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Factors affecting COVID-19 pandemic

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FACTORS AFFECTING COVID-19 PANDEMIC

by

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PUBLICATION THESIS OPTION

This thesis consists of the following two articles, which are formatted in the style used by the Missouri University of Science and Technology:

Paper I, Effects of Information and Communication Technologies and Healthcare Expenditures on COVID-19 Pandemic, can be found on pages 3–23. The paper is intended for submission to a conference and/or journal.

Paper II, Effects of GDP and Population Density on COVID-19 Pandemic, can be found on pages 24-36. The paper is intended for submission to a conference and/or journal.

ABSTRACT

COVID-19 has affected our daily lives in many aspects, such as work, healthcare, education, business, and social. With the quick spread of this new coronavirus, many countries quickly fell into a pandemic control and management mode. It has been more than one year since the discovery of COVID-19, but until now, COVID-19 is still affecting our lives and our daily operations. The research consists of two papers focusing on different factors affecting the COVID-19 pandemic. The first paper studies the effect of ICT and healthcare expenditures on the COVID-19 management and control. The second paper focuses on the impact of GDP and population density on COVID-19. The two research papers provide a glimpse of different factors impacting the spread and control of COVID-19.

ACKNOWLEDGMENTS

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1. INTRODUCTION

A novel coronavirus, which is named COVID-19, was first identified in China. This new coronavirus can be transmitted by close contact with an infected person, making it very easy to spread. As a newly discovered coronavirus, there are no vaccines available at first. According to the Centers for Disease Control and Prevention (CDC), the incubation period for COVID-19 can be up to 14 days and the symptoms vary. COVID-19 soon become a global pandemic after it was first discovered. With the outbreak of COVID-19 pandemic, people's daily lives have been affected to varying degrees. For example, many people must work from home; students need to take online classes, restaurants are closed and provide takeout services, etc. There is no doubt that COVID-19 has a significant impact on the global economy and daily routines. As of March 2021, residents of more than 200 countries have been infected with this new coronavirus and there are more than 130 million infected cases in total.

Controlling the outbreak of COVID-19 effectively and quickly has become a huge challenge for the whole world. Among these more than 200 countries, some of them have low economic levels and poor medical conditions and may not be able to control the spread of COVID-19. Also, not everyone has the correct knowledge and understanding of COVID-19. Due to different cultures, people hold different attitudes toward COVID-19. Because of different backgrounds and circumstances, some countries choose to achieve herd immunity in the early stages without implementing lockdowns, and some people were not supportive of wearing masks (many still do). In contrast, some countries implemented tough lockdown policies to control the spread of COVID-19.

In this information age, many technology applications can help to control the spread of COVID-19. One such technology is tracing apps. Information and communications technology (ICT) play an essential role in this situation. GDP has an impact on ICT. Social distancing is an important technique to control the spread of COVID-19. Population density directly impacts the implementation of social distancing. In this research, we study whether GDP and population density have impacts on the spread of COVID-19.

PAPER

I. EFFECTS OF INFORMATION AND COMMUNICATION TECHNOLOGIES AND HEALTHCARE EXPENDITURES ON COVID-19 PANDEMIC

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ABSTRACT

A new coronavirus, COVID-19, was discovered in Wuhan, China, in December 2019. This new coronavirus spreads like wildfire and becomes a global pandemic. As of April 2021, more than 130 million people are infected, and more than 2.8 million dead. The pandemic has disrupted our lives and world economies. Different countries have responded to the pandemic in different ways with varying results. While various policies can lead to different results, many factors can affect the spread and severity of the COVID-19 pandemic. This research investigates the effects of Information and Communication Technologies (ICT) and healthcare expenditures on the COVID-19 pandemic.

1. INTRODUCTION

For many, the world as they once knew it came to an abrupt end in 2020. The COVID-19 pandemic spread rapidly throughout the world, and measures such as quarantine, shelter in place, and social distancing were introduced to control the infection and death rates. A new normal is with us! Not only has the pandemic caused health issues and death, but it has also disrupted businesses and economies. The pandemic needs to be quickly brought under control.

With the outbreak of COVID-19, different countries have adopted different lockdown policies. The overall trend is for students to learn remotely and people to work from home (Zou, Zhao, and Siau, 2020). Although online/distance education and telecommuting are not new, the pandemic has undoubtedly caused a major change in education and people's daily work routines. Technology is the core of this transformation. Advancement in technology-facilitated remote communication helps people to perform remote work and study, which facilitates the implementation of social distancing and enables non-face-to-face communication.

In this paper, we study the effects of Information and Communication Technologies (ICT) and healthcare expenditures on the COVID-19 pandemic.

2. LITERATURE REVIEW

2.1. INFORMATION AND COMMUNICATION TECHNOLOGIES

Information and communication technologies (ICT) have expanded to encompass nearly every industry globally, from finance and banking to universities and nonprofit organizations. The health care system, which is composed of hospitals, individual physician practices, specialty practices, as well as managed care providers, pharmaceutical companies, and insurance companies, is no exception (Siau, 2003). ICT is currently widely applied to the health care industry. Advanced ICT such as mobile technologies, which are new in healthcare informatics (Siau and Shen, 2006), are also widely used in contact tracing in managing and controlling the spread of COVID-19. Those countries that have a more advanced ICT will be able to capitalize on its ICT strengths to administer contact tracing and pandemic management. ICT can also help with increasing medical knowledge in many aspects. For example, we can take online courses to gain the skill sets that we need, and we can increase general knowledge from others' experiences by searching on the Internet. To protect ourselves from infection, we can learn directly from the World Health Organization (WHO) and the Centers for Disease Control and Prevention (CDC).

In the information age, ICT becomes a vital means of interaction. In COVID-19 pandemic control, one crucial thing is information exchange. Better ICT means that people have access to more information. Advanced ICT enables us to receive the latest news from computers and phones as well as from websites such as Facebook and Twitter.

However, the wealth of information on the web can be contradictory and may confuse individuals about the validity of the information and how to stay safe.

In COVID-19 pandemic control, tracing apps are developed by different countries to manage the spread of COVID-19. Some advanced tracing apps also enable citizens to know how many confirmed cases are around them and where those confirmed people have been to so that they can avoid going to those areas. Thus, ICT can play an essential role in pandemic control.

2.2. HEALTHCARE EXPENDITURES

Healthcare expenditures include expenditures related to all health goods and services. A country's healthcare expenditures as a percentage of GDP reflects the percentage of the government spending on health. Higher healthcare expenditures mean the government is committed to building a more comprehensive medical system. Those countries with higher healthcare expenditures have the financial abilities to support advanced healthcare systems, resources to develop vaccines, and means to support workers and families during the quarantines. Therefore, healthcare expenditures are positively associated with death cases (Khan, Awan, Islam, and Muurlink, 2020).

Further, healthcare expenditures as a percentage of GDP can reflect the importance a country attaches to the medical system, which will also affect the COVID-19 policies to a certain extent. Higher healthcare expenditures enable a country to be more prepared to handle a pandemic and allow the country to commit more resources to combat the pandemic.

3. THEORETICAL FOUNDATIONS AND HYPOTHESES

3.1. GROWTH THEORY

Growth theory explains factors that could affect economic growth and economic development. Adam Smith and many economists have contributed to developing and refining this theory. The Endogenous Growth Theory was proposed by economists such as Romer. P and Lucas. R. It emphasizes the internal forces of knowledge, human capital, and research and development as the main factors that could affect economic growth. In the new growth theory, innovation and technology become influential on economic growth. Economic growth can promote the development of ICT and enhance healthcare expenditures.

3.2. HUMAN CAPITAL THEORY

Human capital theory suggests that individuals and society derive economic benefits from investments in people (Sweetland, 1996). Unlike physical capital, human capital is intangible and comes in the form of public health, education, and training. The theory argues that for economic growth, the role of human capital is more significant than that of physical capital. The human capital theory emphasizes the importance of education, knowledge, health, and fertility in economic growth. Human capital is important in pandemic management and control as well as the development and use of ICT.

Based on the above theoretical foundations, the following hypotheses are proposed:

H1: Countries with higher ICT development levels can better control the COVID-19 pandemic

H1a: Countries with higher ICT development levels have a lower number of cases per million

H1b: Countries with higher ICT development levels have a lower number of total deaths per million

H1c: Countries with higher ICT development levels have a lower death rate

H2: Countries with higher healthcare expenditures (as a percentage of GDP) can better control COVID-19 pandemic.

H2a: Countries with higher healthcare expenditures (as a percentage of GDP) have a lower number of cases per million

H2b: Countries with higher healthcare expenditures (as a percentage of GDP) have a lower number of total deaths per million

H2c: Countries with higher healthcare expenditures (as a percentage of GDP) have a lower death rate

The hypotheses are empirically tested using secondary data on COVID-19 cases, ICT levels, and healthcare expenditures.

4. RESEARCH PROCEDURE AND RESULTS

4.1. DATA COLLECTION

The data used in this study is secondary data obtained from several sources. The ICT data is from the International Telecommunication Union (ITU). Data on healthcare expenditures are obtained from the world bank. COVID-19 data is from Our World in Data. Because the data are from different sources, we only used the countries that were covered in all the sources. After removing outliers, we have more than 160 countries in total as our data points.

4.2. MEASUREMENT

The data we used in this study includes the ICT index, healthcare expenditures, and data related to COVID-19 by countries.

For Information and Communications Technology (ICT), we used the ICT Development Index (IDI) as the indicator for measuring ICT. The range of IDI is from 0.96 to 8.98. The dataset we used is from IDI 2017, which is the latest data set. We divided the countries into two levels based on the IDI median.

The healthcare expenditures dataset we used is also from 2017, which is the latest data set. Healthcare expenditures (percentage of GDP) are from 1.18 to 12.35 after removing outliers that are three standard deviations from the mean. We divided the countries into two groups based on the healthcare expenditure median.

According to the ICT level and healthcare expenditures level, we divided our dataset into four groups: high ICT level with high healthcare expenditures, high ICT level with low healthcare expenditures, low ICT level with high healthcare expenditures, and low ICT level with low healthcare expenditures. Group information can be found in Appendix A.

For COVID-19 data, we focus on the total cases per million, total deaths per million, and the death rates. Total cases and total deaths per million are calculated by dividing the total cases or deaths in a country by the country's population (in millions). This is calculated on the 15th of each month from January 2020 to March 2021. The death rate is total deaths divided by total cases. There are 164 countries from January 2020 to December 2020, and 167 countries from January 2021 to March 2021. Three more countries have the COVID-19 data in 2021.

4.3. RESEARCH RESULTS AND DISCUSSIONS

The purpose of this research is to study there whether there is any relationship between ICT, healthcare expenditures, and control of COVID-19. We first ran the Manova test for each month from April 2020 to March 2021 because we have three dependent variables. If the interaction effect for a month is significant, we ran separate Anova tests to determine whether a dependent variable has a significant interaction effect. After that, we ran the posthoc Tukey test to check the differences between each pair of the four groups. If the Monova test for a particular month shows that the interaction effect is insignificant, we ran the Tukey test to check the main effects. Because very few countries have a significant number of infected people from January to March of 2020, we omitted the Manova tests from January to March 2020.

From the Manova test results, we found that the p-values of the interaction effects between ICT and healthcare expenditures are less than 0.1 for April 2020 and September 2020. For May 2020 to August 2020 and December 2020 to March 2021, the interaction effects are significant at the 0.05 level. These mean the interaction effects between ICT development and healthcare expenditures on COVID-19 are significant ($p<0.05$ or $p<0.1$) during these months. The interaction effects were not significant for October 2020 and November 2020 ($p>0.10$). The main effects of both ICT development and healthcare expenditures on COVID-19 are significant for October 2020 and November 2020 ($p<0.05$). The results of the Manova tests can be found in Appendix B.

Tukey test results in Appendix B for October 2020 and November 2020 depict the differences between each ICT level and healthcare expenditures level. For total cases per million and total deaths per million, the differences are significant for both October and November ($p<0.05$). For the death rate, the differences between ICT groups are not significant for both October and November ($p>0.10$), and the differences between healthcare expenditures are significant in October ($p<0.05$) and November ($p<0.10$).

Figure 1 shows the interaction effects between IDI and healthcare expenditures on total cases per million from April 2020 to March 2021.

There are a few interesting and surprising observations from Figure 1.

(i) From the Anova tests, the interaction effects are not significant from April 2020 to June 2020 and September 2020. In April, countries with high ICT and high healthcare expenditures have, on average, the most number of total cases per million -- almost twice as many infected cases per million when compared to countries with high ICT and low healthcare expenditures.

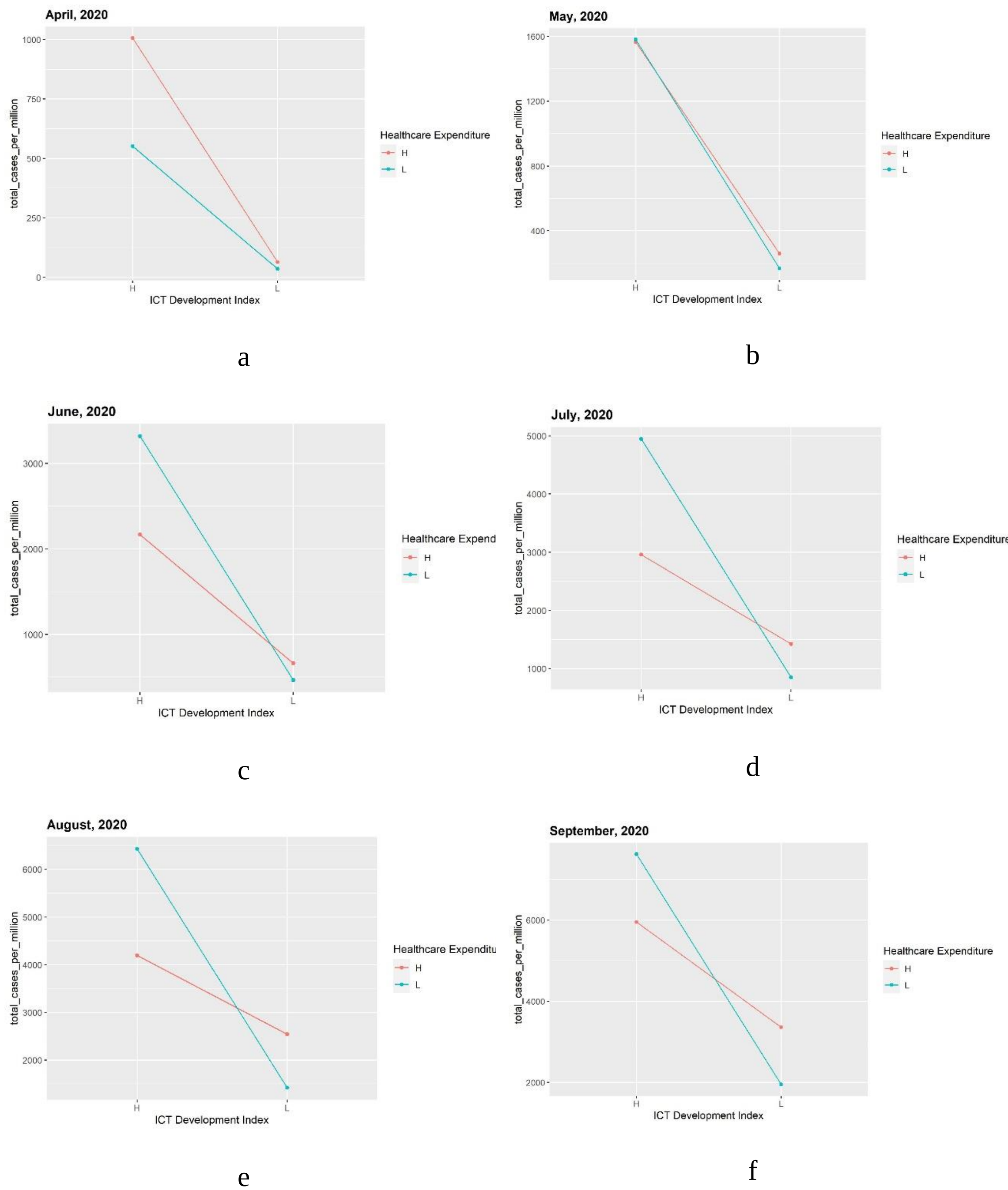
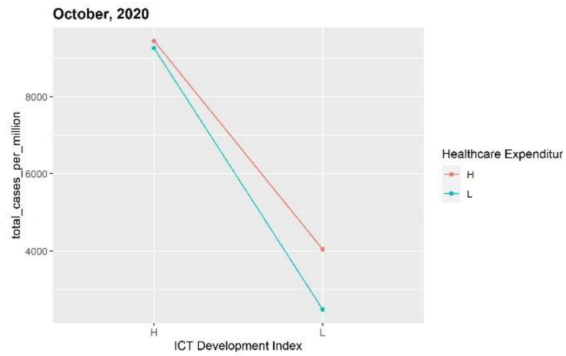
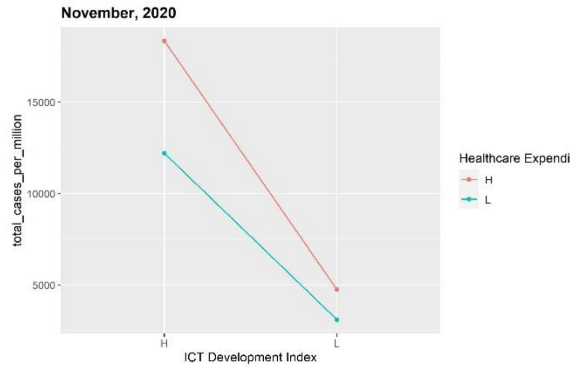


Figure 1. Interaction plots for total cases per million from April 2020 to March 2021. a) interaction plot for April. b) interaction plot for May. c) interaction plot for June. d) interaction plot for July. e) interaction plot for August. f) interaction plot for September. g) interaction plot for October. h) interaction plot for November. i) interaction plot for December. j) interaction plot for January 2021. k) interaction plot for February 2021. l) interaction plot for March 2021.





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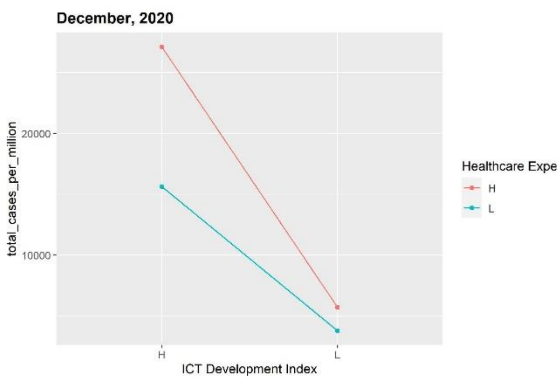

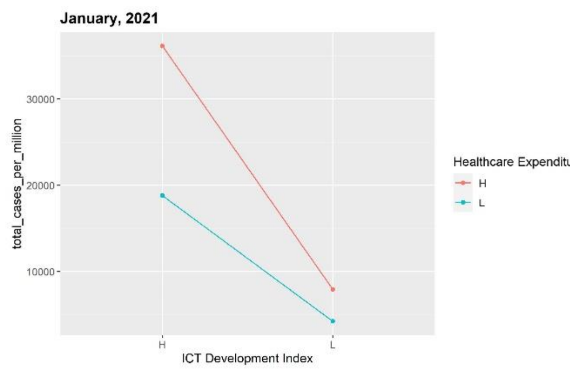

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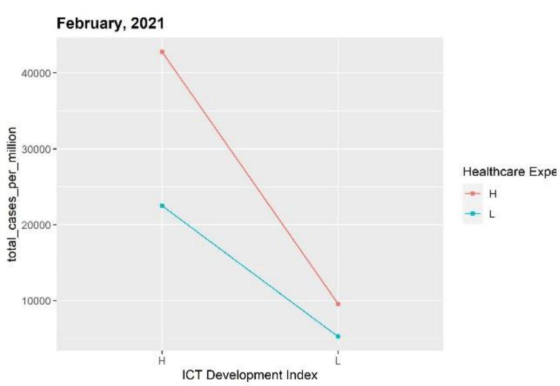

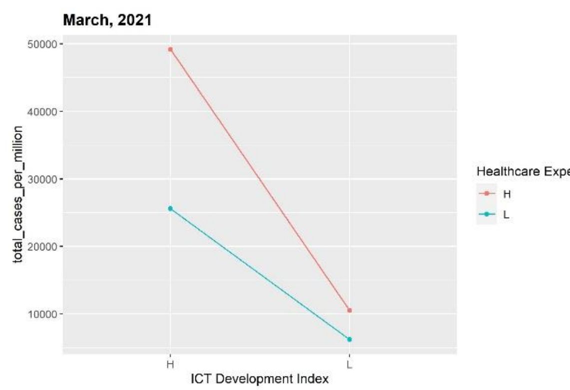

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Figure 1. Interaction plots for total cases per million from April 2020 to March 2021. a) interaction plot for April. b) interaction plot for May. c) interaction plot for June. d) interaction plot for July. e) interaction plot for August. f) interaction plot for September. g) interaction plot for October. h) interaction plot for November. i) interaction plot for December. j) interaction plot for January 2021. k) interaction plot for February 2021. l) interaction plot for March 2021. (con't.)

(ii) Figure 1 shows that countries with lower ICT have lower total cases per million. This is true irrespective of the healthcare expenditures.

(iii) For high ICT level,

a. Countries with high healthcare expenditures have the most number of infected cases in April 2020.
b. Countries with high healthcare expenditures and low healthcare expenditures have roughly the same number of infected cases in May 2020.
c. From June 2020 to September 2020, countries with low healthcare expenditures have the most number of infected cases.
d. Countries with high healthcare expenditures and low healthcare expenditures have roughly the same number of infected cases again in October 2020.
e. From November 2020 to March 2020, countries with high healthcare expenditures again have the most number of infected cases (like in April 2020).

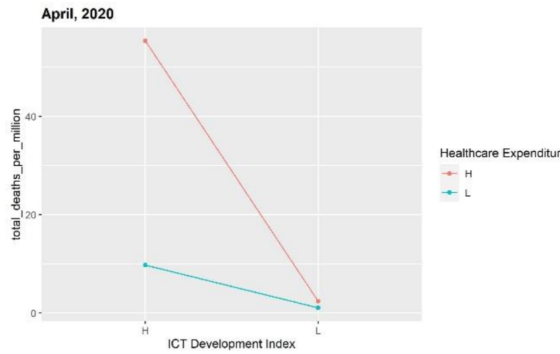
(iv) For low ICT level, in general, the differences between high and low healthcare expenditures are smaller when compared to high ICT level.

Some of these results are counter-intuitive. For example, we would expect countries with high healthcare expenditures to have lower infected cases because they have more healthcare resources. Also, we would expect countries with high ICT to have lower infected cases because of their enhanced abilities to provide information and facilitate communication. The results, thus, came as a surprise!

One possible reason is that people in countries with higher healthcare expenditures are able to be tested for COVID-19. Thus, more cases are detected. Also, residents in countries with higher ICT have more information about this new coronavirus, which will encourage more people to be tested for COVID-19. From December 2020 to March 2021, the pattern is almost the same -- for high ICT, high healthcare expenditures have more cases than low healthcare expenditures; similarly, for low ICT, high healthcare expenditures have more cases. In other words, countries with higher healthcare expenditures might likely have conducted more tests, which leads to more confirmed infected cases.

Figure 2 shows the interaction effects between IDI and healthcare expenditures on total deaths per million from April 2020 to March 2021. The Anova results show that the interaction effects are not significant for August 2020 and September 2020. The diagrams in Figure 2 look somewhat similar. Countries with high ICT and high healthcare expenditures have the most deaths per million whilst countries with low ICT and low healthcare expenditures have the least deaths per million. The number of total deaths per million is based on the number of infected cases.

The results are again unexpected. One would expect countries with high healthcare expenditures to have lower total deaths per million compared to countries with low healthcare expenditures. Similarly, the results may be due to the testing in countries with high healthcare expenditures. A death may not be counted as related to COVID-19 if the person was not tested for COVID-19. More tests will result in more positive cases and more positive cases will lead to more deaths related to COVID-19.



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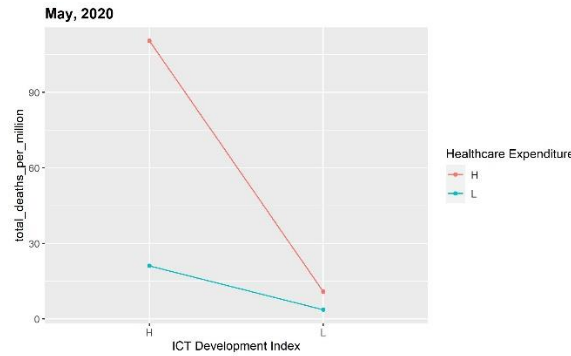

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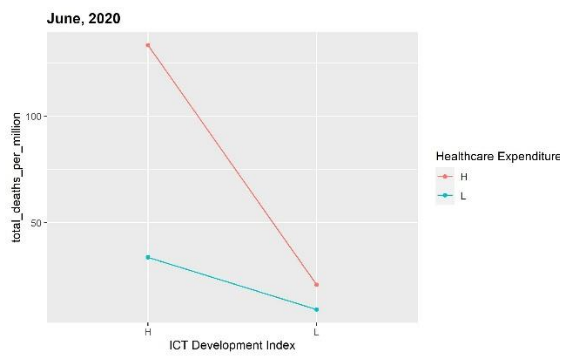

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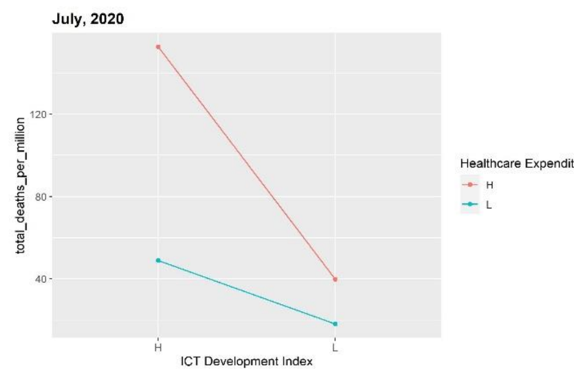

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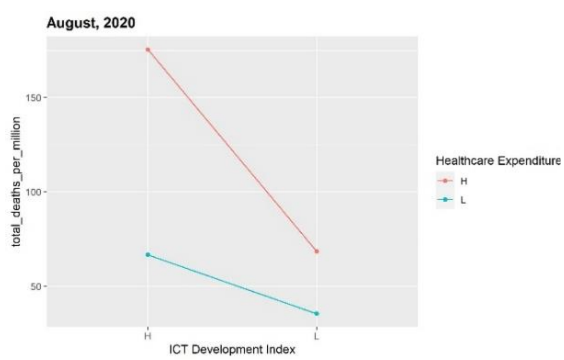

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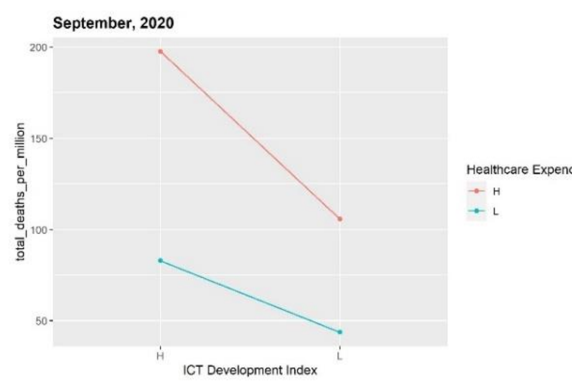

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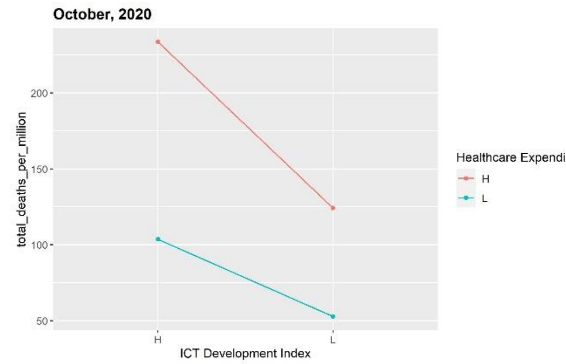
Figure 2. Interaction plots for total deaths per million from April 2020 to March 2021. a) interaction plot for April. b) interaction plot for May. c) interaction plot for June. d) interaction plot for July. e) interaction plot for August. f) interaction plot for September. g) interaction plot for October. h) interaction plot for November. i) interaction plot for December. j) interaction plot for January 2021. k) interaction plot for February 2021. l) interaction plot for March 2021.



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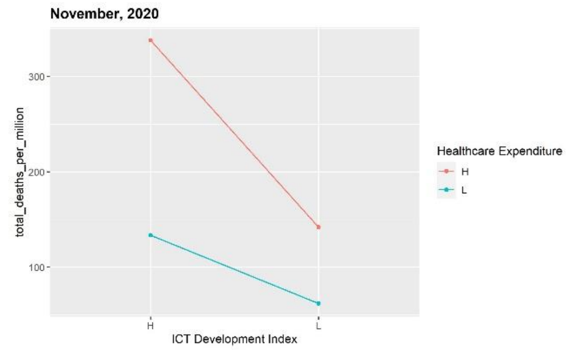

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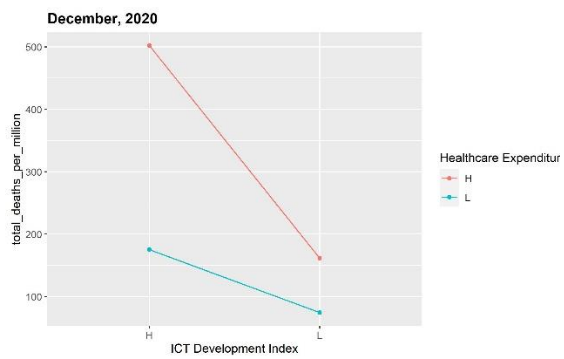

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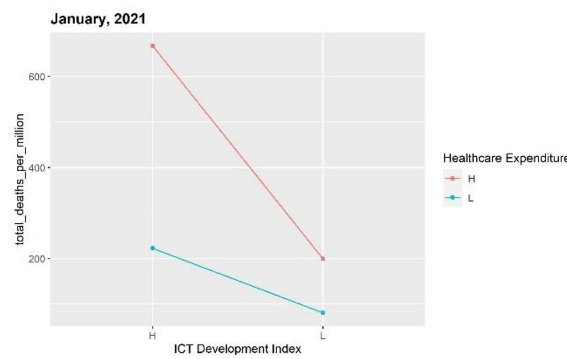

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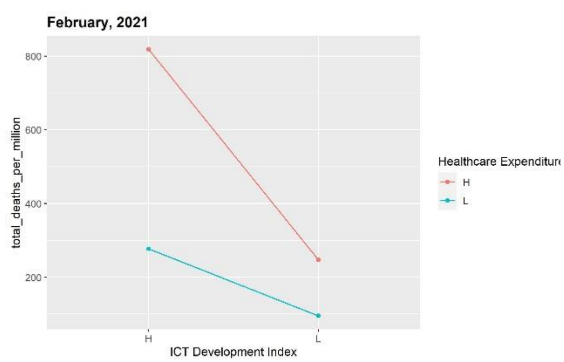

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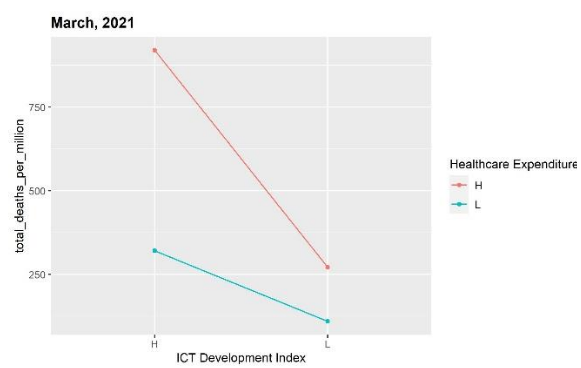

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Figure 2. Interaction plots for total deaths per million from April 2020 to March 2021. a) interaction plot for April. b) interaction plot for May. c) interaction plot for June. d) interaction plot for July. e) interaction plot for August. f) interaction plot for September. g) interaction plot for October. h) interaction plot for November. i) interaction plot for December. j) interaction plot for January 2021. k) interaction plot for February 2021. l) interaction plot for March 2021. (con't.)

Figure 3 shows the interaction effects between ICT and healthcare expenditures on the death rates from April 2020 to March 2021. The death rate is the total number of deaths divided by the total number of infected cases. The death rate can reflect the treatment side of COVID-19 pandemic control. The Anova results show that the interaction effects between ICT and healthcare expenditures are significant for June 2020, July 2020 and August 2020.

From the bar charts shown in Figure 4, we can see that high ICT is associated with high total cases per million for October 2020 and November 2020. Similarly, high healthcare expenditures are also associated with high total cases per million for October 2020 and November 2020.

As a whole, the results are contradictory to common sense and some of the results are not easy to explain. We believe there are several reasons for these interesting and surprising results.

(i) The data collection processes in different countries are different. Some countries are more diligent in collecting and reporting data. Some countries may be more haphazard.

(ii) Countries that provide more testing would have more positive cases whereas countries with smaller healthcare budgets would limit testing.

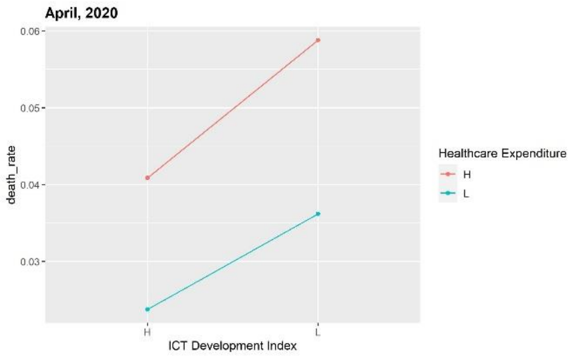
(iii) COVID-19 is a new virus and there is no proven medication for those infected. Most of the time, the patients are expected to recover on their own with their immune systems. Thus, healthcare expenditures may play a less role in treating the sicks.

(iv) One factor that may provide some explanations is the national culture. The behavior of the people may affect the transmission and infection rates of COVID-19. For example, citizens in some nations may obediently comply with the mask and social distance mandates whereas citizens in some countries may not.

Another factor is the transportation system. More developed countries should have better-developed transportation systems. A country that is well-connected to the rest of the world (e.g., an air or sea hub) will be easily exposed to the new virus. Higher population mobility within a country (e.g., rail and land transportation systems) will increase the transmission and infection rates.

5. CONCLUSIONS AND FUTURE RESEARCH

This research studies the effects of ICT and healthcare expenditures on COVID-19 pandemic management and control. Our results show that from April 2020 to September 2020 and from December 2020 to March 2021, ICT and healthcare expenditures have an interaction effect on COVID-19 pandemic control. For October 2020 and November 2020, both high ICT and high healthcare expenditures are associated with a higher total number of cases and total deaths. Several possible explanations were provided to understand the results.



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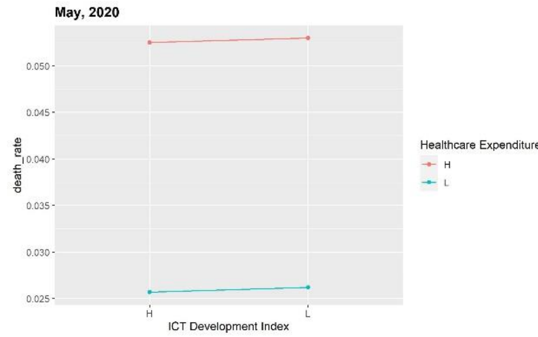

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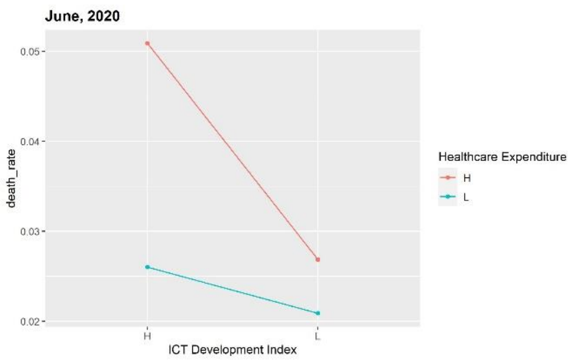

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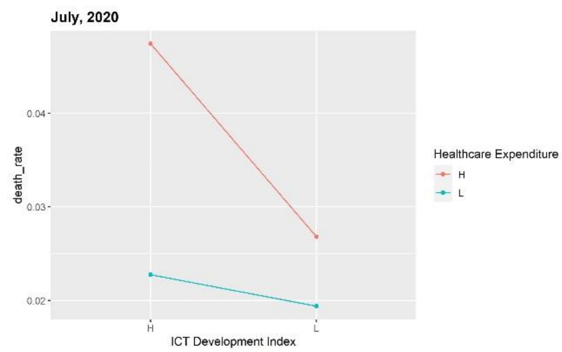

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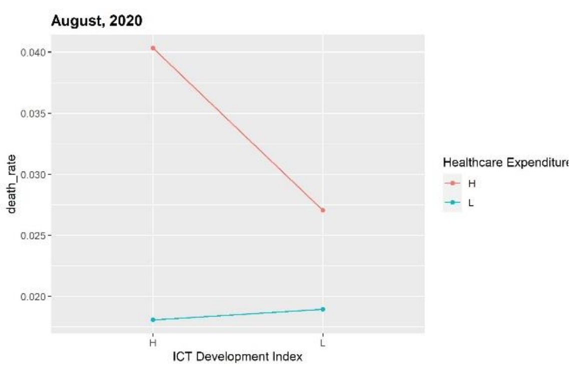

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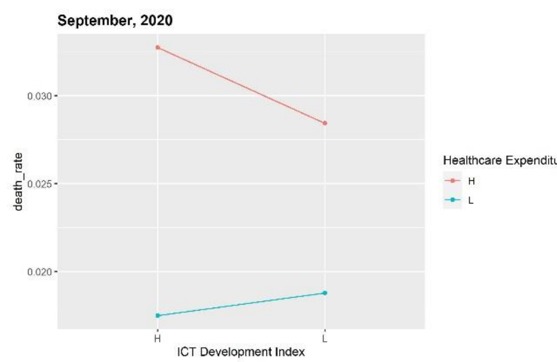

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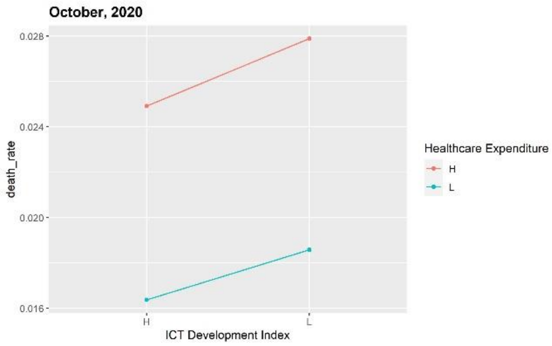
Figure 3. Interaction plots for death rate from April 2020 to March 2021. a) interaction plot for April. b) interaction plot for May. c) interaction plot for June. d) interaction plot for July. e) interaction plot for August. f) interaction plot for September. g) interaction plot for October. h) interaction plot for November. i) interaction plot for December. j) interaction plot for January 2021. k) interaction plot for February 2021. l) interaction plot for March 2021



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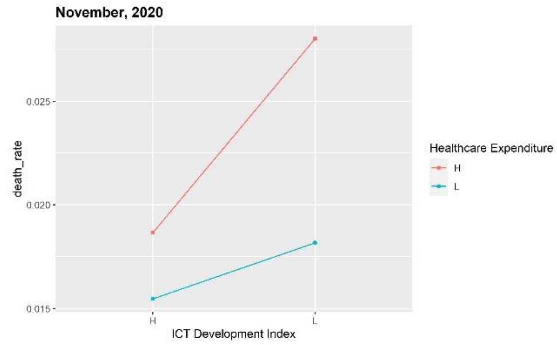

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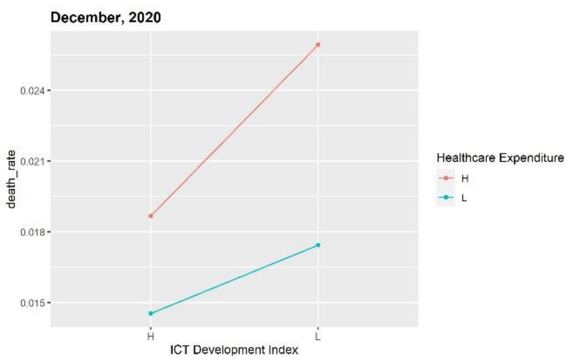

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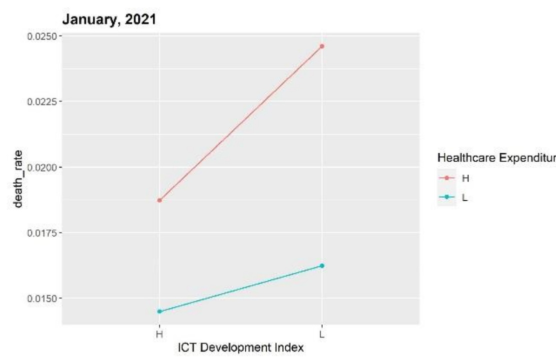

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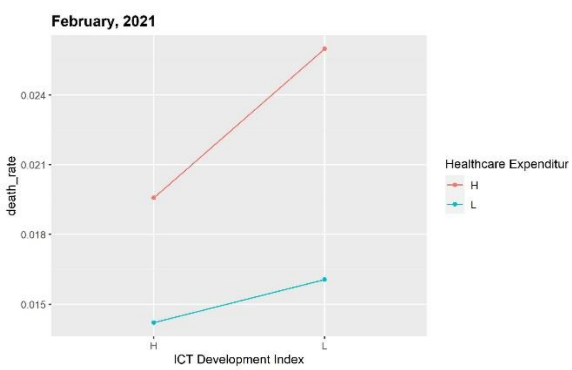

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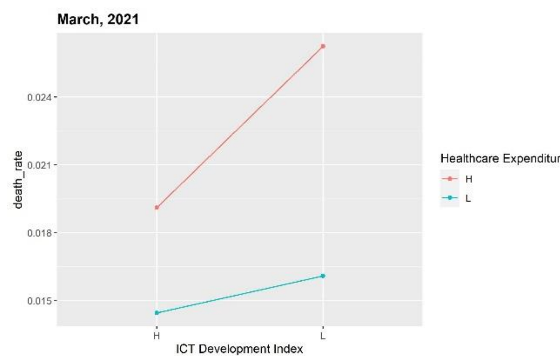

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Figure 3. Interaction plots for death rate from April 2020 to March 2021. a) interaction plot for April. b) interaction plot for May. c) interaction plot for June. d) interaction plot for July. e) interaction plot for August. f) interaction plot for September. g) interaction plot for October. h) interaction plot for November. i) interaction plot for December. j) interaction plot for January 2021. k) interaction plot for February 2021. l) interaction plot for March 2021 (cont.)

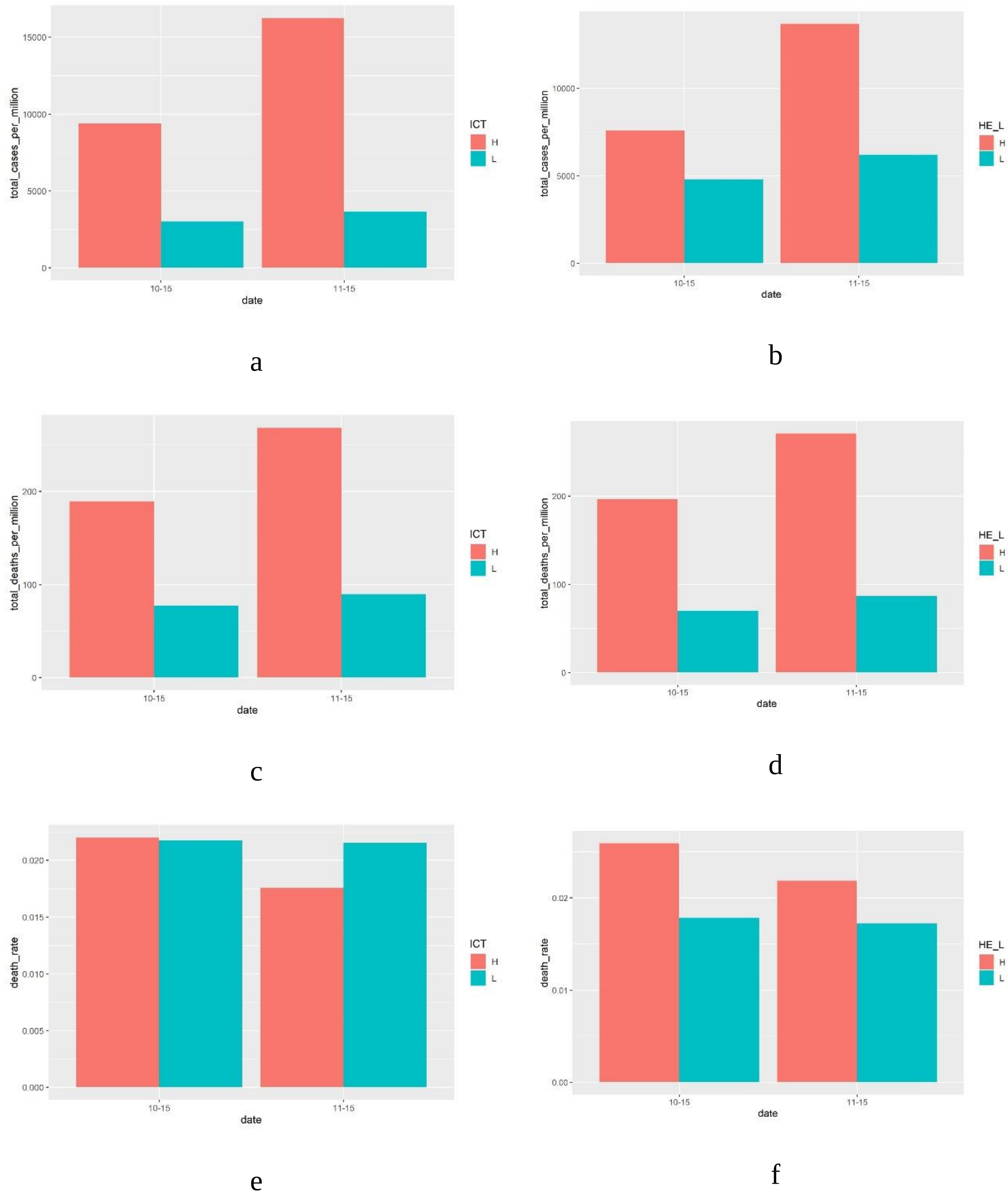

Figure 4. Effect of ICT development and healthcare expenditures on COVID-19 from October to November. a) bar chart for ICT development and total cases per million. b) bar chart for healthcare expenditures and total cases per million. c) bar chart for ICT development and total deaths per million. d) bar chart for healthcare expenditures and deaths per million. e) bar chart for ICT development and death rate. f) bar chart for healthcare expenditures and death rate.

Future studies include looking at factors such as national cultures, testing cases for COVID-19, and humidity levels in understanding the research results. We can use the actual number of ICT development index and healthcare expenditures to run linear regression models instead of classifying countries into groups. Future research can also look at using state or city level data instead of country level. In-depth case studies on a few countries may provide insightful information on the management and control of the pandemic.

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II. EFFECTS OF GDP AND POPULATION DENSITY ON COVID-19 PANDEMIC

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ABSTRACT

As of April 2021, the COVID-19 pandemic is still raging around the world and people's lifestyles have also been changed. COVID-19 can spread through minute droplets, which makes it easy to transmit. At the beginning stage of the pandemic (most part of 2020), vaccines were not available and the most effective way is to control the spread of the virus Social distancing is very important to mitigate the spread of COVID-19 and population density becomes a crucial factor. Wealthy countries begin to develop vaccines in 2020 or invest in pharmaceutical companies to secure the supply of vaccines. Another way to deal with this coronavirus is to develop a vaccine which may take time and money. A country's healthcare expenditures are closely related to its GDP. This research studies the impact of GDP and population density on the spread and control of COVID-19.

1. INTRODUCTION

As of April 2021, COVID-19 has spread to over 200 countries. There are more than 130 million infected cases and more than 2.85 million deaths worldwide reported. Coming into contact with infected individuals is the most common form of infection. The long incubation period (up to 14 days or more) has caused the new coronavirus to spread quickly. Asymptomatic cases present another level of challenge. When there was no vaccine available, the most effective way to reduce the infection rate is to reduce social interactions. Some countries decided to lockdown to curb population flow. Lockdown has varying degrees of impact on the economy depending on the duration of lockdown and the severity of lockdown (Coccia, 2021). In general, lockdown impacts businesses and reduces economic growth.

Until herd immunity is achieved and the pandemic is under control, social distancing and reducing face-to-face interactions between people are the strategies to control the spread of COVID-19 (Wilder-Smith, and Freedman, 2020). If an area has a high population density, the frequency of interaction between people will increase and the risk of infection will increase as well. People’s behavior is difficult to manage -- some people will abide strictly by the isolation requirements, and some may insist on their rights to be not isolated. The success of a lockdown is also related to a country’s enforcement of the lockdown policy. Recent research from Diao et al. (2021) shows that the spread duration is highly correlated with population density in England, Germany, and Japan but not in China due to the strict enforcement of lockdown in China. In their research, they used city-level population density in different countries.

This study researches the effect of GDP and population density on the spread of COVID-19. Contrary to Diao et al. (2021) study, we use GDP per capita and population density at the country level in our research.

2. LITERATURE REVIEW

2.1. GROSS DOMESTIC PRODUCT

Gross Domestic Product (GDP) reflects a country's economic development level. If a country has a higher GDP, the country is more developed and has more resources to deal with the COVID-19 pandemic. On the other hand, more developed countries are more diversified with different viewpoints and value systems. Higher GDP countries are typically associated with more developed transportation systems that enable people to travel more, which increases the possibility of transmission and spreading the virus.

2.2. POPULATION DENSITY

Population Density (PD) reflects the density of population in a country. COVID-19 can be transmitted through direct contact with an infected person. In a high population density area, the infection rate may be higher. But different countries have different policies on COVID-19. Some countries have strict lockdown and quarantine systems such as China. On 23 January 2020, the Chinese government imposed a lockdown in Wuhan and other cities in Hubei in an effort to control the pandemic. Within hours of the Wuhan lockdown, travel restrictions were also imposed on the nearby cities of Huanggang and Ezhou, and were eventually imposed on all 15 other cities in

Hubei, affecting a total of about 57 million people. The number of people affected by the lockdown in Hubei is unprecedented. Although China was the first country to discover the COVID-19 and there was a major outbreak in Wuhan in the early stage, the pandemic was better controlled subsequently because of the strict lockdown policy despite the high population densities in major China cities.

3. THEORETICAL FOUNDATION AND HYPOTHESES

A country's economic growth determines its people's living conditions (Abdullah, and Maamor, 2010). Adolph Wagner first suggested the Wagner's law in 1893, and this principle suggests that public expenditure rises as income growth expands. In other words, GDP is key to government expenditure. In the past few decades, many scholars have tried to verify Wagner's law using data from different countries and different durations.

As the economic growth increases, the government expenditure will increase,. This means that government has the financial ability to support medical workers and provides residents with financial support during the lockdown. Therefore, GDP can affect the spread of COVID-19 in many ways.

Based on our theoretical background, we propose the following hypotheses:

H1: Countries with higher GDP can better control the spread of COVID-19

H1a: Countries with higher GDP per capita have a lower number of cases per million

H1b: Countries with higher GDP per capita have a lower number of deaths per million

H1c: Countries with higher GDP per capita have a lower death rate

H2: Countries with lower population density can better control the spread of COVID-19

H2a: Countries with lower population density have a lower number of cases per million

H2b: Countries with lower population density have a lower number of deaths per million

H2c: Countries with lower population density have a lower death rate

The hypotheses are empirically tested using secondary data on COVID-19, GDP, and population density at the country level.

4. RESEARCH METHODOLOGY

4.1. DATA COLLECTION

The data used in this study are from different sources. The GDP dataset is from Worldometer, and the COVID-19 dataset is from Our World in Data. The population density information is available in the COVID-19 dataset. This research uses the data from four points in time -- the 15th of May 2020, August 2020, November 2020, and February 2021. GDP per capita and population density are divided into two groups according to the medians. We only kept data points that exist in both the GDP and

COVID-19 datasets. We have 171 data points for May 2020, 169 for August and November 2020, 174 for February 2021.

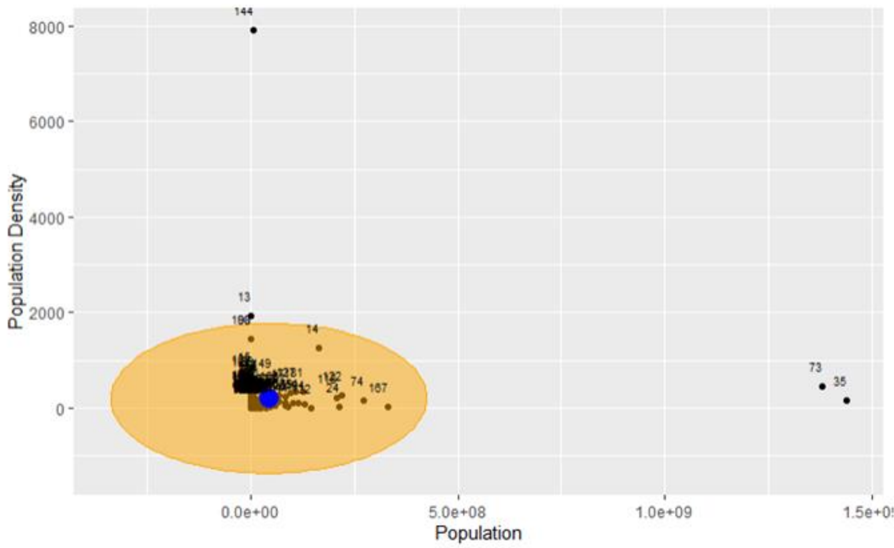


Figure 1. Multivariate outliers

We found that some countries have large populations but low population densities and vice versa. We ran multivariate outliers for each month and we removed four countries from the study. We remove China and India as both of them are outliers because of large populations but low population densities. We also removed Singapore and Bahrain as both of them have low populations but high population densities. After removing the outliers, we have 167 countries for May 2020, 165 for August and November 2020, 170 for February 2021.

4.2. STATISTICAL ANALYSIS

In this study, we first performed Manova tests to determine whether the effect of GDP per capita, population density, and the interaction effect between GDP and population density on COVID-19 is significant.

The results of the Manova tests show that the p-value of the interaction effects between GDP per capita and population density is more than 0.05 for all these four months. For May 2020, the p-value is around 0.088, which is significant at the $p<0.1$ level. The interaction effects are not significant for the other three months.

Because the interaction effect for May is significant, we run separately Anova tests. The result shows that the interaction effect is not significant for the death rate, but the main effect of GDP on the death rate is significant. For total cases per million and total deaths per million, the interaction effect is significant. To better understand the differences between each combination of GDP and PD groups, Tukey tests are used for posthoc analyses for May.

For the other three months (i.e., August 2020, Novembe 2020, February 2021), we run Tukey tests to check whether there are any differences between GPD/PD groups for total cases per million, total deaths per million, and death rate. The results can be found in Appendix C.

5. RESULTS AND DISCUSSIONS

5.1. EFFECTS OF GDP AND PD ON TOTAL CASES PER MILLION

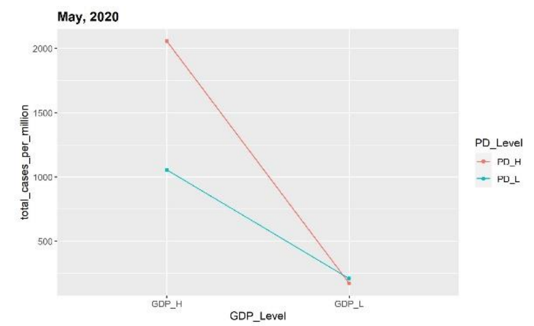
In May, the interaction effect between GDP and PD is significant. From the Tukey test results, the differences between high GDP with high PD with the other three groups (i.e., high GDP/low PD, low GDP/high PD, low GDP/low PD) are significant. We found that high GDP with high PD has the most total cases per million, and the next is high GDP with low PD. Both lower GDP with high PD and low GDP with low PD has relatively fewer infected cases per million.

Thus, the effect of GDP is more significant than population density in May 2020. Countries with high GDP mean these countries are more developed. The result shows that countries that are more developed and have a high PD have the most number of infected cases per million.

For the other three months (i.e., August 2020, November 2020, February 2021), we found that countries with high GDP have more cases per million. This is counter-intuitive as we expect countries with high GDP to be better developed and be able to invest more in health care to better manage and control the pandemic. The result is the opposite of our H1a.

One possible explanation is that more developed countries have better medical services and more knowledge about COVID-19. The number of tested people may also be relatively larger, which leads to more total cases per million. Sometimes people may not know that they have been infected with COVID-19 because some infected people show no symptoms.

For November 2020 and February 2021, high PD has more cases per million. Countries with low PD are expected to have lower numbers of cases because of the ability to practice social distancing. This supports H2a.



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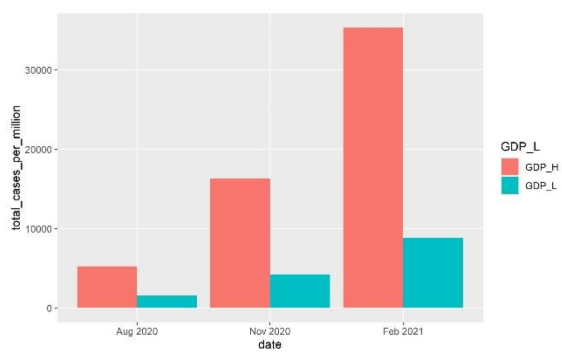

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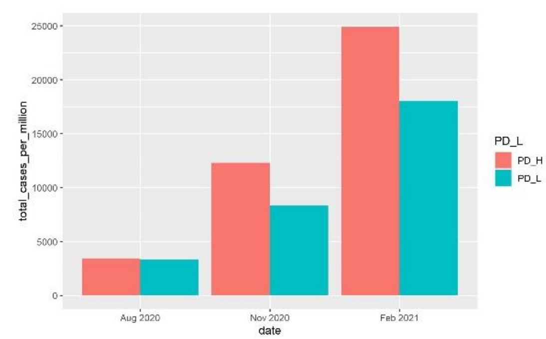

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Figure 2. Plots for effects on total cases per million. a) interaction plot for May. b) Bar chart for effects of GDP on total cases per million. c) Bar chart for effects of population density on total cases per million.

5.2. EFFECTS OF GDP AND PD ON TOTAL DEATHS PER MILLION

From the interaction plot, we observed that in May, high GDP with high population density has the most total deaths per million. This pattern is almost the same as total cases per million in May. Because total deaths are related to total cases, more total cases per million will result in more total deaths per million. More developed countries may have more tested cases, which can lead to more positive cases and more deaths.

For the other three months, the differences between high and low GDP groups are significant for all three months. This supports H1b. On the other hand, the differences between high and low PD groups are not significant for all these three months. This does not support H2b.

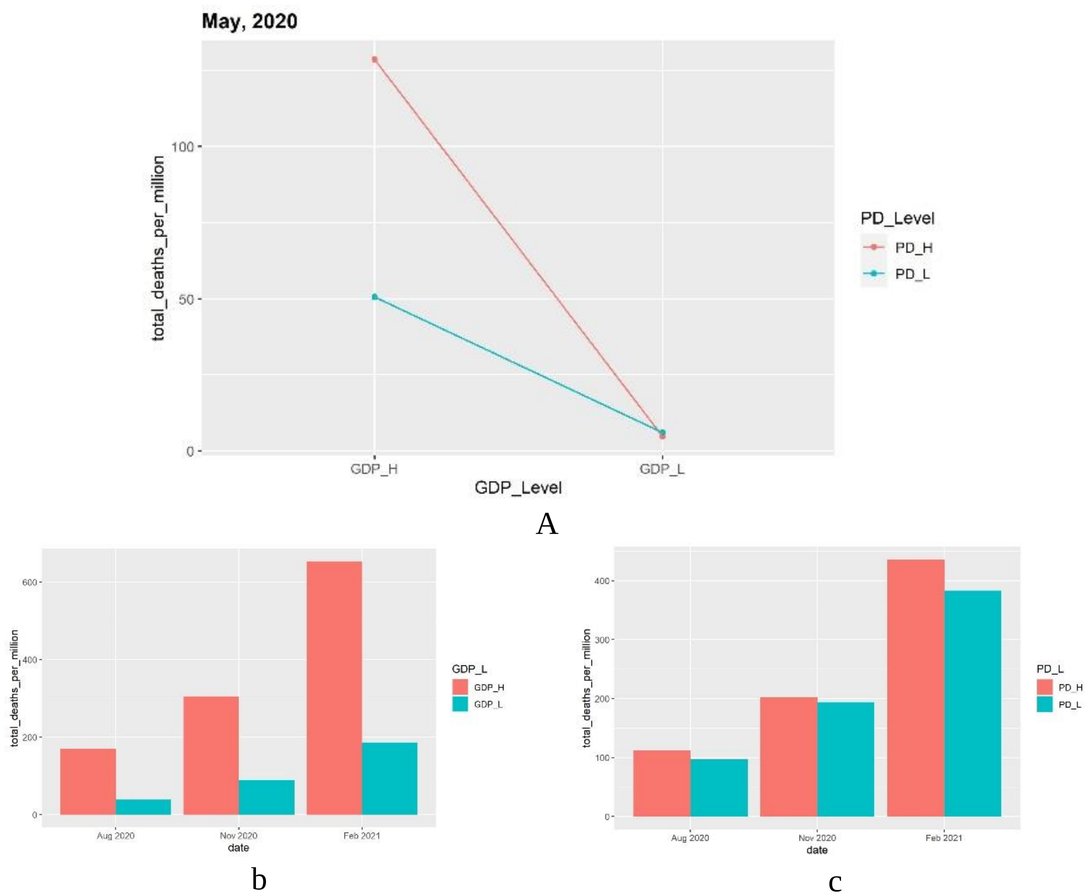

Figure 3. Plots for effects on total deaths per million. a) interaction plot for May. b) Bar chart for effects of GDP on total deaths per million. c) Bar chart for effects of population density on total deaths per million.

Countries with high GDP have more cases per million. Countries with high GDP have a more developed transportation system that provides more chances for people to interact with each other and transmit the virus far and wide. Thus, countries with high GDP have more cases per million and deaths per million.

The lack of significant differences between high and low PD groups is counter-intuitive. We do expect the death rate to be lower in low PD countries. One possible explanation is that the low PD countries may not have a sophisticated healthcare system to take care of infected cases (e.g., the availability of sufficient ventilators).

5.3. EFFECTS OF GDP AND PD ON DEATH RATE

The interaction effect is not significant for May from the Anova test. The main effect of GDP on the death rate is significant. There are no differences between GDP groups for August 2020 and February 2021, and no difference between PD groups for August 2020. For November, the result shows that countries with high GDP have a lower death rate, supporting our H1c.

For November 2020 and February 2021, countries with low PD have a higher death rate, which is against our H2c. A possible explanation is that the PD is at the country level -- in different cities in a country, the population density is very different. The masking and social distancing policies for different countries are also different, which may affect the results.

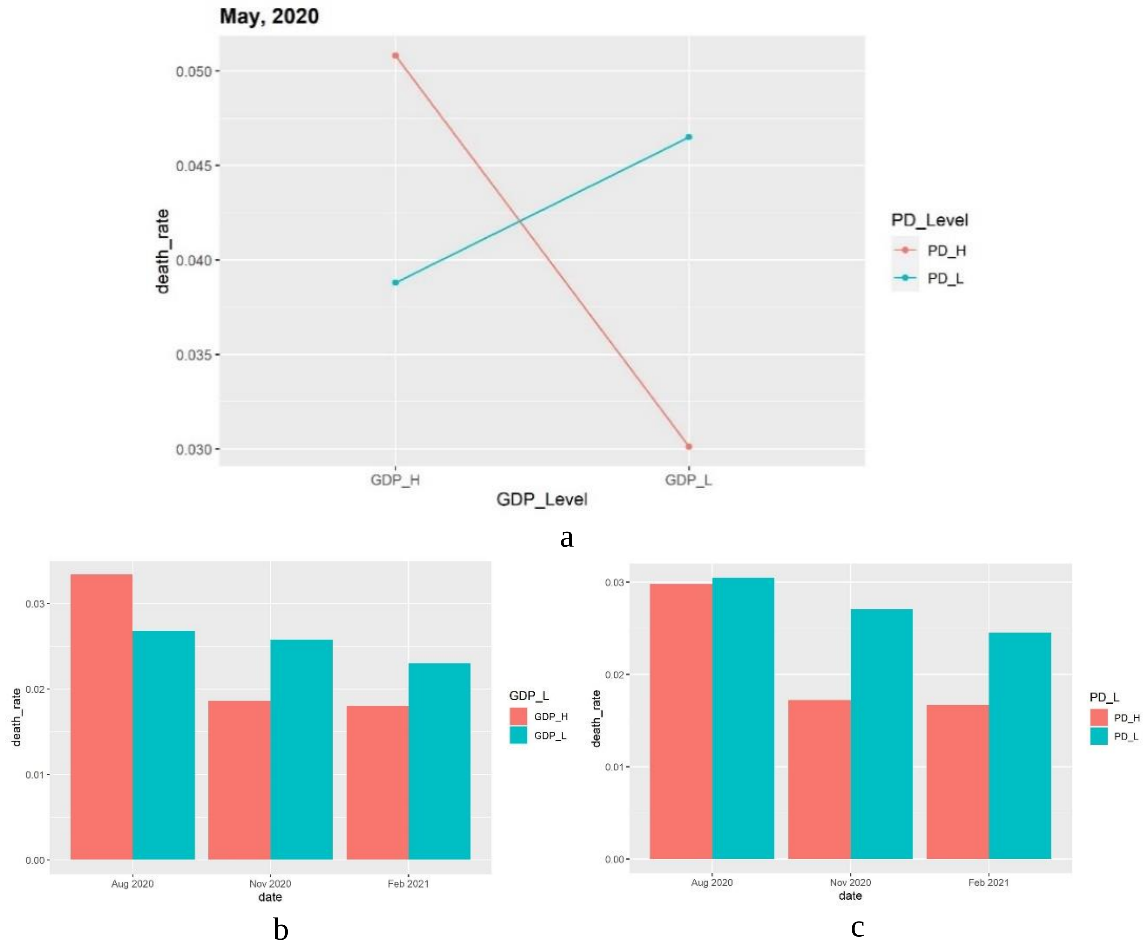

Figure 4. Plots for effects on the death rate. a) interaction plot for May. b) Bar chart for effects of GDP on the death rate. c) Bar chart for effects of population density on the death rate.

6. CONCLUSIONS AND FUTURE STUDY

This study provides insights into the effects of GDP and PD on the spread of COVID-19. Because the population density is at the country level, the results may b affected. In future work, we can use the infection rates of different cities in the same country to check the impact of population density on the spread of COVID-19.

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SECTION

2. CONCLUSIONS AND RECOMMENDATIONS

2.1. CONCLUSIONS

This thesis looks at the effects of four factors on COVID-19 pandemic. The first paper looks at ICT and healthcare expenditures. The results show there is an interaction effect between ICT and healthcare expenditures on COVID-19 from April 2020 to September 2020, and the interaction is not significant for October 2020 and November 2020. The interaction effect is significant again from December 2020 to March 2021.

The second research paper focuses on GDP and population density. The results show that the interaction effect between GDP and population density differs for the four months. The interaction effect is significant for May 2020 but not significant for August 2020, November 2020, and February 2021. Several possible explanations are provided.

2.2. RECOMMENDATIONS

A number of factors were studied in this thesis. Future research can expand this steam of research by looking at other factors such as lockdown durations, vaccines, humidity, and numbers of tested cases. We can also do a time series analysis based on the COVID-19 dataset. Instead of looking at individual countries, future research can study the GDP and PD at the city level. Different cities in the same country have different GDPs and different population densities. To better understand the effect of GDP and population density on the spread of COVID-19, we can use different cities in the same country.

APPENDIX A.

COUNTRIES’ ICT AND HEALTHCARE EXPENDITURE LEVELS

Table A1. Group Information from April 2020 to December 2020

	High Healthcare Expenditures	Low Healthcare Expenditures	Total
High ICT	54	28	82
Low ICT	28	54	82
Total	82	82	164

Table A2. Group Information from January 2021 to March 2021

	High Healthcare Expenditures	Low Healthcare Expenditures	Total
High ICT	54	28	82
Low ICT	28	57	85
Total	82	85	167

APPENDIX B.

MANOVA TEST AND TUKEY TEST RESULTS FOR PAPER I

Table B1. Manova Test Results Along With Anova/Tukey Test Results

		ICT Development Index	Healthcare Expenditure	Interaction Effect between ICT and HE
MANOVA April 2020		< 0.001	< 0.05	> 0.05(0.072)
ANOVA	Total cases per million	< 0.001	> 0.05	> 0.05
	Total deaths per million	< 0.001	< 0.05	< 0.05
	Death rate	> 0.05	< 0.01	> 0.05
MANOVA May 2020		< 0.001	< 0.01	< 0.01
ANOVA	Total cases per million	< 0.001	> 0.05	> 0.05
	Total deaths per million	< 0.001	< 0.01	< 0.05
	Death rate	> 0.05	< 0.001	> 0.05
MANOVA June 2020		< 0.001	< 0.01	< 0.05
ANOVA	Total cases per million	< 0.001	> 0.05	> 0.05
	Total deaths per million	< 0.001	< 0.01	< 0.05
	Death rate	< 0.001	< 0.01	> 0.05 (0.079)
MANOVA July 2020		< 0.001	< 0.01	< 0.01
ANOVA	Total cases per million	< 0.001	< 0.01	> 0.05 (0.051)
	Total deaths per million	< 0.001	< 0.01	> 0.05 (0.059)
	Death rate	< 0.001	< 0.001	> 0.05 (0.082)
MANOVA August 2020		< 0.001	< 0.001	< 0.05

Table B1. Manova Test Results Along With Anova/Tukey Test Results (cont.)

ANOVA	Total cases per million	< 0.001	> 0.05	< 0.05
	Total deaths per million	< 0.001	< 0.01	> 0.05
	Death rate	< 0.01	< 0.001	> 0.05(0.86)
MANOVA September 2020		< 0.001	< 0.01	> 0.05(0.062)
ANOVA	Total cases per million	< 0.001	> 0.05	> 0.05
	Total deaths per million	< 0.001	< 0.01	> 0.05
	Death rate	> 0.05	< 0.001	> 0.05
MANOVA October 2020		< 0.001	< 0.01	> 0.05
TUKEY	Total cases per million	< 0.001	< 0.05	
	Total deaths per million	< 0.001	< 0.001	
	Death rate	> 0.05	< 0.01	
MANOVA November 2020		< 0.001	< 0.001	> 0.05
TUKEY	Total cases per million	< 0.001	< 0.001	
	Total deaths per million	< 0.001	< 0.001	
	Death rate	> 0.05	> 0.05(0.0566)	
MANOVA December 2020		< 0.001	< 0.001	< 0.05
ANOVA	Total cases per million	< 0.001	< 0.01	< 0.05
	Total deaths per million	< 0.001	< 0.001	< 0.01
	Death rate	> 0.05	< 0.01	> 0.05
MANOVA January 2021		< 0.001	< 0.001	< 0.05

Table B1. Manova Test Results Along With Anova/Tukey Test Results (cont.)

ANOVA	Total cases per million	< 0.001	< 0.001	< 0.05
	Total deaths per million	< 0.001	< 0.001	< 0.01
	Death rate	> 0.05	< 0.01	> 0.05
MANOVA February 2021		< 0.001	< 0.001	< 0.01
ANOVA	Total cases per million	< 0.001	< 0.001	< 0.05
	Total deaths per million	< 0.001	< 0.001	< 0.01
	Death rate	> 0.05	< 0.001	> 0.05
MANOVA March 2021		< 0.001	< 0.001	< 0.001
ANOVA	Total cases per million	< 0.001	< 0.001	< 0.01
	Total deaths per million	< 0.001	< 0.001	< 0.01
	Death rate	> 0.05	< 0.001	> 0.05

APPENDIX C.

COUNTRIES' GDP AND POPULATION DENSITY LEVELS

Table C1. Group Information for May 2020

	High Population Density	Low Population Density	Total
High GDP	49	37	86
Low GDP	35	46	81
Total	84	83	167

Table C2. Group Information for August 2020 November 2020

	High Population Density	Low Population Density	Total
High GDP	47	35	82
Low GDP	36	47	83
Total	83	82	165

Table C3. Group Information for February 2021

	High Population Density	Low Population Density	Total
High GDP	45	39	84
Low GDP	36	50	86
Total	81	89	170

APPENDIX D.

MANOVA TEST AND TUKEY TEST RESULTS FOR PAPER II

Table D1. Manova Results and Anova/Tukey Test Results

		GDP per Capita	Population Density	Interaction Effect between GDP and PD
MANOVA	May-20	< 0.001	> 0.05 (0.085679)	> 0.05 (0.088)
ANOVA	Total cases per million	< 0.001	< 0.05	< 0.001
	Total deaths per million	< 0.001	> 0.05 (0.06392)	< 0.01
	Death rate	< 0.05	> 0.05	> 0.05
MANOVA	Aug-20	< 0.001	> 0.05	> 0.05
TUKEY	Total cases per million	< 0.001	> 0.05	
	Total deaths per million	< 0.001	> 0.05	
	Death rate	> 0.05	> 0.05	
MANOVA	Nov-20	< 0.001	< 0.01	> 0.05
TUKEY	Total cases per million	< 0.001	< 0.05	
	Total deaths per million	< 0.001	> 0.05	
	Death rate	> 0.05 (0.0756)	< 0.05	
MANOVA	Feb-21	< 0.001	< 0.05	> 0.05
TUKEY	Total cases per million	< 0.001	> 0.05 (0.0856)	
	Total deaths per million	< 0.001	> 0.05	
	Death rate	> 0.05	< 0.05	

VITA

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