated. Studying how a vaccinated/boosted COVID-19 carrier spreads the virus would be fascinating, especially as research shows that boosted individuals carry a lower viral load when catching the virus (Lippi, Mattiuzzi 2022).

Additionally, the time since vaccination should be considered, as people who are farther from their initial two-dose sequence are less protected from contracting COVID-19 than people who have been recently vaccinated or boosted. Lastly, partial vaccination (1 dose) was not considered in this model. This should be accounted for in future work, as well as the type of vaccine received, since mRNA vaccines are shown to be more protective than alternative vaccines (Bhandari 2021). Another short-term application is to explore the effectiveness of the new CDC quarantine guidelines, to determine if people are still at high-risk of exposure when interacting with people who have only quarantined for 5-days.

From an architectural perspective, the modification of layouts is another alternative to be explored. Preliminary spatial analysis reveals that classroom 4, the room closest to the entrance, had the largest exposure count over time. The exposure count in classroom 4 decreased by a magnitude of 12 when the number of agents was decreased by 50%. However, as decreasing occupancy rates is likely ineffective as a long-term solution, schools should consider staggering entry time or ensuring there are multiple hallway entry points to decrease exposure count over time.

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