COVID 19: Investigating the impact of lockdown compliance on local case numbers

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Author contributions.

M.M. proposed the research question, developed the study, designed and wrote the algorithm, conducted the simulation, collated and analyzed the results, drafted and edited the article, and created the digital graphics.

Abstract.

The novel coronavirus has posed significant challenges to how countries across the world have managed the safety of their populations. The compliance – or lack thereof – of stay-at-home lockdown measures combined with swelling case numbers pose uncertainty in the effectiveness these measures have in stopping the spread of the virus. A crucial factor in determining a lockdown's effectiveness, therefore, lies within the population's acceptance of such measures.

This study aimed to address this uncertainty by simulating two different lockdown compliance rates and analyzing their effect on the number of cases in a densely populated city. A graph-based approach was used to represent networks of people and a modified version of the Breadth-First Search traversal algorithm was used to model the virus spread. The simulation was conducted $t = 1{,}000$ times, with the simulated sample population set at $n = 10{,}000$, for two compliance rates of $c = 20\%$ and $c = 80\%$.

The results found higher compliance rates were associated with a decrease in cases. In all trials, the number of cases recorded with 80% compliance was significantly lower than 20% compliance ($P < 0.0001$; Wilcoxon test one-tailed). The median decrease in the number of cases was 20% ($1{,}776$ cases), indicating substantial effectiveness.

These findings will form a foundation for future COVID-19 prevention research and provide a basis to evaluate the effectiveness of lockdown measures. It will also enable government bodies to reassure populations to comply with restrictions; thereby increasing public acceptance of lockdowns to stop the spread of the virus.

Keywords.

COVID-19, lockdown compliance, virus graphs, random graphs

Introduction.

The effectiveness of different protection measures to combat the spread of COVID-19 has been a perplexing issue across the world (Cohen 2020, 585; MacIntyre and Wang 2020 1950). Since the World Health Organization (WHO) declared the novel coronavirus (COVID-19) outbreak a global pandemic in early 2020 (Cucinotta and Vanelli 2020, 157), many countries have attempted various approaches to mitigate the pandemic. Among these methods have included stay-at-home lockdowns. While numerous studies have shown that lockdown restrictions have significantly helped to curb COVID-19 case numbers (Guzzetta et al. 2020, 3; The Lancet 2020, 1315; Shen et al. 2020, 504), little research has been made into how compliance impacts the effectiveness of a lockdown.

This article aims to answer the research question, *"How does compliance impact the effectiveness of a stay-at-home lockdown in stopping the spread of COVID-19 in a densely populated city?"*[2]. Two levels of compliance will be simulated, namely 20% and 80% compliance, to determine the correlation between the number of people who stay home and the current number of active cases. While other studies have either simulated the pandemic through a graph-based approach (Bhapkar et al. 2020, 15) or simulated the effects of compliance on case numbers (Blakely et al. 2020, 350), few studies have considered a graph-based approach in *relation* to simulating the effectiveness of compliance.

Countries such as the United States, the United Kingdom, and Australia, which have implemented various lockdown measures, have had limited success in maintaining ongoing public compliance (BBC News 2021, par. 5; Maqbool 2020, par. 1; McMillan and Fowler 2021, par. 1). The ramifications of defiance in prevention measures have been severe – there has been an exponential spread of the virus and to date, there have been 169 million cases and 3.5 million COVID-19 related deaths worldwide (World Health Organization 2021, par. 1). However, while other countries, such as Australia, have shown a successful drop in cases through lockdown measures (Saul et al. 2020, 494), criticism and disproval in the public of such measures have been exhibited (Wahlquist 2020, par. 1; Young 2021, par. 8).

Therefore, if it is known through realistic simulation that higher compliance results in fewer cases, the general population may be more likely to obey stay-at-home orders. In turn, a higher compliance rate would result in fewer cases, fewer deaths, and less strain on front-line health care workers (Turner 2020, par. 10).

The remaining sections of this paper will explain and justify the method used in the simulation, present and detail the findings of the simulation, and discuss the significance of the results in greater detail.

Method.

Introduction to the approach.

While there are numerous methods that simulate the spread of a virus, such as agent-based models (Blakely et al. 2020, 350) and decision tree models (Marin-Gomez et al. 2021, 1), a natural way to consider the spread of a virus is through a graph-based approach. The graph theory approach to modeling the COVID-19 pandemic is an effective way of measuring

[2]The original research question was *"How does compliance impact the effectiveness of a stay-at-home lockdown in stopping the spread of COVID-19?"*

the spread of the virus and how best it can be contained as it can model individual people (vertices), who they know (edges), and how the virus spreads (by traversing a connected graph) (Bhapkar et al. 2020, 15).

Algorithm and implementation.
Alg. 1 details the algorithm used in the simulation. The simulation was written in version 17 of the Java SE Platform language using a modified version of the Breadth-First Search (BFS) algorithm for traversing a graph data structure, explained in Fig. 1 to the right. The BFS algorithm is an appropriate traversal algorithm as it considers all neighbors of a vertex at the present depth before traversing down a particular neighbor – analogous to how a single person can infect multiple others at once (Khan 2020, par. 3). This algorithm will produce 1,000 pairs of tuples, (x, y), where x is the number of people infected given 20% of the population obeyed stay-at-home orders and y is the respective number for 80%. Each tuple considers the same adjacency matrix configuration to ensure consistency in testing. Population density was simulated through the inclusion of many edges.

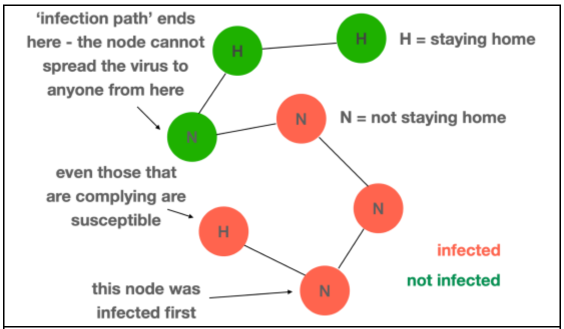

Fig. 1 A sample graph illustration. The algorithm modification ensures that neighbors of 'non-infected' vertices are not added to the list of 'to-visit' vertices. This choice ensures those who have not been exposed to the virus cannot be infected nor infect others.

- Set the population size $n = 10{,}000$ and the compliance rates $c = 0.2, 0.8$.
- For $c = 0.2, 0.8$, repeat the following $t = 1{,}000$ times
  - Create a random collection of n people objects – each person either obeys the lockdown or does not
    - cn people will obey lockdown orders
    - $(1 - c)n$ people will not obey lockdown orders
  - Create a random, dense $n * n$ adjacency matrix, $P_{ij} = \begin{Bmatrix} 1\ if\ i\ knows\ j \\ 0\ if\ i\ does\ not\ know\ j \end{Bmatrix}$
    - This will represent a neighborhood – some vertices will be connected while others will not be
    - The same random matrix will be used in both c values for consistency
  - Infect one random person who is not staying home
  - Starting at this person, go through the matrix and look at all the person's neighbors
    - If the person is staying home, they have an $x = 0.166 + rand(0,1)$ probability of being infected
    - If the person is not home, they have an $y = 0.678 + rand(0,1)$ probability of being infected
  - Keep track of people objects who are infected
    - A person who is infected can continue to infect others (keep looking at neighbors)
    - A person who is not infected cannot infect other people (path ends)

Alg. 1 The algorithm used in the simulation. Note that the lockdown/simulation will last an indefinite period – it will cease when there are no new cases.

Justification of the parameters used.
The parameters used in the simulation were based on previous related simulations. The number of times the simulation was conducted $(t = 1{,}000)$ was replicated from a previous agent-based model by Blakely et al. (2020, 350). The probabilities ($x = 0.166$ and $y = 0.678$), representing the probability of being infected given a person is staying home and the probability of being infected given a person is not staying home, were taken from "Household Transmission of SARS-CoV-2" (Madewell et al. 2020, 1) and "Assessing the Likelihood of Contracting COVID-19 Disease Based on a Predictive Tree Model: A Retrospective Cohort Study" (Marin-Gomez et al. 2021, 5), respectively. A random offset of increase was added to each probability to simulate how each person will have slight variations in becoming infected.

Results.
The results of the simulation indicate that in all 1,000 trials of the simulation, a decrease in the number of cases was exhibited by the population that had an 80% compliance rate (x) when compared to the 20% compliance (y) rate population. Fig. 2 and Fig. 3 on the next page highlight these differences. A one-tailed Wilcoxon matched-pairs signed-rank test was performed on the data using GraphPad Prism version 9.1.1 for macOS with $\alpha = 0.05$. The test found a significant difference between the two medians $(P < 0.0001)$ with significantly effective pairing between the two data sets $(P < 0.0001)$. The median of the differences was equal to the mean of the differences, at 1,776 cases and the 95% confidence interval of this difference was from 1,773 to 1,780 cases. Tab. 1 below summarizes the analysis conducted.

Trials	*Population size*	*Minimum*	*25% Percentile*	*Median*	*75% Percentile*
1,000	10,000	1,623	1,744	1,776	1,805
Maximum	*Mean*	*Std. Deviation*	*Std. Error of Mean*	*Lower 95% CI*	*Upper 95% CI*
1,934	1,776	47.05	1.488	1,773	1,779

Tab. 1 Table of descriptive statistics for the dataset of *Difference in number of cases*. Notice that the range of the CI is quite tight, and that the standard deviation is quite low, indicating a large clustering of case differences around the mean.

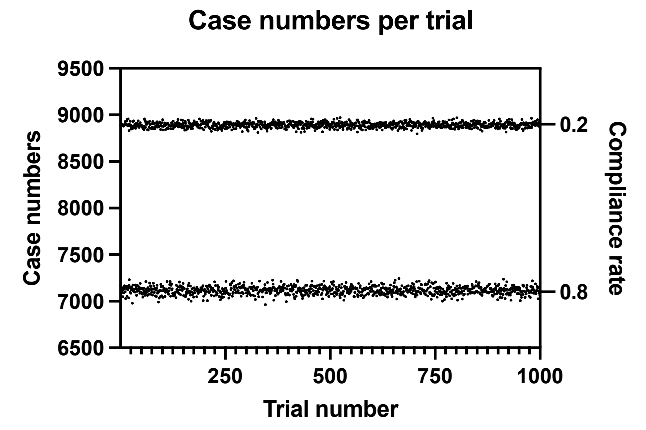

Fig 2. This graph shows the results of each individual trial. It is visible that the trials with a 20% compliance rate had significantly higher case numbers compared to the 80% compliance rate.

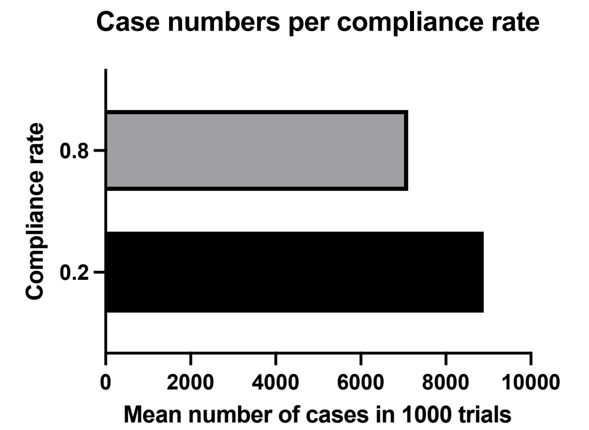

Fig 3. This graph shows the mean results of all trials. It is shown that the mean number of cases recorded in trials with 20% compliance was higher compared to 80% compliance.

Discussion.

Significance of the results.

The findings of the simulation indicate that greater compliance impacts the effectiveness of a stay-at-home lockdown in stopping the spread of COVID-19 in a densely populated area, mainly by reducing the overall number of recorded cases. The one-tailed Wilcoxon matched-pairs signed-rank test gave a highly statistically significant result ($P < 0.0001$), meaning that there is an extremely low probability that the observed difference could have occurred by randomness. The null hypothesis $H_0 \coloneqq \tilde{x} = \tilde{y}$ was rejected and the alternate hypothesis $H_1 \coloneqq \tilde{x} < \tilde{y}$ was thus accepted with high certainty.

Considering that in each trial, each person was given a random increase in contracting COVID-19 (on top of their initial, set probability), it is significant that despite this random factor, all trials of higher compliance had considerably fewer case numbers than their lower compliance counterpart. The minimum and the maximum difference in case number reductions, 1,623 and 1,934, respectively, were also quite close together. This small difference in the range of differences indicates stability in case number reductions. It can therefore be said that greater lockdown compliance can reliably and consistently reduce case numbers irrespective of slight variations in individual contraction probabilities.

Fig 2. shows that the density of case numbers centered around the median in the 20% compliance rate tests was slightly greater than that of those of the 80% compliance rate tests. This indicates that there were slightly more fluctuations in the number of cases recorded for the higher compliance trials than the lower compliance trials. Individual contraction probabilities may have played a greater role in affecting case numbers for those staying home when compared to those who were not, as those staying home were given an initial lower case of contracting the virus.

These findings are consistent with other studies which have examined the relationship between lockdowns and case numbers. Studies such as *"The Probability of the 6-Week Lockdown in Victoria (Commencing 9 July 2020) Achieving Elimination of Community Transmission of SARS-CoV-2"* (Blakely et al. 2020, 350) and *"Impact of Victoria's Stage 3 Lockdown on COVID-19 Case Numbers"* (Saul et al. 2020, 494) found that Victoria's lockdown procedures were effective in reducing COVID-19 case numbers. Considering both these studies, together with the findings stated above, it can be said that higher compliance in obeying lockdown measures correlates to fewer cases.

Limitations and future work.

The simulation had several limitations that might need exploring in future studies. The nature of the algorithm used to create the adjacency matrix being $O(population^2)$ time and space complexity in all cases meant that sample sizes larger than $n = 10{,}000$ could not be considered due to insufficient memory heap space. Future studies could implement a more efficient algorithm so that a larger sample size could be considered. Furthermore, it is also important to note that the simulation did not consider the effectiveness of other – potentially more effective – measures of preventing the spread of COVID-19. Practices such as mask wearing and social distancing were not considered, nor were the effectiveness of these measures evaluated against lockdown compliance. Further studies could be conducted to determine the most effective approach to prevent the spread of the coronavirus in models which consider these other preventative measures.

Conclusion.

In conclusion, the focus of this research paper has been on addressing the research question, *"How does compliance impact the effectiveness of a stay-at-home lockdown in stopping the spread of COVID-19 in a densely populated city?"* through the use of computer simulation. The findings of the study are all consistent with the view that greater compliance drastically reduces the number of cases recorded – irrespective of slight individual probabilistic differences. These results will have significant benefits both in the research world by providing a framework for future COVID-19 prevention research, as well as benefits in the real world by aiding the planning, management, and execution of lockdowns across the world.

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