UNRAVELING THE RELATIONSHIP BETWEEN SOCIAL VULNERABILITY INDEX AND COVID-19 PREVALENCE IN SOUTHERN NEVADA

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Bachelor of Science – Biological Sciences
University of Nevada, Las Vegas
2021

A thesis submitted in partial fulfillment
of the requirements for the

Master of Public Health

Epidemiology and Biostatistics
School of Public Health
The Graduate College

University of Nevada, Las Vegas
May 2024

UNLV | GRADUATE COLLEGE

Thesis Approval

The Graduate College
The University of Nevada, Las Vegas

March 29, 2024

This thesis prepared by

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entitled

Unraveling the Relationship between Social Vulnerability Index and COVID-19 Prevalence in Southern Nevada

is approved in partial fulfillment of the requirements for the degree of

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Abstract

The COVID-19 pandemic was a catastrophic global event that exacerbated public health issues and disparities, especially in socially vulnerable communities. Thus, this study examines areas classified by the CDC's Social Vulnerability Index (SVI) metric, which assesses vulnerable communities experiencing adverse events through sixteen social determinants that impact health. The purpose of this study will be to determine if (1) COVID-19 testing rates and/or COVID-19 vaccination rates mediate SVI and COVID-19 prevalence rates and (2) if COVID-19 testing rate and COVID-19 vaccination rates serially mediate SVI and COVID-19 prevalence rates. In order to achieve this, census tracts within Southern Nevada will be analyzed from January 2020 to June 2022. . Mediation analyses with linear regression were employed to examine complex relationships among SVI, COVID-19 testing, vaccination, and prevalence rates. The 95% confidence intervals of indirect effects were particularly computed using a bootstrap technique to determine whether a mediator was statistically significant. Results display that the COVID-19 testing rate (indirect effect = -3.98; 95% CI = -7.43, -0.11), COVID-19 full-vaccination rate (indirect effect = -1.88; 95% CI = -7.54, -0.95), and COVID-19 follow-up vaccination rate (indirect effect = -11.52; 95% CI = -15.97,-6.49) negatively mediates the relationship between SVI and COVID-19 prevalence rate. Our serial mediation analysis showed that an increase in SVI was significantly inversely associated with a significant total indirect effect of -0.02 (95% CI = -0.03, -0.002) from the sequential pathway from COVID-19 testing rate, COVID-19 full vaccination rate, and COVID-19 follow-up vaccination rate as serial mediators. These findings further highlight the impact of infectious outbreaks from access to vaccination and testing resources in socially vulnerable communities, underscoring the need for public health professionals to develop sustainable interventions.

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1. Introduction

1.1. Background

Coronaviruses come from a large family of enveloped viruses classified in the Coronaviridae family in the Nidovirales order (Fehr & Perlman, 2015; Jaiswal & Saxena, 2020; Wang et al., 2020). Coronaviruses are RNA viruses that contain 16 other non-structural proteins with various functions such as replication, survival signaling, and proofreading (Zhang et al., 2021). Coronaviruses comprise approximately 30,000 nucleotides that generate four organic proteins: the envelope, membrane, nucleocapsid, and spike glycoproteins (Boopathi et al., 2021). Spike glycoproteins are vital components as they mediate the transmission of virions to host cells by targeting respiratory cells in the lower respiratory tract (Jebril, 2020). The protein characteristics and survivability of the coronavirus influence its high virulence, potentially leading to outbreaks. (Ren et al., 2020).

The first report of the infectious coronavirus occurred when chickens had a malicious respiratory infection in the 1940s (Jaiswal & Saxena, 2020). Several researchers at the University of Maryland could view the coronavirus structure from the infected chickens, which appeared as black dots from the electron microscopic images (Lalchhandama, 2020). Virologists identified the first human coronavirus in the 1960s from England by isolating a nasal washing of a male child experiencing common cold-like symptoms (Kahn & McIntosh, 2005). Later, virologists classified it as B814 but changed it to coronavirus due to the crown-like appearance of the spike glycoproteins, as seen in the electronic microscopic images (Huang et al., 2020). Two notable coronaviruses, severe acute respiratory syndrome coronavirus (SARS-CoV) and Middle East respiratory syndrome coronavirus (MERS-CoV), have developed into catastrophic outbreaks (Liu et al., 2020).

SARS-CoV causes SARS and has led to epidemics within a dozen countries in 2002-2004, leading to over 8,000 cases (Morens et al., 2020). The first cases of SARS occurred in China from an unknown source, with theories linking it to food markets selling wild animals (Chen et al., 2013). Approximately 8,000 cases of SARS occurred but it was ultimately contained by travel restrictions, disinfectants, quarantine, and other preventative health guidelines, ending in 2004 (Chan-Yeung & Xu, 2003). Individuals can spread SARS through respiratory droplets, rapidly spreading infection, especially in the Asian continent (Kahn & McIntosh, 2005). The SARS outbreak had accumulated approximately 700 deaths and would not be the last coronavirus to emerge in the upcoming years (Stadler et al., 2003).

MERS-CoV, a virus more fatal than SARS-CoV, emerged in 2012, with the first being reported in Saudi Arabia (Memish et al., 2020). MERS's origin, like SARS, is still widely unknown, with Arabian camels as potential hosts that zoonotically transmit the virus to humans through direct contact (Omrani et al., 2015). MERS has a high case fatality rate with severe pneumonia, fever, diarrhea, and fatigue symptoms (Pustake et al., 2022). According to a study, approximately 2,000 cases and 800 deaths occurred from MERS in various countries in 2019 (Lango, 2020; Memish et al., 2020). Fortunately, the spread of MERS is slowly diminishing due to better hygienic practices in areas using camels (Wu et al., 2020).

Researchers believe that a highly contagious novel virus began its spread in China's Seaford market in early December 2019 (Platto et al., 2021). Infected individuals characterized the symptoms as severe pneumonia with symptoms of fatigue, fever, lung lesions, and gastrointestinal pain (da Rosa Mesquita et al., 2021). The source of the novel virus is still unknown, but some researchers theorized that wildlife food such as bats served in the unregulated market might have led to the infection (El-Sayed & Kamel, 2021). However, identifying the novel coronavirus took approximately one month by a Chinese physician, along with the emergence of similar cases suffering from a severe pneumonia-like disease becoming common reports throughout hospitals. (Li et al., 2020). Afterward, the emergence of the novel virus, later classified as COVID-19, prompted great fear in China to take action to curb the new virus's high transmissibility (Y. Zhang et al., 2021).

Approximately 80,000 COVID-19 cases had occurred in China by early March 2020, just two months after the initial report (Y. Zhang et al., 2021). The suspected seafood market closed on January 1st; 23 days had already passed in Wuhan city of 14 million individuals, unaware of COVID-19 spreading (Zhu et al., 2020). Despite the declared COVID-19 outbreak on January 20 and the enforced quarantine in Wuhan city, there were already 80,000 cases by mid-March (G. Zhang et al., 2021). Nonetheless, action was taken quickly throughout China after COVID-19 reports from hospitals, causing travel restrictions and quarantine in Wuhan (Zhou et al., 2021). Chinese government enforced a lockdown in Wuhan City on January 26, but cases of COVID-19 had already occurred in other countries (G. Zhang et al., 2021; Z. Zhang et al., 2023)

COVID-19 first case outside of China happened in Thailand on January 13, 2020, due to the virus's rapid transmissibility and delay of travel restrictions (Boldog et al., 2020; Y. Zhang et al., 2021). COVID-19 was officially announced as a pandemic on March 11, 2020, by the World Health Organization (WHO), as it had infected approximately 144 countries (Cucinotta & Vanelli, 2020). Subsequently, the spread of the lethal Coronavirus affected all continents except Antarctica towards mid-March 2020, just three months after the first reported case (Shi et al., 2020). In January and March, several countries reported their first COVID-19 death, especially in countries like Italy, with an older population. (Dhar Chowdhury & Oommen, 2020; J. J. Zhang et al., 2023). Over 100,000 COVID-19 cases occurred globally by March, with the first case of COVID-19 occurring on January 20 in the United States (U.S.) (Vannabouathong et al., 2020).

1.2 Impact of COVID-19 pandemic in the U.S.

First COVID-19 case in the U.S. happened on January 20, 2020, when a man rushed to urgent care with symptoms of a severe fever and informed the healthcare workers that he had visited China the past weeks (Holshue et al., 2020). Cases snowballed, as seen with the geographic distribution of COVID-19 prevalence, which occurred mainly in the U.S. southeast and southwest regions (Jackson et al., 2021). Lack of immediate attention to COVID-19 during January prompted the rapid spread of COVID-19 and at least 100,000 cases in the U.S. by late March (Shultz et al., 2020). By the end of December 2021, COVID-19 cases exceeded a million despite implementing multiple public health interventions such as lockdowns, masks, and social distancing (Zhao & Liu, 2022). Unfortunately, the surge of COVID-19 cases, deaths, and preceding public health policies polarized the public's response to the deadly virus through political influence (Hart et al., 2020).

U.S. public response to COVID-19 being declared a public health emergency in January of 2020 was a mixture of apprehension and apathy, as seen by a lack of adherence to public health guidelines for preventing new cases of COVID-19 (Alexander et al., 2022). A study found that many young adult males failed to adhere to guidelines by the Centers for Disease Control and Prevention (CDC), primarily social distancing (Park et al., 2020). Likewise, the governmental reaction to the COVID-19 pandemic was quite late, as the implementation of mandatory lockdowns, masks, and social distancing occurred only in mid-March of 2020 (Parker & Stern, 2022). Medical professionals felt the brunt of the government's late response and the public's attitude toward the early days of the COVID-19 pandemic as strenuous burnout peaked amongst these healthcare workers (Hughes & Rushton, 2022). Especially amongst contact tracers who tracked new cases and transmission of COVID-19, they faced considerable manpower shortages in the early days due to inconsistent funding to state health departments (DeSalvo et al., 2021).

Inadequate funding for contact tracing for COVID-19 in the early days of the pandemic was not the only strain on the healthcare system in the U.S. (Gertz et al., 2022). The pandemic burdened hospitals with shortages of personal protective equipment, healthcare workers, and rooms (Boserup et al., 2021; Janke et al., 2021). Over 40 million Americans became unemployed during the COVID-19 pandemic, and many faced the risk of eviction from their homes (Nande et al., 2021; von Wachter, 2020). A disproportionate social impact occurred amongst minorities at risk for eviction, especially among Black and Hispanic individuals who are highly susceptible to COVID-19 due to financial hardship and racism (Benfer et al., 2021). Racism towards Asian Americans also became more prevalent due to the prejudice and weaponized politicization of the coronavirus origin (Lantz et al., 2023; Wong-Padoongpatt et al., 2022).

Undoubtedly, the consequences of the pandemic exceed the economic and social impact as it also took a toll on the life expectancy of the U.S. public, especially among minorities (Andrasfay & Goldman, 2022). Life expectancy in the U.S. dropped by over a year due to COVID-19, while the total years of life lost was approximately seven million in the early months of the pandemic (Chan et al., 2021). A disproportionate drop in life expectancy occurred amongst Black and Hispanic populations in the U.S. as decreases were the lowest compared to the White population(Silva et al., 2023). Mortality was at an all-time high in the U.S. due to the COVID-19 pandemic; by December of 2021, the number of deaths related to COVID-19 was approximately 300,000 (Stokes et al., 2021). Death due to COVID-19 is highly prevalent among individuals with comorbidities, which signifies the importance of developing COVID-19 testing and vaccination to prevent cases (Djaharuddin et al., 2021) .

1.3 Development of COVID-19 testing in the U.S.

Scientists from China uploaded the novel virus' genomic sequence on various platforms online in early January of 2020 (Rahimi et al., 2021). Afterward, diagnostic testing for COVID-19 began in early March in the U.S. with certified laboratories that had governmental approval bypassing Food and Drug Administration (FDA) requirements (Alexander et al., 2022). COVID-19 infection in the U.S. was initially tested by polymerase chain reaction (PCR) tests that detect the virus's nucleic acid in infected individuals (Shyu et al., 2020). A typical procedure for COVID-19 testing carried out by testing sites is collecting a sample by swabbing the inside of an individual's throat, nasal passage, or saliva (Benda et al., 2021). By the end of April 2020, over 40 tests of two different types (nucleic acid and antibody) were developed, yet the lack of accessibility to these COVID-19 tests prevailed in the U.S. (Ward et al., 2020).

Consequently, late response to the COVID-19 pandemic led to numerous obstructions to the accessibility of testing sites for the virus in the U.S. (Nowroozpoor et al., 2020). A study found that the COVID-19 testing facilities were inaccessible to many individuals located in uninsured, low-income, and rural areas in the U.S. (Rader et al., 2020). Hence, the average time it takes to get to a COVID-19 testing facility is approximately more than an hour for individuals who live in rural areas (Khazanchi et al., 2022). Despite these limitations, by July 2020, the national capacity of testing sites to conduct daily diagnostic tests for COVID-19 had exceeded over 500,000 (Tromberg et al., 2020). Nevertheless, difficulties in abiding isolation from COVID-19 have led to surges in the positivity rate, indicating the need for consistent surveillance for compiling and monitoring testing results in the U.S. (Maya & Kahn, 2023).

State health departments monitored new cases and deaths related to COVID-19 in the U.S. and reported them to the CDC (Stokes et al., 2020). The CDC spearheaded COVID-19 surveillance, yet the U.S. government provided little to no resources to them during the pandemic's beginning (Alexander et al., 2022). The surveillance of COVID-19 cases has some obstructions due to sporadic reporting, cyberattacks on data sites, and lack of consistent monitoring from various states (D. Khan et al., 2023). By the beginning of June 2020, the positivity rate of COVID-19 was approximately over three percent of the U.S. total population (Unwin et al., 2020). Consequently, the surge in the COVID-19 positivity rate in individuals may be due to work and income outside the home, thus indicating the need for a vaccine so individuals could return to their normal lives and financial security (McLaughlin et al., 2021).

1.4 Vaccination roll out during COVID-19 pandemic

Early during the pandemic, developing the first COVID-19 vaccine was prioritized by many biotechnological companies, as over 150 potential vaccines were proposed by July 2020 (Kaur & Gupta, 2020). Subsequently, the first mRNA-based vaccine, “BNT162b2,” was created the following year by BioNTech and Pfizer (Fortner & Schumacher, 2021). BioNTech created a vaccine that targets the spike glycoprotein of SARS-CoV-2 and tested through multiple clinical trials that evaluated the safety in healthy humans through a sample size of over 18,000 participants (Lamb, 2021). It took approximately one year to develop the vaccine to be given to individuals over 16, and was approved by the U.S. FDA in late August 2021 (Bailey & Wilson, 2022). Unfortunately, the uptake of the first COVID-19 vaccine in the U.S. faced severe hesitancy from the public due to misinformation online (Yasmin et al., 2021).

Considering the threat posed by the coronavirus, a survey conducted in 2020 for the U.S. public showed that approximately 30% would take the vaccine, indicating a lack of concern about the pandemic at the time (Bolsen & Palm, 2022). Notable factors that explain the rejection of the COVID-19 vaccine include the lack of health literacy and worries about vaccine safety, as shown in a study conducted in the U.S. (Kricorian et al., 2022). Despite the mRNA-based vaccine being not harmful, the adverse effects are mild or moderate, such as headaches or muscle cramps (Fortner & Schumacher, 2021). Researchers examining vaccination acceptance throughout the U.S. found that hesitancy was more prevalent in individuals with low socioeconomic status and education levels (Yasmin et al., 2021). Towards late August 2021, only below half of the U.S. population received the vaccination, with the lowest rates amongst minority groups (Alfaro et al., 2021).

Researchers conducting a literature review amongst U.S. publications found that individuals from rural areas had limited access to the COVID-19 vaccine primarily due to a lack of transportation to the few vaccine sites (Kuehn et al., 2022). Another study found that minority groups receive a lower percentage of vaccinations than their white counterparts, even in urban areas of the U.S. (Hernandez et al., 2022). The lack of insurance coverage also impacted many individuals to receive the vaccine in the U.S. due to medical avoidance, as shown in a comprehensive analysis (Bazan & Akgün, 2021). A review examining factors related to vaccine hesitancy and interventions that counter them found that concise health information about safety increased COVID-19 vaccination uptake (Batteux et al., 2022). By October 2021, over 700,000 deaths in the U.S. were related to COVID-19, with socially vulnerable communities suffering the most (El-Mohandes et al., 2021). Yet, over 200,00 deaths could have been prevented if individuals had received the vaccine in the beginning within the U.S. (Jia et al., 2023).

1.5 COVID-19 prevalence, testing, and vaccinations in Southern Nevada

The current study closely examines Clark County within Southern Nevada to disentangle the relationship between SVI and COVID-19 prevalence. Clark County had the most cases and deaths from COVID-19 out of all the counties in Southern Nevada, especially among Hispanics, during the first year of the pandemic (Nevada Health Response, 2020a). The first individual, a Clark County resident characterized as an older male who had just traveled to Washington, contracted the coronavirus on March 5 (Southern Nevada Health District, 2020b). It was reported by the health district, and seven days later, the governor announced a public health emergency with lockdown effects throughout the state (Southern Nevada Health District, 2020b). Despite that, towards the end of 2020, there were over 180,000 COVID-19 cases in Clark County due to a lack of adherence to public policies as many protested against masks and casino shutdowns (Las Vegas Review-Journal, 2020c; Nevada Health Response, 2020b). Additionally, the first COVID-19 death happened four days after the first case in Clark County, thus indicating the immediate need for testing to identify individuals with the coronavirus and prevent further transmission to others (Southern Nevada Health District, 2020c).

The Southern Nevada Health District reported that testing for COVID-19 cases would occur on January 29 as concern ensued due to the thriving tourism industry in the state (Elko Daily, 2020; Southern Nevada Health District, 2020). Testing sites were developed at drive-throughs at clinics, hospitals, universities, entertainment centers, or even parking garages of casinos (Las Vegas Review-Journal, 2020a; Las Vegas Sun, 2020a; Las Vegas Sun, 2020b). COVID-19 testing frequently occurs, as there will be approximately 8,000 tests daily in Southern Nevada by August 2020 (Las Vegas Sun, 2020a). By the end of September 2020, over 900,000 COVID-19 had been conducted by health professionals throughout the State of Nevada (Las

Vegas Review-Journal, 2020b). In addition, the state government distributed approximately 600,000 testing home kits to Nevadan residents by January 2022 (Las Vegas Review-Journal, 2020d).

The first vaccines developed by Pfizer-BioNTech were given to residents in Southern Nevada on December 14, 2020 (Southern Nevada Health District, 2020d). By the end of April 2021, over a million vaccine doses had been given to Clark County of Southern Nevada residents (Southern Nevada Health District, 2021a). However, the number of full vaccinations received within Southern Nevada is well below the U.S. average compared to other states (Southern Nevada Health District, 2021b; USA Facts, 2022). Minority groups accounted for the lowest number of vaccinations received in the first year of the pandemic (Nevada Health Response, 2020b). Thus, it is imperative to distinguish factors obstructing access to these resources in socially vulnerable communities, especially when there are approximately 7,000 COVID-19 deaths in Clark County by 2021 (Nevada Health Response, 2020c).

1.6 CDC's SVI defined and implications for socially vulnerable communities

The social vulnerability index (SVI) metric assesses vulnerable communities by classifying U.S. census tracts (i.e., subdivisions of counties) vulnerability through sixteen social determinants that impact health (Xia et al., 2023). Initially, SVI was designed to inform the governmental resources needed for vulnerable communities impacted by natural disasters or disease outbreaks (Tran et al., 2023). Researchers from a CDC program specializing in geospatial public health developed the SVI under four general domains: Socioeconomic status, Household composition, Racial and ethnic minority status, and Housing type or transportation in 2011 (Wolkin et al., 2022). Social determinants considered for the first SVI domain are the federal poverty line, employment status, income, and completion of a high school diploma (Flanagan et al., 2011). An application is shown through a study finding an association between prevalent teenage pregnancies and low socioeconomic status amongst socially vulnerable census tracts, highlighting a need for intervention (Yee et al., 2019).

Subsequently, household composition is the next SVI domain, considering social determinants such as age, disability, and single parenting (Flanagan et al., 2011). A study evaluating SVI combined with a risk assessment for harmful radiological matter from accidents by nuclear power plants to the public found that disability has lead to a significant risk (Pence et al., 2019). The domain of racial and ethnic minority status is an essential determinant of health, as portrayed by Spangler et al. (2019), who found that hazardous hot spots from radiological contamination across the New England region were associated with census tracts of high SVI and minority groups. Lastly, the fourth domain, housing type, involves factors like housing structure, family size, and access to transportation (Flanagan et al., 2011). Individuals seeking safety from natural disasters like Hurricane Harvey can be life-threatening situations for vulnerable communities when lacking transportation or mobility (Karaye et al., 2019).

The use of SVI has aided in identifying health disparities through finding associations among various risk factors and health outcomes throughout the literature. Individuals living in high levels of SVI areas were more likely to be uninsured and lack coverage for cancer screening tests (Bauer et al., 2022). Researchers found that increasing health literacy amongst these groups reduces the disparities, as shown in a study analyzing SVI and the use of costly healthcare resources (Hanlon et al., 2022). Another identified disparity was that socially vulnerable communities are more likely to live in areas with high temperatures, as shown in a U.S. study that looks to identify areas for the allocation of resources (Parsons et al., 2023). Although SVI does not come out without limitations, considering its applicability pertains only to census tracts and restricts use to retrospective data, it can still be utilized to distinguish disproportionate impact on socially vulnerable communities from disasters like COVID-19 (Adepoju & Kiaghadi, 2023).

2. Literature review

2.1 SVI influence on COVID-19 testing, vaccination, and prevalence

As indicated by a number of studies examining this association, COVID-19 testing rates typically trend towards a lower rate amongst areas with a high SVI (Al Rifai et al., 2022). Bilal et al. (2021) also found that a high SVI was associated with lower testing rates throughout three U.S. cities. Factors like individuals older than 65, no health insurance, congested households, and low English proficiency were associated with low COVID-19 testing rates in the U.S. (Troppy et al., 2021). However, one study found that Alabama's COVID-19 testing rate and SVI were not significantly associated (Oates et al., 2021). One study found that high testing rates were associated with factors like minority status, deprived housing, and transportation in Louisiana but low testing rates in Alabama despite similar populations regarding socioeconomics, ethnicity, and region size from both states (Karaye & Horney, 2020; Oates et al., 2021). The variety of associations displays diverse impacts of utilizing SVI in different areas for COVID-19 testing rates (Karaye & Horney, 2020).

A plethora of studies conducted in the U.S. has found that factors related to SVI's SES, like lack of health insurance, low education levels, and low income, are associated with low COVID-19 vaccination rates (Donadio et al., 2021; Khairat et al., 2022; Thakore et al., 2021). Despite that, vaccination rates are higher among individuals who are unemployed and low rates among individuals currently working in the blue-collar sector due to hesitancy to trust the government (Ali & Samin, 2021; King et al., 2021). Individuals over 65 are most likely to be vaccinated, while individuals with a disability in areas classified by SVI are not associated with the COVID-19 vaccination rate (Diesel et al., 2021; Hughes et al., 2021). Several studies found that Black and Hispanic individuals living in zip codes with a high SVI were more likely to be vaccinated compared to White individuals even with a lack of accessibility, as mentioned previously (Kriss et al., 2022; Mody et al., 2022; Wong et al., 2021). Individuals who lived in rural areas reported a lower vaccination rate than urban residents (Baack et al., 2021).

As predicted, a high SVI, and factors like low income and working in an occupational field that requires manual labor are associated with COVID-19 infection prevalence in multiple studies (Ali et al., 2020; DuPre et al., 2021; Paul et al., 2021; Porter et al., 2021). Extreme age ends (e.g., older than 65 and younger than 18) appeared disproportionately impacted by being infected more from COVID-19 within socially vulnerable communities (Amaia et al., 2020; Bhowmik et al., 2021; Muñoz-Price et al., 2020). Individuals with a disability and single-parent households were associated with a higher COVID-19 prevalence rate within areas with a high SVI (Sung, 2021; Tortolero et al., 2021). A vast majority of studies found that COVID-19 infection was more prevalent among Black Americans and Hispanics compared to Whites due to factors related to financial hardship (Dasgupta et al., 2020; Frisco et al., 2022; Gold et al., 2020; Hughes et al., 2021; Matias et al., 2023; Samuel et al., 2021; Tortolero et al., 2021; Wiley et al., 2022; Williams et al., 2022; Wong et al., 2023). Lastly, concerning housing type and transportation, crowded homes, rural areas, and lack of transportation indicated a higher COVID-19 prevalence rate as exposure to the disease is more likely (Megahed et al., 2022; van Ingen et al., 2022; Zegarra Zamalloa et al., 2022).

2.2 COVID-19 testing influence on vaccination and prevalence

COVID-19 testing rate is positively associated with the prevalence rate, especially in countries with a high human development index like the U.S. (Assefa et al., 2022). Early in the COVID-19 pandemic, the testing rate also increased as new cases of COVID-19 arose (Rosenberg et al., 2020). Despite limited access to testing kits, the prevalence of the disease emerged in many individuals who reported higher severity of symptoms (Morlock et al., 2021). Individuals who reported to be Black or Hispanic were shown to test for COVID-19 more and receive more positive results at a higher rate than Whites (Rentsch et al., 2020). However, people who lacked health insurance were also more likely not to get tested for COVID-19 while having the highest prevalence of contracting the virus in 2020 (Gaffney et al., 2022).

The testing rate dropped sharply in 2021, while free at-home COVID-19 testing kits were released to the public by the U.S. in 2022 (Kirby et al., 2023; Usher, 2022). Consequently, there were increases in COVID-19 cases throughout 2021 due to the surge of a new variant where the vaccine's potency dwindled, indicating the need for booster shots (Clarke et al., 2022; Johnson et al., 2023). Cases of COVID-19 spread to individuals who were already infected with the virus early in the pandemic (Ma, 2023). Subsequently, the use of home testing kits decreased as the prevalence of COVID-19 went down during the beginning of 2022 (Rader et al., 2022).

The COVID-19 testing rate is inversely related to the vaccination rate, as individuals were less likely to test after being fully vaccinated (Kuitunen et al., 2022). Subsequently, vaccinated individuals were less likely to test for COVID-19 in the early days of receiving their first dose (Pawlowski et al., 2021). Similarly, the lowest testing rate for COVID-19 was among nursing home employees who were fully vaccinated (White et al., 2023). The number of testing positive is lowered as the vaccination rate increases, as shown among veterans (Rudolph et al., 2021). In addition, people were less likely to vaccinate even if they are at more risk for testing positive for COVID-19 (Reynolds et al., 2022).

Multiple studies examining the efficacy of boosters' shots to combat the new COVID variants are that showing that it does prevent potential infections compared to individuals that have not taken the booster (Butt et al., 2022; Drawz et al., 2022; Sharma et al., 2022).

Subsequently, individuals who received multiple booster shots would also be less likely to be hospitalized for COVID-19 (Ferdinands et al., 2022; Havers et al., 2022; Mehta et al., 2022) Individuals who had received the bivalent booster shot had the lowest COVID-19 prevalence during 2021 and onwards (Johnson et al., 2023).

2.3 COVID-19 vaccination influence on prevalence

COVID-19 vaccination is associated with decreasing the number of new cases, as shown in a study conducted in the U.S. (Yamana et al., 2023). Multiple studies have shown that individuals who received the first COVID-19 dose reduced the chances of receiving SARS-CoV infection in risk areas like socially vulnerable communities or surgery (Jones et al., 2021; Prasad et al., 2022). Individuals who are fully vaccinated are associated with lowering the incidence of COVID-19 compared to individuals who were not vaccinated (Redmond et al., 2022). Even individuals infected with COVID-19 are shielded from having an infection again from the virus after fully vaccination (Cavanaugh et al., 2021). Ultimately, full vaccination lowers the prevalence of COVID-19 at a higher rate than partial vaccination amongst hospitalized patients (Maltezou et al., 2023).

The vaccine was associated with reducing the spread of COVID-19 after eight months of receiving all doses, as seen in a study conducted in multiple hospitals (Petráš et al., 2021) However, many studies noted that the effectiveness of the COVID-19 vaccine through a long-term period slowly diminished over time, indicating a need for more booster shots (Machado et al., 2022; Nordström et al., 2022). Subsequently, the COVID-19 vaccine also manages to reduce the risk of COVID-19 spread, but over time, the effect wanes throughout vulnerable communities like hospital patients (L. Y. W. Lee et al., 2022). The rate of COVID-19 reduced new cases of COVID-19, but that waned as new variants emerged (Glatman-Freedman et al., 2022; Kissling et al., 2022). However, one study conducted in the U.S. found that the effectiveness of the vaccine after six months was still high, though infection from COVID-19 was due to diminishing immunity (Tartof et al., 2021).

Literature is sparse with analysis examining the COVID-19 vaccination rate as a mediator for the relationship between socioeconomic factors and the COVID-19 prevalence rate. However, researchers examining the mediating role of a COVID-19 vaccination rate across the U.S. could dramatically decrease the COVID-19 mortality rate amongst individuals at the poverty level (Goto et al., 2023). One study found that the COVID-19 vaccination coverage rate is the mediator between highly socially vulnerable communities and fatal cases by exacerbating the disparity by improper allocation of vaccines (Chen et al., 2022).

3. Study significance and gaps in knowledge

The COVID-19 pandemic was a life-alternating event for millions in the U.S., especially in vulnerable communities who may be at risk of not having access to a home, food, income, transportation, etc. It is essential to distinguish factors related to testing and vaccination rates in socially vulnerable communities to provide them with adequate resources to combat risk from infectious diseases. Thus, the current study aims to determine if COVID-19 testing and vaccination rates mediate SVI and COVID-19 prevalence. Social vulnerability contributed to an excessive number of deaths from COVID-19 in the U.S., underlying the importance of studies that investigate the variables that may magnify the effect of SVI on the COVID-19 prevalence rate (Motairek et al., 2022). This study is the first to examine the relationship between SVI and COVID-19 prevalence rates mediated vaccination rates in Southern Nevada as of this point in time. It is vital to identify the needs of areas by determining what factors lead to health disparities and vaccine hesitancy and eventually promote health literacy within communities to increase vaccination rates. (Dubé et al., 2015). Moreover, studies in the literature review only included factors like mobility, lifestyle, material deprivation, and neighborhood characteristics as mediators in examining the association (Hu et al., 2021; Razieh et al., 2021; Wong et al., 2022; Yoshikawa & Kawachi, 2021). Mediation studies are limited throughout COVID-19 literature despite the effectiveness of exploring mechanisms between variables that can assess the pre-existing needs for deprived areas like access to vaccination sites (Hayes, 2017).

Subsequently, this is the first serial mediation analysis with the COVID-19 vaccination rate and testing rate as sequential mediators for the association between SVI and the COVID-19 prevalence rate. Likewise, analysis examining mediation roles alone for testing and vaccination rates is scarce throughout the literature. An analysis incorporating testing rate is valuable by identifying factors related to low access to testing kits amongst socially vulnerable communities (R. M. Lee et al., 2022). Research related to the CDC's SVI is also minimal, as it may be challenging to apply the variables it takes into consideration to every community for COVID-19. However, this study highlights the importance of the SVI impacting the COVID-19 prevalence rate in census tracts throughout Southern Nevada, considering strains of COVID-19 are still evolving and spreading in the U.S. (Carabelli et al., 2023).

4. Aims and hypothesis

Health disparities are intensified throughout vulnerable communities by the emergence of the COVID-19 pandemic in the U.S. due to a lack of access to healthcare services, transportation, and financial hardship (Freese et al., 2021). Thus, vulnerable areas with high SVI index are usually associated with an increased risk of contracting COVID-19 (Karaye & Horney, 2020). However, whether the relationship is mediated through testing or vaccination rates is unknown due to the lack of research in this area. More studies are needed to examine the mechanisms that explain the pandemic's disproportionate impact on vulnerable communities. The prevalence of COVID-19 has been high in Southern Nevada, especially in socially vulnerable areas compared to other U.S. regions (Wang et al., 2022). It is essential to understand better the effects of the testing and vaccination rates on the prevalence of SVI so that adequate support and resources for vulnerable communities are ready for future infectious outbreaks. Therefore, this study aims to evaluate whether testing or types of vaccination rates mediate the relationship between SVI and COVID-19 prevalence. We also aim to examine whether the testing and vaccination rates for COVID-19 serially mediate the relationship between SVI and COVID-19 prevalence rates.

The following major research questions will be examined:

Research Question #1: Does the COVID-19 testing rate mediate the relationship between the Social Vulnerability Index and COVID-19 prevalence in Southern Nevada?

> *H_0: COVID-19 testing rate does not mediate the relationship between the Social Vulnerability Index and COVID-19 prevalence rate*
>
> *H_A.: COVID-19 testing rate does mediate the relationship between the Social Vulnerability Index and Covid-19 prevalence rate*

Research Question #2: Does the COVID-19 full or follow-up vaccination rate mediate the relationship between the Social Vulnerability Index and COVID-19 prevalence in Southern Nevada?

H_0: COVID-19 full or follow-up vaccination rate does not mediate the relationship between the SVI and COVID-19 prevalence rate

H_A.: COVID-19 full or follow-up vaccination rate does mediate the relationship between the SVI and COVID-19 prevalence rate

Research Question #3: Do the COVID-19 testing and vaccination rates serially mediate the relationship between the Social Vulnerability Index and COVID-19 prevalence in Southern Nevada?

H_0: COVID-19 testing and vaccination rates do not serially mediate the relationship between the SVI and COVID-19 prevalence rate

H_A.: COVID-19 testing and vaccination rates do serially mediate the relationship between the SVI and COVID-19 prevalence rate

5. Methodology

5.1 Study design

The study utilizes secondary data following a cross-sectional design, including 535 census tracts in Clark County of Nevada via COVID-19 and SVI data. COVID-19 data for testing, vaccination, and prevalence are accessible through reports from Southern Nevada Health Districts. The current study cross-sectionally analyzes the comprehensive data regarding SVI and COVID-19 in U.S. census tracts (Setia, 2016). All COVID-19 data were accumulated from January 2020 to June 2022. The purpose of compiling this data was to better understand the spread, whether enough testing or vaccination happened in Southern Nevada, the risk of being infected with COVID-19, and to assess the vulnerability of Southern Nevada census tracts. The CDC prepared SVI data utilized for this study, and this index has been updated biannually since 2010 (CDC, 2022).

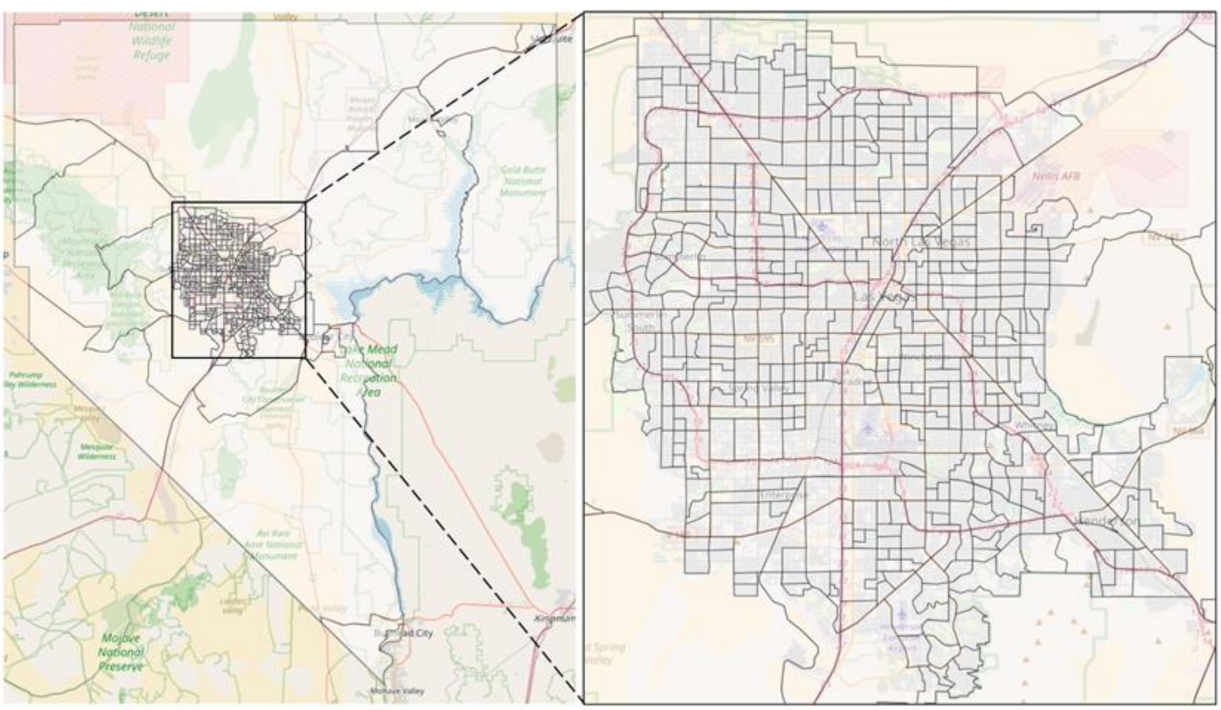
5.2 Ethics

The Office of Research Integrity at the University of Nevada, Las Vegas, did not review the study. The study does not include human subjects since it comprises cumulatively aggregated by census tract. Thus, institutional review board approval was unnecessary as data was accessible online via the CDC website. The confidentiality regarding vaccination, testing, or diagnosis of COVID-19 is protected since the dataset used tract-level FIPS codes for the geographic areas.

5.3 Study Area

The study area revolves around the largest county in Southern Nevada and is the place of residence for over two million individuals. Clark County was created in 1909 and is one of the most heavily populated counties in the U.S. (Borden & Lednicky, 2021). Clark County consists of multiple ethnicities and contains more than seventy percent of the entire Nevada population (Borden & Lednicky, 2021). The Las Vegas metro area contains over 800,000 households and is the base of a flourishing tourism industry (Census Reporter, n.d.). The exact study area focused on will be in Clark County, the Las Vegas metropolitan area. It includes three major cities in Southern Nevada: Henderson, North Las Vegas, and Las Vegas, with the boundaries via census tracts displayed in Figure 1 (Encylcopedia Britannica, n.d.).

Figure 1. Census tract boundaries in Clark County, NV



5.4 Study instrument and data collection

The SVI data in 2020 comes from a federal agency that utilized U.S. census variables to develop the SVI via its Geospatial Research, Analysis, and Services program. The purpose was to distinguish vulnerable communities and provide more support to them when they face catastrophic events like infectious outbreaks (Flanagan et al., 2011). The SVI ranks the social vulnerability of each census tract within the U.S. based on 16 social variables (CDC, 2022). The information used to update the SVI from multiple databases such as the U.S. Bureau Census, Tribal database, and more (CDC, 2022). The current study utilizes the relative social vulnerability rankings of Southern Nevada.

The University of Nevada, Las Vegas faculty compiled the COVID-19 dataset from 2020 to 2021 and is utilized for this current study. The FIPS state and county, leading to the census tract code, served as the unit for aggregating the geocoded COVID-19 testing, vaccination, and prevalence rates. As geocoding may not be entirely accurate, the current study utilizes only data with 100% address matching and verification through ESRI and SMARTY geocoding services (Esri, n.d.; Smarty, n.d.). ESRI and SMARTY provide geographic info databases that can verify addresses' existence and identify their coordinates. About 95% of incidence, vaccination, and testing records combined were confidently geocoded with a matching score of 100%.

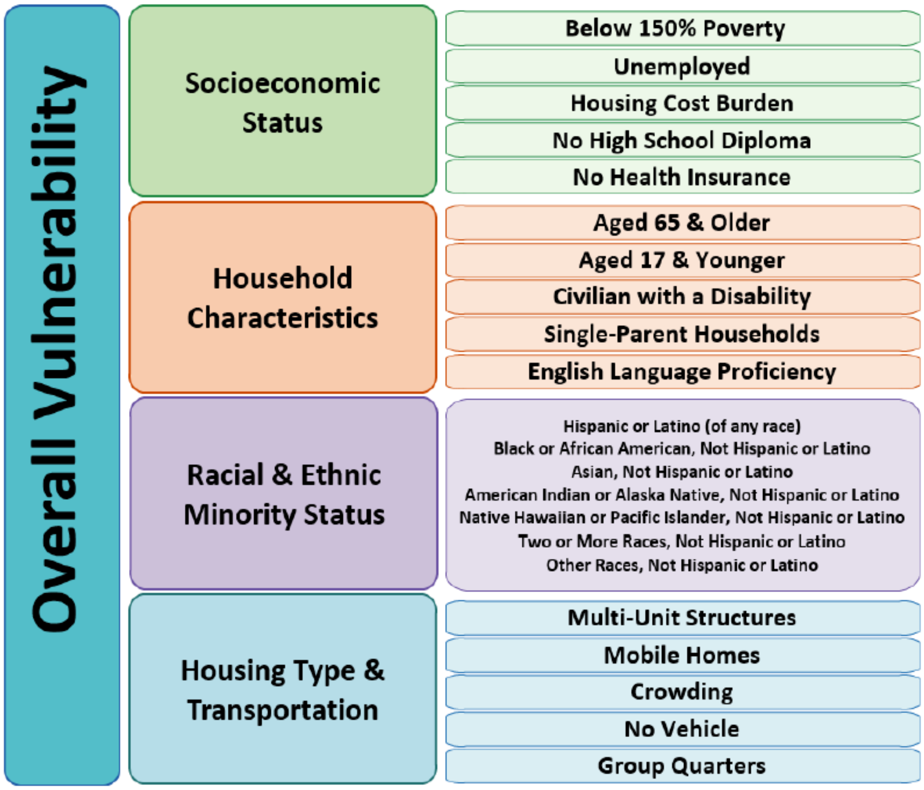
5.5 Variable definitions

5.5.1 Main dependent variable and predictor

The main dependent variable is the COVID-19 prevalence rate, which will be later log-transformed. It will also be age-adjusted by the county's populations through categories of 0-4, 5-17, 18-24, 25-49, 50-64, 65+ year-old. The main predictor for this study is the SVI as originally developed by the CDC and Agency of Toxic Substances and Disease Registry's Geospatial Research, Analysis, and Services Program (Flanagan et al., 2011). SVI is utilized to rank census tracts on sixteen social condition variables that relate to socioeconomics and individual characteristics like ethnicity (Agency for Toxic Substances and Disease Registry, 2022). The 16 variables that make up the SVI are displayed in Figure 2.

These 16 social variables are 5-year estimates from the American Community Survey from 2016 to 2020 and attributed to four themes in terms of household characteristics, racial and minority status, housing type and transportation, and socioeconomic status (Agency for Toxic Substances and Disease Registry, 2022; U.S. Census Bureau, 2016). The estimates are later on converted to percentile ranks and the summation of these percentile ranks from all of the social variables is the SVI (Agency for Toxic Substances and Disease Registry, 2022). The purpose

Figure 2. SVI 16 variables and 4 themes. Reprinted from CDC SVI Documentation 2020 by Agency for Toxic Substances and Disease Registry. Retrieved from https://www.atsdr.cdc.gov/placeandhealth/svi/documentation/SVI_documentation_2020.html



behind these variables was to distinguish populations that may be socially vulnerable to be aware of potential adverse events and how to prepare for it (Agency for Toxic Substances and Disease Registry, 2022; Flanagan et al., 2011).

5.5.2 Mediators

The mediators for the study are the COVID-19 testing rate, full vaccination rate, and follow-up vaccination rate, which are all age-adjusted and log-transformed. Full vaccination includes individuals who received two COVID-19 vaccine doses. In contrast, follow-up vaccination is booster doses for COVID-19 administered after the full vaccination.

5.5.3 Covariates

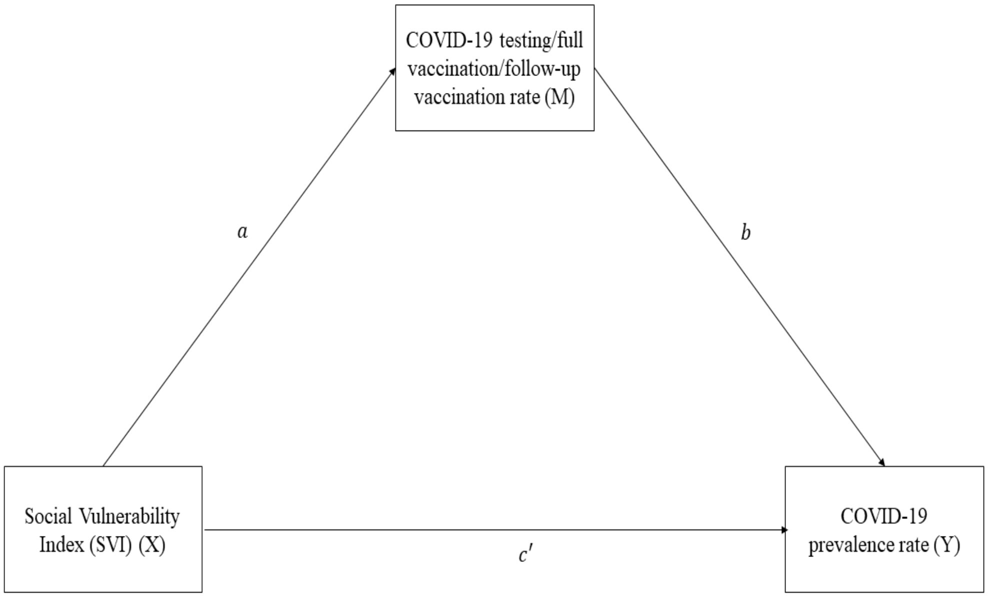
Covariates related to COVID-19 were incorporated into the study as well. These covariates include inactive commuting, park deprivation, retail density, housing inadequacy, segregation, and population density. These covariates fill specific gaps not covered in SVI while not violating multicollinearity, such as inactive commuting. Inactive commuting is the percentage of individuals who are 16 or older and go to work without using transit, cycling, or walking. Park deprivation is the percentage of the population residing more than half a mile from a park beach or open space larger than 1 acre. Retail density is the employment density of retail, entertainment, services, and education jobs acre on unprotected land. Housing inadequacy is the percentage of households that lack kitchen facilities and plumbing. Segregation is the index of dissimilarity (Krieger et al., 2017). The index estimates the unequal spread of the selected subgroups in the areas where a low score indicates the same amount of both groups, and high scores indicate that the social groups do not reside in the area together (Krieger et al., 2017). Lastly, population density is simply the number of inhabitants divided by the area in square miles. All of the raw data will be downloaded from the American Community Survey, Smart Location Database, and the U.S. Department of Housing and Urban Design. These covariates will be transformed into percentile ranks like those social condition variables in the SVI.

5.6 Statistical analyses

The study acquired descriptive statistics by utilizing the percentile of census tracts to compute the coefficient of the linear regression between the SVI mediators (i.e., COVID-19 testing and vaccination rates) and the COVID-19 prevalence rate. The sample was from 535 census tracts within the Las Vegas Metro area in Southern Nevada, with over 2 million individuals of diverse ethnic composition (Census Reporter, n.d.). Multiple studies highlight SVI's existing relationship with the COVID-19 prevalence rate, as shown in the current study literature review. The covariates included in this study were more likely to be related to the SVI and influence the COVID-19 prevalence rate.

Mediation analyses assessed the effect between the predictor and dependent variables via a third variable utilized by the current study to answer whether testing and vaccination rates mediate the association between SVI and the COVID-19 prevalence rate. These statistical methods test hypotheses regarding not only how the SVI affects the dependent variable but also how it transmits its influence onto the COVID-19 testing rate or vaccination rate, causing variation in the COVID-19 prevalence rate, as shown in Figure 3. The conceptual diagram for the mediational analysis conducted for the current study is displayed below in Figure 3.

Figure 3. Conceptual diagram of research question 1 & 2



The linear regression equations for the mediation analysis are:

Model 1. $M_1 = i_{M_1} + aX + \sum_{i=1}^{6} \gamma_i Covariate_i + e_M$

$$Y = i_Y + c' X + bM_1 + \sum_{i=1}^{6} \gamma_i Covariate_i + e_Y$$

Model 2. $M_2 = i_{M_2} + aX + \sum_{i=1}^{6} \gamma_i Covariate_i + e_M$

$$Y = i_Y + c' X + bM_2 + \sum_{i=1}^{6} \gamma_i Covariate_i + e_Y$$

Model 3. $M_3 = i_{M_3} + aX + \sum_{i=1}^{6} \gamma_i Covariate_i + e_M$

$$Y = i_Y + c' X + bM_3 + \sum_{i=1}^{6} \gamma_i Covariate_i + e_Y$$

, where

Y = log-transformed COVID-19 age-adjusted prevalence

X = SVI

M_1 = log-transformed COVID-19 age-adjusted testing rate

M_2 = log-transformed COVID-19 age-adjusted full vaccination rate

M_3= log-transformed COVID-19 age-adjusted follow-up vaccination rate

$Covariate_i$ = the i^{th} covariate

$(i_{M_1},\ i_{M_2}, i_{M_3,}\ i_Y)$ = regression intercepts

$(a, b, c',\ \gamma_i)$ = regression slopes

(e_M, e_Y) = error terms

The methodology behind computing all the unknown parameters, total, direct, and indirect effects, is the ordinary least squares regression, which determined the linear relationship of the SVI and COVID-19 prevalence rate by reducing deviation between the sum of squares' difference between data points of COVID-19 prevalence rate versus estimated values. The SVI's direct, indirect, and total effects via testing and vaccination rate were further analyzed. The direct effect is how two cases differ by one unit on the SVI diverge by yielded c' units on the COVID-19 prevalence rate with the mediator held constant. The indirect effect is computed from the product of a and b, which can be explained as ab units differ on the COVID-19 prevalence rate via the mediator when two cases differ by a single unit on SVI. The total effect is denoted as c, which is equal to the sum of the direct and indirect effects of SVI (i.e., $c = c' + ab$). The total effect quantifies how much two values deviate by one unit on the SVI are estimated to differ on the COVID-19 prevalence rate.

The confidence intervals derived from the linear regression are procured for the indirect effect from the mediators (e.g., COVID-19 testing rate, prevalence rate, vaccination rate) with bootstrapping due to sample distribution's nonuniformity regarding the product ab. The steps for bootstrapping follow the same usual resampling technique regarding sampling a dataset;

however, the percentile bootstrapping for the indirect effects are ranked from low to high while estimating upper and lower bounds of the confidence interval from these equations:

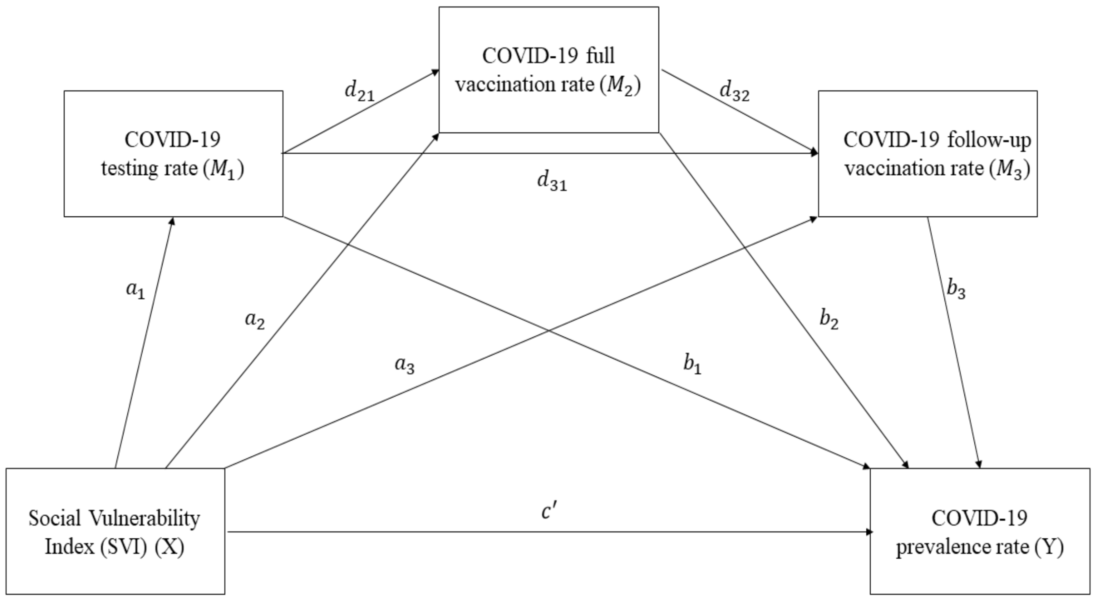
$$\text{Upper bound: } 0.005(100 - ci)]$$

$$\text{Lower bound: } k[1 - 0.005(100 - ci)]$$

, where ci is the selected confidence interval, and k represents the number of times the original sample was bootstrapped, which was set to 5,000 in this study (Hayes, 2017).

Serial mediation analyses test for the same effects but involve more than one mediator in a sequential order; thus, the current study analyzed whether the SVI effect transmitted to the COVID-19 testing rate, then to the COVID-19 full vaccination rate, and then to the follow-up rate effect on to the COVID-19 prevalence rate. The sequential order of the serial mediation analysis is justified that the prevention of COVID-19 infections is through testing and obtaining vaccination. Individuals who test are more likely to receive the vaccination to prevent infection from COVID-19. Thus, the first mediator, COVID-19 testing rate, will come before the second mediator, COVID-19 full vaccination rate. Subsequently, COVID-19 follow-up vaccination rate will come next in the sequential order since this can only be obtained if the individual receive two doses of the vaccine. The current study conceptual diagram for the serial mediation analysis is displayed in Figure 4.

Figure 4. Conceptual diagram of research question 3



The linear regression equations for the serial mediation analyses are:

Model 4. $M_1 = i_{M_1} + a_1X + \sum_{i=1}^{6} \gamma_i Covariate_i + e_{M_1}$

$$M_2 = i_{M_2} + a_2X + d_{21}M_1 + \sum_{i=1}^{6} \gamma_i Covariate_i + e_{M_2}$$

$$M_3 = i_{M_3} + a_3X + d_{31}M_1 + d_{32}M_2 + \sum_{i=1}^{6} \gamma_i Covariate_i + e_{M_3}$$

$$Y = i_Y + c'X + b_1M_1 + b_2M_2 + b_3M_3 + \sum_{i=1}^{6} \gamma_i Covariate_i + e_Y$$

, where

Y = log-transformed COVID-19 age-adjusted prevalence

X = SVI

M_1 = log-transformed COVID-19 age-adjusted testing rate

M_2 = log-transformed COVID-19 age-adjusted full vaccination rate

M_3= log-transformed COVID-19 follow-up vaccination rate

$Covariate_i$ = the i^{th} covariate

$(i_{M_1}, i_{M_2}, i_{M_3}, i_Y)$ = regression intercepts

$(a_1, a_2, a_3, b_1, b_2, b_3, d_{21}, d_{31}, d_{32}, \gamma_i)$ = regression slopes

(e_M, e_Y) = error terms

The methodology for computing the effects and unknown parameters of serial mediation analysis is the same as that of simple mediation analysis. However, its indirect effects depend on three mediators. The computation for the indirect effects (e.g., ab) is by multiplying the values of the regression coefficients related to each step within the indirect effect pathway by SVI towards the COVID-19 testing rate and sequentially to the COVID-19 vaccination rate. They are depicted as estimated differences in the COVID-19 prevalence between two cases that differ by one unit on SVI through the previously mentioned sequential order to the mediators and then the prevalence rate. Finally, the total number of the indirect effect is cumulatively summed as the SVI's total indirect effect, and the direct effect is summed for the total effect of the serial mediation model.

Model selections were especially conducted in the serial mediation model for deriving significant findings in the total, direct, and indirect effects (total and individual) by considering all combinations among covariates starting from single covariate to all six covariates. Subsequently, a model with the most significant total, direct, and total indirect effects is sought out as it indicates the pathways between SVI and COVID-19 prevalence rates work through the serial mediators. A lack of significance through the direct effect would highlight that the entire model should be changed, as there is no association between SVI and the COVID-19 prevalence rate. A lack of significant total effect (i.e., the sum of direct and indirect effects) and total indirect effect (i.e., the sum of all mediator’s effects simultaneously) would indicate that the effect from SVI and COVID-

19 is not carried through the serial mediators; thus, only partial or lack of mediation. The absence of a significant individual indirect effect pathway (e.g., COVID-19 testing rate -> COVID-19 full vaccination rate) shows that the effect for mediating SVI and COVID-19 prevalence is not carried out through one of the mediators in the serial mediation analysis. Additionally, the lack of pathways being significantly associated is another sign that no serial mediation is happening. The serial mediation effect tables display the significant status of all effects with all combinations from no covariate to six covariates to find the most significant model (see Appendix Table A1~Table A7). A serial mediation model analyzed in SAS with three covariates displayed the most significant values for the total, direct, total indirect, and one indirect individual effect of -0.02 with 95% CI = -0.04, -0.01 strictly less than 0 (see Appendix Table A4). Every other analyzed model through PROCESS macro, including 0,1,2,4,5,6 covariates, displayed fewer significant values. Thus, the serial mediation model with mediators COVID-19 testing rate, COVID-19 full vaccination, COVID-19 follow-up vaccination, and covariates park deprivation, retail density, and segregation was selected.

The estimated coefficient for these variables, like COVID-19 prevalence, testing, and vaccination rates, were derived from the log-log regressions. A log-log regression is a regression analysis that will change the values on the dataset to be linearized and displayed on a logarithmic scale. The reason why our model is a log-log regression is because each variable, such as the COVID-19 prevalence rate, COVID-19 testing rate, COVID-19 full vaccination rate, and COVID-19 follow-up vaccination, is log-transformed to adjust and remove influence from outliers. The log-log regression computes the coefficient from this as it is the approximated percent change in the COVID-19 prevalence through the percent change in the mediators. Meanwhile, a 1% increase in the mediators will lead to a β% increase in the expected COVID-19 prevalence. The beta or coefficient indicates the estimated average change in our dependent variable, the COVID-19 prevalence rate, by the unit change in SVI.

The assumptions for all linear regression models were also tested. Linearity was checked regarding the COVID-19 prevalence being linearly related to SVI by checking if the plots displayed a nonlinear pattern. The Durbin-Watson statistic, Shapiro-Wilk, and White tests via SAS tested the independence, normality, and equal variance assumptions. A p-value of less than 0.05 for each test indicates the violation of corresponding model assumptions. Multicollinearity was also checked to rule out whether SVI was highly correlated with the other variables, where the variance inflation factor (VIF) with a value of over ten indicates the existence of multicollinearity.

The significance level for these associations was set to 0.05. SAS Studio Online (SAS Institute Inc., NC, Cary) was used to conduct all the mediation and serial mediation analyses via the PROCESS macro (Hayes, 2017).

6. Results

6.1 Descriptives

COVID-19 prevalence rate ranged from 4.40 to 989.26 cases per 1,000 people, where the average was 233.45 cases per 1,000 people (Standard deviation [SD] = 78.58). COVID-19 testing rates ranged from 49.86 to 12476.19 cases per 1,000 people, where the average was 1851.3 tests per 1,000 people (SD = 757.59). The COVID-19 full vaccination rate ranged from 45.70 to 17371.41 vaccinations per 1,000 people, with an average of 611.49 cases per 1,000 people (SD = 808.93). However, there were two outliers for the COVID-19 full vaccination rate (17371.41 and 7927.198 vaccinations per 1,000 people), which may be due to the free accessibility to the vaccine to even individuals who are not residents and staying in the strip of Las Vegas. The COVID-19 follow-up vaccination rate ranged from 0.00 to 1270.61 cases per 1,000 people, with an average of 281.26 per 1,000 people (SD = 124.75).

Summary statistics for the 16 social condition variables are shown in Table 1. The SVI ranged from 1.45 across to 13.33 percentile rankings, where the average was 7.79 percentile rankings (SD = 2.55). The correlation matrix bivariate relationships can be found below in Table 2. There were several significant correlations amongst the COVID-19 and SVI measures, where significantly negative correlations coefficients were -0.26 between SVI and COVID-19 testing rate (95% CI = -0.33, -0.18).

Figure 5. Geospatial distribution of SVI and COVID-19 measures

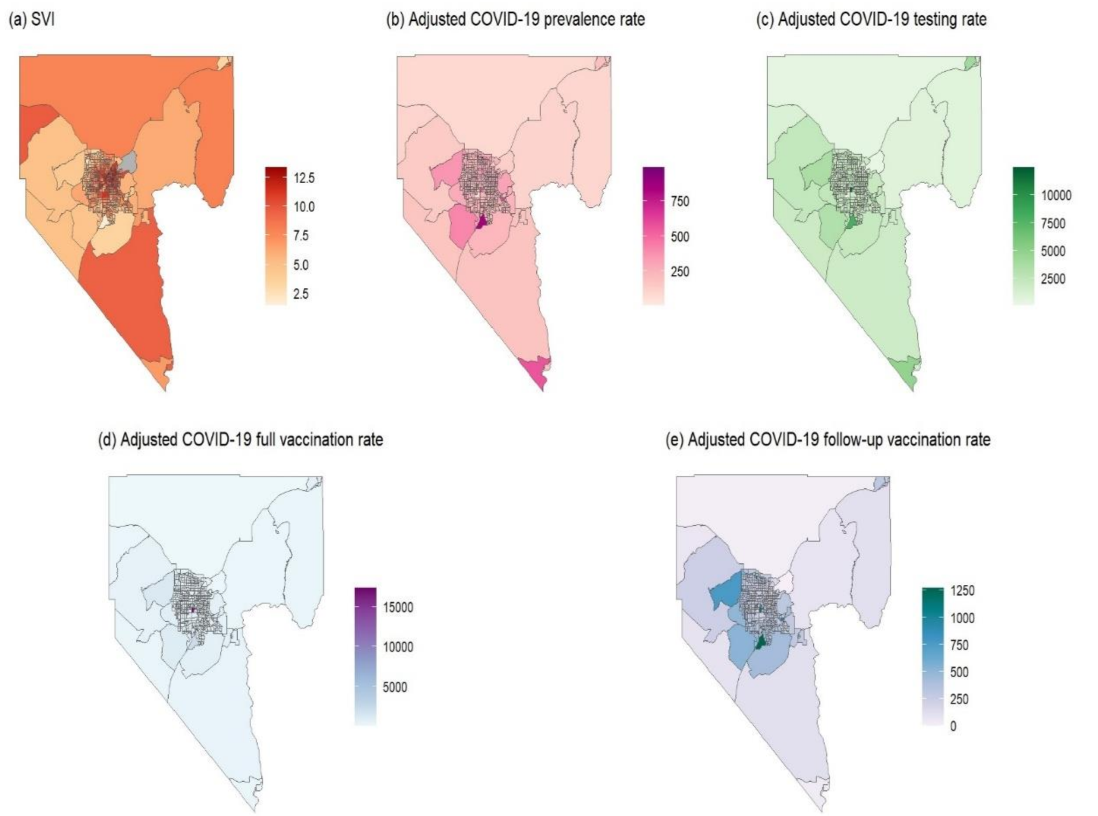


Table 1. Summary statistics of the SVI and COVID-19 measures

Variable	Mean	SD	Min	Q1	Median	Q3	Max
SVI	7.79	2.55	1.45	5.74	7.64	9.90	13.33
COVID-19 Prevalence rate	233.45	78.58	4.40	193.29	224.66	260.02	989.26
COVID-19 testing rate	1851.30	757.59	49.86	1558.21	1756.14	1995.45	12476.19
COVID-19 full vaccination rate	611.49	808.93	45.70	492.57	546.36	616.19	17371.41
COVID-19 follow-up vaccination rate	281.26	124.75	0.00	213.89	260.92	323.84	1270.61

Abbreviation: SVI = Social Vulnerability Index; SD = Standard deviation; Q1 = First quartile;

Q3 = Third quartile

Subsequently, the correlation coefficient of -0.13 between SVI and COVID-19 full vaccination rate (95% CI = -0.21, -0.04) and -0.58 between SVI and COVID-19 follow-up vaccination rate (95% CI = -0.63, -0.52) were shown in Table 2. In addition, the COVID-19 prevalence rate was positively and moderately associated with COVID-19 testing, vaccination, and follow-up vaccination rates with a correlation coefficient of 0.78 (95% CI = 0.75, 0.81), 0.31 (95% CI = 0.24, 0.39), and 0.55 (95% CI = 0.48, 0.60), respectively. The COVID-19 testing rate was highly associated with the COVID-19 full vaccination rate, where the correlation coefficient was 0.71 (95% CI = 0.66, 0.75), and the COVID-19 follow-up vaccination rate, where the correlation coefficient was 0.72 (95% CI = 0.67, 0.75). Lastly, the COVID-19 full vaccination rate was also moderately and positively associated with the follow-up vaccination, as shown by the coefficient of 0.52 (95% CI = 0.46, 0.58).

Table 2. Pearson's correlation among the SVI and log-transformed COVID-19 measures

Variable	COVID-19 prevalence rate	COVID-19 testing rate	COVID-19 full vaccination rate	COVID-19 follow-up vaccination rate
SVI	-0.07 (-0.15, 0.02)	-0.26 (-0.33, -0.18)	-0.13 (-0.21, -0.04)	-0.58 (-0.63, -0.52)
COVID-19 Prevalence rate	-	0.78 (0.75, 0.81)	0.31 (0.24, 0.39)	0.55 (0.48, 0.60)
COVID-19 testing rate	-	-	0.71 (0.66, 0.75)	0.72 (0.67, 0.75)
COVID-19 full vaccination rate	-	-	-	0.52 (0.46, 0.58)

Abbreviation: SVI = Social Vulnerability Index

6.2 Mediation Analysis of COVID-19 testing rate as mediator

After removing missing data, the mediation analysis for research question one examined 534 samples for COVID-19 testing as the mediator of the relationship between SVI and COVID-19 prevalence rate. SVI was found to be significantly inversely associated with COVID-19 testing rate. Figure 6 shows that, after controlling all covariates, SVI significantly decreased the adjusted COVID-19 testing rate by -47.04 cases per 1,000 people (95% CI = -82.98, -11.11; p-value = 0.0104) on average. Subsequently, the adjusted COVID-19 testing rate was found to be a significant mediator over SVI and COVID-19 prevalence rate. Moreover, a 1% increase in the adjusted COVID-19 testing rate significantly increased 0.08% (95% CI =0.08, 0.09; p-value < 0.0001) in the adjusted COVID-19 prevalence rate. This indicates that the adjusted COVID-19 testing rate is proportionately related to the adjusted COVID-19 prevalence rate, where there is more testing among infected individuals. The indirect effect was -3.98 with a 95% CI = (-7.43, -0.11) strictly lower than 0, proving the testing rate to be a significant mediator.

Figure 6. Diagram of COVID-19 testing rate as mediator. Parentheses show 95% confidence intervals.

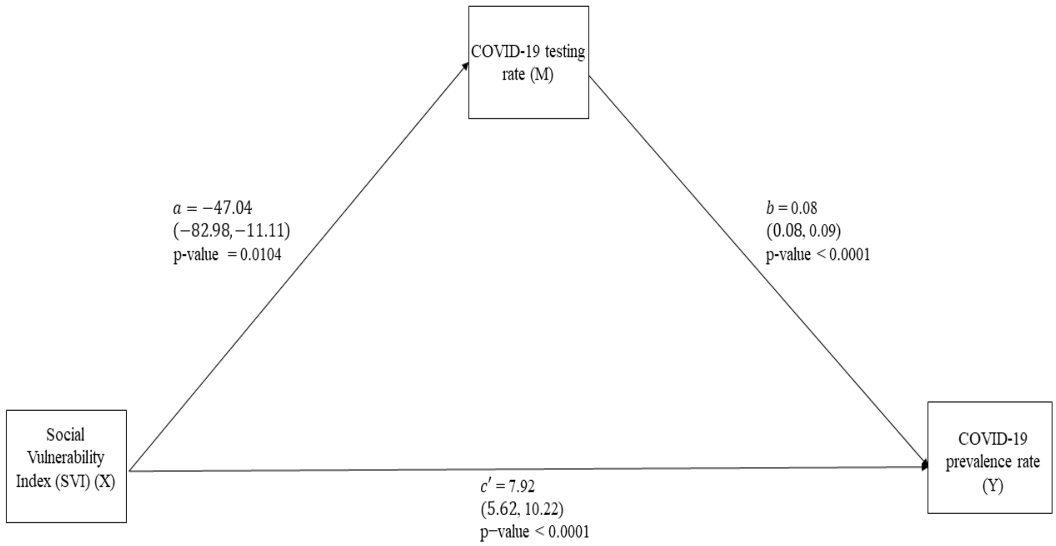


Table 3. Mediation analysis of the adjusted COVID-19 testing rate as the mediator between the SVI and adjusted COVID-19 prevalence rate.

Path[§]	Effect[§§]	95% CI	P-value
Total Effect (c)	3.94	(0.14, 7.74)	0.0423
Direct Effect (c')	7.92	(5.62, 10.22)	< 0.0001
a	-47.04	(-82.98, -11.11)	0.0104
b	0.08	(0.08, 0.09)	< 0.0001
Indirect effect (ab)	-3.98	(-7.43, -0.11)	-

§ a: SVI → Adjusted COVID-19 testing rate. b: Adjusted COVID-19 testing rate → Adjusted COVID-19 prevalence rate.
§§ All effects were adjusted by covariates.
Abbreviation: CI = Confidence interval

Subsequently, both of the direct effect (7.92; 95% CI = 5.62, 10.22; p < 0.0001) and total effect (3.94; 0.14, 7.74; p = 0.0423) were all positively significant, shown in Table 3.

Several covariates were found to be statistically significant and associated with the mediation model regarding testing rate as a mediator, such as segregation (p-value = 0.0009), population density (p-value < 0.0001), park deprivation (p-value = 0.0141), and retail density (p-value < 0.0001).

Overall, the mediating effect for this effect from COVID-19 testing rate towards SVI and COVID-19 prevalence was statistically significant. Therefore, to answer the hypothesis for the first research question, "Does the COVID-19 testing rate mediate the relationship between the Social Vulnerability Index and COVID-19 prevalence in Southern Nevada?", the null hypothesis is rejected to conclude that '*COVID-19 testing rate does mediate the relationship between the Social Vulnerability Index and Covid-19 prevalence rate.'*

6.3 COVID-19 full and follow-up vaccination rate as a mediator

Similarly to the previous research question, research question 2 regarding full vaccination rate as mediator analyzed 534 samples for the relationship between SVI and COVID-19 prevalence. After controlling all covariates, the SVI was found to be significantly inversely related to the adjusted COVID-19 full vaccination by -59.00 cases per 1,000 people (95% CI = -98.78, -19.23; p-value = 0.0037) on average as shown in Figure 7. Additionally, Table 5 displays the adjusted COVID-19 full vaccination rate significantly mediating the relationship between the SVI and the adjusted COVID-19 prevalence rate. Since a 1% increase in the adjusted COVID-19 full vaccination rate significantly increases 0.03% (95% CI = 0.02, 0.04; p-value < 0.0001) in the adjusted COVID-19 prevalence rate. Another sign of the adjusted COVID-19 full vaccination being a significant mediator is through the indirect effect being -1.88 with a 95% CI = (-7.54, -0.95) strictly less than 0. In addition, both the direct effect (5.82; 95% CI = 2.20, 9.43; p-value = 0.0017) and the total effect (3.94; 95% CI = 0.14, 7.74; p-value = 0.0423) were positively significant, shown in Table 4.

Figure 7. Diagram of COVID-19 full vaccination rate as mediator. Parentheses show 95% confidence intervals.

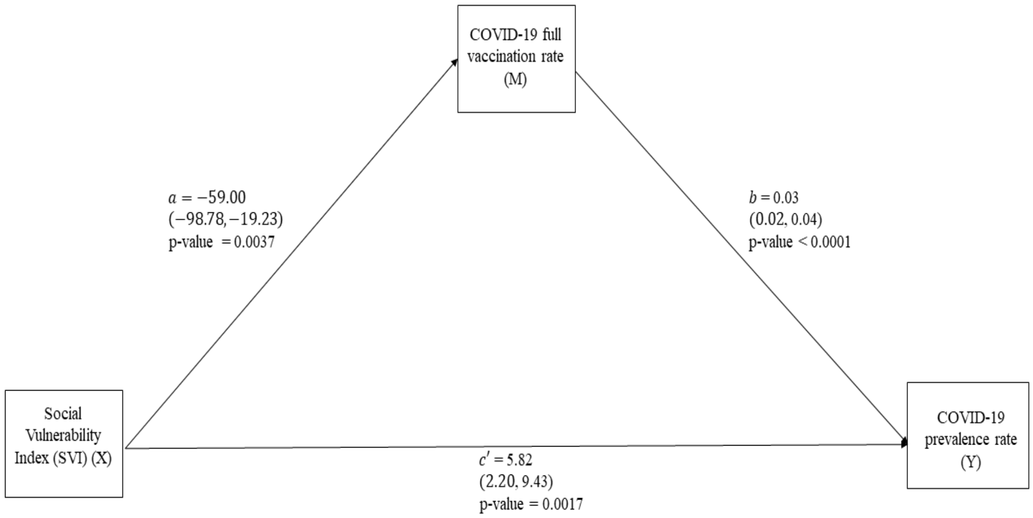


Table 4. Mediation analysis of the adjusted COVID-19 full vaccination rate as the mediator between the SVI and adjusted COVID-19 prevalence rate.

Path[§]	Effect[§§]	95% CI	P-value
Total Effect (c)	3.94	(0.14, 7.74)	0.0423
Direct Effect (c')	5.82	(2.20, 9.43)	0.0017
a	-59.00	(-98.78, -19.23)	0.0037
b	0.03	(0.02, 0.04)	< 0.0001
Indirect effect (ab)	-1.88	(-7.54, -0.95)	-

§ a: SVI → Adjusted COVID-19 full vaccination rate. b: Adjusted COVID-19 full vaccination rate → Adjusted COVID-19 prevalence rate.
§§ All effects were adjusted by covariates.
Abbreviation: CI = Confidence interval

There were a couple of covariates were found to be statistically significant associated with mediation model regarding full vaccination rate as a mediator such as park deprivation (p-value = 0.0309), retail density (p-value = 0.0069), segregation (p-value = 0.0496) and population density (p-value = 0.0076). Other covariates significantly associated with the mediation model with COVID-19 prevalence rate included retail density (p-value < 0.0001), segregation (p-value = 0.0114), and population density (p-value = 0.0205).

The mediation analysis for research question two regarding follow-up vaccination rate was also examined within 534 samples for SVI and COVID-19 prevalence rate association. After controlling all covariates, SVI was significantly associated with decreasing the COVID-19 follow-up vaccination rate by -24.10 cases per 1,000 people (95% CI = -29.07, -19.13; p-value < 0.0001) and significantly associated with increasing the COVID-19 prevalence rate by 15.46 cases per 1,000 people (95% CI = 12.25, 18.68; p-value < 0.0001) as shown in Figure 8.

Moreover, a 1% increase in the adjusted COVID-19 follow-up vaccination rate significantly increased the adjusted COVID-19 prevalence rate by 0.48% (95% CI = 0.43, 0.53;

Figure 8. Diagram of COVID-19 follow-up vaccination rate as a mediator. Parentheses show 95% confidence intervals.

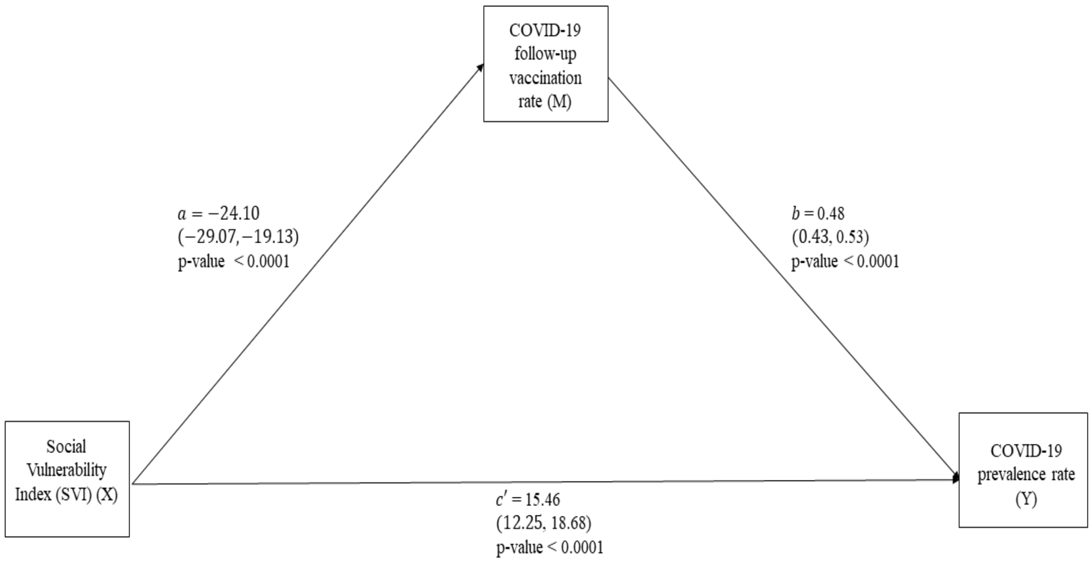


Table 5. Mediation analysis of the adjusted COVID-19 follow-up vaccination rate as the mediator between the SVI and adjusted COVID-19 prevalence rate.

Path§	Effect§§	95% CI	P-value
Total Effect (c)	3.94	(0.14, 7.74)	0.0423
Direct Effect (c')	15.46	(12.25, 18.68)	< 0.0001
a	-24.10	(-29.07, -19.13)	< 0.0001
b	0.48	(0.43, 0.53)	< 0.0001
Indirect effect (ab)	-11.52	(-15.97, -6.49)	-

§ a: SVI → Adjusted COVID-19 follow-up vaccination rate. b: Adjusted COVID-19 follow-up vaccination rate → Adjusted COVID-19 prevalence rate.
§§ All effects were adjusted by covariates.
Abbreviation: CI = Confidence interval

p-value < 0.0001). The COVID-19 follow-up vaccination rate was proved to be a significant mediator as its indirect effect was -11.52 with a 95% CI = (-15.97, -6.49) strictly lower than 0 (Table 5). Furthermore, both the direct effect (15.46; 95% CI = – 12.25, 18.68; p-value < 0.0001) and total effect (3.94; 95% CI = 0.14, 7.74; p-value = 0.0423) were positively significant.

Few covariates were found to be statistically significant associated with the mediation model regarding follow-up vaccination rate as a mediator, such as park deprivation (p-value = 0.0001), segregation (p-value = 0.0040), and population density (p-value = 0.0002). However, the covariates associated with the mediation analysis with the COVID-19 prevalence rate variable was only retail density (p-value < 0.0001).

Overall, the mediating effect from COVID-19 full/follow-up vaccination rate towards SVI and COVID-19 prevalence was statistically significant. Therefore, to answer the hypothesis for the second research question, "Does the COVID-19 full/follow-up vaccination rate mediate the relationship between the Social Vulnerability Index and COVID-19 prevalence in Southern Nevada?", the null hypothesis is rejected to conclude that '*COVID-19 full/follow-up vaccination rate does mediate the relationship between the Social Vulnerability Index and Covid-19 prevalence rate.'*

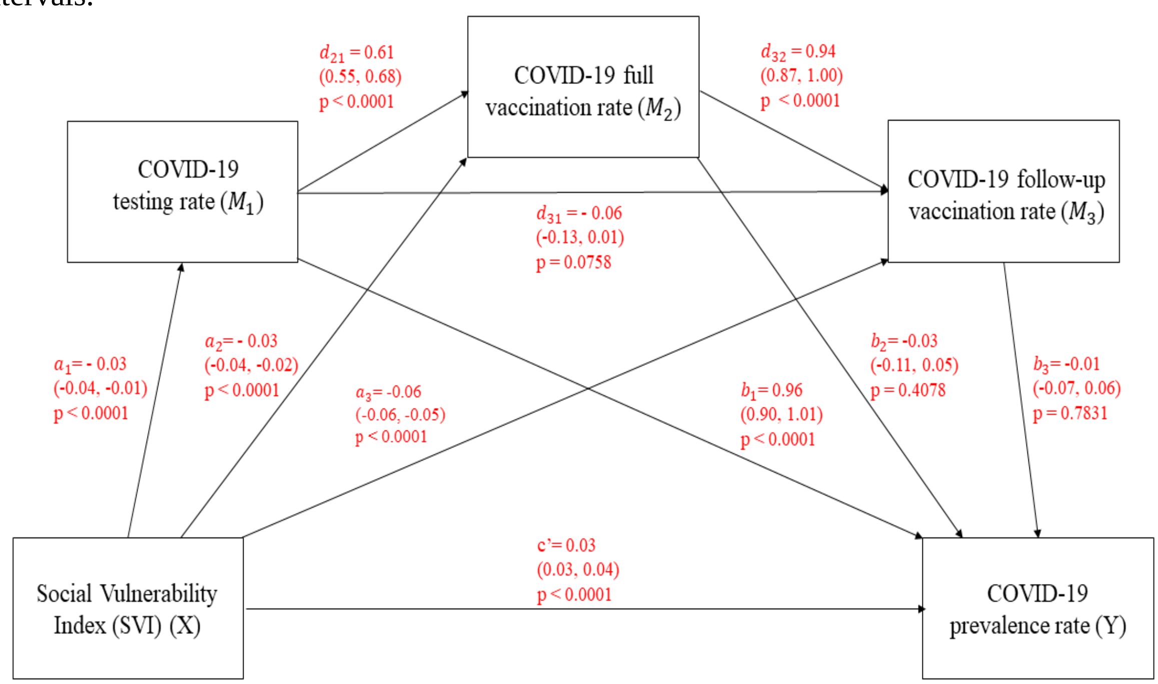
6.4 Serial mediators COVID-19 testing and vaccination rates

Now on to the third research question for serial mediation, where 534 samples are analyzed amongst COVID-19 testing rate, COVID-19 full vaccination rate, and COVID-19 follow-up vaccination rates as mediators over the association between SVI and COVID-19 prevalence rate. A unit change in the SVI was found to be significantly inversely associated with decreasing the COVID-19 testing rate by -0.03 cases per 1,000 people (95% CI = -0.04, -0.01; p-value <

0.0001), as shown in Figure 9. Similarly, SVI was significantly inversely associated with decreasing the COVID-19 full vaccination rate by -0.03 cases per 1,000 people (95% CI = -0.04, -0.02; p-value < 0.0001), as shown in Table 6. Subsequently, SVI was inversed significantly associated with decreasing COVID-19 follow-up vaccination rate by -0.06 cases per 1,000 people (95% CI = -0.06, -0.05; p-value < 0.0001). Lastly, SVI was positively significantly associated with increasing COVID-19 prevalence by 0.03 cases per 1,000 people (95% CI = 0.03, 0.04; p-value < 0.0001).

A 1% increase in the first mediator (i.e., adjusted COVID-19 testing rate) significantly increased the adjusted COVID-19 full vaccination rate and prevalence rate by 0.61% (95% CI = 0.55, 0.68; p-value < 0.0001) and 0.96% (95% CI = 0.90, 1.01; p-value < 0.0001), respectively. However, there was no significant association between the adjusted COVID-19 testing rate and

Figure 9. Diagram of the Serial mediation analysis. Parentheses show 95% confidence intervals.



-0.02; p-value < 0.0001), as shown in Table 6. Subsequently, SVI was inversed significantly associated with decreasing COVID-19 follow-up vaccination rate by -0.06 cases per 1,000

the follow-up vaccination rate. Moreover, a 1% increase in the second mediator (i.e., adjusted COVID-19 full vaccination rate) was significantly positively associated with increasing the adjusted COVID-19 follow-up vaccination rate by 0.94% (95% CI = 0.9, 1.00; p-value < 0.0001). Subsequently, full vaccination and follow-up vaccination rates were found to be not significantly associated with the COVID-19 prevalence rate.

The serial mediation analysis for COVID-19 testing rate, COVID-19 full vaccination rate, and COVID-19 follow-up vaccination rate total indirect effect was significant as it was -0.02 with a 95% CI = (-0.03, -0.002) strictly less than 0, shown in Table 6. However, only one individual indirect effect was significant for the serial mediation analysis, as shown in Table 6. In addition, both the direct effect (0.03; 95% CI = 0.03, 0.04; p-value < 0.0001) and total effect (0.01; 95% CI = 0.001, 0.02; p-value = 0.0354) were positively significant.

Table 6. Serial mediation analysis of the adjusted COVID-19 testing and vaccination rates as the mediator between the SVI and adjusted COVID-19 prevalence rate.

Path[§]	Effect[§§]	95% CI	P-value
Total Effect (c)	0.01	(0.001, 0.02)	0.0354
Direct Effect (c')	0.03	(0.03, 0.04)	< 0.0001
a_1	-0.03	(-0.04, -0.01)	< 0.0001
a_2	-0.03	(-0.04, -0.02)	< 0.0001
a_3	-0.06	(-0.06, -0.05)	< 0.0001
b_1	0.96	(0.90, 1.01)	< 0.0001
b_2	-0.03	(-0.11, 0.05)	0.4078
b_3	-0.01	(-0.07, 0.06)	0.7831
d_{21}	0.61	(0.55, 0.68)	< 0.0001
d_{31}	-0.06	(-0.13, 0.01)	0.0753
d_{32}	0.94	(0.87, 1.00)	< 0.0001
Total indirect effect (ab)	-0.02	(-0.03, -0.002)	-
Individual indirect effect 1	-0.02	(-0.04, -0.01)	-
Individual indirect effect 2	0.001	(-0.01, 0.007)	-
Individual indirect effect 3	0.001	(-0.01, 0.02)	-
Individual indirect effect 4	0.001	(-0.01, 0.004)	-
Individual indirect effect 5	-0.00	(-0.002, 0.004)	-
Individual indirect effect 6	0.0003	(-0.003, 0.01)	-
Individual indirect effect 7	0.0001	(-0.002, 0.01)	-

§a_1: SVI → Adjusted COVID-19 testing rate. a_2: SVI → Adjusted COVID-19 full vaccination rate. a_3: SVI → Adjusted COVID-19 follow-up vaccination rate. b_1: Adjusted COVID-19 testing rate → Adjusted COVID-19 prevalence rate. b_2: Adjusted COVID-19 full vaccination rate → Adjusted COVID-19 prevalence rate. b_3: Adjusted COVID-19 follow-up vaccination rate → Adjusted COVID-19 prevalence rate. d_{21}: Adjusted COVID-19 testing rate → Adjusted COVID-19 full vaccination rate. d_{31}: Adjusted COVID-19 testing rate → Adjusted COVID-19 follow-up vaccination rate. d_{32}: Adjusted COVID-19 full vaccination rate → Adjusted COVID-19 follow-up vaccination rate.
§§ All effects were adjusted by covariates.
Abbreviation: CI = Confidence interval

Among the four models in the serial mediation analysis, only two covariates were statistically significant in terms of segregation in the third model with the adjusted COVID-19 follow-up vaccination rate (p-value = 0.04) and retail density (p-value < 0.0001) in the fourth model with the adjusted COVID-19 prevalence rate.

Overall, the serially mediating effect from COVID-19 full/follow-up vaccination rate towards SVI and COVID-19 prevalence was statistically significant. Therefore, to answer the hypothesis for the third research question, "Do the COVID-19 testing and vaccination rates serially mediate the relationship between the Social Vulnerability Index and COVID-19 prevalence in Southern Nevada?", the null hypothesis was rejected to concluded that '*COVID-19 testing and vaccination rates do serially mediate the relationship between the SVI and COVID-19 prevalence rate'*.

All the models for testing and vaccination rates, as mediators, were tested across four assumptions for linear regression. Unfortunately, normality and independence assumptions were violated for every model as their p-values were less than 0.05 as shown in Table 8.

Table 7. Model diagnostics of each model in the mediation and serial mediation analysis, where X indicates assumption violation.

Model #	Outcome	Linearity	Independence	Normality	Equal variance	Multicollinearity
1	M_1		X	X		
	Y		X	X		
2	M_2		X	X		
	Y		X	X		
3	M_3		X	X		
	Y		X	X		
4	M_1		X	X		
	M_2		X	X		
	M_3		X	X		
	Y		X	X	X	

In addition, Model 4 also violated the equal variance assumption, with its p-value being 0.0251. The largest VIF displayed by models was 4.9. Thus, none of the models suffered from multicollinearity since the values were always less than 10.

7. Discussions

7.1 Comprehensive findings of the three research questions

This is the first study to examine COVID-19 testing and vaccination rates as mediators for census tracts SVI and COVID-19 prevalence rate in the United States as far as we know from the literature now. As hypothesized, census tracts with a higher SVI are negatively associated with a lower testing rate for COVID-19 thus, lower cases of COVID-19 being reported. It is a significant finding that is consistent with a study by Bilal et al. (2021), which found that communities with a higher SVI score across all domains were less likely to test for COVID-19 through three highly populated urbanized cities in the U.S. It appears that adverse socioeconomic circumstances potentially lead to inaccessibility to access to testing sites or payment for testing kits that may prevent further spread of COVID-19 to others.

Additionally, this study reveals that the COVID-19 full and follow-up vaccination rates was negatively associated with SVI score, thus more cases of COVID-19. Similarly, individuals living in areas with a higher SVI score were less likely to obtain a follow-up vaccination, leading to further infection from COVID-19. No studies have analyzed vaccinations as mediators over SVI and COVID-19 prevalence rate, but previous research has found that vaccination uptake has varied throughout regions and themes from a new index adapted by the SVI (e.g., lack of English speaking associated with being likely vaccinated vs. lack of access to medical facilities with vaccination) (Saelee et al., 2023). However, the results from our study appear to indicate that individuals are less likely to obtain a vaccine in census tracts with a high SVI score.

Serial mediation analyses display that COVID-19 testing and vaccination rates significantly mediate the relationship between the proportional relationship of SVI and the COVID-19 prevalence rate. Our results show that the sequential pathway displays (a) SVI is negatively associated with the COVID-19 testing rate, where individuals are less likely to test from a census tract with high SVI; (b) The COVID-19 testing rate is proportionately related to the full COVID-19 vaccination rate; (c) COVID-19 full vaccination rate is proportionately related to the COVID-19 follow-up vaccination rate; (d) The COVID-19 follow-up vaccination rate is not significantly negatively associated with the COVID-19 prevalence rate, as shown by the total indirect effect. However, the path was not significant, but it does imply that an increase in the SVI score was associated with a decrease in the COVID-19 testing rate, proportionally associated with the COVID-19 full vaccination rate, and subsequently proportionally associated with COVID-19 follow-up vaccination, which leads to less reported cases of COVID-19. Thus, the analyses indicate that census tracts with a high SVI score will decrease the COVID-19 testing and vaccination rate; thus, individuals are more likely to be infected with COVID-19 from these areas, as shown by the total indirect effect.

These key findings highlight the importance of a sequential pathway, for individuals facing the risk of infection from the COVID-19 pandemic within a metropolitan setting in Southern Nevada. This pathway starts with the SVI score, which influences the COVID-19 testing rate, affecting the full vaccination rate, followed by the follow-up vaccination rate, and finally, the COVID-19 prevalence rate. While no study has conducted a serial mediation analysis, previous studies have found that individuals from socially vulnerable communities are less likely to be able to receive a vaccine and test for COVID-19, thus leading to more cases of COVID-19 (Bhuiyan et al., 2023).

7.2 The association between SVI and COVID-19 prevalence.

All mediation analyses conducted in this study has shown that SVI is significantly and negatively associated with the COVID-19 prevalence rate. Interestingly enough the follow-up vaccination rate from our studies' mediation analyses showed the highest rate of COVID-19 cases associated with SVI. Even in studies that don't examine SVI as a predictor have found that domains related to it such as socioeconomic status, minority status, and low-income backgrounds are positively associated with individuals being more likely to be infected with COVID-19 (McPhearson et al., 2020; Ransome et al., 2021; Tan et al., 2021). Previous studies that incorporate SVI as a predictor have shown to be associated with COVID-19 prevalence, thus further supporting the findings from the current study.

For example, a study in Florida examined SVI and found that the number of COVID-19 cases appeared to increase in counties with a higher SVI score (Backer et al., 2022). Multiple studies also found a significant association between areas with a high SVI and COVID-19 mortality (Ali, 2022; Zegarra Zamalloa et al., 2022) An ecological assessment also showed new cases of COVID-19 were associated with SVI (Islam et al., 2021), while a study following an ecological design in Texas found that socioeconomic status and minority status from SVI were strongly associated with new cases of COVID-19 (Tortolero et al., 2021). Lastly, census tracts within Louisiana with a higher score on the SVI was found to be strongly associated with the COVID-19 infection especially amongst minorities (Biggs et al., 2020).

Other indexes also classify areas based on socioeconomic status and accessibility to transportation, which are similar to the SVI and are found to share a relationship with more COVID-19 cases. For example, the Area Deprivation Index (ADI) that does not include racial/minority status has also been associated with the COVID-19 prevalence rate for smaller areas than SVI (Knighton et al., 2016). A study conducted by Tipirneni et al. (2022) found that additional indexes like "The COVID-19 Community Vulnerable Index", "Minority Health-Social Vulnerability Index," and ADI shared a positive and proportional relationship with COVID-19 prevalence. Evidence from these studies supports our findings of a strong association between COVID-19 prevalence rate and SVI as socially vulnerable communities face a disproportionate burden (Tipirneni et al., 2022).

7.3 COVID-19 testing rate as a mediator

The COVID-19 testing rate was a significant mediator over the SVI and COVID-19 prevalence rate. As hypothesized, a high SVI amongst census tracts would render a lower testing rate for the area, thus contributing to lower COVID-19 cases. Subsequently, looking at the total effect, it was shown that variability across two census tracts with SVI was proportionally related to the COVID-19 prevalence rate. In addition, it is shown through the direct effect that SVI and COVID-19 prevalence rates are proportionally related after controlling for COVID-19 testing. As previously mentioned, the significant indirect effect implies that COVID-19 testing mediates the association between SVI and prevalence which may be underestimated due to lack of reporting and asymptomatic carriers. Additionally, very few studies evaluated testing as an independent variable and nonetheless as the mediator, so this study provides insight to the mechanisms underlying testing rates amongst vulnerable communities and the inaccessibility to testing. However, recently, a study analyzing the mediating effect of the COVID-19 testing rate through elementary schools in Illinois was negatively associated with the COVID-19 positivity rate, thus supporting the findings (Ivanov et al., 2024).

7.4 The association between SVI and COVID-19 testing

Few studies have examined the association between COVID-19 testing rate and SVI, as there are other indexes that other researchers may use for their study. For example, it has been shown that the testing rate is negatively associated with the ADI analyzing at the census tract level in Virginia (Hendricks et al., 2023). Moreover, one study found that a lower COVID-19 testing rate was associated with a higher SVI score amongst zip code areas throughout three U.S. cities (Bilal et al., 2021). Furthermore, Dryden-Peterson et al. (2021) found that a lower socioeconomic status from the SVI was also associated with decreasing testing and access to resources within Massachusetts. While even low accessibility to testing was associated with census block groups classified with an increased SVI amongst thirty U.S. cities (Mullachery et al., 2022)

7.5 The association between COVID-19 testing and prevalence

The association between the COVID-19 testing rate and the COVID-19 prevalence rate has yet to be thoroughly analyzed in the literature, as many studies focus on factors related to test positivity (Ferguson et al., 2021; Iwata & Miyakoshi, 2022; Lieberman-Cribbin et al., 2021). This may be due to the invalidity and inaccuracy of COVID-19 testing taken at sites and laboratories within the U.S. during the early pandemic (Alvarez et al., 2023). However, a study has found that a higher number of COVID-19 tests by each individual was associated with lower odds for COVID-19 fatality during the beginning of the pandemic (Kannoth et al., 2022). In contrast, an international study analyzing several countries, including the U.S., found that mortality rate and the number of tests were not strongly associated (Iwata & Miyakoshi, 2022). A recent study found that lower testing rates in Central Florida were associated with the likelihood of more COVID-19 hospitalizations (M. M. Khan et al., 2023). There is a clear depiction of the variability of association for COVID-19 testing. At the same time, one of our primary findings found that COVID-19 testing rates played a significant role as a mediator and were positively associated with COVID-19 prevalence. This also indicates that there is an underestimation of the results as many individuals did not test due to lack of symptoms or tested at home.

7.6 Full and follow-up vaccination rate as mediators

Another primary finding of the study is that the full vaccination rate or the two doses of the COVID-19 vaccine was less likely to be received by individuals within census tracts with a higher SVI score. Thus, more cases of COVID-19 are more likely to happen due to the lack of protection. Similarly, additional doses or the COVID-19 follow-up vaccination rate were also negatively associated with the SVI. This association indicates that socially vulnerable communities within these census tracts will also have more COVID-19 cases or reinfection from the viruses. These are unique findings as no study has evaluated the COVID-19 vaccination as a mediator for SVI and COVID-19 prevalence rate. However, one mediation analysis study utilizing the SVI as a predictor found that socially vulnerable communities in minority states were more likely to be near vaccine sites in the U.S. (Thakore et al., 2021).

7.7 The association between SVI (or any other similar index) and COVID-19 vaccination

As previously mentioned, our mediation analysis found that an increase in SVI is associated with a decrease in the COVID-19 full vaccination rate; thus, individuals from these census tracts are less likely to be vaccinated. Besides this study, no other paper has explicitly examined the COVID-19 full vaccination rate as a mediator towards the relationship between SVI and the COVID-19 prevalence rate. However, recently, a geospatial study throughout multiple U.S. states analyzed the association, finding that the socially vulnerable counties were more likely to have a lower COVID-19 vaccination rate (Alphonso et al., 2024). Additionally, a study examining counties in Wisconsin found that a higher SVI score shared a relationship with low COVID-19 vaccination rates, thus supporting the findings of our study (Xu & Jiang, 2022).

Even another index called "COVID-19 Community Vulnerability" found a higher vaccination rate if the vulnerability was low amongst counties in the U.S. (Brown et al., 2021).

7.8 The association between COVID-19 vaccination rate and prevalence for any other COVID-19 measure

In the current study, it was also found that the COVID-19 full and follow-up vaccination rate was associated with the COVID-19 prevalence rate. Similar to other explored associations in our study, very few studies have even examined the relationship between the COVID-19 vaccination rate and the COVID-19 prevalence rate in the U.S. However, a study analyzing the full vaccination rate in the United Kingdom found that it was negatively associated with the rising COVID-19 cases (Damijan et al., 2022). Another study supporting our findings was a population analysis in U.S. states that a low COVID-19 vaccination rate was associated with an increased risk of COVID-19 hospitalization (Hongru et al., 2023). Lastly, an analysis of Medicare data through U.S. counties found that a high vaccination rate is associated with a low risk of COVID-19 cases, fatalities, and hospitalization (Samson et al., 2021).

7.9 Importance of booster shots and new strains

The COVID-19 full vaccination rate was analyzed in this study as two doses of the vaccine for the individuals. However, the emergence of new variants of the coronavirus has been on the rise each year, thus indicating the importance of the COVID-19 follow-up vaccination, which was also analyzed in this study. For example, the new Omicron variant was first seen in Africa in 2021, indicating the increased risk of individuals being reinfected with COVID-19 (Ri & Chen, 2022). Booster shots must be developed to combat new variants since they can pose a real danger to millions. (Mohammed Shadab & Mohammed Asadullah, 2023). Additionally, the effectiveness of the COVID-19 vaccine waned over time (Margaret et al., 2022). Overall, evidence-based research has shown that booster shots provided much more protection than individuals who only received the full COVID-19 vaccine (Grewal et al., 2023)

7.10 The association between COVID-19 testing and vaccination

A serial mediation analysis was conducted that found significant serial mediators: a.) COVID-19 testing rate b.) COVID-19 full vaccination rate c.) COVID-19 follow-up vaccination rate for the association between SVI and COVID-19 prevalence rate. Additionally, this analysis found proportional, positive relationships between COVID-19 testing, COVID-19 full vaccination rate, and COVID-19 follow-up vaccination rate. Thus, the impact of the SVI score on the census will have the same inverse effect throughout this pathway, beginning this COVID-19 testing rate mediator. As discussed beforehand with the other relationships regarding COVID-19 measures, there have also been very few studies that have investigated the association between COVID-19 testing and vaccination rates. However, one analysis conducted in New Jersey found that individuals from socially vulnerable communities who have taken diagnostic tests for COVID-19 were more likely to be vaccinated thus supporting our finding (Campbell et al., 2023). Correspondingly, another study also found that even healthcare professionals in the United Kingdom were less likely to vaccinate if they had never tested for COVID-19 beforehand (Martin et al., 2021). However, individuals who were fully vaccinated were less likely to test positive for COVID-19 (Roberts et al., 2022).

8. Strengths and limitations

8. 1 Strengths

Our study employed a mediation analysis approach, which yielded significant findings that enhanced our understanding of the COVID-19 pandemic's impact, particularly on socially vulnerable communities. We examined a comprehensive index that assess vulnerability in communities and its association with COVID-19 testing and vaccination rates. This is the first study to use COVID-19 testing rates as mediators between SVI and COVID-19 prevalence rates, a crucial factor in preventing further infections. We also prioritized access to testing for socially vulnerable groups, acknowledging the potential limitations in the number of testing kits. Furthermore, our study is pioneering in using COVID-19 full and follow-up vaccination as mediators, aiming to gather more information on vaccination resource accessibility, a critical aspect of gaining immunity from the virus.

Other studies related to COVID-19 vaccination have used vaccine site density and coverage rate as mediators rather than just the vaccination rate (Donadio et al., 2021; Thakore et al., 2021). The scarcity of studies on these topics could be due to the sudden emergence of COVID-19 or delays in publishing research. As the peak of the pandemic subsides, fewer researchers may be interested in studying the early stages of the pandemic. However, the emergence of variant strains, which pose a significant threat, especially to socially vulnerable communities, underscores the need for continued research. Our study contributes to this effort by being among the first to examine the serial mediation pathway of COVID-19 testing and vaccination rate for SVI and COVID-19 prevalence rate. We also delve into the relationship between the SVI and the prevalence rate of COVID-19, considering comprehensive factors such as racial and ethnic minority status, housing type, socioeconomic status, and household characteristics.

Most studies that discuss the SVI index typically use only one of the 16 characteristics, such as housing type or minority status, as their predictor (Hu et al., 2021; Oishi et al., 2021; Razieh et al., 2021; Saarinen et al., 2022; Yoshikawa & Kawachi, 2021). In contrast, our study takes a more comprehensive approach by considering all 16 characteristics of the SVI. This approach allows us to capture a more accurate and nuanced picture of social vulnerability in a large and diverse sample population, encompassing a wide range of race/ethnicity and age groups. By doing so, we hope to contribute to a more thorough understanding of the impact of COVID-19 on socially vulnerable communities.

8.2 Limitations

However, there are some limitations to the study, such as the applicability of the SVI from our study, which may not translate well to other states' varying numbers and sizes of census tracts. Mediation analysis cannot explain whether the independent variables are the actual cause behind the linear relationship. However, the serial mediation model did not show an association between the COVID-19 vaccination rates and the COVID-19 prevalence rate due to the violated equal variance assumption of differing variances amongst vaccine uptake in the sample. Other drawbacks arose with the serial mediation model despite the significance of the total indirect effect.

Additionally, several model violations with the serial mediation analysis and a minuscule coefficient behind our total indirect effect indicate unreliability. However, a small coefficient from mediation analysis is commonly derived due to being the product of many mediators (Walters, 2019). Multiple studies conducting serial mediation analysis have found significant small coefficients for their total indirect effect (Satici et al., 2022; Yang et al., 2022; Zhao et al., 2021). In addition, mediation analysis tends to be much more sensitive to test for model assumptions as more indirect effects are computed (Alfons et al., 2021; Hayes, 2017). Overall, the serial mediators, COVID-19 testing, and vaccination rate still appear to influence the association between SVI and COVID-19 prevalence rate, especially regarding resources amongst socially vulnerable communities.

9. Conclusion

Our main findings have led us to believe that individuals from highly socially vulnerable communities are more susceptible to being infected during an outbreak like COVID-19 due to a lack of resources such as testing and vaccinations. The study takes a multifaceted approach by examining three different mediators that deepen our understanding of the transmission of the virus in the U.S. amongst vulnerable communities. Additionally, the study underscores the potential development of public health interventions for increasing accessibility to more testing sites and vaccination resources for vulnerable communities. This study will contribute to literature related to preparation for future pandemic outbreaks by contributing to the literature for other public health researchers to utilize for similar samples such as urban and diverse cities. Therefore, it will influence policymakers to adjust U.S. public health policies managing pandemics and allocating governmental resources related to COVID-19 or infectious outbreaks in socially vulnerable communities. Overall, the benefits of this study serve as a powerful resource for the public health field and is an excellent addition to the literature regarding the COVID-19 pandemic. However, more research is essential as this study may be the first to examine the complex association between variables necessary for the preventive care of the spread of diseases.

9.1 Future work

The mediation and serial mediation analysis we conducted have provided significant insight into the influence of COVID-19 on socially vulnerable communities. Specifically, they shed light on the correlation between living in a census tract with high SVI and COVID-19 testing and vaccination rates and the risk of infection. However, it is essential to note that mediation analysis cannot establish causation. Therefore, other researchers should conduct longitudinal studies to confirm that these associations remain over a long period of time.

While our serial mediation analyses demonstrate a chain linking our mediators concerning COVID-19 testing and vaccination, the effect is still relatively weak. This underscores the need for more future studies to investigate the replicability of COVID-19 full vaccination and COVID-19 follow-up vaccinations, significantly as the vaccine's effectiveness diminishes over time. Furthermore, future studies that explore how each factor from SVI influences COVID-19 testing and COVID-19 vaccination rate towards COVID-19 prevalence will provide invaluable insights. More research may lead to identifying specific barriers to the accessibility issues surrounding testing kits and vaccination sites for individuals from socially vulnerable communities.

Appendix

Table 8. Serial mediation effects of no covariates include in the model COVID-19 testing, full vaccination, and follow-up vaccination rate as mediators

Effect			
Total	Direct	Indirect(Total)	Indirect (Individual)
	X	X	1

Table 9. One covariate included in each serial mediation model

Covariate						Effect			
Z1	Z2	Z3	Z4	Z5	Z6	Total	Direct	Indirect (Total)	Indirect (Individual)
■							X	X	1
	■						X		1
		■				X	X	X	1
			■				X	X	1
				■			X	X	1
					■		X	X	1

Note. Z1 = inactive commuting, Z2 = park deprivation, Z3 = retail density, Z4 = housing inadequacy, Z5 = segregation, Z6 = population density

Table 10. Two covariates included in each serial mediation model

Covariate						Effect			
Z1	Z2	Z3	Z4	Z5	Z6	Total	Direct	Indirect (Total)	Indirect (Individual)
■	■						X		1
■		■				X	X		0
■			■			X	X		1
■				■			X		1
■					■		X		1
	■	■				X	X	X	1
	■		■				X	X	1
	■			■			X	X	1
	■				■		X	X	1

Z1	Z2	Z3	Z4	Z5	Z6	Total	Direct	Indirect (Total)	Indirect (Individual)
		■	■			X	X		1
		■		■		X	X	X	1
		■			■		X		1
			■	■			X	X	1
			■		■		X	X	1
				■	■		X	X	1

Note. Z1 = inactive commuting, Z2 = park deprivation, Z3 = retail density, Z4 = housing inadequacy, Z5 = segregation, Z6 = population density

Table 11. Three covariates included in each serial mediation model

Covariate						Effect			
Z1	Z2	Z3	Z4	Z5	Z6	Total	Direct	Indirect (Total)	Indirect (Individ ual)
■	■	■				X	X		0
■	■		■			X	X		1
■	■			■			X		1
■	■				■		X		1
■		■	■			X	X		0
■		■		■		X	X		0
■		■			■	X	X		0
■			■	■		X	X		1
■			■		■		X		1
■				■	■		X		1
	■	■	■			X	X		1
	■	■		■		X	X	X	1
	■	■			■		X		1
	■		■	■			X	X	1
	■		■		■		X		1
	■			■	■		X	X	1
		■	■	■		X	X		1
		■	■		■	X	X		1
		■		■	■	X	X		1
			■	■	■		X		1

Note. Z1 = inactive commuting, Z2 = park deprivation, Z3 = retail density, Z4 = housing inadequacy, Z5 = segregation, Z6 = population density

Table 12. Four covariates included in each serial mediation model

Covariate						Effect			
Z1	Z2	Z3	Z4	Z5	Z6	Total	Direct	Indirect (Total)	Indirect (Individ ual)
■	■	■	■			X	X		0
■	■	■		■		X	X		0
■	■	■			■	X	X		0

Z1	Z2	Z3	Z4	Z5	Z6	Total	Direct	Indirect (Total)	Indirect (Individual)
■	■		■	■		X	X		1
■	■		■		■		X		1
■	■			■	■		X		1
■		■	■	■		X	X		0
■		■	■		■	X	X		0
■		■		■	■	X	X		0
■			■	■	■	X	X		1
	■	■	■	■		X	X		1
	■	■	■		■	X	X		1
	■	■		■	■	X	X		1
	■		■	■	■		X		1
		■	■	■	■	X	X		1

Note. Z1 = inactive commuting, Z2 = park deprivation, Z3 = retail density, Z4 = housing inadequacy, Z5 = segregation, Z6 = population density

Table 13. Five covariates included in each serial mediation model

Covariate						Effect			
Z1	Z2	Z3	Z4	Z5	Z6	Total	Direct	Indirect (Total)	Indirect (Individual)
■	■	■	■	■		X	X		0
■	■	■	■		■	X	X		0
■	■	■		■	■	X	X		0
■	■		■	■	■	X	X		0
■		■	■	■	■	X	X		0
	■	■	■	■	■	X	X		1

Note. Z1 = inactive commuting, Z2 = park deprivation, Z3 = retail density, Z4 = housing inadequacy, Z5 = segregation, Z6 = population density

Table 14. Six covariates included in each serial mediation model

Covariate						Effect			
Z1	Z2	Z3	Z4	Z5	Z6	Total	Direct	Indirect (Total)	Indirect (Individual)
■	■	■	■	■	■	X	X		0

Note. Z1 = inactive commuting, Z2 = park deprivation, Z3 = retail density, Z4 = housing inadequacy, Z5 = segregation, Z6 = population density

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Curriculum Vitae

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EDUCATION

Master of Public Health (Epidemiology and Biostatistics) Expected May 2024
University of Nevada, Las Vegas
Advisory Committee Chair: Dr. Lung-Chang Chien
Committee Co-Chair: Dr. Lung-Wen Antony Chen
Committee Member: Dr. Courtney Coughenour
Committee Member: Dr. Erika Marquez
Graduate Representative: Dr. Szu-Ping Lee

Bachelor of Science in Biological Sciences August 2017 - August 2021
University of Nevada, Las Vegas

WORK EXPERIENCE

Project Coordinator Jan 2024 – Present

University of Nevada, Reno Extension Center

- Responsible for coordinating projects for Southern Nevada Farmer's Market

Research Assistant Sept 2024 – Present

University of Nevada, Reno Extension Center

- Literature review, data entry, statistical analyses (SAS, SPSS, and R)

Research Assistant August 2022 – June 2023

University of Nevada, Reno Extension Center

- Drafts regarding health disparities in substance use, data management (Qualtrics, SAS)

Registered Behavior Technician August 2021 – August 2022

Center for Autism & Behavior Analysis, LLC

- Implements behavioral health plan for individuals with autism and collect data