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Modeling Recurrent Emergency Department Trends in the United States

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ABSTRACT
Emergency departments around the United States struggle with staff shortages and overcrowding following the COVID-19 pandemic and resulting shutdowns. This study aims to create and examine models representing the probability of patients requiring multiple emergency department visits during treatment to better understand why some patients require recurrent emergency department treatments. The two models considered in this experiment are the Poisson Process and the "Frequent Flyer" Hypotheses. Ultimately, analyzing the data provided by the National Center for Health Statistics revealed that the Poisson Process does not accurately represent the realities of recurrent emergency department visits, but the "Frequent Flyer" Hypothesis does in some situations. It also revealed that there may be several lurking variables that compound to determine if a patient will require multiple emergency department visits, accounting for the inconsistencies of the "Frequent Flyer" Hypothesis.

KEYWORDS
Recurrent Emergency Room Visits; Repeated and Frequent Emergency Department Visitors; Overcrowding; Emergency Department; Poisson Process; Frequent Flyers; Mathematical Modeling; Healthcare Management; Healthcare Outcomes

INTRODUCTION

The emergency room started with four physicians in 1961 but has grown to see hundreds of millions of patients yearly in the United States alone.[1] Even after the development of urgent care facilities, which generally decrease the number of emergency department visits necessary per year,[2] the emergency department continues to play a crucial role in the American healthcare system. This paper will explore why people go to the emergency department and, more specifically, investigate why some people require multiple emergency department visits yearly.

Healthcare workers who specialize in emergency medicine are known for treating car crash injuries, gunshot wounds, broken bones, heart attacks, strokes, and other potentially fatal conditions. However, according to the Agency for Healthcare Research and Quality's Healthcare Cost and Utilization Project, patients in 2018 also sought help treating abdominal pain, digestive disorders, respiratory infections, urinary tract infections, skin infections, nausea and vomiting, pregnancy complications, and viral infections.[3]

Unfortunately, the recent COVID-19 pandemic proved how fragile the US healthcare system can be, but no department was hit quite as hard as the Emergency Department. While the total number of patients seen in emergency departments decreased during the pandemic, the number of patients with urgent and emergent conditions increased dramatically, forcing patients to wait much longer for adequate treatment because of unprepared hospitals and a phenomenon called overcrowding.[4]

Overcrowding, as defined by the American College of Emergency Physicians, occurs when there is a larger demand for emergency treatment than can be provided by the current emergency department staff and resources.[5] To begin solving this problem, it is essential to understand not only why people go to the emergency department but also why some of those patients will require multiple visits.

Researchers and healthcare administrators have been investigating emergency department overcrowding and have deduced that many structural insufficiencies may account for its recent increase: lack of access to primary care, triage and consultation time, delays in receiving test results, declining numbers of ER and hospital beds, and staffing shortages.[6] For example, 84% of emergency department nurses have an inflated patient-to-nurse ratio of 4:1 according to the American Nursing Association, which decreases their performance and leads to stress and job burnout.[7] Unfortunately, this often causes nurses to quit, worsening the problem.[6]

The National Center for Health Statistics, a branch of the Centers for Disease Control and Prevention,[8] has collected data showing that over the last twenty-six years, a significant portion of the population has required multiple emergency department visits yearly.[9] While emergency medicine physicians may not be able to control outside factors like the number of emergencies that will occur, the number of patients that will arrive at the emergency department at any given time, and the time it takes to consult, diagnose, and treat patients properly,[6] they should take the time to determine why so many of their patients require multiple visits to be appropriately cared for and treated.

Researchers have been analyzing the significant amount of emergency department data collected across the globe for decades. Recently, they have begun to investigate the characteristics of recurrent emergency department patients and determine what increases the likelihood of a patient needing multiple visits. One study in Switzerland discovered two types of ED patients: "frequent" patients who presented with different symptoms each visit and "repeated" patients who returned with the same symptoms each time.[10]

The National Center for Health Statistics conducts a National Health Interview Survey where they ask approximately 87,500 noninstitutionalized American civilians,[11] "During the past 12 months, how many times have you gone to a hospital emergency room about your own health?" and to include emergency department visits that resulted in hospital admissions.[12] This data has been collected from 1997 to 2019 and processed according to the associated US Census data to determine the appropriate standard errors.[11] The calculated response rates were used to estimate the total percentage of the US population who had gone to an emergency department each year.[11] Then, the data were broken down into two main groups: people who went to the emergency department one or more times that year and people who went to the emergency department two or more times that year.[9]

This research aims to create models that will analyze the data by examining the different processes that may contribute to the percentage of recurrent patients treated in the emergency department yearly. This paper will first begin by describing the original data set. Then, it will explain the development and investigation of the two original hypotheses. Finally, it will discuss an interpretation of the data, explore possible explanations for these results, and suggest areas that may benefit from additional research.

METHODS AND PROCEDURES

Visualizing the data

A scatter plot of the raw values was created to begin visualizing the data provided by the National Center for Health Statistics. It became apparent that there were three main clusters in the data: one representing the group of patients who visited an emergency department one or more times per year, another representing the group of patients who visited an emergency department two or more times per year, and the final group representing the standard errors for each percentage calculated by the National Center for Health Statistics. By removing the standard error values, the two different clusters could be plotted as two separate lines, with the x coordinate representing the year the data was collected from and the y coordinate representing the percentage of people in each category. While the data originally appeared random, it became clear that the percentage of patients requiring recurrent emergency department visits was consistently smaller than that of patients requiring one or more visits.

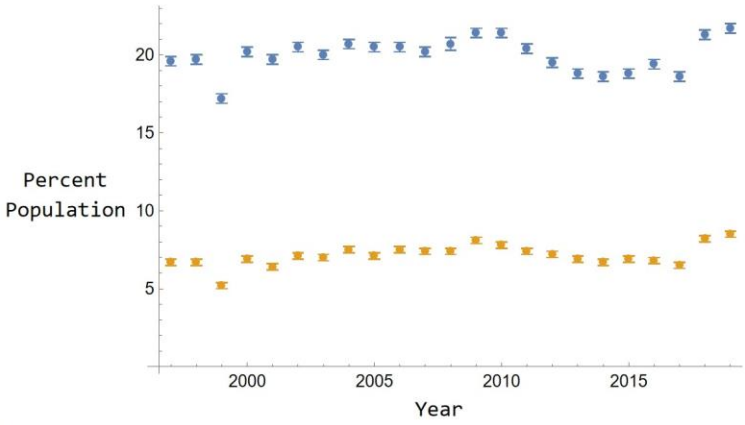

Figure 1. Examining the Percentage of Patients Requiring Single and Multiple Emergency Department Visits Every Year. This graph represents the trends of patients requiring single and multiple emergency department visits from 1997 to 2019, with error bars related to the standard errors determined by the Centers for Disease Control and Prevention's National Center for Health Statistics. The blue data represents the percentage of patients requiring one or more emergency department visits per year, while the orange data represents the percentage of patients requiring two or more emergency department visits per year.

Many different processes can be used to model this data. One way to predict emergency department visits would be to use the Poisson Process. This mathematical model demonstrates the likelihood of random events occurring.[13] For example, it has been used to determine the duration of a wait time for a soda at McDonald's, the chances of a substance suffering from radioactive decay, and the arrival time of public transportation.[13] Another model, the Bernoulli Process, can show a similar series of independent and identical events.[14] However, there may be several outside factors that influence whether a patient decides to go to the emergency department or not, meaning a new model may need to be developed to properly represent the complexity of emergency department visits.

Considering these models, two main hypotheses could explain this data. Hypothesis 1, **the Poisson Hypothesis**, states that all trips to the emergency department result from random events that are independent and rare. However, Hypothesis 2, **the Frequent Flyer Theory**, states that there are likely two groups of people: one that only goes to the emergency department when random, independent, and emergent events occur and one that consistently goes to the emergency department and is nicknamed the "frequent flyers."

Modeling the Poisson Process

Because the data was broken down into people who went to the emergency department one or more times a year and those who went to the emergency department two or more times a year, the second group was contained entirely within the first group. The percentage of people who went two or more times a year was subtracted from the percentage of people who went one or more times a year, leaving only the isolated group of people who went to the emergency department once a year. The data was then transposed into coordinate pairs where the x coordinate represented the percentage of the population who only went to the emergency department once per year while the y coordinate represented the percentage of the population who went to the emergency department two or more times per year.

To determine the validity of the Poisson Hypothesis, two equations were created to represent the Poisson Process. The first function, referred to as **Equation 1**, is

$$n\,p\,(1-p)^{n-1} = p_0 \qquad \textbf{Equation 1.}$$

where n equals three-hundred-sixty-five, and p_0 equals the percentage of the population the National Center for Health Statistics recorded as going to the emergency department once.

This equation can then be solved for p, which represents the daily probability of someone going to the emergency department exactly once a year. This equation does have multiple solutions for p. However, a single solution can be derived by limiting the solutions to values that fall between zero and approximately 0.0027, which is equivalent to 1/365 and represents the chance of going to the emergency department on exactly one day out of the three-hundred-sixty-five days in one year. These restrictions allow a single solution to be derived by the Mathematica program for the development of the Poisson Hypothesis model.

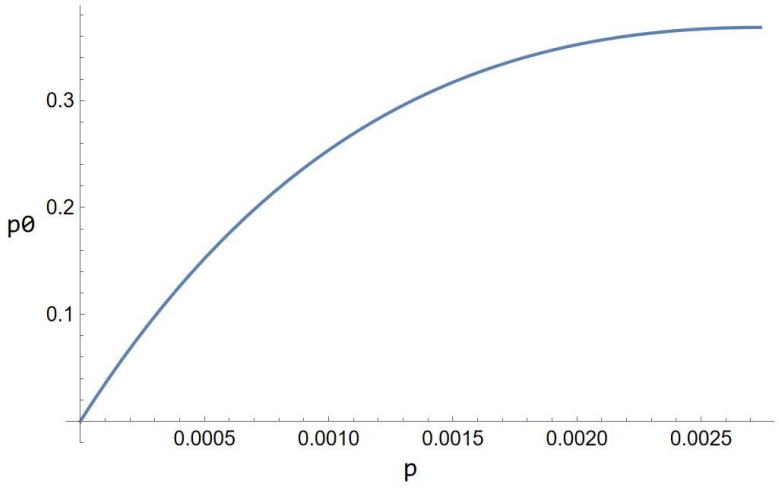

Figure 2. Proving the Validity of Equation 1. This graph demonstrates that there is only one solution to **Equation 1** when p is restricted to values that fall between zero and 1/365 (approximately 0.0027).

The second function, referred to as **Formula 1**, is

$$1 - (1 - p)^n + n\,p\,(1 - p)^{n-1}$$ **Formula 1.**

where n equals the number of days from one to three-hundred-sixty-five and p equals the daily probability of a person needing to go to the emergency department only once a year for an independent emergency. When using the calculated p from **Equation 1**, this formula can be evaluated to determine the probability of a person going to the emergency department two or more times a year.

Modeling the Frequent Flyer Theory

The Frequent Flyer Theory suggests that there are two different populations: "frequent flyers," or patients who visit the emergency department often due to chronic physical, mental, or social issues,[15] and "non-frequent flyers," or people who only seek out emergency medical care during an actual emergency, if at all.

To evaluate the validity of this theory, mathematical models were created using the Poisson Process to represent the probability of four different scenarios. These included the daily probability of non-frequent flyers seeking emergency medical treatment, the probability of an individual going to the emergency department exactly once a year, the probability of an individual not requiring an emergency department visit at all over a year, and the probability of an individual requiring more than one emergency department visit per year.

In our models, we defined two different populations, p_1 and p_2, as the following:

$$p_1 = h * q$$ **Equation 2.**

$$p_2 = f + g * q$$ **Equation 3.**

where p_1 is the percentage of people who go to the emergency department only once, p_2 is the percentage of people who go to the emergency department more than once, h is the probability of someone going to the emergency department exactly once according to the Poisson Process, q is the proportion of people that are not considered frequent flyers, f is the proportion of people who are considered frequent flyers, and g is the probability that someone goes to the emergency department more than once according to the Poisson Process. By understanding how f can be defined using these variables, the following equation is derived:

$$\frac{p_1}{h} = \frac{(1-p_2)}{(1-g)}$$ **Equation 4.**

By substituting 1 - g with α + h, where α represents the probability of someone not visiting the emergency department at all according to the Poisson Process, and isolating p_1 and p_2 on one side of the equation:

$$\frac{(\alpha+h)}{h} = \frac{(1-p_2)}{p_1}$$ **Equation 5.**

By simplifying this equation and substituting variables with their definitions:

$$\frac{\alpha}{h} = \frac{(1-(p_1+p_2))}{p_1} = \frac{(1-\alpha)}{(365\alpha)} = x$$ **Equation 6.**

where x is a useful variable that will simplify the following equations. This equation can then be used to derive the daily probability of a person requiring an emergency department visit when that person is not considered a "frequent flyer" using the following equation:

$$a = \frac{1}{(1+365x)}$$ **Equation 7.**

Using **Equation 7**, a new equation, represented by h, can be derived to determine the probability of an individual going to the emergency department exactly once a year, as dictated by the Poisson Process. This equation is:

$$h = 365a\,(1 - a)^{364}$$ **Equation 8.**

Equation 7 can also be used to derive a new equation, represented by α, to calculate the probability of an individual not needing to visit the emergency department for a year, as dictated by the Poissonα Process. This equation is:

$$\alpha = (1 - a)^{365} \quad \textbf{Equation 9.}$$

Equation 7 can also be used to derive a separate equation, represented by g, to calculate the probability of an individual requiring multiple emergency department visits within a year, as dictated by the Poisson Process. This equation is as follows:

$$g = 1 - (h + \alpha) \quad \textbf{Equation 10.}$$

Equations 7 and 8 can then be used to derive a new equation, represented by q, to calculate the proportion of the population not considered "frequent flyers." This new equation is:

$$q = \frac{p_1}{h} \quad \textbf{Equation 11.}$$

Finally, **Equation 11** can be used to derive an equation, represented by f, that can calculate the proportion of the population that is considered "frequent flyers." This equation is:

$$f = 1 - q \quad \textbf{Equation 12.}$$

Equation 12 is what was ultimately used to create the scatter plots seen below.

RESULTS

Testing the Poisson Process

To visualize these processes and compare them to the actual data, **Formula 1** was plotted as a function of **Equation 1** on a graph, with the x-axis representing the percentage of the population who only went to the emergency department once per year and the y-axis representing the percentage of the population who went to the emergency department two or more times per year. Once the continuous curve representing the Poisson Process was plotted, the National Center for Health Statistics data was plotted for comparison and is shown below.

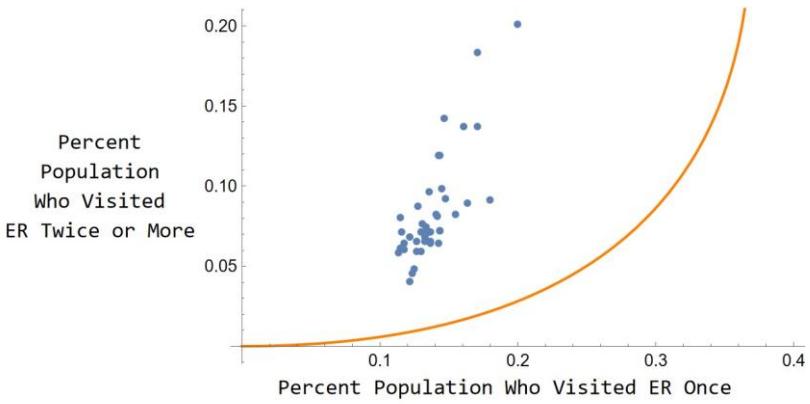

Figure 3. Testing the Poisson Hypothesis. This graph compares the data from the National Center for Health Statistics and the predicted data described by the Poisson Process. The blue line represents the raw data, while the orange line represents the hypothesized Poisson Process trend.

A Chi-Square Goodness of Fit test with one degree of freedom and a sample size of 87,500[11] was performed. The smallest t-statistic calculated was 7,363.78. The Mathematica program could not calculate an exact p-value from this t-statistic because the resulting answer is smaller than the smallest machine number. However, it reported the value as less than e^{-3686}, indicating that $p < 10^{-1600.81}$.

Testing the Frequent Flyer Theory

Equation 6 was incorporated into another function, **Frequent Flyer Proportion**, which subtracted the percentage of people who went to the emergency department two or more times from the percentage of people in each category who went one or more times, leaving only the percentage of people who went to the emergency department exactly once. This function generated p_1 and p_2 values that could be used in the Frequent Flyer model.

Plugging these values back into **Equation 6** provided the x value that served as the foundation for the Frequent Flyer model. Each subsequent equation was solved using the variable calculated by the equation before it. **Equation 12** ultimately allowed the percentage of people in each category that could be classified as a "frequent flyer" to be calculated. The resulting values were then arranged into coordinate pairs where the x value represented the year from 1997 to 2019 and the y value represented the percentage of people classified as frequent flyers.

Testing frequent flyer covariates

In addition to being broken down by year, the data provided by the National Center for Health Statistics was also broken down according to various patient demographics, including age, sex, percentage of the poverty level, type of insurance, geographic region, and location of residence. The graphs produced by the Frequent Flyer Model were sorted according to these demographics to see if these characteristics influence the presence of "frequent flyers" in a population.

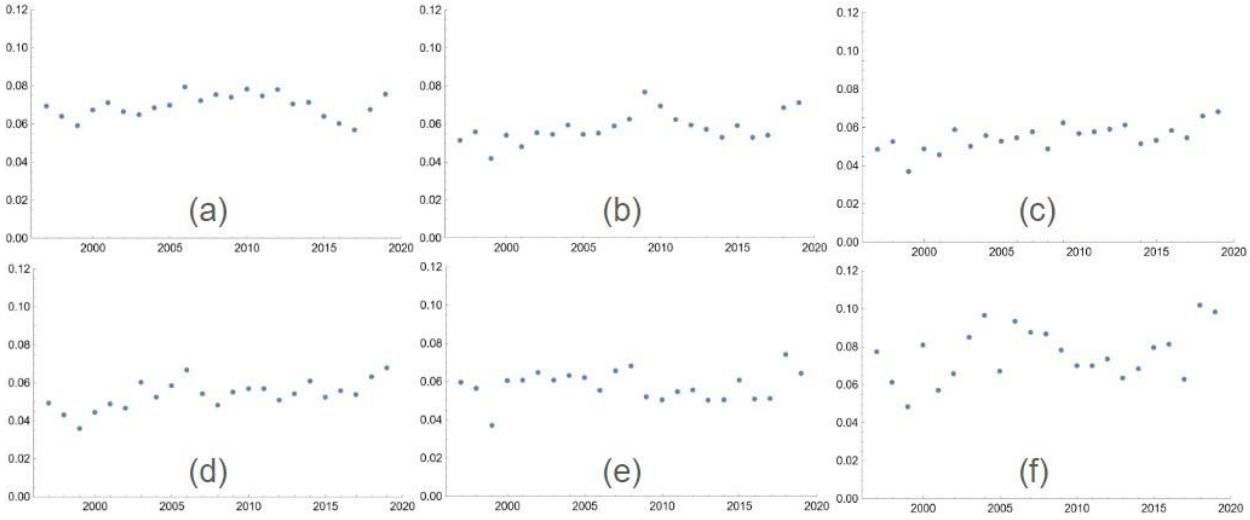

Figure 4. The Frequent Flyer Theory and Age. These scatter plots demonstrate a relationship between time and the percentage of patients who are deemed annual "frequent flyers" in different age groups, including (a) 18 to 24-year-olds, (b) 25 to 44-year-olds, (c) 45 to 54-year-olds, (d) 55 to 64-year-olds, (e) 65 to 74-year-olds, and (f) 75-year-olds and older. In each graph, the x-axis represents the year, and the y-axis represents the percentage of people who go to the emergency department two or more times a year.

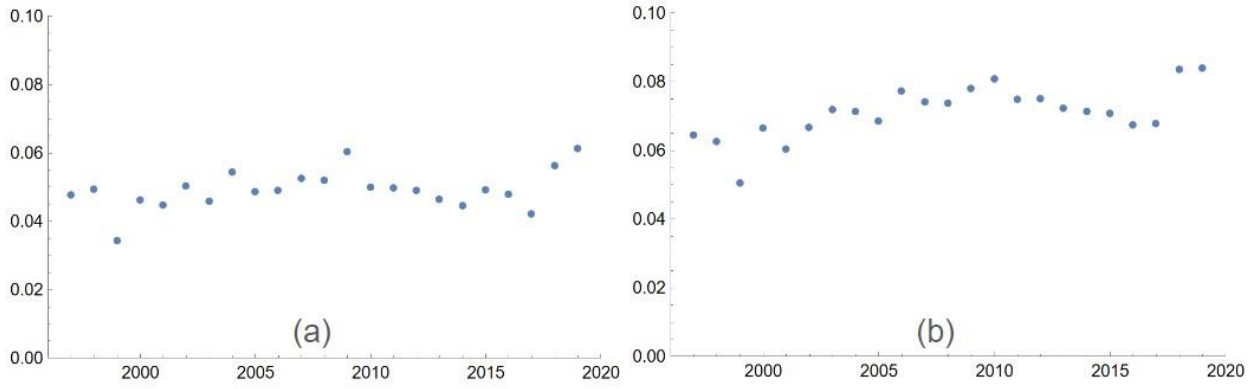

Figure 5. The Frequent Flyer Theory and Sex. These scatter plots demonstrate a relationship between time and the percentage of the population who are deemed annual "frequent flyers" when considering patients who differ according to their biological sex, including (a) males and (b) females. In each graph, the x-axis represents the year, and the y-axis represents the percentage of people who go to the emergency department two or more times a year.

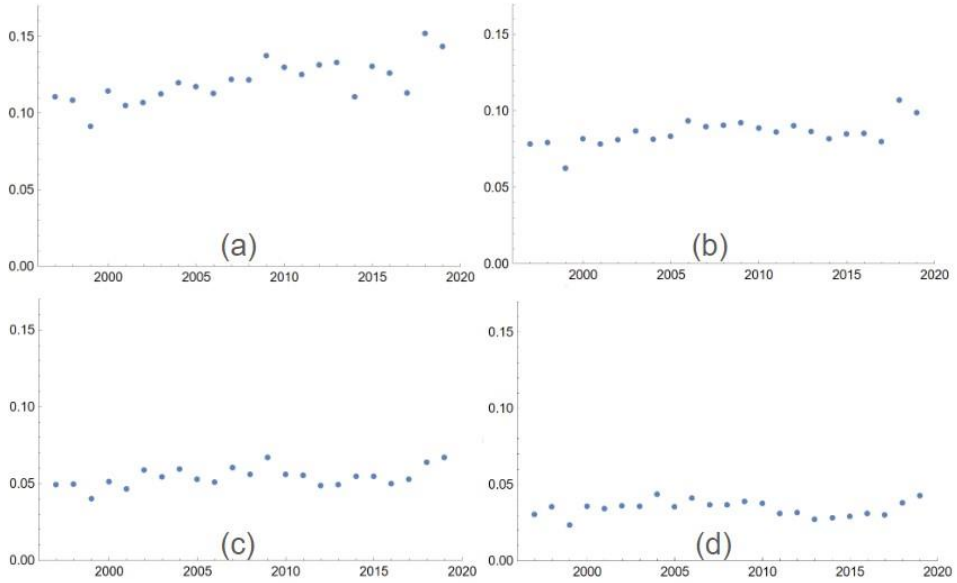

Figure 6. The Frequent Flyer Theory and Percentage Poverty Level. These scatter plots demonstrate a relationship between time and the percentage of the population who are deemed annual "frequent flyers" when patients fall within different percentages of the poverty level, including (a) below 100%, (b) between 100%-199%, (c) between 200%-399%, and (d) 400% or more. In each graph, the x-axis represents the year, and the y-axis represents the percentage of people who go to the emergency department two or more times a year.

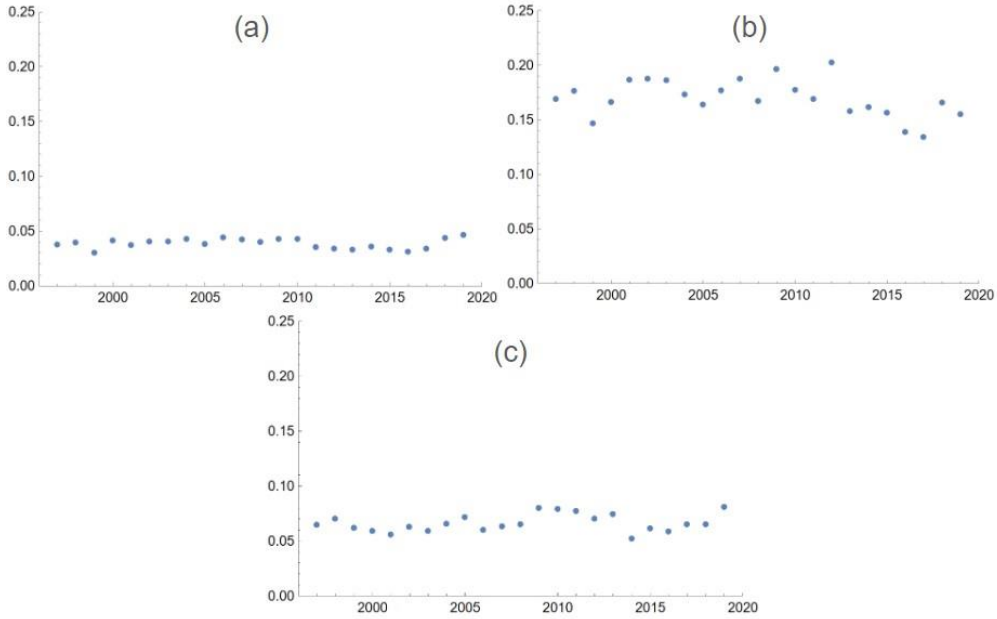

Figure 7. The Frequent Flyer Theory and Type of Insurance. These scatter plots demonstrate a relationship between time and the percentage of the population who are deemed annual "frequent flyers" when patients have different types of insurance, including (a) private insurance, (b) Medicaid, and (c) no insurance. In each graph, the x-axis represents the year, and the y-axis represents the percentage of people who go to the emergency department two or more times a year.

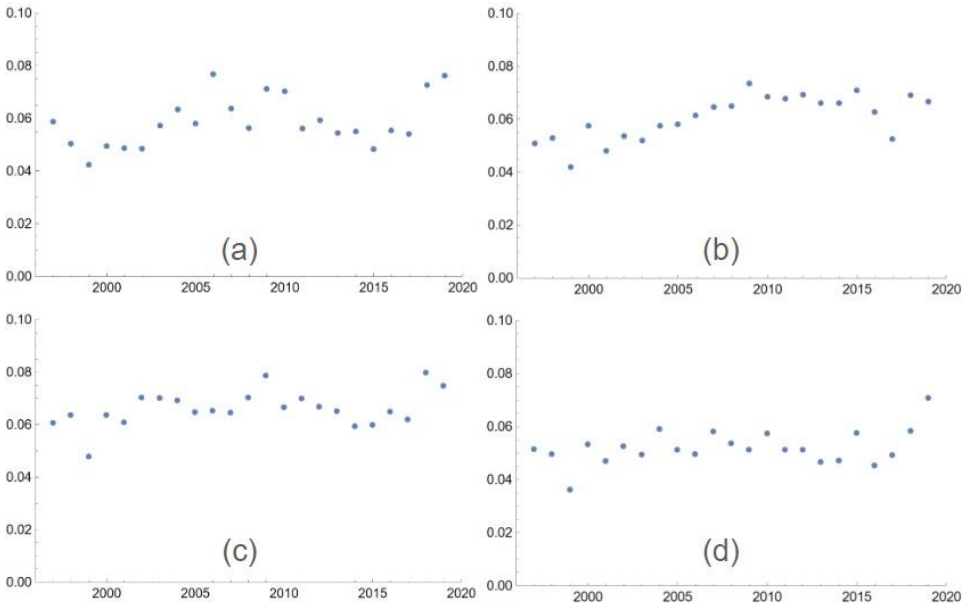

Figure 8. The Frequent Flyer Theory and Geographic Region. These scatter plots demonstrate a relationship between time and the percentage of the population who are deemed annual "frequent flyers" when patients live in different geographical regions, including the (a) northeast, (b) midwest, (c) south, and (d) west. In each graph, the x-axis represents the year, and the y-axis represents the percentage of people who go to the emergency department two or more times a year.

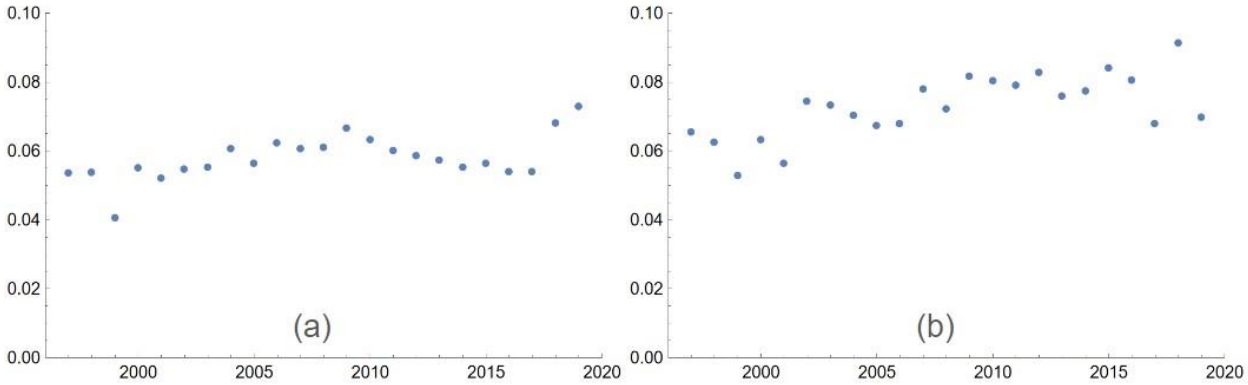

Figure 9. The Frequent Flyer Theory and Location of Residence. These scatter plots demonstrate a relationship between time and the percentage of the population who are deemed annual "frequent flyers" when patients differ according to how close they live to urban areas, including (a) those who live in or close to a city (within an MSA) and (b) those who do not live in or close to a city (outside an MSA). In each graph, the x-axis represents the year, and the y-axis represents the percentage of people who go to the emergency department two or more times a year.

DISCUSSION

Analysis of mathematical models

The data did not follow trends predicted by the Poisson Curve. Instead of following the hypothesized gradual curve, the data formed a straight line with a much steeper positive slope. Even manipulating and enlarging the curve to make the hypothesized line appear straight did not help the raw data align with the theoretical curve. The raw data points were also plotted significantly higher on the y-axis than the Poisson Curve suggested they should be. The incredibly large t-statistic and minuscule p-value calculated through the Chi-Square Goodness of Fit Test confirmed that this model could not accurately predict recurrent emergency department visit trends. Because of these reasons, the Poisson Process is not a good model for the National Center for Health Statistics data and should be rejected as the null hypothesis.

The data followed the Frequent Flyer Model much better in some cases, as represented by the nearly horizontal trendlines in some covariate graphs above, indicating that the percentage of "frequent flyers" in these populations remains relatively constant from year to year. However, this hypothesis still did not adequately represent the reality of the emergency department in all cases,

as demonstrated by the non-horizontal trendlines and random scatter of sporadically increasing or decreasing data points seen in other covariate graphs above. These observations indicate that the percentage of "frequent flyers" in these populations fluctuates as time passes. Random but short periods of dramatic increasing or decreasing frequent flyer percentages could mean that other lurking variables likely impact these values. Possible lurking variables that were not considered in our mathematical models but may require further investigation will be discussed below.

Analysis of frequent flyer covariates

Qualitative analysis of the covariate graphs generated above allows us to understand the relationship between the Frequent Flyer Theory and the covariates collected in the data. When considering age, the Frequent Flyer Theory best represents patients 18 to 24 years old (**Figure 4a**) and 65 to 74 years old (**Figure 4e**) who require multiple emergency department visits per year. The trendlines present in **Figures 4a** and **4e** are generally horizontal, indicating that a consistent proportion of the population requires multiple emergency department visits per year regardless of how much time passes. This proportion consists of the "frequent flyers" and is consistent with the Frequent Flyer Theory. The proportion of frequent flyers seen in patients between the ages of 18 and 24 is slightly larger than the proportions seen in other age groups.

The trendlines in **Figures 4b**, **4c**, and **4d** generally have a positive slope, indicating that the proportion of the population requiring recurrent emergency department visits increases as time passes in patients ages 25 to 44 (**Figure 4b**), 45 to 54 (**Figure 4c**) and 55 to 64 (**Figure 4d**). This finding is not consistent with the Frequent Flyer Theory. **Figure 4f**, which represents patients 75 years and older, is also inconsistent with the Frequent Flyer Theory because its data points randomly increase and decrease as time passes without following a general pattern. Some of the largest recorded proportions of patients requiring recurrent emergency department visits in one year are seen in patients 75 years or older.

When considering sex, the Frequent Flyer Theory seems to best represent male patients who require multiple emergency department visits per year. The trendline in **Figure 5a** is generally horizontal, indicating a consistent proportion of male patients who require recurrent emergency department visits yearly and act like "frequent flyers" from year to year. Conversely, the trendline in **Figure 5b**, which represents female patients who require recurrent emergency department visits yearly, is not horizontal. It has a generally positive slope, indicating that the proportion of female patients who require multiple emergency department visits yearly increases as time passes. This is not consistent with the Frequent Flyer Theory. It also appears that more female patients require recurrent emergency department visits per year than male patients.

When considering poverty, the Frequent Flyer Theory is good at describing the existence of frequent flyers in various populations. **Figures 6b**, **6c**, and **6d**, which represent people who fall between 100% and 199% of the poverty level, 200% and 399% of the poverty level, and 400% or more of the poverty level, respectively, generally have horizontal trendlines. These trendlines indicate that consistent proportions of these populations require multiple emergency department visits every year and act like "frequent flyers" from year to year. However, **Figure 6a**, which represents people who fall below 100% of the poverty level, has a positive trendline, indicating that the proportion of the population that requires multiple emergency department visits per year increases as time passes. This is not consistent with the Frequent Flyer Theory. It also appears that a larger proportion of patients require recurrent emergency department visits when they fall below 100% of the poverty level (**Figure 6a**) as compared to other populations.

When considering the type of insurance patients have, the Frequent Flyer Theory best describes the need for recurrent yearly emergency department visits in patients who have private insurance (**Figure 7a**). The trendline in **Figure 7a** is nearly completely horizontal with little variation in data points, indicating that a consistent population of privately insured individuals seek recurrent emergency department visits from year to year and act as "frequent flyers." The Frequent Flyer Theory is also reasonably consistent with **Figure 7c**, which represents uninsured people. There is slightly more variation in this primarily horizontal trendline as compared to **Figure 7a**, and it also shows a slightly larger proportion of uninsured patients requiring recurrent emergency department visits as compared to privately insured patients. The Frequent Flyer Theory is not consistent with **Figure 7b**, which represents patients with Medicaid. This trendline is not horizontal. Instead, data points randomly increase and decrease from year to year. These data points are also significantly larger than those seen in **Figures 7a** and **7c**.

When considering geographic regions, the Frequent Flyer Theory does not describe the proportion of patients requiring multiple emergency department visits every year in the northeast (**Figure 8a**), midwest (**Figure 8b**), south (**Figure 8c**), or west (**Figure 8d**). None of the trendlines in **Figures 8a**, **8b**, **8c**, or **8d** are horizontal. Instead, they all seem to have positive non-zero slopes. This indicates that the proportion of these populations requiring recurrent emergency department visits every year increases as time passes. This finding is not consistent with the Frequent Flyer Theory.

Finally, when considering patients' residential location, the Frequent Flyer Theory does not describe the proportion of patients requiring multiple emergency department visits in urban areas within MSAs (**Figure 9a**) or rural areas outside MSAs (**Figure 9b**). **Figures 9a** and **9b** do not have horizontal trendlines. Instead, they have positive, non-zero trendlines, indicating that the proportion of these populations requiring recurrent emergency department visits increases as time passes. This is not consistent with the Frequent Flyer Hypothesis. However, it does seem that there is a larger proportion of people requiring recurrent emergency department visits in rural areas located outside of MSAs than in urban areas within MSAs.

Analysis of possible causes of frequent flyers and additional lurking variables

In addition to dire emergencies, there are many reasons why patients may need to have repeat visits to the emergency department that might explain the existence of frequent flyers or the potential lurking variables invalidating the Frequent Flyer Model in certain populations. For example, some medical conditions require specialized treatment only the hospital can provide due to their serious nature.[12] These conditions may require hospital intervention to return patients to their baseline, especially when their conditions are not adequately managed at home.[16, 17] Other patients may have certain risk factors that make them prone to requiring emergency treatment, such as having a substance abuse disorder [18, 19] or being an inexperienced or reckless driver.[19] Still, some patients may get sick or injured at night or on weekends when their primary care physician is not working or be unable to schedule an appointment when these things occur during normal business hours.[12] All of these situations may cause patients to seek treatment in emergency departments even when "emergencies" have not occurred.

People may also choose to go to the emergency department instead of their primary care physician if they cannot afford healthcare insurance or office visits but still need treatment. Since Congress passed the Emergency Medical Treatment and Active Labor Act (EMTALA) in 1986, the emergency department has been required to treat all patients regardless of their ability to pay for their services.[20] Primary care physicians are not required to follow this law because they are considered private businesses.[21, 22] Patients who choose to replace their primary care provider with the emergency department can be seen multiple times a year depending on how often they develop various medical conditions.

Still, patients may develop conditions that require a specialist to diagnose and treat them. Sometimes, these specialists can have full schedules, preventing patients from being seen quickly. Even if patients can be seen by the specialists, they may not be able to schedule elective procedures or surgeries soon enough. When this happens, patients may be left with no choice other than to go to the emergency department to receive faster, and sometimes temporary, treatment. Moreover, while waiting to see specialists for diagnosis or treatment, their condition may progress from chronic to acute, requiring emergent intervention.

Overprescribing narcotic pain relievers in healthcare has led to the development of patients with drug-seeking behaviors, or patients who are addicted to substances that they cannot readily acquire, causing them to speak and act in ways that will convince healthcare providers to prescribe and administer their drug of choice.[23] This epidemic began in the 1990s when healthcare professionals began overprescribing narcotic pain relievers when drug companies misrepresented the medications' addictive qualities.[24] As a result, hundreds of thousands of emergency department visits occur unnecessarily as some patients seek a reliable source of narcotics.[24]

Some patients also require multiple emergency department visits because they cannot tell when they are sick enough to constitute emergent medical intervention.[15] It is common for young patients ranging in age from toddlers to young adults to visit the emergency department for already-healing insect bites or the flu.

Sometimes, patients may discover something abnormal or develop new symptoms and need reassurance from a doctor. However, patients who cannot be consoled by negative tests and discussions with their doctors may have an illness anxiety disorder. This disorder occurs when patients needlessly believe that they are or are about to become sick and seek unnecessary treatment.[25] Erving Goffman's Role Theory may also explain some of these recurrent emergency department visits. According to Goffman, people are assigned various roles throughout their lives that dictate how they interact with other individuals and society.[26] In this case, if a person believes their role in society is to be a patient, they may be more inclined to seek healthcare, even unnecessarily, since that is what patients are expected to do. The reasons discussed in this section should be further explored to better understand the applications and limitations of the Frequent Flyer Theory model.

CONCLUSIONS

Even though the data from the National Center for Health Statistics aligns with some characteristics of each hypothesis while disproving other parts, it is more likely that the Frequent Flyer Theory correctly depicts the reality of the emergency department. However, the reasons for some of the inconsistencies among various covariates remain unknown.

These models have some limitations. One limitation is that they were created from a small data set containing only slightly more than twenty data points. There may not have been enough data to represent the emergency department accurately. Another limitation is that there are several social and emotional factors that may lead a patient to require multiple emergency department visits that are not considered true emergencies or "frequent flyer" behavior. These situations were not considered in these models and may explain some of the inconsistencies discovered in the Frequent Flyer Theory model.

Future research is necessary to determine why there is considerable variability among recurrent emergency department visits from year to year. Researchers should also investigate how the potential explanations of recurrent emergency department visits detailed in the *Discussion* section work together to create the overflow of recurrent patients observed in the emergency department. Answering these questions will help emergency medicine physicians avoid overcrowding and provide better care to patients who come to the emergency department.

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The data analyzed in this project can be downloaded using the following link (March 2025):
https://ftp.cdc.gov/pub/Health_Statistics/NCHS/Publications/Health_US/hus20-21tables/edad.xlsx

Conflict of Interest/Protection of Persons

The author declares no conflict of interest. All patient and participant data were protected in accordance with the regulations set forth by the Centers for Disease Control and Prevention.

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PRESS SUMMARY

The purpose of this study is to create models that can accurately depict the likelihood of patients requiring multiple emergency department visits to better understand when and why patients will require multiple emergency department visits to heal completely. These models were created by analyzing data from the National Center for Health Statistics at the Centers for Disease Control and Prevention. They will be useful since emergency departments in the United States became busier while struggling to staff enough medical professionals to care for the influx of patients following the COVID-19 pandemic. The analysis revealed that while the theory that some patients require recurrent emergency department visits due to various physical and social needs accounted for the percentage of recurrent emergency department visits in the United States better than the theory that all emergency department visits occur by random chance, there may be additional reasons not considered in these models that should be considered in the future.

Caregiver Burden in Parents Providing Care for Children with Serious Mental Illness: A Systematic Review and Meta-Analysis

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ABSTRACT
Aim: The main purpose of this investigation is to explore and identify the factors that contribute the most to the exacerbation of caregiver burden for informal caregivers of individuals with serious mental illnesses (SMIs).
Procedure: Literature searches comprised 18 combinations of search terms related to caregiver burden and serious mental illness. Across eight databases, 1532 articles were identified. After removing 596 duplicates, 936 articles were screened for inclusion criteria, resulting in three studies that met the criteria. This small number of articles included were due to the specificity of our inclusion criteria. From these articles, correlations between caregiver burden and any other variable were extracted. Meta-analysis was conducted using a three-level meta-analytic model.
Results: A total of five factors were identified across the included articles: parent age, parent education, parent health, social support, and care recipient characteristics. The three-level meta-analytic model identified the factors parent health, ($\tilde{z}$ = .314, CI [.138, .490], *se* = .074, $t(7) = 4.222$, $p = .004$), and social support ($\tilde{z}$ = -.155 CI [-.282, -.027], *se* = .056, $t(9) = -2.750$, $p = .022$), to have significant overall effect sizes. The remaining factors did not yield significant overall effect sizes.
Conclusions: This review reveals that there is still limited research on caregiver burden for caregivers providing support to individuals with SMIs, to the level of specificity that accounts for the different relationships in caregiver-care recipient dyads. However, from the data available, variables that had the largest impact on caregiver burden measures were parental health and social support. These aspects may be possible targets for informal caregiver support.

KEYWORDS
Caregiver Burden; Caregiver Burnout; Serious Mental Illness; Informal Caregiver; Parental Caregiver; Risk Factors; Systematic Review; Meta-Analysis

INTRODUCTION

Serious mental illnesses (SMIs) are prevailing mental, behavioral, and emotional disorders that result in the impairment of daily functioning.[1] This impairment of functioning often leads to difficulties in maintaining employment, strained interpersonal relationships, homelessness, and incarceration.[2] As of 2021, data from the National Survey on Drug Use and Health (NSDUH) estimated that 5.5% (14.1 million) of non-institutionalized adults have an SMI.[3]

The specific disorders considered to be SMIs vary across the literature.[4] The term SMI is not a category found in official diagnostic manuals, such as the DSM, but generally includes mental disorders that are considered to be debilitating and cause serious functional impairment.[4] The term SMI was first created to categorize psychiatric disorders for grants funding research on mental illness.[5] As such, the definition was originally created to be flexible. The consensus across current literature is the inclusion of psychotic spectrum disorders and bipolar disorders under the category of SMIs.[6] However, the inconsistencies lie in the inclusion by some researchers of other psychiatric disorders such as mood disorders, anxiety disorders, eating disorders, and personality disorders. Some consider substance use disorders as part of SMIs, while others consider this category as a comorbidity.[7] Before publication of the DSM-5, obsessive compulsive disorder (OCD) and post-traumatic stress disorder (PTSD) were considered SMIs under the category of anxiety disorders.[8,9] However, PTSD was sometimes viewed as a comorbid disorder that frequently co-occurred with SMIs.[10] This pattern was also observed with OCD, where the disorder was considered as either a comorbidity or a SMI, depending on the study.[11,12] For the purposes of this meta-analysis, we used the operational definition from the Agency for Healthcare Research and Quality, which included the following disorders: severe anxiety disorders, major depression, bipolar disorder, psychotic disorders, as well as severe eating and personality disorders.[2] This definition includes a

wide range of psychiatric disorders while eliminating disorders that are sometimes considered comorbid conditions, as previously listed.

Current literature identifies that most SMI patients are cared for outside of healthcare institutions, where the enrollment of outpatient care was the most common.[13,14] Following the deinstitutionalization movement in the 1960s, public healthcare institutions that fully support individuals with SMIs have yet to be established.[15] This shift caused psychiatric patients to be transferred out of institutional care and into communities instead.[16] Therefore, most SMI patients who were not incarcerated depended on family members for the majority of care.[15] Familial caregivers are considered to be informal caregivers, which may be defined as individuals who provide care without professional training or compensation with regards to their caregiving responsibilities.[13] From 2015 to 2020, the number of family caregivers in the United States has increased by 9.5 million– with 5% of the care recipients reporting the main problem to be mental or emotional illness.[17] Given that these individuals have less resources and support in comparison to formal caregivers, namely healthcare providers, they are more likely to experience physical and mental strain due to caregiving tasks.[18]

The term caregiver burden has been used to describe the negative experiences that arise due to an individual's caregiving responsibilities– including psychological and physical impacts. The experience of strain has been described to be a product of caregivers delaying their needs to provide care for long periods of time.[19] Caregiver burden can be defined as the persistent difficulties, stress, and psychological hardship experienced by caregivers due to looking after another individual with a given disorder.[20,21] Current literature on caregiver burden has been concentrated on caregiving for individuals with dementia and physical illnesses, given the aging population and the corresponding disabilities of the demographic.[22] The specific experiences of caregiving, especially between parent and children, are also well documented in neurodevelopmental disorders.[23,24] However, a much smaller proportion of the literature is dedicated to caregiving for individuals with SMI, despite the nature of current treatment in which patients have limited options for institutional care.[25] Additional difficulties providing care for individuals with SMI may also include the comorbidity of substance dependency and a high relapse rate of symptoms.[2] These complications oftentimes require more support, in addition to regular caregiving needs. Thus, having a diagnosis of SMIs is often debilitating for the diagnosed individual as well as those within their social circle.

The Current Study

The purpose of the present research was to use a systematic review and meta-analysis to identify and assess the relative strength of risk factors that contributed to caregiver burden among parents caring for children with SMIs. Given that caregiver burden in SMIs have not been as well documented in comparison to other conditions, this study will also identify the gaps in literature that can be addressed in future research. For this analysis, studies were included in which care recipients had the following diagnoses: severe anxiety disorders, major depression, bipolar disorder, psychotic disorders, as well as severe eating and personality disorders.[2] Additionally, only studies assessing informal parental caregivers [i.e., parents who provide care for a child without prior training or financial compensation][13] were included. To date, there has not been a meta-analysis that explores the different risk factors and its effects on caregiver burden.

METHODS

The present research consisted of a systematic literature review following the PRISMA-P Protocol,[26] which was pre-registered on Open Science Framework (OSF) prior to data collection and analysis (https://osf.io/gm65x). Systematic literature review data were managed through adapted templates provided by Moreau & Gamble.[27]

Inclusion Criteria

To be included in data analysis, articles were screened according to the following criteria: (1) must be a study that investigates factors associated with caregiver burden, defined as persistent difficulties, stress, and psychological hardship experienced by nonprofessional caregivers due to looking after another individual with a given disorder; (2) the care recipient must be diagnosed with an SMI, which includes psychotic disorders, bipolar disorder, major depression, severe anxiety, eating and personality disorders; (3) the caregiver figure must be informal, defined as individuals providing care without prior training or financial compensation for their caregiving role; (4) the study population must be parent caregivers and children (any age) care recipients; (5) the study is peer reviewed and published; (6) the study must be available in English; and, (7) the study must have provided a sample size and corresponding Pearson correlation coefficient for measures associated with caregiver burden.

Studies were excluded according to the following criteria: (1) did not investigate caregiver burden and associated factors; (2) the care recipients did not have SMIs, as defined above; (3) the caregivers were not informal, as defined above; (4) did not investigate the stated population of interest (i.e. parent caregiver); (5) was not available in English; (6) was not peer reviewed/published; (7) a

review or meta-analysis; (8) was not an empirical research article (i.e., editorial, book, qualitative or theoretical study); (9) did not represent a unique dataset from other included research.

Information Sources & Search Process

The systematic literature review (summarized in **Figure 1**) utilized article searches from the following electronic databases: PsychInfo, PubMed, PsychArticles, ScienceDirect, Web of Science, Gale OneFile: Psychology, GoogleScholar, and ProQuest. The search terms were based on variations of commonly used keywords in literature associated with caregiver burden and SMI. A total of 18 combinations of search terms were used in each electronic database. These 18 combinations represent a subset of all 30 possible combinations of five variations of caregiver burden (i.e., caregiver burden, caregiver strain, compassion fatigue, caregiver stress, caregiver burnout), three variations of SMI (serious mental illness, severe mental illness, mental illness), and either risk factors or informal caregiving (**Table 1.1**). Searches that produced over 100 results were excluded from review. All searches were conducted between June and July of 2023.

Search Term 1	*AND* Search Term 2	*AND* Search Term 3
"caregiver burden"	"serious mental illness"	"informal caregiver"
"caregiver burden"	"risk factors"	"serious mental illness"
"caregiver burden	"risk factors"	
"caregiver burden"	"risk factors"	"informal caregivers"
"caregiver burden"	"informal caregiver	"serious mental illness"
"caregiver burden"	"informal caregiver"	"mental illness
"caregiver burden"	"mental illness"	
"caregiver burden"	"informal caregiver"	"severe mental illness"
"caregiver burden"	"risk factors"	"severe mental illness"
"caregiver strain"	"informal caregivers"	"serious mental illness"
"compassion fatigue"	"serious mental illness"	
"caregiver stress"	"informal caregiver"	"serious mental illness"
"caregiver stress"	"risk factors"	"serious mental illness"
"caregiver burnout"	"risk factors"	"serious mental illness"
"caregiver burnout"	"informal caregiver"	"serious mental illness"

Table 1.1 Search Strings Utilized in Each Database

Searches yielded 1532 total results. After removing 596 repeated articles, 936 article abstracts were reviewed by the first author and by one of the other authors for inclusion. This process was carried out using the predetermined inclusion criteria. If the abstract was unclear, the contents of the article were evaluated for inclusion or exclusion. There were no discrepancies in the inclusion or exclusion of articles across reviewers. This review process resulted in nine potential articles for full evaluation, which were conducted independently by the first and second author. Based on this full evaluation, we identified six articles that did not meet the inclusion criteria, specifically three did not include variables and/or population of interest, and three did not provide adequate data for inclusion in meta-analysis. As such, three articles had sufficient data for further analysis (**Table 1.2**).

	Cook *et al.*[28]	**Greenberg *et al.*[29]**	**St-Onge & Lavoie[30]**
Sample Size	222	105	99
Gender	55% mothers 45% fathers	100% mothers	100% mothers
Age	36 to 84 years (M = 55)	55 to 89 years (M = 66; SD = 6.69)	43-79 years (M = 62.1) 63.6% were 60 or older
Ethnicity	83% White, 11% African American 4% Asian 1% Hispanic/Latino .5% Native American .5% Multi-ethnic	NA	NA

Education	Education ranged from seven to 22 years, with a mean of 14 years	81% completed high school 42% completed some college	17.2% some post-secondary education 6% some university education
Annual Family Income	Mean annual family income in the $30,000-$40,000 range (USD)	Median annual family income was $25,000 (USD)	Mean annual family income in the $20,000 and $24,999 range (CAD)
Recruitment	Participants were interviewed by research staff after their children began treatment at a large psychiatric rehabilitation agency in Chicago, United States.	Majority of respondents were recruited though state/county service providers, others through stage agency on aging, and current participant nomination. All participants resided in Wisconsin, USA.	Recruited through general and psychiatric hospitals in Quebec, Canada.
Child SMI Diagnosis	52% schizophrenia 48% other diagnoses (e.g., mood or personality disorder)	70% schizophrenia 19% bipolar disorder 7% major depression 4% other SMI	psychotic disorders (i.e., schizophrenic, schizophreniform or schizo-affective disorders, or atypical psychosis)

Table 1.2 Sample Characteristics of included studies

Data Extraction

Given the small number of articles that met the search criteria, associations between caregiver burden and any variable were extracted. These included: (1) Pearson's r values for any correlations between any measured variable and caregiver burden, (2) sample size for that correlation, (3) all reported sample characteristics, (4) specific measures used for caregiver burden, and (5) specific measures of associated variables.

RESULTS

Identifying Factors

From the three articles, correlates with caregiver burden were identified and grouped for meta-analysis into five factors (**Table 2**). Parent age was assessed in three studies (Cook *et al.*[28]; Greenberg *et al.*[29]; St-Onge & Lavoie[30]), all measuring age in years. Parent education was assessed in two studies (Cook *et al.*[28]; St-Onge & Lavoie[30]). Cook *et al.*[28] assessed years of completed formal schooling. St-Onge & Lavoie[30] did not specify how education was assessed but reported on the average level of schooling completed as university-level and postsecondary education. Thus, it is most likely that correlations were calculated utilizing an ordinal measurement. The parent health factor assessed physical/mental health of caregivers across two studies (Cook *et al.*[28]; St-Onge & Lavoie[30]). Cook *et al.*[28] assessed parent health using the Symptom Checklist-90,[31] which measures parent's perception of their physical and psychological wellbeing. St-Onge & Lavoie[30] used an adapted scale from Brook *et al.*[32] and Platt *et al.,*[33] which measured parent's perception of their physical health. The social support factor assessed caregivers' perceptions of social support across two studies (Greenberg *et al.*[29]; St-Onge & Lavoie[30]). Greenberg *et al.*[29] measured social support based on Antonucci's[34] Social Support measure in which participants indicate the number of people they felt a special connection with. Additionally, participants indicated the extent to which they perceived their social connections as supportive. St-Onge & Lavoie[30] measured social support using Perceptions of Social Support from Friends and Family,[35] and the Kaplan Intimacy and Adaptation Scale.[36] The care recipient functioning factor was assessed across three studies (Cook *et al.*[28]; Greenberg *et al.*[29]; St-Onge & Lavoie[30]). Cook *et al.*[28] measured the caregiver's perceptions of the care recipient's functional impairment using the Global Assessment Scale.[37] Greenberg *et al.*[29] used Bruininks, Hill, Weatherman, & Woodcock's[38] count of up to eight maladaptive behaviors manifested by the care recipient. St-Onge & Lavoie[30] used Parker & Rosen's[39] Life Skills Profile, which assess the presence and impact of care recipient maladaptive behaviors.

Data Analysis

Fisher's Z transformation and variance were calculated using the Wilson Practical Meta-Analysis Effect Size Calculator.[40] As there were multiple measurements used to assess caregiver burden and factors associated with it within and across each study, we conducted a three-level meta-analytic model in R using the methods described in Assink & Wibbelink.[41] As such, for each factor we assessed overall effect size, overall measurement heterogeneity, and within-study and between-study variance. There were not enough studies that met inclusion criteria to quantitatively assess sources of within and between-study heterogeneity (e.g., moderators). As such, we present qualitative analysis of factors that may have impacted within-study and between-study variance.

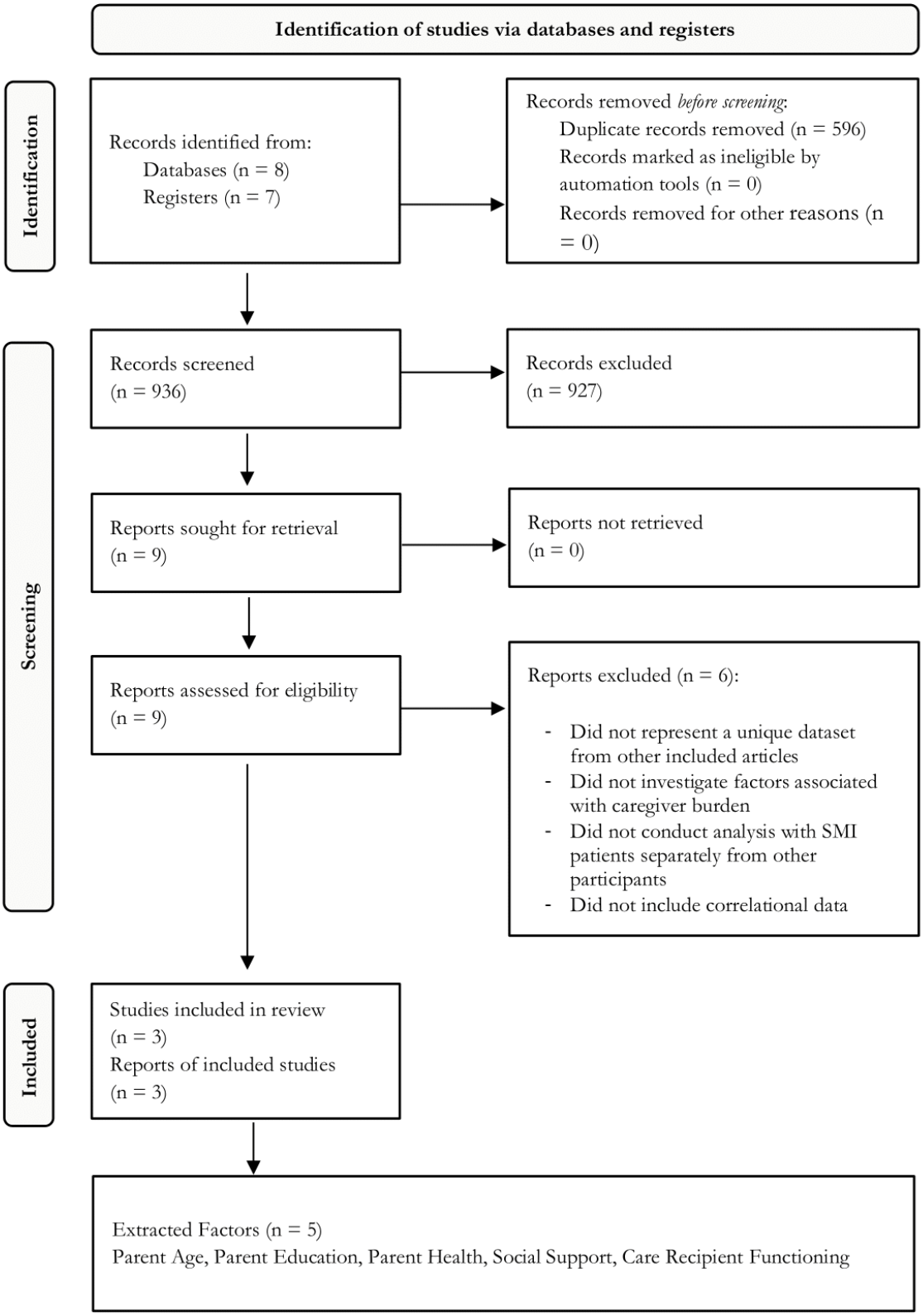

Figure 1. Search Summary

Meta-analytic Results

The parent age variable consisted of 12 effect sizes extracted from three studies (**Table 2**). The estimated overall effect size was not significant ($\bar{z}$ = .031 CI [-.051, .113], *se* = .037, $t(11)$ = .831, p = .424), indicating that parent age did not have a significant effect on measures of caregiver burden. The test of heterogeneity between all effect sizes was significant ($Q(11)$ = 25.236, p = .008), indicating significant differences across effect sizes. Constraining the within-study variances to zero significantly decreased the fit of the model (ΔAIC = -4.470, p = .011), indicating that the within-study variance was statistically different from zero. This indicates that there were significant differences in effect sizes within each study. These differences are most likely attributed to measurement, most notably within Cook *et al.*[28] This study assessed caregiver burden with the adapted Thresholds Parental Burden Scale.[42,43] This measure consisted of six dimensions [i.e., feelings of connection to care recipient (connection), preoccupation with and worry about care recipient (cognitive), perceptions of ongoing responsibility for care recipient (responsible), perceptions that care recipients behavior was unmanageable (behavior), familial discord and disagreement about care recipient (disagree), and concerns about care recipient's prognosis and future (future)], with correlations of the independent variables recorded for each dimension (**Table 2**). Cook *et al.*[28] concluded that age was differentially predictive of caregiver burden based on measurement, specifically that older parents experienced higher cognitive burden while younger parents experienced higher behavior burden.

Similarly, Greenberg *et al.*[29] and St-Onge & Lavoie[30] both used two distinct measurements of caregiver burden, although differences across measurement was not a focus of either study as it was in Cook *et al.*[28] Greenberg *et al.*[29] utilized a repeated measures design, where participants completed two measures of caregiver burden at two time points three years apart. Caregiver burden was assessed using the Zarit Burden Interview,[44] which measures caregiver subjective burden resulting from a range of problems including well-being and social relationships, and the Center for Epidemiological Studies-Depression Scale,[45] which assesses depressive symptomology. St-Onge & Lavoie[30] included two measures of burden, one assessing psychological distress, the other assessing perceived impact from caregiving like isolation and confinement. Given the variability in measurement within each study, the differences in effect sizes for factors that rely on more than one measure for a particular construct are not surprising.

Constraining the between-study variances to zero did not significantly change the fit of the model (ΔAIC = 2.000, p = 1.000), indicating that the between-study variance was not statistically different from zero. This indicates no significant differences in effect sizes across the three studies. Measurement invariance for age is likely given that all age data were collected in the same way. Additionally, the three samples are somewhat similar in composition (e.g., all from North America, moderate SES) (**Table 1.2**).

The parent education variable consisted of eight effect sizes extracted from two studies (**Table 2**). Both studies used parent education level as a demographic variable, rather than a main independent variable. Correlations extracted from these studies were primarily negative and weak to moderate in strength. The estimated overall effect size was not significant ($\bar{z}$ = -.106 CI [-.265, .053], *se* = .067, $t(7)$ = -1.576, p = .159), meaning that parent education did not have a significant effect on measures of caregiver burden. Additionally, the test of heterogeneity between all effect sizes was not significant ($Q(7)$ = 13.926, p = .053). Given effect size homogeneity, we did not expect significant within or between-study variances. As expected, constraining the within-study variances to zero did not significantly decrease the fit of the model (ΔAIC = .540, p = .227), indicating that the within-study variance was not statistically different from zero. Likewise, constraining the between-study variances to zero did not significantly decrease the fit of the model (ΔAIC = 1.605, p = .530, indicating that the between-study variance was not statistically different from zero. The homogeneity across effect sizes is not surprising given the consistently weak correlations across measurements and studies.

The parent health variable consisted of 8 effect sizes extracted from two studies (**Table 2**). The estimated overall effect size was significant, ($\bar{z}$ = .314 CI [.138, .490], *se* = .074, $t(7)$ = 4.222, p = .004), meaning that parent health had a significant negative effect on measures of caregiver burden. The test of heterogeneity across all effect sizes was significant, ($Q(7)$ = 32.687, p < .001). Constraining the within-study variance to zero significantly decreased the fit of the model (ΔAIC = -10.568, p = .000), indicating significant differences in effect sizes based across different measurements used within each study. As mentioned in the parental age section, Cook *et al.*[28] assessed caregiver burden across six subscales from one measure and St-Onge & Lavoie[30] used two distinct measures. Although the correlations extracted from both studies were all positive in direction, they ranged from weak to moderate. This supports the previous assessment from parental age that aspects of caregiver burden are differentially associated with other outcomes.

Constraining the between-study variance to zero did not significantly decrease the fit of the model (ΔAIC = 1.948, p = .821), indicating that the between-study variance was not statistically different from zero. This indicates no significant difference in effect sizes across the two studies, despite different measures used to assess both caregiver burden and parent health. Cook *et al.*[28]

assessed parent's perception of their physical and psychological wellbeing, while St-Onge & Lavoie[30] assessed parent's physical health only. As noted in the parental age section, the samples are also relatively similar (**Table 1.2**).

The social support variable consisted of 10 effect sizes extracted from two studies (**Table 2**). The estimated overall effect size was significant, ($\bar{z}$ = -.155 CI [-.282, -.027], *se* = .056, $t(9)$ = -2.750, p = .022), meaning that social support had a significant negative effect on measures of caregiver burden. The test of heterogeneity between all effect sizes was not significant, ($Q(9)$ = 13.603, p = .137). Given effect size homogeneity, we did not expect significant within or between-study variances. As expected, constraining the within-study variances to zero did not significantly decrease the fit of the model (ΔAIC = 1.263, p = .391), indicating that the within-study variance was not statistically different from zero. Likewise, constraining the between-study variances to zero did not significantly decrease the fit of the model (ΔAIC = 1.833, p = .167), indicating that the between-study variance was not statistically different from zero. The homogeneity across effect sizes within and between studies suggests that the negative association between social support and caregiver burden may be more generalizable across measurement of both constructs. Measures of caregiver burden are described in the above sections. Greenberg *et al.*[29] assessed social support via the size of the caregiver's social network and St. Onge & Lavoie[30] assessed three aspects of social support: the quality of relationships with close confidants (Kaplan Intimacy and Adaptation Scale)[36], and perceived social support from family and friends (separate subscales assessed with Perceived Social Support from Friends and from Family)[35]. Homogeneity across these measures may indicate that the positive benefits of social support on various aspects of caregiver burden do not depend exclusively on a single aspect of the social network.

The care recipient functioning variable consisted of 12 effect sizes extracted from three studies (**Table 2**). The estimated overall effect size was not significant ($\bar{z}$ = .211 CI [-.062, -.483], *se* = .139 $t(11)$ = 1.516, p = .129), meaning that care recipient functioning overall did not have a significant effect on measures of caregiver burden. The test of heterogeneity between all effect sizes was significant ($Q(11)$ = 76.308, p < .001). Constraining the within-study variances to zero significantly decreased the fit of the model (ΔAIC = -4.550, p = .011), indicating that the within-study variance was statistically different from zero. This heterogeneity within studies is likely due to the variability in caregiver burnout measurement.

Constraining the between-study variances to zero significantly decreased the fit of the model (ΔAIC = -4.868, p = .009). The differences in effect sizes across the three studies could be a result of the differences in measures of caregiver burden or care recipient functioning. Cook *et al.*[28] assessed functional impairment of the care recipient using the Global Assessment Scale.[37] Greenberg *et al.*[29] assessed care recipient behavioral problems.[29,38] St-Onge & Lavoie[30] assessed care recipients' negative symptoms resulting from their disorder (Life Skills Profile).[39] Thus, between-study variability may be due to the difference of operationalizing care recipient functioning. And as previously discussed, all three studies used different measures for caregiver burden, further facilitating the differences in effect sizes across the three studies.

Factor: Parent Age	**N**	**Parent Age Measure**	**Measure of Caregiver Burden**	***r***
Cook *et al.* (1994)	222	Age in years	Parental burden: Connection[a]	0.14
			Parental burden: Cognitive[a]	0.12
			Parental burden: Responsible[a]	0.16
			Parental burden: Behavior[a]	-0.17
			Parental burden: Disagree[a]	-0.05
			Parental burden: Future[a]	0.01
Greenberg *et al.* (1997)	73	Age in years	Burden (Time 1)[b]	-0.01
			Burden (Time 2) [b]	-0.07
			Depression (Time 1)[c]	0.09
			Depression (Time 2) [c]	-0.03
St-Onge & Lavoie (1997)	99	Age in years	Psychological distress[d]	-0.09
			Daily and social life burden[e]	0.23
Factor: Parent Education	**N**	**Measure: Parent Education**	**Measure: Caregiver Burden**	***r***
Cook *et al.* (1994)	222	Years of formal schooling	Parental burden: Connection[a]	-0.26
			Parental burden: Cognitive[a]	-0.21

			Parental burden: Responsible[a]	-0.16
			Parental burden: Behavior[a]	-0.1
			Parental burden: Disagree[a]	0.01
			Parental burden: Future[a]	-0.2
St-Onge & Lavoie (1997)	99	Unspecified	Psychological distress[d]	0.01
			Daily and social life burden[e]	-0.04
Factor: Parent Health	**N**	**Measure: Parent Health**	**Measure: Caregiver Burden**	***r***
Cook *et al.* (1994)	222	Parent symptoms[f]	Parental burden: Connection[a]	0.33
			Parental burden: Cognitive[a]	0.36
			Parental burden: Responsible[a]	0.01
			Parental burden: Behavior[a]	0.37
			Parental burden: Disagree[a]	0.27
			Parental burden: Future[a]	0.2
St-Onge & Lavoie (1997)	99	Perceptions of health[g]	Psychological distress[d]	0.54
			Daily and social life burden[e]	0.25
Factor: Social Support	**N**	**Measure: Social Support**	**Measure: Caregiver Burden**	***r***
Greenberg *et al.* (1997)	73	Size of social network[k]	Burden (Time 1)[b]	-0.07
			Burden (Time 2) [b]	-0.14
			Depression (Time 1)[c]	0.24
			Depression (Time 2) [c]	-0.07
St-Onge & Lavoie (1997)	99	Confidant relationship[l]	Psychological distress[d]	-0.08
			Daily and social life burden[e]	-0.04
		Social support: Family[m]	Psychological distress[d]	-0.39
			Daily and social life burden[e]	-0.28
		Social support: Friends[m]	Psychological distress[d]	-0.09
			Daily and social life burden[e]	-0.29
Factor: Care Recipient Characteristics	**N**	**Measure: Care Recipient Characteristics**	**Measure: Caregiver Burden**	***r***
Cook *et al.* (1994)	222	Functional impairment[h]	Parental burden: Connection[a]	0.09
			Parental burden: Cognitive[a]	-0.01
			Parental burden: Responsible[a]	0.05
			Parental burden: Behavior[a]	-0.25
			Parental burden: Disagree[a]	-0.02
			Parental burden: Future[a]	-0.09
Greenberg *et al.* (1997)	73	Behavioral problems[i]	Burden (Time 1)[b]	0.49
			Burden (Time 2) [b]	0.27
			Depression (Time 1)[c]	0.24
			Depression (Time 2) [c]	0.06
St-Onge & Lavoie (1997)	99	Disability[j]	Psychological distress[d]	0.38
			Daily and social life burden[e]	0.42

Table 2. Measures and Correlation Coefficients Organized by Factor. [a]Thresholds Parental Burden Scale[42,43]; [b]Zarit Burden Interview[44]; [c]Center for Epidemiologic Studies Depression Scale (CES-D)[45]; [d]Psychiatric Symptom Index (PSI)[46,47]; [e]Cantor[48]; Pai and Kapur[49]; and Platt *et al.*[33]; [f]Symptom Checklist-90[50]; [g]items from Brook *et al.*[32]; Platt *et al.*[33]; [h]Global Assessment Scale[37]; [i]Bruininks, Hill, Weatherman, & Woodcock[38]; [j] Life Skills Profile (LSP)[39]; [k]Antonucci[34]; [l]Kaplan Intimacy and Adaptation Scale; adapted by Lin, Dean, and Ensel[36]; [m]Perceptions of social support from Friends and from Family[35]

DISCUSSION

This meta-analysis identified factors that predicted caregiver burden for parental caregivers of individuals with SMI. We used a three-level meta-analytic model to assess the impact of five factors: parent age, parent education, parent health, parent social support, and care recipient functioning. There were significant effects of parent health and social support on caregiver burden. Although there was not sufficient data to carry out moderator and mediator analysis, variance within and between studies was discussed qualitatively. We suggest that variability in measures used for caregiver burden and associated factors impacts associations between these variables. As such, we caution about generalizing findings in this field beyond specific measures. Further, we highlight the impact of parent health and social support on caregiver burden and note that associations with social support may be less subject to measurement variance.

As discussed previously, there was a very small number of studies that met the inclusion criteria of parent-child dyads of caregiving. Specifically, 106 studies were excluded because they assessed parent-child dyads within larger groups of familial caregivers, but did not provide separate analysis for parental caregivers. There is evidence that points to the differing effects of the nature of the relationship between caregiver and care recipient, and the burden experienced. For example, Chen & Lukens[51] found that sibling caregivers reported better emotional well-being in comparison to parent caregivers, and that parent caregivers reported more depressive symptoms than sibling caregivers. This suggests that the relationship between the caregiver and care recipient does, in some way, moderate the caregiving experiences and subsequent outcomes. While it would be relevant to assess differences across relational contexts, this was not possible for our analysis without original datasets for combined samples. Future research would benefit from separating or comparing the differential effects of caregiving in accordance with the relationship status between caregiver and care recipient. We hope that the present research will highlight the need for more research on parental caregivers of individuals with SMI.

For this meta-analysis only published data was used, which may have created sampling bias as data from gray literature were not included. Thus, the conclusions made in this study may not be representative of all data available on this topic. Further, a bias analysis on each included article was not conducted due to time constraints. Instead, sample characteristics in studies were noted and discussed as part of the qualitative analysis. Two of our studies only included mothers in their analysis rather than both parents; and although mothers more commonly take on the role of a primary caregiver, caution should be taken when generalizing our findings. Given that a very small number of studies met our inclusion criteria, and that the sample sizes of each included study were relatively small, there are further limitations with regards to the power of the analysis itself. This further limit the generalizability of our findings. Additionally, due to resource limitations, we did not consider searches yielding over 100 results. This may have impacted on the small number of studies identified that met the inclusion criteria. Despite these limitations, our systematic review highlights a dearth of literature focusing specifically on caregiver burden among parental caregivers of individuals with SMIs. Further, our findings indicate that parental health and social support significantly impacted caregiver burden—pointing towards potential aspects to focus on for future interventions and support programs.

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PRESS SUMMARY

This meta-analysis investigates the risk factors that most significantly exacerbate feelings of caregiver burden in parents providing care for their adult children with SMIs. The results showed that parental health and social support were significantly associated with caregiver burden, such that individuals with better health and more social support were less likely to experience caregiver burden. However, this investigation also identified a need for more research on caregiver burden experienced in parents caring for another with mental health disorders. A higher level of specificity in this research would greatly assist this high risk, but often overlooked, population.

The Influence of Gender on the Support and Confidence of Students in Undergraduate STEM Majors

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ABSTRACT
Gender can have an impact on the intended career pathways in the science, technology, engineering, and mathematics (STEM) fields. This has important implications for research on gender issues in STEM education in larger contexts. In particular, this is essential to gain a better understanding of gender representation, academic confidence, STEM confidence, and career progression in higher education. Using a quantitative questionnaire-based research design approach, this study analyzes the experiences of undergraduate students currently pursuing and enrolled in STEM disciplines at a four-year land-grant university in North Carolina. With family members, friends, peers, classmates, and professors playing a role in supporting undergraduate STEM students, this data signifies a trend of men/self-identified males (males) demonstrating more confidence than women/self-identified females (females).

KEYWORDS
STEM Confidence, STEM Identity; Undergraduate Support; Gender Representation; Gender Identification; Higher Education; Scientific Confidence; Underrepresented Students; Undergraduates

INTRODUCTION

Science, technology, engineering, and mathematics (STEM) institutions have historically excluded people on the basis of gender and race.[1] As a result many STEM fields still suffer from a lack of gender and racial and ethnic diversity, especially as people persist through higher level graduate degrees.[2] Ecology, evolution, and conservation fields specifically have a drastic overrepresentation of people who identify as white relative to people of color,[3] though there is some evidence that gender diversity is improving.[2,4] Despite this representation, women in these fields still experience implicit bias, discrimination, and societal pressure to have and raise children relative to their colleagues who are men.[5] Efforts to better understand the factors that support and hinder women in these fields are important. The development of innovative policy and change is also crucial as this historical exclusion reduces the sense of comfort and belonging that students must have as they pursue higher education.[1]

Scientific Confidence

Scientific confidence refers to an individual's perception that they can be successful in science. This includes their ability to systematically understand and apply knowledge in the natural, social, and life sciences.[6] It stems from science identity, which refers to the extent to which an individual identifies as a member of a science field[7] and perceives that other people view them as such.[8] People's experiences, upbringing, and socialization inform how they develop this confidence.[9] Because gender is intimately tied to socialization,[10] gender may impact an individual's scientific confidence.

This socialization can come from both school and familial support systems. For example, instructors can affect how students perceive a scientific field and their abilities within it. One study of high school students and teachers demonstrated the role that instructors play in imparting biases to their students which resulted in students attributing feminine characteristics to the humanities while attributing masculine characteristics to the sciences.[10] For this study, instructors and students were surveyed, and these surveys accounted for gender role biases and gender-based teaching methods. Furthermore, various studies have demonstrated both instructors and students in the classroom perceive that male students perform better than their female

counterparts.[10,11] Interestingly, despite these perceptions, some studies indicate that female students outperform male students in various science disciplines.[11]

Other studies have looked at how socialization in the home affects students' scientific confidence. Longitudinal studies suggest that when parents value gender roles, this can increase the likelihood that children will pursue careers dominated by members of their gender.[12] Furthermore, parents can impose perceptions of science on their children. For example, parents are more likely to perceive that science is less interesting and more difficult for their daughters relative to their sons, and as such, use more technical language when discussing science with their sons.[13] There is also evidence that parents who value science are more likely to push their sons, rather than their daughters, to scientific careers.[14] This upbringing affects the norms that children develop. This is important because studies have shown that males who adhere to traditional norms of masculinity are more likely to pursue scientific majors in college,[15] while females who identify as more feminine are less likely to pursue scientific majors.[16] Given that scientific confidence is related to how suitable an individual perceives that they fit into science and how others perceive that they belong in the field, socialization in the home may affect scientific confidence.

This study explores the influence of gender on the support and confidence of undergraduate science majors. While other factors like race or ethnicity, socioeconomic status, and an individual's personality may affect their scientific confidence,[17–19] our study focused on the impacts of gender. While these other variables are often held constant across children in various households or may have less of an impact on how they are raised, as discussed above, children often receive different upbringing and support based on their gender. Thus, we wanted to better understand how a student's gender affected their perceived systems of support in selecting a science career as well as their scientific confidence.

METHODS AND PROCEDURES

This study utilized a quantitative approach to investigate the experiences of undergraduate students enrolled in an introductory, in-person environmental science course at a four-year land grant university. Data were collected through a Qualtrics™ survey containing a series of demographic questions about gender, race, academic major, and career interest. We measured personal support levels from various individuals (family members, friends, peers, classmates, and professors), and personal STEM confidence using Likert scale questions. STEM confidence was measured using the Perceived Identity Compatibility Between Gender and Major/Career[20] and Self-efficacy for Learning and Doing Science[21] constructs. We evaluated the dataset utilizing independent sample t-tests to determine if there were differences in level of support and STEM confidence by gender.

Altogether, n = 237 students were recruited to participate in the study. Over 95% of participants were between the ages of 18 and 24. Additionally, there was approximately an equal percentage of male (53.2%) and female (45.2%) participants in this study (**Table 1**). There were 37.6% of the students classified as freshmen, 36.7% as sophomores, 16.0% as juniors, and only 9.7% as seniors. A large proportion of students self-identified as White or Caucasian (73.0%), while the remainder self-identified as students of color, other or declined to provide information on their race/ethnicity (**Table 1**).

Participant Demographics	Percentage (%)
Gender	
Female	45.2
Male	53.2
Age	
18 - 24 years old	95.8
25 - 34 years old	2.9
35 - 44 years old	1.3
Classification	
Freshman	37.6
Sophomore	36.7
Junior	16

Senior	9.7
Race/Ethnicity	
American Indian/Alaskan	1.2
Asian	11.1
Black/African American	6.8
Hispanic/Latino	5.6
Native Hawaiian/Pacific Islander	0.8
White/Caucasian	73.0
Other	1.2
Decline to Answer	0.4

Table 1. Demographics of the Participants (n = 237).

RESULTS

The results of the study indicate that a larger percentage of male undergraduates agreed with statements that imply their STEM confidence (**Figure 1**). Self-reported data indicated that there is a trend of male undergraduates demonstrating more confidence than their female counterparts. About 62% of males and 32% of females reported that they think their personal identity/gender and major are very compatible. A larger percentage of males (76%) do not think their personal identity/gender will affect how well they will do in their major. A few females (20%) do not think that their personal identity/gender will affect how others view them in their major. The data reveal that more males (43%) than females (18%) think they are good at understanding science topics.

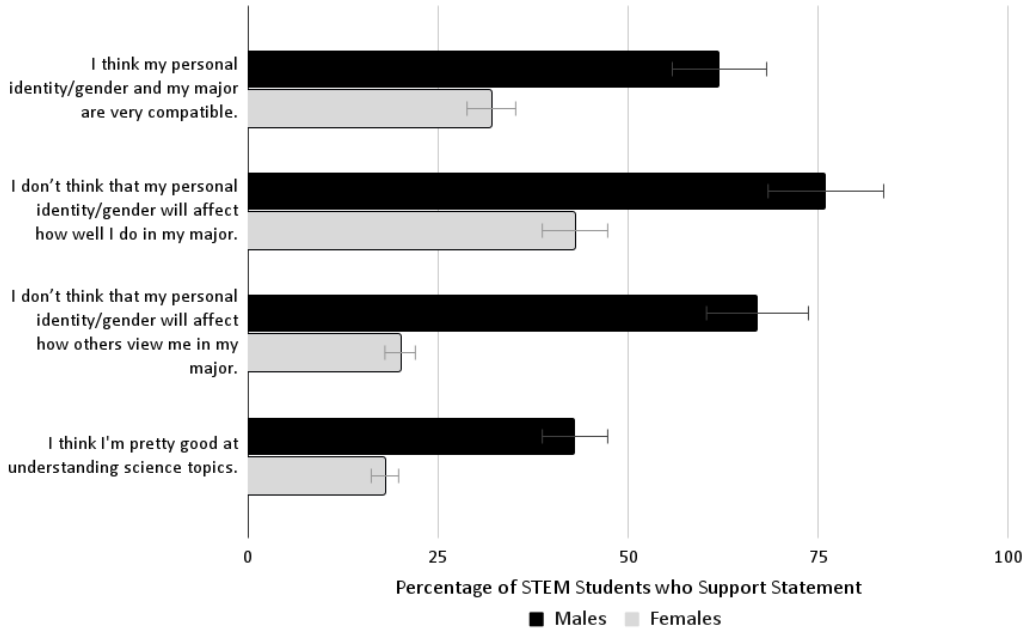

Figure 1. Questionnaire Results of the Confidence of STEM Majors of Opposite Genders (n = 237). The lines to the right of the bars are error bars, representing the potential variability of the data from its reported value.

Gender Representation in Higher Education

Female students reported less support from their classmates, peers, parents, and siblings (**Figure 2**). The results also found that male undergraduates were more likely to indicate support from individuals they frequently interact with. While professors and

friends generally supported male and female students equally, classmates, peers, fathers, mothers, and other relatives were likely to support males 10% more than their female counterparts (**Figure 2**). Additionally, the results indicated that siblings supported their brothers 20% more than their sisters who pursue STEM fields.

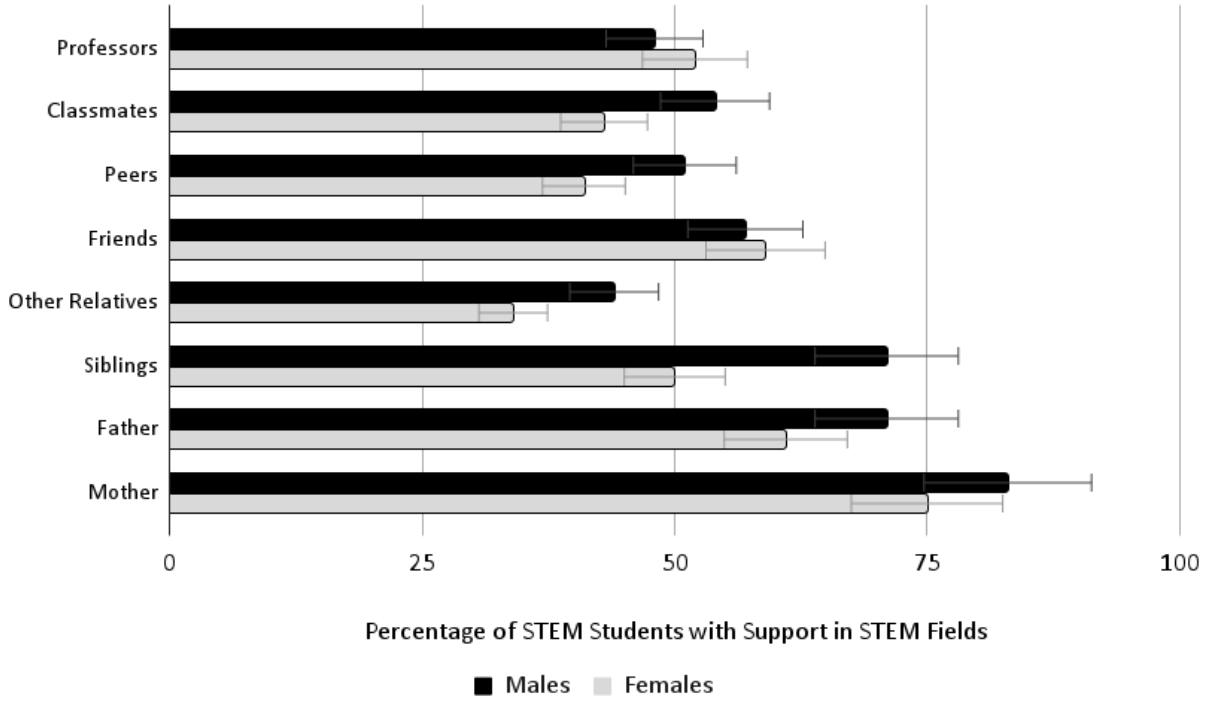

Figure 2. Results of Undergraduate Support Levels for STEM Majors of Opposite Genders (n = 237).

Overall, students felt that their gender did not influence their STEM confidence, although males reported higher confidence on average (**Table 2**). While female students were more likely to perceive that gender would lead to challenges in their major ($p < 0.01$) and impact their career choice ($p < 0.01$), both male and female students generally disagreed that gender directly affected their experiences or career decisions. This was further supported by perceptions of how others would view them in their major and their perceptions of how well they would do in their major. While male students were less likely to perceive that their gender affected how others view them in their majors ($p < 0.01$) and how well they would perform in their major ($p < 0.01$), both tended to agree that there was not an effect. There was a trend for male students being more likely to perceive that their major and gender were compatible ($p = 0.08$) and that they were good at understanding science ($p = 0.09$), though both male and female students agreed about both statements. Finally, there was no difference between how male and female students perceived that their gender affected their choice in professional fields ($p = 0.11$), though both groups did tend to agree that gender affected their field (**Table 2**).

Confidence Statements	Gender	N	Mean	Std. Deviation	Std. Error Mean	Sig. (2-tailed)
I don't think that my personal identity/gender will affect how others view me in my major.	Man/Male	125	5.86	1.71	0.15	<0.01
	Woman/Female	106	4.81	2.03	0.19	
I don't think that my personal identity/gender will affect how well I do in my major.	Man/Male	125	6.22	1.42	0.13	<0.01
	Woman/Female	106	5.64	1.77	0.17	

I think my personal identity/gender and my major are very compatible.	Man/Male	125	5.86	1.49	0.13	0.08
	Woman/Female	106	5.52	1.46	0.14	
I think I may experience difficulties in my major because of my personal identity/gender.	Man/Male	125	1.72	1.12	0.10	<0.01
	Woman/Female	106	2.77	1.82	0.18	
I think my personal identity/gender will be an important factor in the type of career I decide to pursue.	Man/Male	125	2.56	1.79	0.16	<0.01
	Woman/Female	106	3.26	1.78	0.17	
I don't think I would pursue certain fields because of my personal identity/gender.	Man/Male	125	2.39	1.78	0.16	0.11
	Woman/Female	106	2.78	1.93	0.19	
I think I'm pretty good at understanding science topics.	Man/Male	125	5.49	1.27	0.11	0.09
	Woman/Female	106	5.22	1.10	0.11	

Table 2. Independent T-test Results of the STEM Confidence Levels Between Male and Female STEM Undergraduates (n = 237). Mean equals average response where 1=strongly disagree and 7=strongly agree.

There were no significant differences between how male and female STEM undergraduates perceived support in their choices about their majors from those around them. Specifically, there was no difference in perceived support from mothers ($p = 0.49$), fathers ($p = 0.15$), siblings ($p = 0.25$), other close relatives ($p = 0.99$), friends ($p = 0.39$), peers ($p = 0.97$), classmates ($p = 0.70$), and professors ($p = 0.60$). While not statistically significant, there was a trend that female students may perceive less support from fathers in their choice of major than male students do, even though there was no difference at all for mothers (**Table 3**).

How supportive the following individuals are about the choice of major:	Gender	N	Mean	Std. Deviation	Std. Error Mean	Sig. (2-tailed)
Mother	Male	126	6.53	1.22	0.11	0.49
	Female	106	6.42	1.32	0.13	
Father	Male	126	6.39	1.33	0.19	0.15
	Female	102	6.11	1.57	0.16	
Siblings	Male	125	6.18	1.47	0.13	0.25

	Female	102	5.95	1.59	0.16	
	Male	104	6.06	1.42	0.14	
Other Close Relatives						0.99
	Female	86	6.06	1.32	0.14	
	Male	126	6.1	1.25	0.11	
Friends						0.39
	Female	106	6.25	1.27	0.12	
	Male	126	5.89	1.33	0.12	
Peers						0.97
	Female	106	5.9	1.38	0.13	
	Male	126	5.85	1.42	0.13	
Classmates						0.70
	Female	106	5.77	1.55	0.15	
	Male	126	5.99	1.27	0.11	
Professors						0.60
	Female	106	5.9	1.52	0.15	

Table 3. Independent T-test results comparing the Levels of the Support from various Individuals for Levels for Male and Female STEM Undergraduates (n = 237). Mean equals average response where 1=strongly disagree and 7=strongly agree.

DISCUSSION

While gender representation in certain fields is improving in certain STEM fields like ecology, evolution, and conservation biology,[2,4] issues with discrimination and bias still persist.[5] Our results support that conditions may be improving, but that there are still persistent issues today. While male and female students perceived that they were supported by various groups of people and that their gender did not affect their scientific confidence, male students still reported higher levels of scientific confidence than female students.

Scientific confidence is important because it relates to an individual's perception that they can be successful in science. This includes their ability to systematically understand and apply knowledge in the natural, social, and life sciences.[6] This study is supported by several others that suggest that gender affects students' confidence in STEM fields,[19,20,23] though other studies have suggested that other factors may also contribute to scientific confidence.[18–20] Gender differences in scientific confidence are important because they can have far-reaching implications for the future. Differences in confidence can result in different levels of test anxiety with resulting significant differences in exam scores.[24] However, more recent research is suggesting that confidence in STEM fields and cultural perceptions of the appropriateness of certain fields for people who identify with certain genders is related to the pay gap between males and females in STEM fields.[25] Additionally, it is important to consider how scientific confidence may parallel findings outside of STEM. Studies in business and leadership have also shown that women experience lower confidence than men, which can hinder their progression into leadership roles. These similarities suggest that confidence barriers for women may be a societal issue rather than a STEM-specific one.

While our study suggested that there were no differences in the support students received for selecting a science major, previous studies have suggested that parental support can be an impacting factor.[26] Fathers were the only group from whom students perceived near significant differences in support, with male students perceiving greater support. Students conversely perceived that they had equal levels of support from mothers regardless of gender. Our findings may also support previous research on the relevance of parental support, while contributing to research on student-professor interactions by investigating perceived support. While several studies have investigated the link between same-gender instructors and student success[27,28] scientific confidence,[29] few have looked at perceived support.

Another study of undergraduate students revealed that female students experienced lower scientific confidence if there were no female instructors, but male and female students experienced scientific confidence equally when there was gender diversity among instructors.[11] Thus, students' scientific confidence may be affected by their peers and instructors, yet there is some evidence this confidence may not have a measured effect on how they perform.

This study was limited in scope as it was bound to a sample of undergraduate students at a single university in North Carolina. Furthermore, we did not investigate the differences in perceived support by the gender of the person providing support. Given our findings on the differences between perceived support from mothers and fathers, investigating how support differs from other groups by gender may have been informative. Future research should investigate the degree to which gender effects support from peers, professors, and non-parental family members. We were also unable to include students who identify as gender diverse in our study due to a limited sample, though research suggests that support from professors is especially important for these students to succeed in academia.[30]

Despite these limitations, this research has implications to combat the generalization that STEM fields are male-dominated. Developing a sense of scientific confidence is essential when it comes to a female student's academic achievement and success in a science career.[24,25] We specifically suggest that interventions are needed earlier on in students' lives to counter this socialization, as our results suggest that it may begin in the home with parents. Furthermore, efforts to train teachers to address these biases in students and themselves may be meaningful.

CONCLUSIONS

This study examined the associations between support levels and confidence among students by gender. Overall, male students had higher levels of scientific confidence, but both genders perceived that they were exhibited scientific confidence and were supported by their networks. Our work contributes to research on gender in STEM fields by looking at the intersection between support systems and scientific confidence. While this study suggests that there are no significant differences in STEM support levels for male and female students, more research is needed to examine the influence of other identities on scientific confidence. In particular, the examination of intersectional identities would allow for a better understanding of how scientific confidence and support levels interact with other identities. Beyond STEM fields, confidence gaps between genders have also been reported in other areas, such as business and leadership, suggesting that the issues women face in STEM may be part of a broader trend in society. Ultimately, this study is important for institutions seeking to promote diversity, equity, and inclusion within STEM fields.

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PRESS SUMMARY

This study examines the influence of gender on the support and confidence of STEM undergraduate students. The findings suggest a trend of males demonstrating more confidence and support in comparison to females.

In silico Analysis of a Nonsense Mutation Linked to Autosomal Recessive Hypercholesterolemia Type 4

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ABSTRACT
Autosomal recessive familial hypercholesterolemia-4 (FHCL4) is a genetic disorder caused by mutations in *LDLRAP1*, a gene encoding a protein that allows the LDL receptor to be endocytosed and degraded in the liver. *In silico* tools were used to examine the rs121908325 variant linked to FHCL-4. The variant protein LDLRAP1^{Q136X} affects the coding region of *LDLRAP1*, resulting in a glutamine amino acid being changed into a stop codon, truncating the protein at amino acid 136. Phylogenetic analysis of ten different animal species demonstrated that glutamine 136 is 100% conserved in the LDLRAP1 protein from the human protein to flies and frogs. An NCBI Conserved Domain Search for LDLRAP1 indicated that the LDLRAP1^{Q136X} variant truncates the protein within a peptide binding domain, a phosphoinositol binding domain, as well as a domain that specifies the Pleckstrin protein superfamily of signaling proteins. IntFold 3D rendering of wild type (WT) and LDLRAP1^{Q136X} proteins showed that the variant has a significant alteration in 3D structure, based on the loss of 172 amino acids. Further *in silico* analysis using amino acid interaction software showed that the LDLRAP1^{Q136X} protein was missing its phosphotyrosine binding pocket. The rs121908325 mutation is rare, and none of the 70 genomes analyzed during a nutrition course at a large research I university carried this allele. These *in silico* studies demonstrate that the nonsense mutation at position glutamine 136 would impact specific domains of LDLRAP1, ultimately inhibiting the protein's ability to perform its function of facilitating removal of the LDL receptor from cell surfaces, leading to increased circulating cholesterol levels and potential cardiovascular health complications.

KEYWORDS
Cholesterol; Hypercholesterolemia; Low density lipoprotein; LDL; LDLR; LDLRAP1; Autosomal recessive hypercholesterolemia-4 (FHCL4); heart disease

INTRODUCTION

Cholesterol is a waxy substance used to synthesize steroid hormones, make bile, insulate nerves, and form cell membranes. Its metabolism is regulated by exogenous and endogenous sources. In the endogenous pathway, the liver and extrahepatic tissues synthesize cholesterol, which enters circulation via lipoproteins secreted into bile. In the exogenous pathway, cholesterol from dietary and biliary sources is absorbed in the intestine and enters the bloodstream via chylomicrons. Humans consume about 300700 mg of cholesterol each day and about 1000 mg is secreted into bile, leaving a total of 1300-1700 mg of cholesterol to be metabolized in the intestines daily.[1]

Cholesterol is hydrophobic and is transferred throughout the body by two types of carriers. LDL carriers circulate cholesterol through the blood, and HDL carriers sequester cholesterol from the blood to the liver for recycling or degradation.[2] Elevated LDL cholesterol is tightly linked to atherosclerosis and cardiovascular disease. When cholesterol is stuck in the bloodstream arteries become more rigid, thicker, and harder.[3] Following an endothelium injury, an inflammatory response can result in a lesion. The lesion develops into a fatty streak with monocytes, platelets, and oxidized LDL accumulating in the injured area. Monocytes turn into macrophages and gorge the LDL using the LDL receptor (LDLR) on their cell surface. They then turn into foam cells. The fatty streak continues to grow and develops into plaque. A fibrous cap can form over the plaque, which occludes the blood vessel.[4] If a clot forms and blood flow stops completely, a myocardial infarction or stroke may occur. Although lifestyle factors contribute to these risks, hypercholesterolemia is often inherited, as some individuals simply make more cholesterol by *de novo* synthesis.[5]

Autosomal recessive familial hypercholesterolemia (FHCL) can be divided into four subtypes, each with variants within different genes along the cholesterol metabolism pathway. FHCL1 is associated with mutations of the *LDLR* gene, but also can have associated mutations in *APOA2*, *EPHX2* and *GHR*.[6] FCHL2 is associated with mutations in *APOB*, which acts as a ligand for

LDLR, while FHCL3 is caused by mutations in PCSK9 which binds to LDLR and inhibits LDL uptake.[6] The focus of this research is on the fourth type, FHCL4, which is linked with mutations in the gene encoding the low-density lipoprotein receptor adaptor protein 1 (*LDLRAP1*).[6] The main treatments for FHCL4 are lifestyle modifications: a diet low in saturated and trans fats, regular physical activity, weight control, and smoking cessation.[7] Statins can be used starting as early as age eight.[8] These lipid-lowering medications reduce the activity of hydroxymethyl glutaryl coenzyme A reductase, the enzyme responsible for cholesterol synthesis.[8] Statins are safe and effective for most patients of any age or gender, minimizing the risk of major CAD events by about 30 percent.[2,8]

LDLRAP1 interacts with the cytoplasmic tail of LDLR.[9-11] When this interaction occurs, LDLR is endocytosed into cells, resulting in removal of about 70% of LDL from circulation, decreasing plasma total cholesterol levels.[3,12] This process occurs in the liver and in macrophages, where the receptor with LDL can be degraded.[13] This process serves as a protective mechanism against hypercholesterolemia and injuries to the arterial wall. Deficiencies in *LDLRAP1* also cause macrophages to be unable to internalize and degrade LDL in the liver, leading to an increase in circulating cholesterol.[13,14] When circulating cholesterol is high, plaque is deposited in the coronary arteries and proximal aorta. The risks of an *LDLRAP1* defect are tendon xanthomas, atherosclerosis, and premature coronary artery disease (CAD). These risks are similar to those in individuals whose hypercholesterolemia is a consequence of their lifestyle.[14]

FHCL4 is caused by homozygous variants in the *LDLRAP1* gene, and as such is a recessively inherited condition.[9] The *LDLRAP1* gene is localized to chromosome 1, spanning 25 kb with 9 exons and 8 introns.[9,15,16] A single nucleotide variant (SNV) in *LDLRAP1*, rs121908325, has been found in a few families but is extremely rare, with an alternate allele prevalence of 0.003%.[17] The variant results in a premature stop codon, or nonsense mutation.[3,17] Only five studies describe patients with this variant, but none examined the functional consequences of this variant.[3,14,18-20] The first article describing this variant was from 1973[19], followed by an article from 2001 describing the location of *LDLRAP1* on chromosome 1p36.[3] In the 2001 article, rs121908325, along with five other variants, were identified as affecting the protein coding region of the gene.[3] It was not until 2016 when Farhed and colleagues described the Q136X variants as a founder mutation in Lebanese ancestry.[18]

The objective of this study was to evaluate the consequences of the rs121908325 nonsense mutation in the LDLRAP1^{Q136X} variant protein. This work tests the hypothesis that *in silico* tools can be used to predict how the variant protein, LDLRAP1^{Q136X} loses its intended purpose of removing LDL, leading to FHCL4.

METHODS AND PROCEDURES

In silico methods were used to study the LDLRAP1 protein and the variant associated with FHCL4.

Initial identification of the variant

A 2001 genome linkage study by Garcia and colleagues was initially used to identify the rs121908325 variant as the variant of interest for this study.[3] The study included four families with FHCL4: two Lebanese and two Sardinian. The individuals that inherited FHCL4 were the result of consanguineous mating. Studies by Sirinian and Nagai were also observed to further observe the interactions between LDLRAP1 variants and LDLR.[21,22]

Sequence analysis of LDLRAP1

The NCBI protein sequence database was used to obtain protein sequence for LDLRAP1.[15] The "FASTA" tool was used to obtain the amino acid sequence of the reference protein sequence. Since the variant is a nonsense mutation, the variant amino acid sequence was constructed manually by deleting all amino acids following amino acid 136 (LDLRAP1^{Q136X}).[16,17] These two sequences were compared with the amino acid sequence from other animals using the NCBI orthologs database[15] and the COBALT Constraint-based multiple alignment/phylogenetic analysis tool.[23] *Homo sapiens* gene (NP_056442.2), *Mus musculus* (NP_663529.2), *Rattus norvegicus* (NP_001102741.1), *Danio rerio* (NP_001074104.1), *Xenopus tropicalis* (NP_001017114.1) *Macaca mulatta* XP_001107620.3), *Bos taurus* (NP_001077137.1), *Gallus gallus* (XP_015153218.2), *Canis lupus familiaris* (XP_855049.1), and *Sus scrofa* (XP_003127756.1) were selected. To observe conserved domains, the Conserved Domains database was used.[24] The gene name, *LDLRAP1*, was searched to find the cd13160 phosphotyrosine binding PH-like fold domain.

3D structural analysis of LDLRAP1 WT and variant sequences

The FASTA sequences from the WT LDLRAP1 protein sequence (NP_056442.2) and the manually constructed variant sequence LDLRAP1^{Q136X} were pasted into the IntFold feature of the Biomedics Web Servers Model.[25,26] The Protein Databank (PDB) files were downloaded, and PyMol[27] was used for molecular imagining. These images were compared visually to identify differences between the structure of the reference and LDLRAP1^{Q136X} proteins.

FunFold Analysis of Protein Domain Interactions

The Biomedics Web Servers Model subprogram FunFold directly predicts possible ligand interactions.[28] The prediction was done using the amino acid sequences for both proteins and data for ligand interaction, as amino acids interacting with each ligand were collected. The PDB files were downloaded from FunFold and visualized using PyMol[27] software.

ClinVar database analysis of SNP positions.

The ClinVar database through NCBI[15,29,30] was used to link to Variation Viewer which shows the location of 52 pathogenic variants along the length of the *LDLRAP1* gene. This information was captured as a screenshot which was further annotated to produce the figure.

GTEX analysis of gene expression

GTEX multiple gene expression portal analysis[31] was used to compare the expression pattern of the LDL receptor mRNA (LDLR) and LDLRAP1. Both gene names were put into the search bar on the GTEX multi-gene query box with all tissues selected. The data showed the levels of the mRNA from each gene in tissues from the database.

SNP analysis in DNA dataset

Participants aged 20-23 enrolled in a Nutrition course at Research I university took part in a double-blind study that analyzed their genotypes and phenotypes (IRB protocol #24-150, approved as exempt). Each participant sent in a saliva sample via a 23andMe® kit and used numeric identifiers to upload their SNP data to a secure database site. The participants also completed surveys on health status. In the post-survey completed after receiving their 23andMe® kit results, participants were asked, "Do you know your cholesterol levels?" The results from the survey were compared with the raw genotype data received from the 23andMe® kit results.

RESULTS

The first step in analyzing the *LDLRAP1* gene was to compare the amino acid sequence of the protein across species and determine the homology. HomoloGene[15] showed that the glutamine at position 136 was well-conserved across species. As shown in **Figure 1**, comparison on the LDLRAP1 sequence from *Homo sapiens* (NP_056442.2) with *Mus musculus* (NP_663529.2), *Rattus norvegicus* (NP_001102741.1), *Danio rerio* (NP_001074104.1), *Xenopus tropicalis* (NP_001017114.1) *Macula mulatta* (XP_001107620.3), Bos taurus (NP_001077137.1), Gallus gallus (XP_015153218.2), Canis lupus familiaris (XP_855049.1), and Sus scrofa (XP_003127756.1) indicated a 100% conservation of glutamine 136 in these species, suggesting its importance in the structure and function of the LDLRAP1 protein. Based on the NCBI BLAST analysis and RefSNP report, the LDLRAP1^{Q136X} protein generated by rs121908325 ended at amino acid 136 due to a nonsense mutation converting glutamine to a stop codon, truncating the protein.[16,17] Furthermore, 100% of the amino acids immediately following the position of the stop codon caused by rs121908325 were conserved. Overall, there were only 22 amino acids in the human sequence which differ or were absent compared to other species in our analysis. This yielded an overall conservation of the protein between species of 93%.

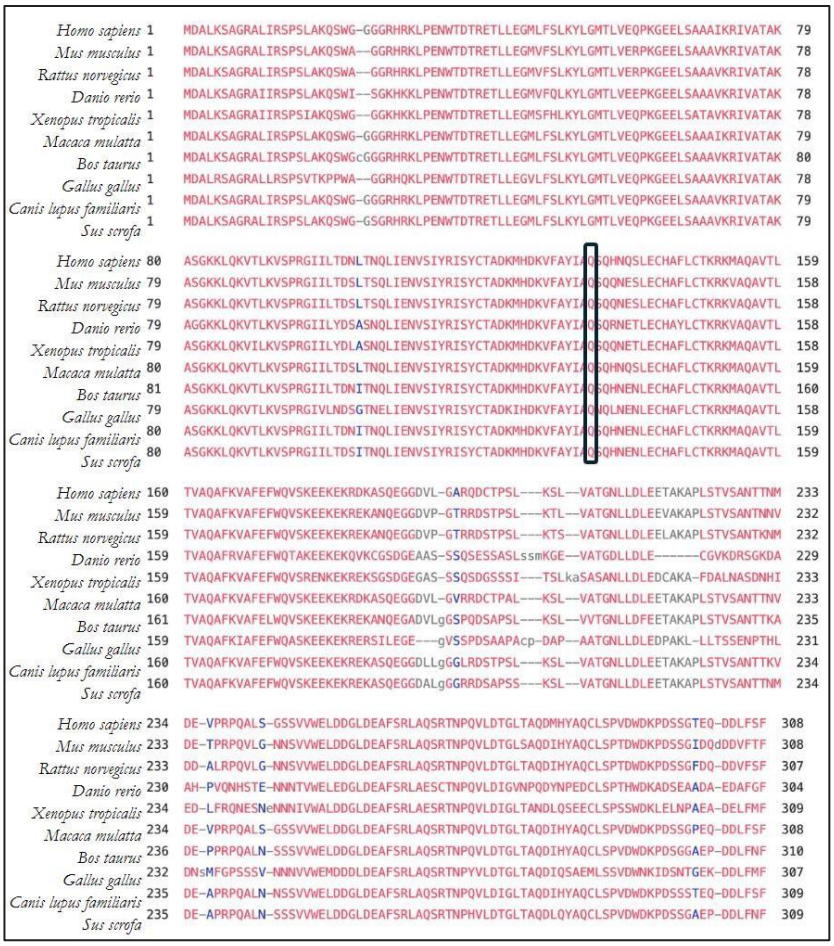

Figure 1. Phylogenetic analysis of LDLRAP1 orthologs. The amino acid sequences of *Homo sapiens* (NP_056442.2) *Mus musculus* (NP_663529.2), *Rattus norvegicus* (NP_001102741.1), *Danio rerio* (NP_001074104.1), *Xenopus tropicalis* (NP_001017114.1) *Macula mulatta* (XP_001107620.3), *Bos taurus* (NP_001077137.1), *Gallus gallus* (XP_015153218.2), *Canis lupus familiaris* (XP_855049.1), and *Sus scrofa* (XP_003127756.1) from top to bottom. The glutamine at position at 136 which is mutated by rs121908325 is indicated by the black box and is 100% conserved. Amino acids that differ from the reference sequence are colored in blue, while identical and homologous (charge, polarity, etc.) amino acids are in red. Grey amino acids are shown when that sequence is absent in one or more of the analyzed homologues. Dashes indicate spacing differences between sequences.

The 3D renderings for both the WT and the variant protein as predicted by the Biomedics Web Servers Model IntFOLD program[25,26] were compared in **Figure 2**. The LDLRAP1 reference protein model was quite large, whereas the variant protein, LDLRAP1^{Q136X}, was far less extensive due to the nonsense mutation that truncated it at position 136. In the reference protein, several domains are present past serine 135, which are missing in the mutant protein, including a large loop that connects to an alpha helix and to the end of the protein. The significance of these domains was not specifically tested using the modeling. However, the NCBI conserved domain database[15] was used to determine whether the nonsense mutation removed or altered any binding domains. The results of this analysis showed that the LDLRAP1 protein contains a phosphotyrosine binding/phosphotyrosine-interaction domain (**Figure 3**). Notably, the nonsense mutation that truncates the protein at amino acid 136 for LDLRAP1^{Q136X} is in the middle of that binding domain.

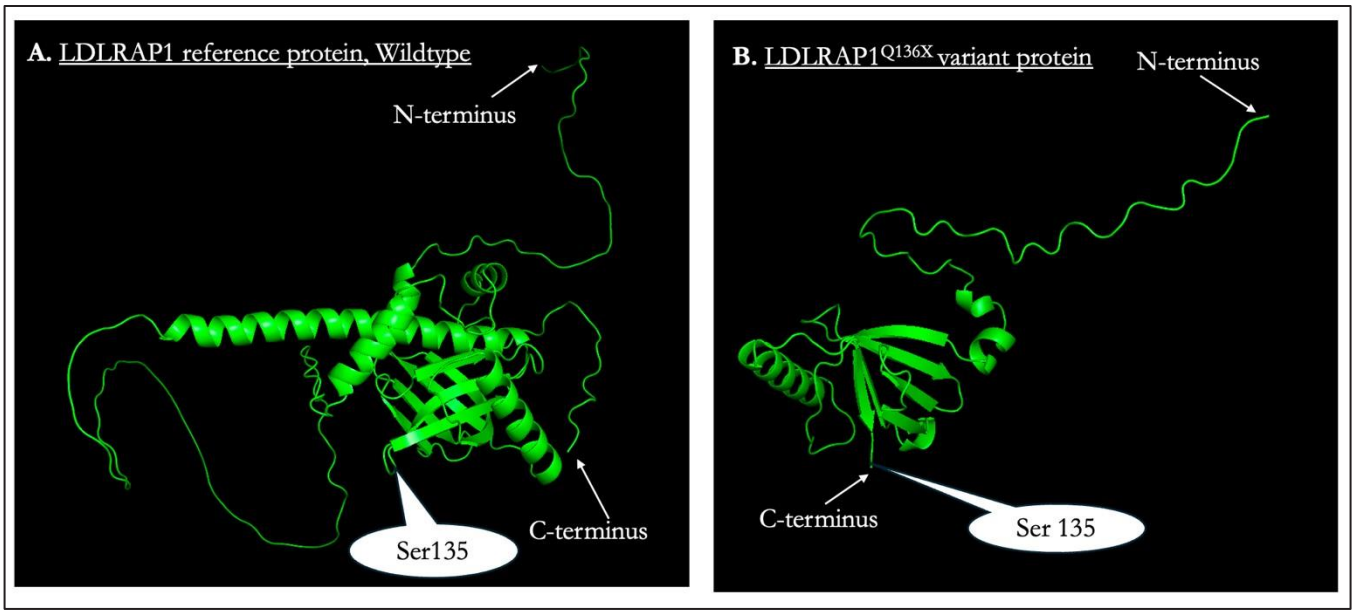

Figure 2. IntFOLD 3D rendering of LDLRAP1. A. The reference protein sequence[9] was input into the IntFOLD server.[25,26] **B.** The LDLRAP1^{Q136X} sequence containing the deletion found in rs121908325 was generated by modification of the reference project sequence and input into the IntFOLD server. The N- and C- terminus, along with the position of serine 135 which is the last amino acid before the deletion is shown for both structures. The IntFOLD server was used with the datafiles displayed using PyMol.[27]

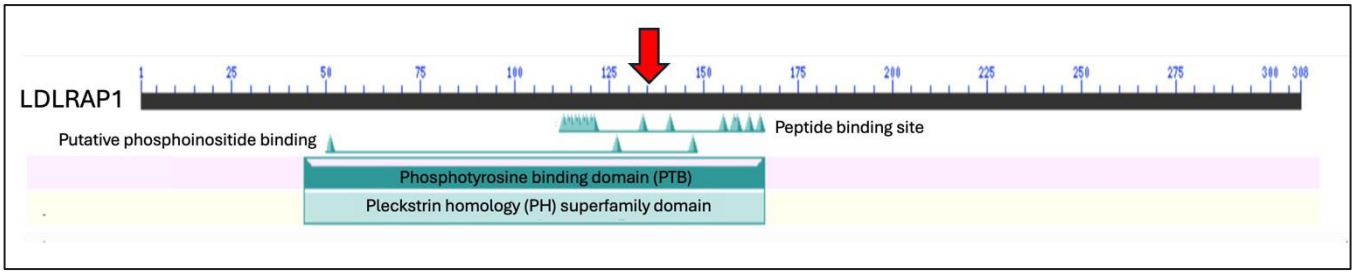

Figure 3. NCBI Conserved Domain Search for LDLRAP1. The LDLRAP1^{Q136X} variant protein is truncated at amino acid 136, indicated by the red arrow. This region of the protein contains a peptide binding site, and a phosphinositol binding site, with interacting amino acids indicated by triangles. This region includes the mammalian phosphotyrosine binding domain, indicated by the dark green color (PTB), and is in a region that defines the Pleckstrin homology (PH)like superfamily of proteins, a large family of signaling proteins, indicated by the lighter green box.

FunFold database[28] was used to identify amino acid-ligand interactions in the reference and variant proteins. As shown in **Figure 4**, the reference protein contains a predicted tyrosine binding pocket that is missing in the variant protein LDLRAP1^{Q136X}, although the software highlights two tyrosine residues in the variant protein. These two residues are far upstream (amino acids 114 and 122) of the predicted interaction site with LDLR (amino acids 259 (Phe), 262 (Ala), 263 (Leu), 266 (Arg), 272 (Leu), 274 (Thr)) in the reference protein.

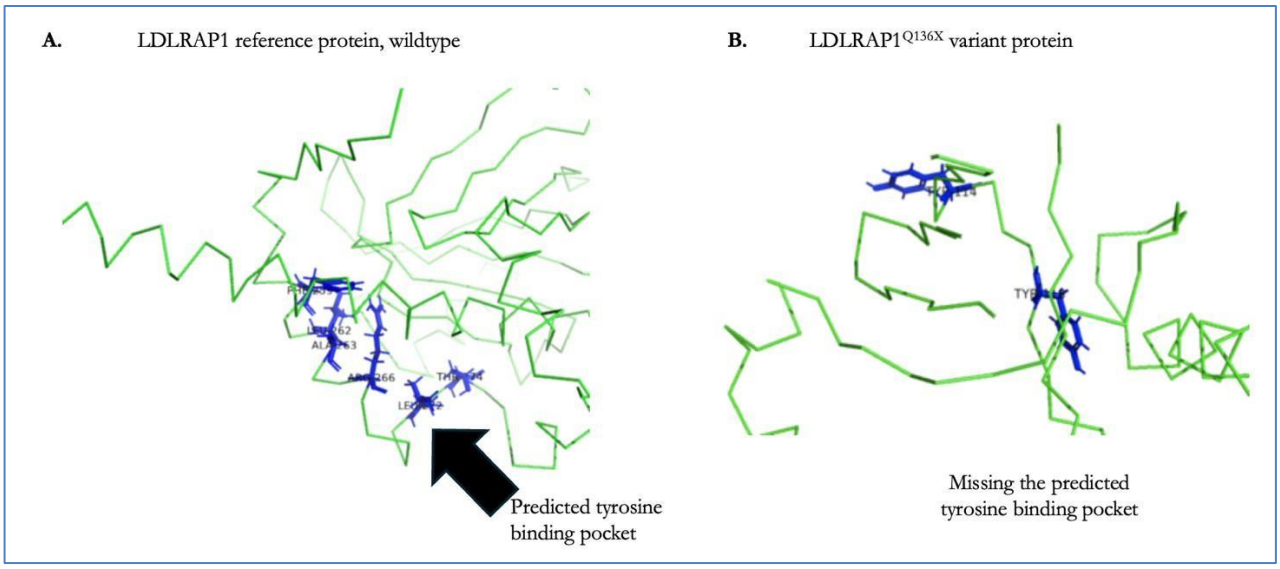

Figure 4: Amino acid interaction predictions. A. LDLR is phosphorylated following LDL binding, and LDLRAP1 binds to phosphotyrosine on LDLRAP1 at the PTB binding domain (arrow). The tyrosine interaction sites are at amino acids 259 (Phe), 262 (Ala), 263 (Leu), 266 (Arg), 272 (Leu), 274 (Thr) **B.** LDLRAP1^{Q136X} is missing the predicted tyrosine binding pocket, with tyrosine amino acids indicated (Tyr 114 and Tyr 118) indicated in blue, but these amino acids further upstream than the predicted site in the reference protein, and not part of the predicted binding site for the reference protein. This structure is predicted not to bind to LDLR by the FunFold software.

Analysis of clinical pathogenic and likely pathogenic variants along the length of the *LDLRAP1* gene using ClinVar database[29,30,32] demonstrated that there are pathological variants located 3' to the position of rs121908325 (**Figure 5**). There are 29 pathogenic variants prior to rs121908325, and 22 following rs121908325. These data suggest that important functional domains are removed by the early termination that occurs for carriers of this variant.

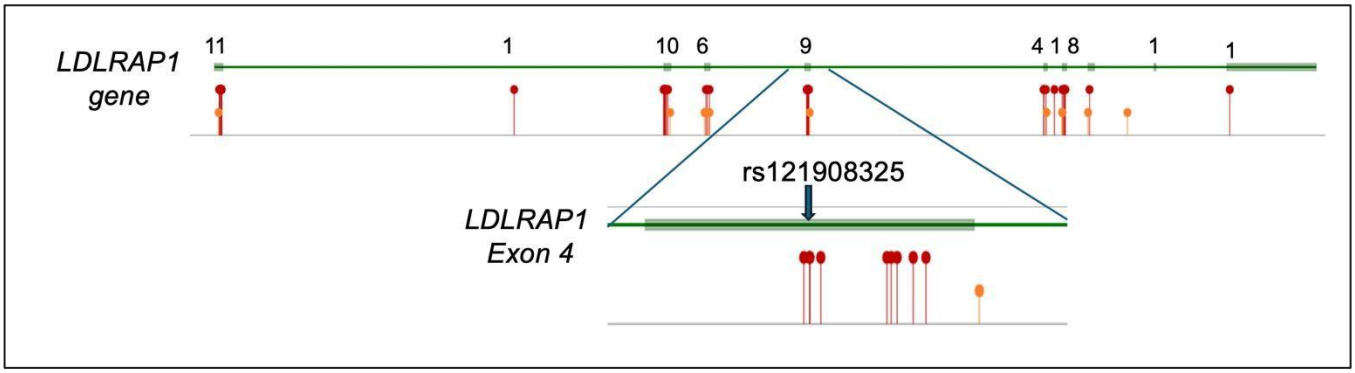

Figure 5: Pathogenic variants in LDLRAP1. The intron exon structure of the *LDLRAP1* gene is shown, with the locations of the pathogenic (red markers) and likely pathogenic (orange markers) variants shown, as mapped by the CLINVAR database.[29,30,32] The number of variants is shown above each exon/intron area for reference. Exon 4 is highlighted as is the position of rs131908325.

LDLRAP1 is an accessory protein for the LDL receptor, LDLR. GTEX multiple gene expression analysis[31] was used to examine co-expression of LDLR and LDLRAP1 to identify tissues that would be affected in rs121908325 carriers. As shown in **Figure 6**, LDLR and LDLRAP1 have similar mRNA expression levels in tissues with some notable differences. LDLR is highly expressed in the lung, adrenal gland, fallopian tube, esophagus, ovary, and cultured fibroblasts, while LDLRAP1 is highly expressed in the spleen, cervical region of the spinal cord, cerebellum, and cerebellar hemisphere. Both have moderate expression in the liver and blood cells.

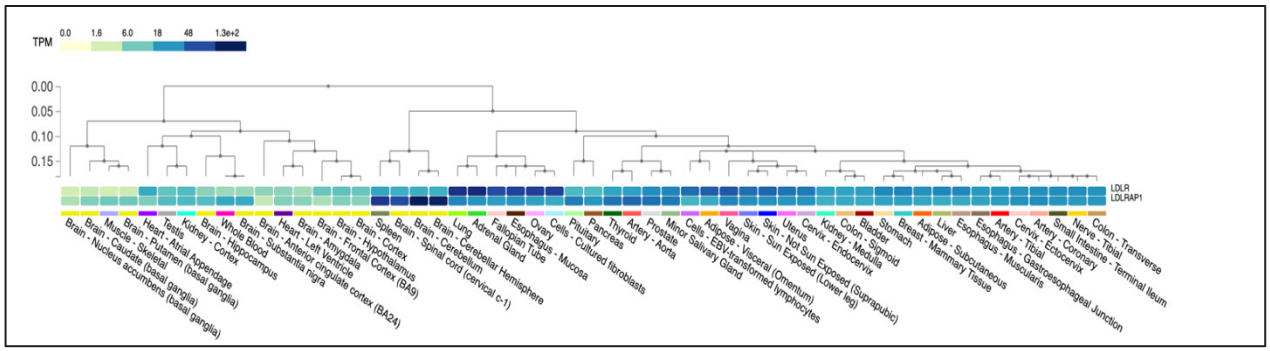

Figure 6. GTEX multiple gene expression analysis showing the co-expression level interaction between LDL and LDLRAP1. The Genotype Tissue Expression (GTEX)[31] online software was used to generate this figure.

Variant rs121908325 is rare, with NCBI reporting a worldwide alternate allele frequency of 0.003%.[17] Analysis of the raw data from 134 participants who took a 23andMe® test found only the reference genotype of CC for the rs121908325 variant, meaning that all participants had a normal genotype for this variant and would be expected to produce the full length LDLRAP1 protein. From the survey, 53 students did not know their cholesterol levels, six students reported high cholesterol levels, 68 reported normal cholesterol levels, and seven reported low cholesterol levels.

DISCUSSION

The rs121908325 variant of *LDLRAP1* results in a nonsense mutation at amino acid 136 and early termination of the protein. While the variant has been previously reported, no additional *in silico* studies had been done to map the region lost by the early termination. Based on the findings from our *in silico* analysis, the hypothesis that this variant would disrupt protein function is supported. The results predict that LDLRAP1^{Q136X} cannot serve its function of removing LDL, resulting in FHCL4.

In addition, the amino acid glutamine, located at the position of the termination event, was well-conserved across species, suggesting that its function within this area is also conserved across species. Because a few of the lower species were missing a few amino acids after glutamine, this area may be susceptible to changes in the amino acid sequence. However, no species tested was missing the entire domain of the protein past amino acid position 136.

The area of LDLRAP1 around amino acid 136 contains binding sites for signaling proteins. As a result, the mutated protein will likely not communicate with other cells and bind LDLR. The 3D rendered shape of the variant LDLRAP1 protein was utterly distinct from that of the full-length WT protein. The change in structure likely results in a change of function. In particular, the variant LDLRAP1 protein is missing the phosphorylated tyrosine binding pocket, so signaling proteins that use a tyrosine amino acid to interact with LDLRAP1 cannot bind to the tail of LDLR. With the loss of those domains, it is predicted that LDLR cannot serve its function of shuttling LDL out of the bloodstream and into hepatocytes or macrophages for degradation.

LDLRAP1 and LDL were expected to be most highly expressed in the liver. However, GTEX expression analysis revealed that LDLRAP1 was highly expressed in the adrenal gland, fallopian tube, esophagus, ovary, and cultured fibroblasts. This means that the protein may associate with other receptors and serve a different function in those tissues.[23] LDLRAP1 also have other binding partners whose cellular locations could be affected by this variant.[21] LDLR was most expressed in the lung, adrenal gland, fallopian tube, esophagus, ovary, and cultured fibroblasts. This supports the role of LDL in metabolism and synthesis of steroid hormones.

None of the participants included in the 23andMe™ study had the LDLRAP1^{Q136X} variant, as was expected due to its worldwide population rarity. However, this variant has been shown to be a founder variant for individuals of Lebanese or Turkish descent.[18] In analyzing the 23andMe™ results, 19 students indicated Eastern European ancestry, which includes Turkish ancestry, and nine students indicated Northern African ancestry, which includes Lebanese ancestry. Our dataset did not further delineate ancestry data from these main groupings on the 23andMe report. Six participants in the study reported high cholesterol despite having the normal allele studied for the gene, meaning that other genetic variations and lifestyle factors played a role in serum cholesterol levels for these individuals. Given that the population in this study has an average age of 21.4 years, many participants had not yet had their cholesterol levels checked.

A previously published study found that in people who have two *LDLRAP1* variant alleles, hepatic LDLR function is impaired, resulting in clearance of LDL from the blood at a slower rate and reduction of HDL.[3] In our *in silico* analysis, LDLRAP1 expression was high in brain as well, and further studies should examine how brain function or neurons are impaired by variants

in LDLRAP1. These could include cognitive testing of carriers, or even cell-culture based studies to examine the role of LDLRAP1 protein in neurons. Furthermore, other work has found that LDLRAP1 is only recruited to the membrane after LDL binds, so a mutation would decrease its efficiency in binding to the receptor.[19] The data suggests that LDLRAP1 protein activity may be specific to LDLR function in polarized cells such as hepatocytes. This is consistent with the hypothesis that LDLRAP1 recycles LDLR from the lysosome to the basolateral cell surface.[3] Furthermore, another study found that patients with an *LDLRAP1* deficiency had over 20 times the amount of LDLR on the cell surface and 27 times the amount of LDLR outside of coated pits, upholding the information cited in the Garcia study.[3,12] The researchers concluded that *LDLRAP1* is required for LDL to bind to its receptor efficiently, and that function is impaired in patients with FHCL4.[12] Additional studies have shown that LDLRAP1 escorts megalin through endosomes and recycles endosomes in the Golgi region.[21] Megalin plays a role in the endocytosis of diverse proteins such as albumin, beta-2-microglobulin, Vitamin D binding protein, Vitamin A/retinol binding protein and even angiotensinogen in the renin-angiotensin system of blood pressure regulation.[33] Thus, it appears that interaction between LDLRAP1 and LDLR is essential for LDL clearance, but that LDLRAP1 may be involved in many other pathways.

CONCLUSIONS

The findings from our *in silico* work confirmed that the *LDLRAP1*^{Q136X} variant terminates the protein at position 136, resulting in loss of 172 amino acids. Given the loss of a significant portion of the protein, it is not surprising that this variant contributes to AHR. However, our new findings show that this deletion impacts the putative tyrosine amino acid binding domains of LDLRAP1, suggesting how and why the nonsense mutation impacts cell signaling in target tissues. We also provide new modeling that shows how deletion alters the predicted 3D structure of the remaining domains of the protein translated upstream to the deletion. Furthermore, our results allow us to predict that the presence of pathogenic variants in the DNA sequence downstream of rs121908325 impacts additional regions of the protein that are necessary to perform its function of removing LDL from circulation. Overall, these findings suggest that the truncation of LDLRAP1 due to the Q136X variant impairs its ability to efficiently remove LDL from circulation, potentially contributing to the development of cardiovascular diseases

Future research should focus on the mechanism by this variant in LDLRAP1 leads to FHCL4. For example, *in vitro* studies comparing the function of the LDLRAP1 and the variant in liver or brain cells, and in particular its interaction with LDLR would elucidate the variant's biological impact in cholesterol metabolism. Greater insight on this can lead to the discovery of treatments for hypercholesterolemia in general as the domains lost in rs121908325 variant are likely important signaling domains for the protein. Examination of the functions of LDLRAP1 and LDL in anatomical structures outside of the liver, and the effect of LDLRAP1 variants on megalin-associated pathway should be examined to determine if variants in this pathway are linked to the dysfunction in other tissues.

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Caroline Gardner graduated in May 2024 from Virginia Tech with a degree in Human Nutrition, Foods, and Exercise. She began her research in a Virginia Tech course called Eating For Your Genes and presented a poster at the Dennis Dean Undergraduate Research Conference. She plans to spend her first few years out of college as a medical scribe in Blacksburg, VA, then pursue a career as a physician assistant.

PRESS SUMMARY

Autosomal recessive familial hypercholesterolemia-4 (FHCL4) is a genetic condition caused by a defect in *LDLRAP1*. This gene makes a protein that helps the body get rid of LDL, or "bad" cholesterol. The researchers studied a variant called rs121908325 in this gene using online *in silico* databases and analyses, including those from the National Center for Biotechnology Information (NCBI). Their analysis showed that the rs121908325 polymorphism causes the protein to terminate early, likely rendering it incapable of removing LDL cholesterol. Using population analysis through NCBI, they found that this change is very rare. The rs121908325 variant has been associated with heart problems.

Investigation of a Photovoltaic Thermal-Direct Expansion Solar-Assisted Heat Pump (PVT-DXSAHP) Collector with Different Photovoltaic Characteristics in Cold Climates

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ABSTRACT
In this paper, the performance of a direct expansion solar-assisted heat pump (DX-SAHP) with a photovoltaic thermal (PVT) collector made with different solar cells was investigated. A thermodynamic model of a direct expansion solar-assisted heat pump with a PVT collector and a 180 L water tank for thermal energy storage was developed. The model was implemented in MATLAB, with the CoolProp library for the retrieval of working fluid thermodynamic properties. The solar collector cells considered were ®Solartech, ®LG, ®Prime, ®VOLT, and ®VSUN. The performance of the system is characterized by the coefficient of performance, thermal efficiency, electrical efficiency, heat pump ratio and auxiliary heat ratio. The highest average coefficient of performance of the heat pump was with ®Solartech solar cells on a sunny day in winter was 4.08 , and 7.91 on a sunny summer day. On a cloudy summer day, the ®Prime solar cell had the highest average coefficient of performance at 6.45. The highest electrical efficiency of the collector was observed with ®Prime solar cells, with an efficiency of 14.4%, 16.5% and 13.6%, respectively, from a sunny day in winter, a sunny day in summer and a cloudy day in the summer. The highest thermal efficiency was obtained by ®Solartech solar cells for all weather conditions. With a collector area of 5 m^2 and a consumer load of 0.001 kg/s, the heat pump meets an average of 15.6% of the total heat needed for domestic hot water demand on a sunny winter day. This increases to 38.2% and 49.0% on cloudy and sunny summer days, respectively.

KEYWORDS
Coefficient of Performance; Direct Expansion; Heat Pump Ratio; Photovoltaic Thermal ; Water Heating; Solar-Assisted Heat Pump

INTRODUCTION

In 2019, Canada's residential water heating use accounted for 263.9 PJ of energy or about 17% of the total energy in the residential sector. About 12.4 million Canadians have standard water heaters and 5.5 million of those water heaters use natural gas as the energy source, while 5.6 million use electricity.[1] This leads to about 11.13 megatons of carbon dioxide equivalent emitted from residential water heating.[2] To meet this energy demand with minimal emissions, alternative and clean energy technologies are essential.

Heat pumps are emerging as a clean alternative to conventional systems. When powered by clean electricity, they have the potential to meet the heating and cooling needs with minimum emissions. However, in cold climates, the performance of heat pumps degrades with decreasing outdoor air temperatures. Thus, combining or replacing heat pumps with solar thermal collectors is emerging as an effective means of enhancing their performance. The direct expansion solar-assisted heat pump (DX-SAHP) is a class of solar-assisted heat pump (SAHP) systems that uses a solar collector directly as the evaporator of the heat pump system. The heated refrigerant vapor is then compressed to a higher pressure and temperature and used to heat a water tank for specific residential applications. A prototype DX-SAHP developed in the Sustainable Thermal Energy Systems Research lab at the University of Calgary by Elgamal et al. this prototype consists of a 2.3 m^2 flat solar plate with no glazing, a scroll compressor rated at 3500 rpm, an electronic expansion valve, copper piping at a length of 25 m, a pitch of 19.05 mm and bend diameter of 100 mm and hot water storage tank. The theoretical results of this setup were obtained using the combined Hottel-Whillier-Bliss equations, and the first law of thermodynamics showed coefficients of performance (COP) from 3.4 - 4.5.[3] The results of experimental tests conducted on the prototype achieved a COP of 3.1 on a sunny winter day and raised the water tank temperature from 16.1 ^oC to 50.3 ^oC in 4.5 hours. While on an overcast summer day, the COP average was 3.0, and the water tank temperature increased from 27.3 ^oC to 49.5 ^oC in 3.5 hours.[4] Bonding the tubing to the collector is one of the important factors that affect the performance of

evaporator in DX-SAHPs. Moreover, the tubing pattern used can influence performance of the heat pump. Different flow patterns have been used for plate-and-tube and roll bond collectors. Using a fractal T-shape pattern, the coefficient of performance (COP) and heating capacity of the heat pump enhanced the system by 14.6% and 17.3% respectively compared to the parallel channel pattern. A similar but smaller improvement was achieved with a honeycomb-shaped pattern in the same study, with an increase in the COP of 5.9% and an increase in the heat capacity of 6.2%.[5] A different study looked at SAHP where the collector was adapted to include a heat pipe in the collector itself and to work in two modes. One of these modes is called the heat pipe mode, which moves the refrigerant straight to the condenser during times of large solar insolation; the other mode is a heat pump which didn't bypass the compressor before going into the condenser.[6]

Solar collectors are based on the flat plate collector technology which are easy to design and relative less expensive to make, however they don't take advantage of the simultaneous generation of both electric and thermal energy thus leading to lower useful energy efficiencies. There are four main types of solar collectors currently used in solar-assisted heat pumps: flat solar collectors, evacuated tube solar collectors, parabolic solar trough collectors and photovoltaic-thermal (PV-T) collectors. The flat plate solar collector is the simplest collector, mostly rectangular in shape, with a collector tube on the back of the plate with insulation under it. The evacuated tube solar collector is like the plate solar collector. However, the space in between the absorber plate and the glass cover is a vacuum to minimize heat loss, which is applicable in cold climates. Parabolic solar trough collectors are shaped like a parabola, which helps concentrate the solar light/radiation to a line, increasing the intensity of the light to a line where the absorber tube will sit and collect the heat. PV-T collectors add photovoltaic (PV) cells to the absorber surface where all the solar light concentrates while having collector's tubes behind the collector with the refrigerant to extract what is not collected by the PV cells to be then used in a heat pump, water or air heating system. Thus, PV-T solar collectors provide additional benefits of generating electricity that can be used to meet part of the energy required by the heat pump, water or air heating system.
An interesting study used a façade integrated PVT water heating system to explore the use of building-integrated solar technology for water heating. They showed that the electrical efficiency reached an average of 8.56% and a thermal efficiency of 38.9% late in the summer for Hong Kong.[7] The same group studied a PV-thermal air system built into the house and examined its winter performance. The polycrystalline silicon cell modules had an electrical conversion of about 11.2% to 11.4%, depending on whether there was a Teflon cover on the cells. Amorphous silicon cells had a reduction in the electrical efficiency of about 3.6% compared to polycrystalline silicon cells. The thermal efficiency was about 29.2% without glass covers and 36.9% with glass covers.[8]

Modifications of PV/T collectors enhance the performance of combined PV/T water collector thermodynamic efficiencies. PV/T collectors that added reflectors showed that the ideal angle of the collector surface should be 45° horizontal from the ground and the reflectors should be placed at different angles in the season: 5° in December and 38° in June perpendicular to the collector surface to optimize the thermodynamic efficiency of a PV/T water collector.[9] Kalogirou et al. looked at PV/T systems in Nicosia, Athens and Madison using two types of photovoltaic cells in their simulations.[10] They used polycrystalline and amorphous silicon cells connected to a water heat extraction unit and tested them against PV modules of similar cells. Results showed that the overall performance of the photovoltaic modules increased and that these hybrid units had a better chance of success compared to any of the PV amorphous or polycrystalline modules. They showed the systems to be more economically viable for locations across Nicosia and Athens. The study showed that the type of PV cells significantly affects the performance and cost of the system.

Besides the type of cells, the absorber tube configuration on the PV-T collector is an important factor in determining the overall system performance. Kazem et al. performed a study in Oman, looking at the electrical, thermal and overall efficiencies of different flow configurations of a PV-T water cooling system.[11] Their results showed that the spiral flow type gave an improved thermal performance while also achieving 9.1% electrical efficiency. The overall efficiencies were about 35% for the spiral flow type, the highest of all the PVT systems studied by Kazem's research group. A similar study numerically and experimentally investigated the type of channel configurations (serial, parallel, bionic) for roll–bond heat exchangers.[12] They found that the outlet water temperature of the bionic configuration was the lowest and had the lowest pressure drop. All PV-T water collector systems had improved electrical efficiency compared to a PV-only module.

One of the first studies looking at integrating PVT collectors and heat pumps was called an integrated-type solar-assisted heat pump. They found that the system was 76% more thermally efficient than solar water collectors.[13] Given the benefits of PV-T water collector heating and cooling systems, using them in direct expansion heat pump systems results in better performance and promising economics. As such, several researchers are looking into direct-expansion solar-assisted heat pumps with photovoltaic cells. Ammar et al. showed that using a photovoltaic/thermal–direct-expansion solar-assisted heat pump with R134a as the refrigerant, the electrical efficiency reached about 11.9% percent with a maximum hourly thermal efficiency of 88.7% and an average COP of 6.14.[14] Another study found that a PVT-heat pump provided a maximum COP of 8.4, with a maximum condenser capacity of 2.4 kW. The average electrical efficiency was 13.7% with the cooling effect of the refrigerant.[15] A similar

study with a double glass cover on the collector showed a higher electrical efficiency of 15.2% and a COP of 2.96.[16] James et al. used a variable frequency drive (VFD) compressor-based PV-THPWH system in Calicut City, India.[17] They found that the VFD compressor control feedback system improved the energy performance and life by making the mass flow rate of the refrigerant proportional to the evaporator load.

As the literature shows, several researchers have investigated DX-SAHP, different configurations of PVT collectors, and their combinations with heat pumps and solar water collectors. However, the study of commercially available photovoltaic cells on the collectors of DX-SAHPs in cold climates has not been studied in detail. Especially for climates that are cold and have yet to open up to its significant solar resources, such as the city of Calgary in Alberta. The aim of this study was to develop a model of a PVT-DXSAHP and investigate its performance in a cold climate with different photovoltaic cells on its collector.

METHODS AND PROCEDURES

Description of the system

Figure 1 represents the configuration of the PVT-DXSAHP system, which comprises a heat pump with a PVT collector, compressor, condenser and expansion valve. Connected to the condenser is a water loop that uses a pump to drive the heated water inside the water tank. Using the heat from the condenser, water in the tank is heated up and used for residential applications at a temperature of 50 ^{o}C when needed.

The refrigerant starts as a two-phase liquid when it exits the expansion valve (4); as it passes through the PVT collector or the evaporator, where it gains heat from solar radiation or surroundings, causing the refrigerant to change state to a superheated vapor state (1). When it passes through the compressor, the refrigerant temperature and pressure increase to a superheated vapor (2). The refrigerant then goes into a condenser where it transfers heat to the water loop, losses energy and changes its phase to a sub-cooled liquid (3). This cycle continues, provided the heat pump is in operation.

Figure 2 provides the temperature-entropy (T-s) diagram detailing the heat pump processes. Process 1-2s represents the ideal isentropic compression process, while 1-2 shows the actual compression process. Process 3-4 represents an enthalpic process across the thermostatic expansion valve.

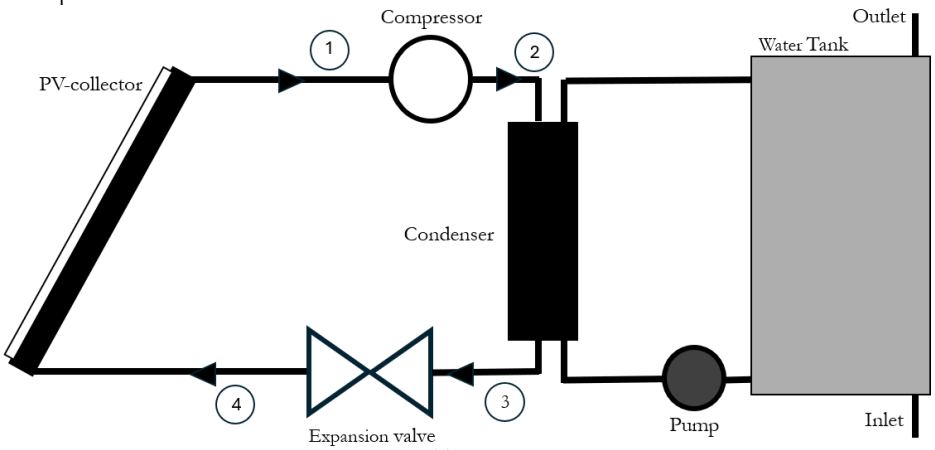

Figure 1. PVT-DXSAHP system

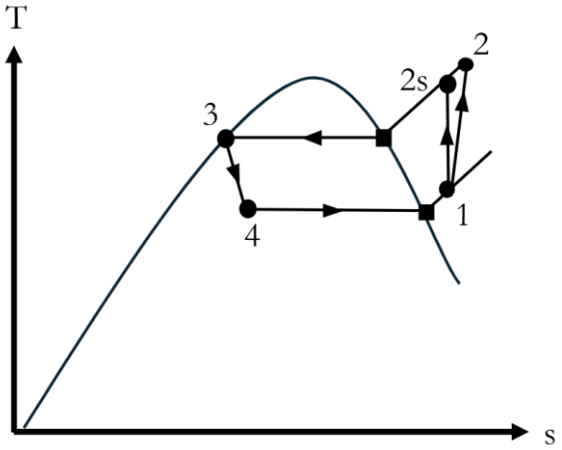

Figure 2. Thermodynamic process of the heat pump system

Solar Cell Types

Table 1 shows the photovoltaic solar cells used in this study. The solar cells produced by ®LG, ®Prime, ®VOLT, and ®VSUN are all monocrystalline silicon solar cells but with different efficiencies. ®Solartech solar cells are polycrystalline silicon solar cells. The reference efficiency indicates the efficiency of the solar cell at 1 AM at 25 °C. The temperature coefficient helps indicate the trend of the solar cell's efficiency as it varies with temperature.

Solar Cell	Temperature Coefficient, β_r (1/K)	Reference Efficiency	References
®LG	-0.0033	20.9%	18
®Solartech	-0.0046	13.5%	19
®Prime	-0.0030	25.0%	20
®VOLT	-0.0039	22.9%	21
®VSUN	-0.0032	20.2%	22

Table 1. Table of simulated solar cells with their characteristics of temperature coefficient and reference efficiency.

Meteorological Data and Load Profile

Figures 3, **4** and **5** show meteorological data for Calgary, Alberta used in this study. A sunny winter day, a sunny summer day and a cloudy sunny day in summer day, were respectively used in this study. In the MATLAB simulation, a constant water load of 0.001 kg/s from 8 am to 8 pm was assumed to evaluate the performance of this PVT-DXSAHP system. A constant water load was used because it provides a general approximation of the residential water use during a 12-hour period. This data was used as an input parameter in the analysis of the PV-DXSAHP system.

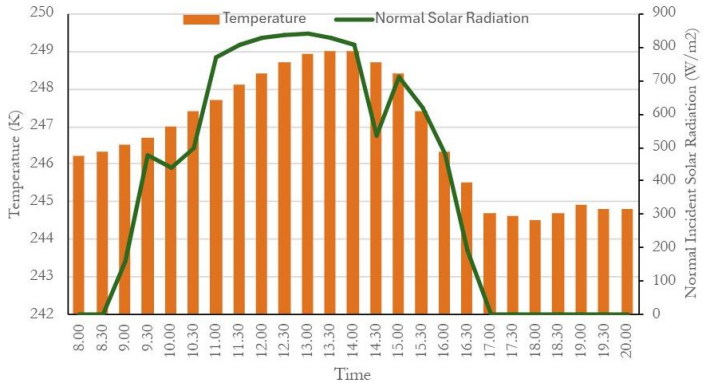

Figure 3. Temperature and solar radiation on a tilted surface in Calgary, Alberta, 2022, January 4th.

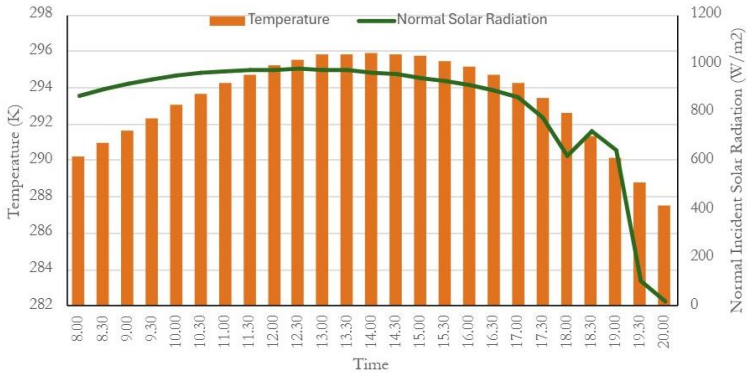

Figure 4. Temperature and solar radiation on the tilted surface in Calgary, Alberta, 2022, June 10th.

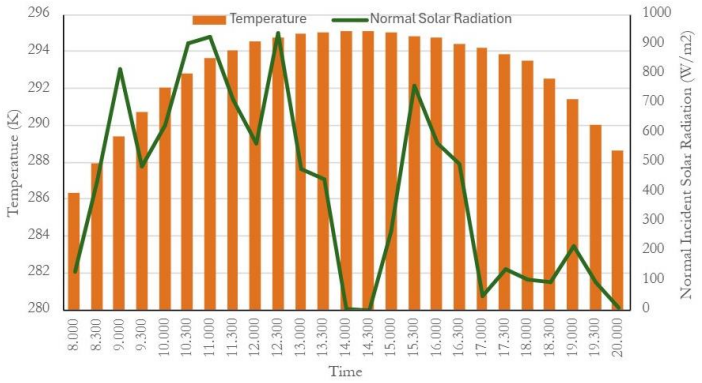

Figure 5. Temperature and solar radiation on the tilted surface in Calgary, Alberta, 2022, June 18th.

Mathematical Model

In this section, the mathematical model developed in MATLAB that describes the photovoltaic/thermal–direct-expansion solar-assisted heat pump is shown. In the later sections, the validation procedure used for this model is reported. This model follows similar assumptions in Bardia Thesis.[23] The mathematical model is also extended based on the Hotel-Whillier model for photovoltaic/thermal flat-plate collectors.[24] All components are assumed to operate steadily, except the water tank, where temperature changes with time.

The additional assumptions are:

i. Pressure drop in the refrigerant lines is negligible.
ii. Isenthalpic throttling process through the expansion valve.
iii. The heat losses through the edge of the collector are negligible.
iv. The properties of the collector are independent of temperature.
v. Heat losses from the heat exchanger/condenser to the ambient are negligible.
vi. The power input into the water pump is negligible compared to the compressor power input.
vii. In the evaporator, the tube temperature is equal to the evaporating temperature.

First, the energy picked up by the refrigerant through the evaporator is,

$$\bar{Q}_u = \tilde{m}_r(h_1 - h_4) \qquad \textbf{Equation 1.}$$

Where $\tilde{m}_r$ is the mass flow rate of the refrigerant. h_1 is the enthalpy of the refrigerant leaving the collector while h_4 is the enthalpy of the refrigerant entering the collector. This process from 1 to 4 is shown in **Figure 2**.
The volumetric efficiency of the compressor is given by.[25]

$$\eta_{vol} = 0.959 - 0.006422\,\frac{P_c}{P_e} \qquad \textbf{Equation 2.}$$

Where P_c is the pressure of the refrigerant through the condenser and P_e is the pressure of the refrigerant through the evaporator. The mass flow rate of the refrigerant can be calculated from the knowledge of compressor characteristics as

$$\bar{m}_r = \frac{\eta_{vol} n V_d \rho_r}{60}$$ **Equation 3.**

n is the speed of the compressor, V_d is the volumetric displacement of the compressor and ρ_r is the density of the refrigerant.

The work input into the compressor is given by equation (4), process 1-2, shown in the T-s diagram in **Figure 2**.

$$W_c = \frac{\dot{m}_r(h_2 - h_1)}{\eta_{is}}$$ **Equation 4.**

Where η_{is} is the isentropic efficiency of the compressor.[25]

$$\eta_{is} = 0.874 - 0.0135\frac{P_c}{P_e}$$ **Equation 5.**

Where P_c is the condenser pressure and P_{evap} is the evaporator pressure.

The thermal loss that occurs at the top of the photovoltaic cells without glazing is the sum of the radiation and convective losses.

The respective heat transfer coefficients are given by **Equations (6)** and **(7). Equation(6)** is found in [26] and **Equation (7)** is found in Bardia's Thesis.[23]

$$h_{r,PV-amb} = \varepsilon_{PV}\sigma({T_{PV}}^2 + {T^2}_{amb})(T_{PV} + T_{amb})$$ **Equation 6.**

$$h_{c,PV-amb} = 2.8 + 3u_{amb}$$ **Equation 7.**

Where **Equation (6)** is the radiative heat transfer coefficient representing the loss that occurs from the photovoltaic cells on the top of the collector to the ambient air, **Equation (7)** is the convective heat loss coefficient from the photovoltaic cells to the ambient air.

The thermal resistance arising from convection and radiation that occurs in the ambient air

$$R_{r-c} = \frac{1}{h_{r,PV-amb} + h_{c,PV-amb}}$$ **Equation 8.**

The conduction thermal resistance which occurs through the photovoltaic cell is

$$R_{PV} = \frac{\delta_{PV}}{k_{PV}}$$ **Equation 9.**

Where k_{PV} is the thermal conductivity of the photovoltaic cell and δ_{PV} is the thickness of the of the photovoltaic cell on the collector.

The bottom heat loss coefficient is

$$U_{Bottom} = \frac{k_b}{\delta_b}$$ **Equation 10.**

Where k_b is the thermal conductivity of the insulation or padding on the back of the collector, δ_b is the thick of that padding or insulation.

The total heat loss coefficient for the collector is

$$U_L = \frac{1}{R_{c-r} + R_{PV}} + U_{Bottom}$$ **Equation 11.**

Combining **Equation (6)** through **(7)** into **Equation (8)** and **Equations (9)** and (**10)** all into **Equation (11)**

$$U_L = \frac{1}{\frac{1}{h_{r,PV-amb} + h_{c,PV-amb}} + \frac{\delta_{PV}}{k_{PV}}} + \frac{k_b}{\delta_b}$$ **Equation 12.**

The electrical collector efficiency can be calculated as,

$$\eta_c = \eta_r[1 - \beta_r(T_{PV} - T_r)]$$ **Equation 13.**

Where η_r is the reference efficiency of the collector tested at 1.5 AM at 25°C. β_r is the temperature coefficient of the photovoltaic cells, and T_r is the reference temperature.

The current/local ambient collector electrical efficiency can be calculated by

$$\eta_{amb} = \eta_r[1 - \beta_r(T_{amb} - T_r)] \quad \textbf{Equation 14.}$$

This is a condition where the PV cells are at the temperature of the ambient air. Both **Equation (13)** and **(14)** come from Kalogirou et al.[27]

For photovoltaic thermal collectors, the modified heat loss coefficient can be calculated by Florschuetz.[24]

$$\bar{U}_L = U_L - \frac{S}{\alpha}\eta_c\beta_r \quad \textbf{Equation 15.}$$

Where α is the absorptivity of the whole array of photovoltaic cells on the collector.

The modified solar radiation can be calculated according to Florschuetz as,[24]

$$\bar{S} = S(1 - \frac{\eta_{amb}}{\alpha}) \quad \textbf{Equation 16.}$$

h_{fi} is the coefficient of heat transfer of the two-phase refrigerant given by Turaga et al.[28]

$$h_{fi} = \frac{0.0082k_l}{D_i}\left(\frac{J\,\Delta x h_{fg}}{L}\right)^{0.4} \quad \textbf{Equation 17.}$$

Where k_l is the thermal conductivity of the refrigerant; Re is the Reynolds number, J is the design constant, Δx is the quality difference between the phase of the outlet and the exit of the collector and h_{fg} is the latent heat of the refrigerant.

The collector efficiency factor is given by Duffie and Beckmann.[26]

$$F' = \frac{1/\bar{U}_L}{W[\frac{1}{\bar{U}_L[D+(W-D)F]}+\frac{1}{C_b}+\frac{1}{\pi D_i h_{fi}}]} \quad \textbf{Equation 18.}$$

W is the distance between each tube, D is the diameter of the absorber tube, C_b is the conduction bond conductance between the absorber tube and the collector plate. F is the fin efficiency of the collector defined by Duffie and Beckman as,[26]

$$F = \frac{tanhtanh\,[\,m(W-D)/2]}{m(W-D)/2} \quad \textbf{Equation 19.}$$

Where m is given by

$$m = \sqrt{\frac{\bar{U}_L}{k_P\delta_P}} \quad \textbf{Equation 20.}$$

In which, k_P is the thermal conductivity of the collector plate, and δ_P is the thickness of the collector plate.

The modified useful heat of the collector is then calculated as

$$\bar{Q}_u = A_c[\bar{S}(1 - \eta_c) - \bar{U}_L(T_P - T_a)] \quad \textbf{Equation 21.}$$

Instead of the plate temperature, the evaporator temperature can be used with a modified equation as

$$\bar{Q}_u = F'A_c[\bar{S}(1 - \eta_c) - \bar{U}_L(T_e - T_a)] \quad \textbf{Equation 22.}$$

An energy balance between the plate and the refrigerant in the absorber tube gives

$$\bar{Q}_u = \frac{L(T_p - T_e)}{\frac{1}{\pi D_i h_{fi}}+\frac{1}{C_b}} \quad \textbf{Equation 23.}$$

The electrical energy which is extracted from the collector plate can be calculated by

$$Q_e = \bar{S}A_c - Q_u - \bar{U}_L A_c(T_p - T_a) \quad \textbf{Equation 24.}$$

The energy loss which occurs throughout the ambient air and the aluminum plate of the collector can be identified as

$$\frac{T_P - T_a}{R_{r-c}+R_{PV}} = \frac{T_{PV} - T_p}{R_{PV}} \quad \textbf{Equation 25.}$$

Using algebra in **Equation (25)**, the cell temperature can be obtained and calculated. Examining the steady state flow of the thermal energy transferred into the refrigerant without ambient losses, we can write the following equations. The energy transferred to the water in the tank is

$$Q_c = \dot{m}_w C_p (T_{wo} - T_w) \quad \textbf{Equation 26.}$$

Where T_{wo} and T_w are the outlet water temperature of the water heat exchanger and the water tank inlet temperature.

The heat loss from the condenser, however, can be expressed as

$$Q_c = U_c A_C \Delta T_{lm} \quad \textbf{Equation 27.}$$

The term ΔT_{lm} is the mean log temperature of the heat exchanger in the condenser.

$$\Delta T_{lm} = \frac{(T_2 - T_{wo}) - (T_c - T_w)}{lnln\left(\frac{T_2 - T_{wo}}{T_c - T_w}\right)} \quad \textbf{Equation 28.}$$

The simplified energy balance for non-stratified tanks is.

$$MC_p \frac{T_{w,i+1} - T_{w,i}}{\Delta t} = m_{sup} C_p T_{sup} - m_{load} C_p T_w + m_r (h_2 - h_3) - U_t A_t (T_w - \dot{T}_{at}) - C_p T_w (m_{sup} - m_{load}) \quad \textbf{Equation 29.}$$

The electrical efficiency that occurs in the collector can be described as

$$\eta_{ele} = \frac{Q_e}{SA_c} \quad \textbf{Equation 30.}$$

While the thermal efficiency can be written as

$$\eta_{therm} = \frac{Q_u}{SA_c} \quad \textbf{Equation 31.}$$

Lastly, the coefficient of performance is the useful heat extracted by the collector divided by the compressor work.

$$COP = \frac{Q_u}{W_c} \quad \textbf{Equation 32.}$$

The heat pump ratio represents the amount of energy that is transferred to the water in the water tank by the heat pump to the total required to reach the water set point temperature of 50°C.

$$r_{HP} = \frac{Q_u}{Q_{Total}} \quad \textbf{Equation 33.}$$

Q_{Total} is the total heat required to raise the water temperature to 50 °C. The auxiliary heating ratio is the amount of energy required to increase the water temperature to 50 °C after the heat pump uses solar radiation to warm the water in the tank in cases of insufficient solar energy.

$$r_{AUX} = \frac{Q_{Total} - Q_u}{Q_{Total}} \quad \textbf{Equation 34.}$$

VALIDATION

The MATLAB model developed through this work were compared with the work of Ji et al.[29] The validation was completed using the same conditions, i.e. the average hourly solar and ambient temperature data for Hefei, Central China, on the day of the experiments in November. The wind speed used in our simulation for this validation was a constant average wind velocity of 3.05 m/s. However, the original study used a wind profile between 2.4 and 3.7 m/s; since this profile was not given in the paper, an average constant value was taken.

Figure 6 shows the comparison of the current study's COP with the COP from Ji et al.[29] As shown, there is excellent agreement between our results and those in this study, with a maximum deviation of 7.3% and an average root mean square error of 2.4%

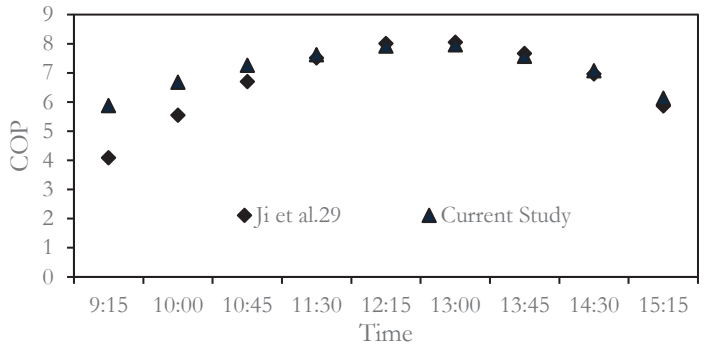

Figure 6. COP variation over time for Ji et al.[29] study and our current study

Figure 7 shows the electrical efficiency over time in comparison with Ji et al.[29] As shown, the same trend is observed with a maximum deviation of 12.0% and an average root mean square error of 5.1 %. This difference is likely due to the difference in operating conditions during experiments such as wind speed which was not presented in the study, and had been assumed constant in this model. Another possible source of deviation is the difference in the temperature coefficient of the photovoltaic cells used in the simulation. The study didn't indicate their temperature coefficient. It could also be due to startup and shutdown issues during the experiment, as the highest deviations are indicated at these times. Overall, the same trend is shown, and the average root mean square error is reasonable.

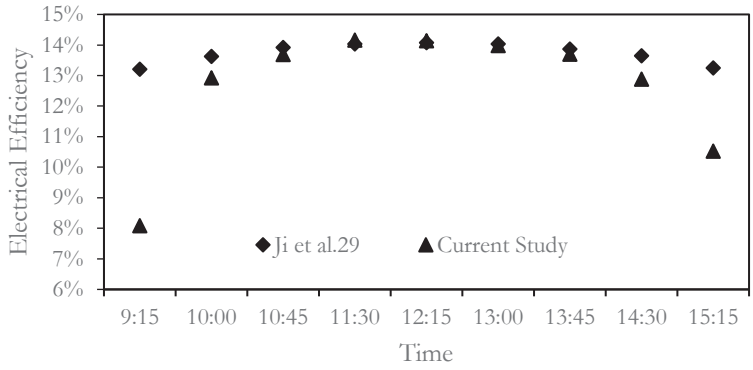

Figure 7. Electrical efficiency variation over time for Ji et al.[29] study and our current study

RESULTS & DISCUSSION

In this section, the COP, electrical efficiency, thermal efficiency, heat pump ratio and axillary heat ratio of the PVT-DXSAHP with different types of photovoltaic cells on solar collector plates are presented and discussed.

On a sunny day in winter, the COP increases as the day approaches noon, as shown in **Figure 8**. The data points show a parabolic rise in COP as it approaches noon time and then drops or rises depending on the time of the day (morning or evening). This is mainly because as time approaches noon, more solar radiation is received by the collector. This increases the amount of the collector's useful thermal energy. As the collector's useful thermal energy increases, it raises the evaporator temperature (line 4-1) in Figure 2, decreasing the amount of compressor work required to reach the condenser pressure according to **Equation (4)**. Both effects lead to an increase in the COP, as inferred by **Equation (32)**. Regarding the variation of COPs for the different solar cells, the cells which have the lowest electrical efficiency provide a larger useful heat gain of the collector than cells with higher collector efficiency, refer to **Equation (21**). The average COP on a sunny winter day for ®LG, ®Prime, ®VOLT and ®VSUN collector solar cells are, respectively, 3.91, 3.83, 3.88, and 3.92. The highest COP is provided by ®Solartech collector solar cells at 4.08.

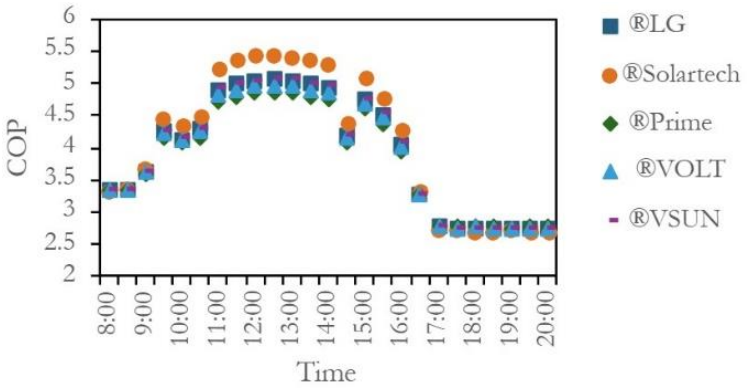

Figure 8. COP variation over time, with 5 different solar collector cells. On a sunny day in winter

The electrical efficiency of the photovoltaic cells on a sunny winter day increases parabolically as it approaches noon, as shown in **Figure 9**. Although it is a very flat parabolic maxima, each set of data points has its highest values at noon and drops during the morning and evening. This variation is because the modified solar radiation increases the amount of energy that is available for extraction by the photovoltaic cells at noon, according to **Equation (24)**. The drop in the electrical efficiency across every type of photovoltaic cell is due to the manufacturing of these cells. We can see that using ®LG, ®VOLT, ®VSUN and ®Prime gives a higher electrical efficiency because they are all mono-type solar cells, while the ®Solartech is a poly-type of solar cells. The daily average electrical efficiency on a sunny winter day for ®LG, ®Solartech, ®VOLT, and ®VSUN collector solar cells are, respectively, 12.5%, 8.3%, 13.2% and 12.2%. The highest daily electrical efficiency is provided by ®Prime collector solar cells at 14.4%.

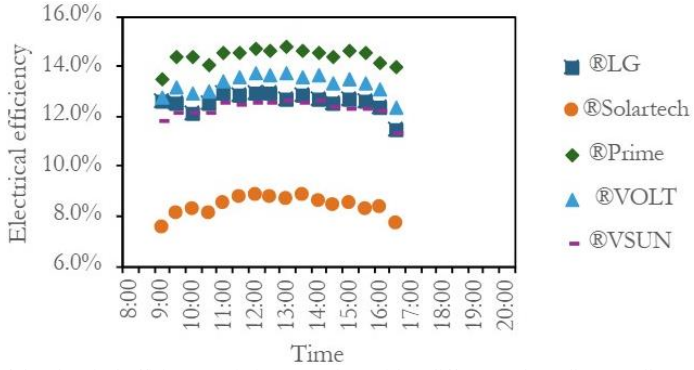

Figure 9. Variation of the electrical efficiency variation over time with 5 different solar collector cells on a sunny day in winter.

Figure 10 shows the thermal efficiency with time. As shown, during a sunny winter day, the thermal efficiency slightly decreases as it approaches noon and increases after that. As solar radiation increases as the day approaches noon, the ambient and collector temperatures increase, leading to higher heat transfer losses from the collector. This increase in photovoltaic temperature and ambient temperature raises the radiative and convective heat transfer losses, increasing the total heat loss coefficient and thereby decreasing thermal efficiency. The daily thermal efficiencies on a sunny day in winter for ®LG, ®Prime, ®VOLT, and ®VSUN collector solar cells are, respectively, 27.1%, 25.5%, 26.6 % and 27.3 %. The highest daily thermal efficiency is given by ®Solartech solar cells at 30.6%. The combined solar PVT- heat pump system differs in thermal efficiency for the different solar cells used. As the electrical efficiency of the solar cells decreases across selected solar cells, the modified useful heat gain of the collectors will increase accordingly. This increase in the modified useful heat of the collector causes an increase in thermal efficiency according to **Equation (31)**.

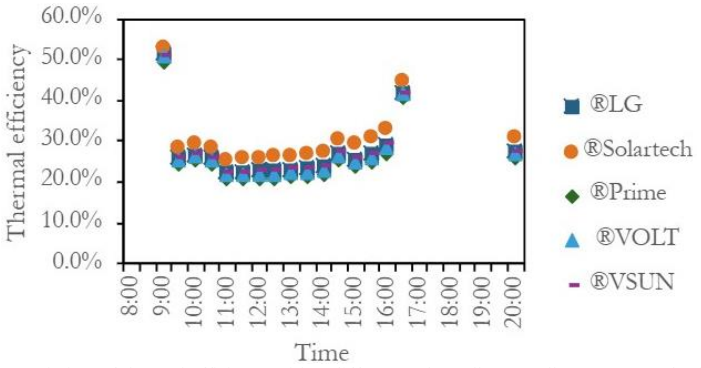

Figure 10. Variation of thermal efficiency with 5 different solar collector cells on a sunny day in winter.

Looking at a sunny day in the summer, the COP follows a decreasing trend but is larger than the COP on sunny winter days, as shown in **Figure 11**. The data sets show a decreasing trend from the start of the day to the end of the day. This is because there is sufficient heat from the outdoor air and solar radiation to heat the water to high temperatures. As the water temperature increases, the condenser temperature increases, requiring more compressor work and, thus, lower COPs. In the summer, the sun's rays are more direct during the summer in the northern hemisphere. The daily average COP on a sunny day in summer for ®LG, ®Prime, ®VOLT, and ®VSUN collector solar cells are, respectively, 7.46, 7.21, 7.33, and 7.48. The highest daily COP is provided by ®Solartech collector solar cells at 7.91. Again, the cells with the highest electrical efficiency yield the highest coefficient of performance (COP).

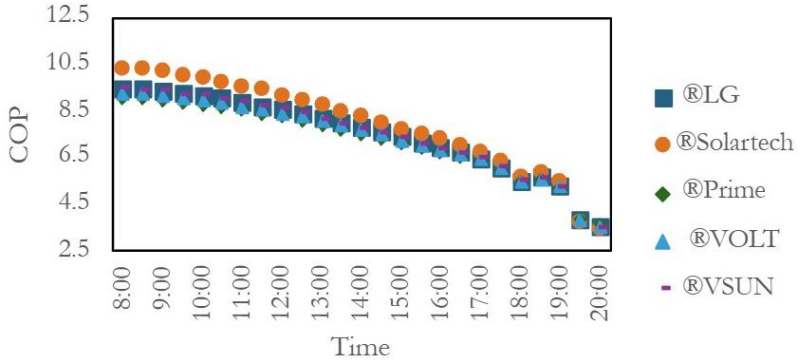

Figure 11. COP variation over time for 5 different solar collector cells on a sunny summer day.

The electrical efficiency of the solar cells in **Figure 12** follows the same trend as the solar cells in winter. However, the electrical efficiency is higher in the summer than in the winter. Comparing the meteorological data of a sunny winter and summer day in **Figure 3** and **Figure 4**, there are larger values of solar radiation on a sunny summer day compared to a sunny winter day for the 12-hour simulation. This leads to higher photovoltaic energy being collected, thus increasing the electrical efficiency according to **Equation (30)**. The other likely reason for higher efficiencies in the summer is the lower thermal losses and the more useful heat gain from the outdoor air, according to **Equation (24)**. The daily average electrical efficiencies on a sunny summer day for ®LG, ®Solartech, ®VOLT, and ®VSUN collector solar cells are, respectively, 14.9%, 11.2%, 15.7% and 14.6%. The highest daily electrical efficiency is provided by ®Prime collector solar cells at 16.5%, which has the lowest coefficient.

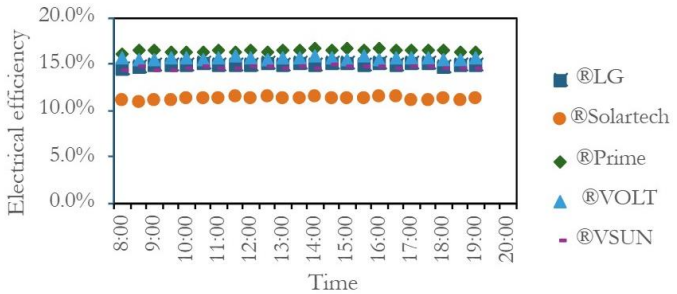

Figure 12. Electrical efficiency as a function of time for 5 different solar collector cells on a sunny day in summer.

Figure 13 shows the thermal efficiency for a sunny summer day. This trend is similar to the thermal efficiency in **Figure 9**. However, the thermal efficiency is higher in the summer than on a sunny winter day. Higher solar radiation, higher outdoor air temperatures and lower thermal losses contribute to the efficient operation of the collector. The daily thermal efficiencies on a sunny day in winter for ®LG, ®Prime, ®VOLT, and ®VSUN collector solar cells are, respectively, 50.6%, 48.1%, 49.3% and 50.9%. The highest daily thermal efficiency is provided by ®Solartech collector solar cells at 55.4%. As previously discussed, the lower the solar cell's electrical efficiency is, the larger the system's thermal efficiency will be.

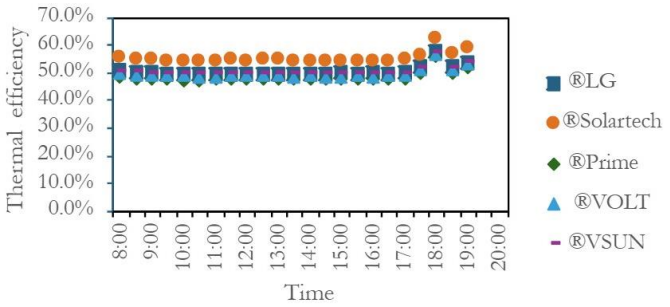

Figure 13. Thermal efficiency variation over time for 5 different solar collector cells on a sunny day in summer.

The COP on a cloudy summer day contains a scattered distribution trend which rises and falls at certain times of the day. This is shown in **Figure 14**, the data sets peak at 9:00, 11:00, 12:15 and 15:30 and drop after those times and rise again. This distribution can be explained by the fact that at some points in the day, shown in **Figure 5**, cloud cover occurs, and the solar radiation drops at those points in time, reducing the useful energy gain from the collector and thus reducing heat pump COP. The daily average COP on a cloudy day in summer for ®LG, ®Solartech, ®VOLT and ®VSUN collector solar cells are, respectively, 6.16, 6.02, 6.10, and 6.18. The highest daily COP is provided by ®Prime collector solar cells at 6.45.

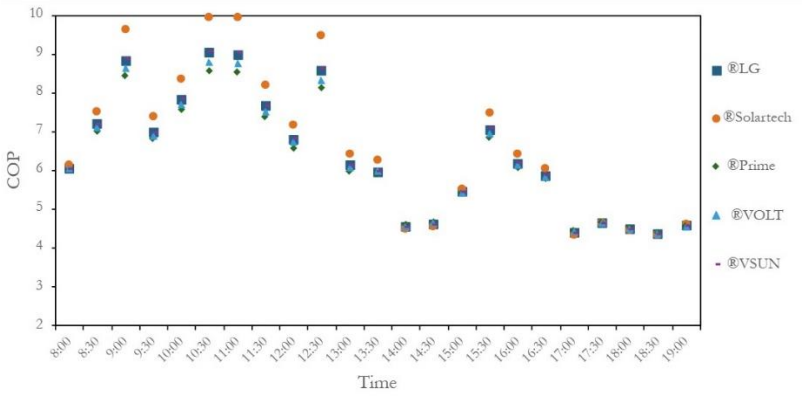

Figure 14. COP variation over time for 5 different solar collector cells on a cloudy day in summer.

The electrical efficiency of the collector on a cloudy shown in **Figure 15**, has a similar trend as that on a sunny summer. However, there are times when the electrical efficiency is zero at some points in the day due to cloud cover totally obstructing the sun above the collector, thus leading to very little or almost no solar energy reaching the photovoltaic cells. The daily average electrical efficiencies on a cloudy day in summer for ®LG, ®Solartech, ®VOLT and ®VSUN collector solar cells are 12.0, 8.7, 12.7 and 11.8 %, respectively. The highest daily electrical efficiency is provided by ®Prime collector solar cells at 13.6 %.

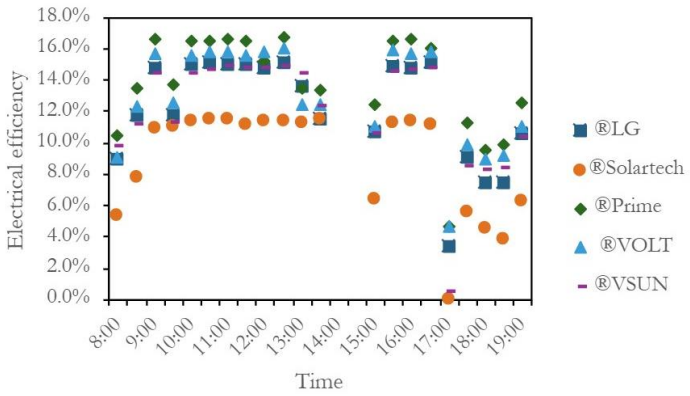

Figure 15. Electrical efficiency variation over time for 5 different solar collector cells on a cloudy day in summer.

The thermal efficiency of the collector on a cloudy day, shown in **Figure 16,** can be described as a random distribution that follows the solar radiation earlier presented. The thermal efficiency randomly fluctuates, following the trend of solar radiation. Cloud cover causes a drop in the solar energy reaching the collector. This results in a rise in thermal efficiency because as the solar radiation decreases, the thermal efficiency increases, according to **Equation (31)**. This is in part because the solar collector is able to utilize the outdoor air to provide useful heat gain even when there is no solar radiation. Their ability to absorb energy from outdoor air is one of the reasons direct-expansion solar-assisted heat pumps are advantageous compared to traditional solar collectors. Thus, every time cloud cover is present, the efficiency rises, and then when clouds do not obstruct the sun, the data will resemble thermal efficiency values close to those of a sunny summer day in **Figure 13**. The daily average thermal efficiencies on a cloudy day in summer for ®LG, ®Prime, ®VOLT, and ®VSUN collector solar cells are, respectively, 61.3, 58.3, 60.0and 61.8%. The highest daily thermal efficiency is provided by ®Solartech collector solar cells at 67.4%.

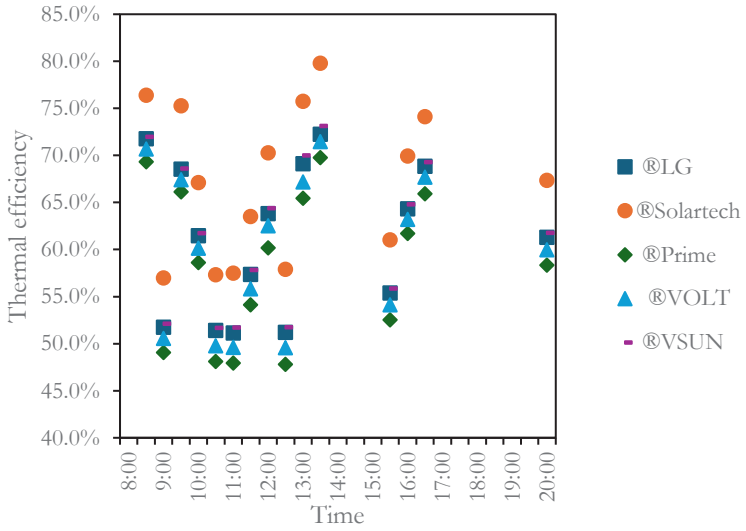

Figure 16. Thermal efficiency variation over time for 5 different solar collector cells on a cloudy summer day.

The heat pump ratio is defined as the ratio of the energy delivered by the heat pump to the total energy required to heat the water to its target temperature. As expected, this value is the lowest for sunny winter days and the highest for sunny summer days. **Table 2** shows the heat pump ratio for the considered summer and winter conditions. This is because the availability of solar radiation on sunny summer days is greater than the cloudy days and sunny winter days, as shown in **Figures 3** to **5**. The more the available solar radiation, the higher the energy supplied to the heat pump to heat the refrigerant to heat the water in the tank and the less the auxiliary heat required. Thus, a higher heat pump ratio is desired to ensure that most of the heat is supplied by the more efficient heat pump system rather than the less efficient auxiliary heating system.

The same variation is expected for the auxiliary heat ratio. It is lowest on a sunny summer day and the highest on a sunny winter day, as shown in **Table 2**. The sun's availability on sunny winter days is lower than on cloudy and sunny summer days. This leads to less solar radiation collected by the collector and used in the heat pump, requiring he compressor to work harder in order to reach the refrigerant temperature necessary to heat the water in the water tank. Therefore, a lower auxiliary heat ratio is desirable, as it indicates that less auxiliary heat is required to raise the water temperature to its desired value.

	Heat pump ratio	Auxiliary heat ratio
Cloudy Summer	38.2%	66.0%
Sunny Winter	15.6%	86.7%
Sunny Summer	49.0%	57.1%

Table 2. Heat pump ratio and Auxiliary heat ratio average across all solar collector cells on the three 12 hour simulated days for all solar cells

Looking at the difference in the performance parameters across all the photovoltaic cells. The COP of the highest to lowest system differs by about 0.7 across each of the three types of days considered. The thermal efficiency of the photovoltaic cells differs by about 6% from the highest to the lowest thermal efficiency over the three types of days considered. It is evident from the foregoing discussion that the solar cells, which give the highest COP and thermal efficiency for the heat pump across the three types of days, show noticeable differences in the performance parameters. When identifying the most effective photovoltaic cell to use in the PV-DXSAHP, over the three types of days considered in this study, the ®Prime cells are advantageous over the other PV cells for the PV-DXSAHP system owing to their higher electrical efficiency. The solar cells have a larger electrical efficiency than the rest of the solar cells and remain within a maximum of 0.7 and 6% range of COP and thermal efficiency, respectively, compared with the other solar cells.

CONCLUSION

In this study, a detailed thermodynamic model of a solar photovoltaic-thermal-direct expansion solar-assisted heat pump was developed and validated. Using the developed model, the performance of the system in cold climates was undertaken for different commercially available solar cells. The solar collector cells that provided the largest COP were the ®Solartech cells, electrical efficiency was the ®Prime cells, and thermal efficiency was the ®Solartech cells. At the end of a 12-hour simulation, the average heat pump ratio was 38.2% on a cloudy summer day, 15.6% on a sunny winter day and 49.0% on a sunny summer day. The average axillary heat ratio was 66.0% on a cloudy summer day, 86.7% on a sunny winter day and 57.1% on a sunny summer day. Overall, results show that the solar cells with the lowest electrical efficiencies gave the higher COP across all three days.

ACKNOWLEDGMENTS

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NOMENCLATURE

$\bar{Q}_u$	modified useful energy gain (W)
$\tilde{m}_r$	mass flow rate of refrigerant (kg/s)
ρ_r	density of the refrigerant (m^3/kg)
h_1	enthalpy of refrigerant exiting the collector (kJ/kg)
h_4	enthalpy of refrigerant entering the collector (kJ/kg)
η_{vol}	volumetric efficiency of refrigerant (unitless)
P_c	pressure in the condenser of the heat pump (kPa)
P_{eva}	pressure in the evaporator of the heat pump (kPa)
n	speed of the compressor (rpm)
V_d	volumetric displacement of compressor (m^3)
$h_{r,PV-amb}$	radiative heat transfer coefficient with Photovoltaic cells and ambient air (W/m^2K)
ε_{PV}	emissivity of Photovoltaic cells (-)
σ	Stephan-Boltzmann constant (W/m^2K^4)
T_{PV}	photovoltaic cell temperature (K)
T_{amb}	ambient air temperature (K)
$h_{c,PV-amb}$	convective heat transfer coefficient with Photovoltaic cells and ambient air (W/m^2K)
u_{amb}	wind speed of ambient air (m/s)
R_{r-c}	heat resistance from ambient across ambient air to Photovoltaic cells (m^2K/W)
R_{PV}	heat resistance across Photovoltaic cells (m^2K/W)
δ_{PV}	photovoltaic cell thickness (m)

k_{PV}	thermal conductivity of photovoltaic cell (W/mK)
U_{Bottom}	back loss coefficient (W/m²K)
k_b	thermal conductivity of back insulation (W/mK)
δ_b	thickness of back insulation (m)
U_L	total heat loss coefficient (W/m²K)
η_c	collector efficiency (%)
η_r	collector reference efficiency (%)
β_r	photovoltaic temperature coefficient (1/K)
T_r	reference temperature of the photovoltaic cell (K)
η_{amb}	collector efficiency at ambient temperature (K)
$\bar{U}_L$	modified total heat loss coefficient (W/m²K)
S	solar radiation (W/m²)
α	absorptivity of photovoltaic (-)
$\bar{S}$	modified solar radiation (W/m²)
h_{fi}	coefficient of heat transfer of two-phase refrigerant (W/m²K)
k_l	thermal conductivity of refrigerant (W/mK)
D_i	Internal diameter of the absorber tube (m)
Re	Reynolds number (-)
J	design constant (-)
L	length of the absorber tube across collector (m)
Δx	quality difference inlet and outlet of collector (-)
h_{fg}	latent heat of refrigerant (W/m²K)
F'	collector efficiency factor (-)
W	distance between each row of absorber tube in the collector (m)
F	fin efficiency parameter (-)
C_b	conduction bound of absorber tube to absorber plate (W/mK)
D	outer diameter of the absorber tube (m)
h_{fi}	heat transfer coefficient between the fluid and the tube walls (W/m²K)
m	boundary condition constant (-)
k_p	thermal conductivity of the absorber plate (W/mK)
δ_P	thickness of the absorber plate (m)
A_c	area of the collector (m²)
T_p	temperature of the absorber plate (K)
T_e	evaporating temperature (K)
W_c	compressor work (W)
h_2	enthalpy of refrigerant exiting the compressor (kJ/kg)

h_1	enthalpy of refrigerant entering the compressor (kJ/kg
η_{is}	isentropic efficiency of the compressor (%)
Q_c	useful energy transferred from the condenser to the water tank via heat exchanger (W)
$\dot{m}_w$	mass flow rate of water into the tank (kg/s)
C_p	heat capacity of water (kJ/K)
T_{wo}	temperature of outlet water of heat exchanger (K)
T_w	water tank temperature (K)
U_c	heat loss coefficient at the condenser (W/m²K)
A_C	area of the condenser (m²)
ΔT_{lm}	log-mean temperature difference (K)
T_2	temperature exiting the compressor (K)
T_c	condenser temperature (K)
M	water mass in the tank (kg)
$T_{w,i+1}$	load water temperature next time step (K)
$T_{w,i}$	load water temperature current time step (K)
Δt	timestep (s)
$\dot{m}_{\text{sup}}$	mass flow of water load supplied to the water tank (kg/s)
T_{sup}	supplied water temperature (K)
$\dot{m}_{load}$	mass flow of water load exiting the water tank (kg/s)
U_t	heat loss coefficient of water tank (W/m²K)
A_t	area of the water tank (m²)
T_{at}	air temperature surrounding the water tank (K)

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PRESS SUMMARY

This study investigates the performance of a heat pump driven by solar radiation using various types of photovoltaic cells on the evaporator of the heat pump. A mathematical model was developed to understand how well the heat pump increases the temperature of water used in residential homes in cold climates.

Ground-dwelling Invertebrate Community Composition Changes between Coastal Sage Scrub Community of San Diego and Tijuana with Urbanization

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ABSTRACT
Invertebrates are some of the most diverse and abundant groups of terrestrial organisms. They provide important functions within an ecosystem and can rapidly respond to environmental changes, such as urbanization, making them excellent ecological indicators for ecosystem function and health. Urbanization, and the disturbance and introduction of exotic plants often associated with it, affects invertebrate taxa, changing community composition, structure, diversity, and abundance of invertebrates. Some invertebrate taxa can exploit these changes and increase in abundance; while others exhibit sensitivity and are at risk of extirpation. The San Diego and Tijuana region has been increasing in urbanizing pressure for decades. Tijuana, in particular, has experienced exponential population growth over the past 30 years, and urbanization threatens the integrity of much of the remaining coastal sage scrub, an endangered and rare ecosystem unique to the coasts of southern California and northwestern Mexico composed of many coastal deciduous shrubs and annual wildflowers. However, the invertebrates currently residing in these semi-disturbed landscapes have rarely been sampled. In this study, ground-dwelling invertebrates from a native plant nursery in an urbanizing area of Tijuana at Vivero Hormiguitas and a protected site in Border Field State Park in San Diego were sampled to compare the changes in coastal sage scrub ground-dwelling invertebrate community composition in response to urbanization. Beetle abundance and richness decreased in the urbanizing site in Tijuana, while spider abundance and richness increased in Tijuana compared to the protected site in San Diego. Particularly, we noted decreases in Tenebrionidae abundance and failed to detect Silphidae, suggesting slower decomposition rates in the urbanizing Tijuana site. Although spider abundance in general increased, mostly due to increased prevalence of one genus, *Xysticus*, Gnaphosidae abundance decreased in the Tijuana site. Lastly, non-native invertebrate taxa, especially isopods, showed dramatic increases in abundance at the urbanizing Tijuana site, contributing to overall increases in invertebrate abundance in Tijuana compared to the protected site in San Diego. These results indicate that urbanization has negatively affected ecosystem functions in coastal sage scrub communities and that it has drastically impacted the diversity and health of this rare ecosystem, much of which is already fragmented, and actions need to be taken to protect this rare habitat as much of its range continues to become more urbanized.

KEYWORDS
Beetle; Coastal Sage Scrub; Community Composition; Disturbance; Invasive Species; Invertebrates; San Diego; Tijuana; Spider; Urbanization

INTRODUCTION

Invertebrates are one of the most diverse and abundant groups of organisms in terrestrial ecosystems.[1] They are ubiquitous to almost every terrestrial habitat and contribute to many important ecological processes. Invertebrates are often the first facilitators of decomposition and can influence the rate at which nutrients are recycled in food webs.[2] Invertebrates also play important roles in the reproduction of other species through mechanisms such as pollination and seed dispersal.[3] Invertebrates often provide important food sources for higher trophic levels and can serve as biological control, increasing an ecosystem's resilience to change.[4] The health of an ecosystem and food web integrity can be reflected by the diversity and community structure of its invertebrate taxa.[5] However, these ecological processes, including those involving invertebrates, often fall out of balance when a habitat is altered due to human activities, resulting in changes in invertebrate community composition.[2, 5]

Using ground-dwelling invertebrates as bioindicators for ecosystem health is a well-established method within ecological studies for ecological impact assessment and restoration ecology.[6, 7] Recently, bioindicators have been categorized into three distinct categories: (i) environmental indicators, which indicate the abiotic and biotic states of an ecosystem, (ii) ecological indicators,

which reveal changes in an ecosystem and evidence for impacts from changes caused by natural or human processes, and (iii) biodiversity indicators, which correspond to the diversity of taxa and community of an area.[8, 9] Changes in invertebrate assemblage and composition can reflect environmental change, especially when using ground-dwelling invertebrate taxa such as spiders (Araneae) (ex: Gnaphosidae), ground beetles (Carabidae), rove beetles (Staphylinidae), and ants (Formicidae) as bioindicators.[10–14]

Ground-dwelling invertebrates are good ecological and biodiversity indicators as they are particularly sensitive to changes in microhabitat and ecosystem structure and are more abundant and diverse than many vertebrate species.[10, 15, 16] Short generation times and high mobility of ground-dwelling invertebrates allow for rapid response to degraded or changing environments, enabling rapid detection of biodiversity change.[17] For example, urbanized spaces in southern California have decreased beetle abundance and diversity, especially larger beetles, contributing to slower decomposition rates of carrion.[5] Additionally, spider communities, in particular, are sensitive to a wide variety of environmental factors such as habitat structure, type, wind exposure, temperature, and moisture, potentially providing important information on the ecological health of a system or assessment of restored ecosystems.[12, 14, 18–20] Invertebrate bioindicators can be classified into three groups based on their response to environmental change: (i) detectors, which are sensitive to environmental stress and respond by decreasing, (ii) exploiters, which can increase in abundance by exploiting the environmental changes, and (iii) accumulators, which often accumulate toxins from the environment that can be measured to assess environmental toxin levels.[7]

Urban landscapes provide perhaps some of the best examples of how invertebrates reflect the health of an ecosystem.[7] One of the most deleterious human impacts is modern development and design of urban landscapes.[21, 22] Urbanization often involves significant disturbance of native soil and plant communities, which facilitates the spread of invasive species, in particular, plants that are disturbance-tolerant, ruderal, pioneer, and/or generalists.[23–27] Invasive plants can alter soil chemistry and nutrient cycling,[28–31] change community structure through trophic interactions,[32– 35] and facilitate further invasion of exotic species.[36, 37] Changes in the community structure can negatively affect invertebrate diversity, especially habitat specialists such as many carabid beetles.[38–41]

Marschalek and Deutschman found that for ground-dwelling taxa, abundance of beetles in the family Silphidae (carrion beetles) and Staphylinidae (rove beetles) exhibited a strong negative correlation with urbanized landscapes and showed a positive correlation with sage scrub habitat, a rare and endangered habitat in southern California and northwestern Mexico.[5] Spiders, on the other hand, have been found to increase in richness within urban landscapes.[42] Depending on the taxonomic group, diversity and abundance can be affected either negatively or positively.[5, 42] Such alterations create trophic effects down the food chain by affecting parasitoids and predators, which may also be directly affected by plant diversity,[32-35] changing the invertebrate community assemblage and structure of an ecosystem.[43–45] Urbanization can also alter insect-mediated ecological processes, including insect herbivory and tritrophic interactions.[46–49]

Tijuana, Mexico is a rapidly urbanizing municipality on the US-Mexico border. Tijuana's rapid development is due to ample employment opportunities, both within the city and across the border in San Diego, California.[50] Adverse possession laws in Tijuana allows the acquisition of land as private property upon showing proof of continuous and exclusive possession.[51] These laws encourage squatting and incentivize the poorest residents of the municipality to build homes in precarious areas that result in intensifying social risk and serious ecological consequences. The area surrounding the urban centers exhibits intense anthropogenic disturbance, including pollution due to industry, lack of waste management, and massive stripping of native plants and topsoil within canyons and on the crest of hillsides.[52, 53] These disturbances facilitate the establishment of many aggressive invasive plant species. Much of Tijuana and San Diego sits on coastal sage scrub habitat, much of which is fragmented in San Diego and the majority of which is under threat of urbanization in Tijuana.[52, 53] Coastal sage scrub is dominated by deciduous Shrubs; it is very similar to the chaparral habitat of southern California, except that the majority of the shrubs are deciduous and not evergreen. In these rapidly changing landscapes, evaluating the health of this rare and endangered ecosystem are of great importance not only for conservation, but for human health.[54] By using invertebrate sampling to obtain information on ecosystem function and structure, it will be possible to understand some of the effects of this rapid development on the system.

Although the Tijuana region shares similar plant communities and ecotypes to San Diego, such as coastal sage scrub and chaparral, the invertebrate communities have not been well sampled, and areas within the canyon have little to no records for their current invertebrate communities.[55–57] With urbanization and invasive species disturbances, the invertebrate community composition of Vivero Hormiguitas, Tijuana is expected to exhibit some key differences from similar, undisturbed habitats in San Diego within the Border Field State Park. For instance, habitat loss appears to be the primary driver of decreased invertebrate diversity and beetle abundance in coastal southern California.[5] Adams et al. found insect diversity and abundance was over 30% higher at sites with native or drought tolerant plants.[58] Exotic insects are also found in higher abundance at urbanized sites with low native plant diversity.[58] These results support the idea that invertebrate communities within disturbed Tijuana sites may be

experiencing, or already have experienced, a rapid change in community structure and taxonomic diversity compared to protected areas within San Diego.

Sampling the sites within Tijuana and San Diego allows not only for a unique opportunity to understand current invertebrate composition in the rapidly developing Tijuana area but also for the study of how invertebrate communities may be expected to change with urbanization. This work in the southern California and northern Baja California region will provide information on the current ecological health and function of each area and will assist in creating roadmaps for site restoration in the future.

In this study, invertebrates sampled at the disturbed and rapidly urbanizing Tijuana site and the protected site in San Diego will be used as bioindicators for ecosystem function and health; comparison of invertebrate samples at these sites will enable assessment of how invertebrate communities are changing. Currently, some of the hypotheses that explain invertebrate community compositions across urban-rural gradients include: (i) the increasing disturbance hypothesis, which state that species richness monotonously decreases from rural to urban areas as disturbance increases;[42] (ii) the matrix species hypothesis, which claims that matrix (open habitat) species dominate disturbed open habitats and abundance increases with urbanization;[42] (iii) the opportunistic species hypothesis, which predicts that opportunistic and disturbance tolerant species should increase in urban areas;[36, 37, 42] and (iv) the habitat specialist hypothesis, which posits that the abundance and richness of specialist species decreases with disturbance and therefore also in urban areas while generalists are less affected.[42]

Based on these hypotheses proposed by past research, the diversity and abundance of ground-dwelling spiders are predicted to increase in the urbanizing Tijuana site. This follows the habitat specialist hypothesis and the matrix species hypothesis as ground-dwelling spiders, such as those in Lycosidae and Agelenidae are mostly generalists, which have been found to be affected less by disturbances and in some cases, increase in abundance and diversity due to the penetration of matrix spider species into disturbed sites.[59] Beetle abundance and diversity are hypothesized to be greater in less urbanized spaces. This follows the habitat specialist hypothesis as many beetle species are habitat and diet specialists and often require specific microhabitats, that are easily destroyed by urbanization.[60] Abundance of invasive or exotic invertebrate species are expected to be greater at the urbanizing Tijuana site, following the opportunistic species hypothesis as many successful invasive or exotic invertebrate species often thrive in disturbed and urban environments.[42] Finally, following the increasing disturbance hypothesis, there should be a higher invertebrate abundance but a lower Shannon diversity index (H') value in the disturbed site of Tijuana due to increases in disturbance tolerant and/or non-native species.[42]

METHODS AND PROCEDURES

Study sites

An area located at the coordinates 32.513363, -117.091483 of approximately 3000 m² in Tijuana, Mexico was sampled (**Figure 1a**). The site is situated on a slight slope near a canyon peak and much of the surrounding area has been disturbed by urbanization and unofficial settlements. The site is granted by the city of Tijuana and is managed as a native plant nursery known as Vivero Hormiguitas, Tijuana (TJ). The nursery is often disturbed by weedy, invasive plants, and the areas surrounding it are disturbed by illegal dumping, clearing of vegetation, and sediment transfers from construction. Vivero Hormiguitas contains some remnant plantings of native plants, as well as horticultural exotic species such as *Schinus terebinthifolia* (Brazilian peppertree) and *Selenicereus unatus* (white-fleshed pitahaya). Much of the landscape here now is sparse and open, dominated by weedy invasive grasses and forbs such as *Glebionis coronaria* (garland daisy), *Salsola tragus* (prickley Russian thistle), *Silene gallica* (small-flowered catchfly), *Malva spp.* (mallows), *Bromus spp.* (brome grasses), and *Erodium spp.* (stork's bills) among other annual invasives. There are a few annual, native species that occur in low abundance, including *Lupinus succulentus* (arroyo lupine), *Calochortus splendens* (splendid mariposa lily), *Primula clevelandii* (Padre's shooting star), and *Sisyrinchium bellum* (western blue-eye grass). Some perennial native plants also occur in low abundance, including: *Isocoma menziesii* (coastal goldenbush), *Cneoridium dumosum* (bushrue), *Solanum parishii* (Parish's nightshade), *Hazardia orcuttii* (Orcutt's goldenbush), *Rhus integrifolia* (lemonade berry), *Eriogonum fasciculatum* (California buckwheat), *Baccharis sarothroides* (desert broom), *Acmispon glaber* (deerweed), *Artemisia californica* (California sagebrush), *Malacothamnus fasciculatum* (chaparral mallow), and *Malosma laurina* (laurel sumac). Much of this slope before disturbance would have been dominated by coastal deciduous and perennial shrub-like species such as *Salvia apiana* (white sage), *Salvia mellifera* (black sage), *Encelia californica* (California brittlebush), succulents like *Dudleya spp.* (Dudleyas), and coastal cactus species mixed with evergreen chapparel plants such as *Malosoma laurina, Rhus integrifolia, and Baccharis sarothroides*. Diversity of annual forbs would likely have been higher including *Eschscholzia californica* (California poppy) and many Boraginaceae and Asteraceae species.

An area located at the coordinates 32.538950, -117.105543 of approximately 3000 m² in San Diego Border State Field Park, San Diego (SD) was also sampled (**Figure 1b**). The site is situated on the foothill rise of the northeast side of Bunker Hill, CA. Vegetation here is more intact and less disturbed, as areas around this site are protected due to the cultural and historical significance to the Kumeyaay. indigenous people. Native plants, and especially shrubs dominate the landscape, although invasive

species such as *Erodium spp*., *Bromus spp*., *Urtica urens* (dwarf nettle) and other invasive grasses and weeds are still present in small quantities on the hillside. *Malosma laurina*, *Rhus integrifolia*, *Claytonia perfoliata* (miner's lettuce), *Nuttallanthus texanus* (Texas toadflax), *Ferocactus viridescens* (San Diego barrel cactus), *Dudleya pulverulenta* (chalk dudleya), *Salvia apiana, Salvia mellifera*, *Lupinus succulentus*, *Pseudognaphalium biolettii* (bi-colored rabbit tobacco), *Heteromeles arbutifolia* (toyon), *Sairocarpus sp.* (snapdragons), *Encelia californica*, *Camissoniopsis sp.* (suncups), *Solanum sp.* (nightshades), and various other native shrubs and annuals characteristic of coastal sage scrub exist in the sampling site. The invasive annual forbs at this site was generally spread evenly throughout, using any little bit of open space between the large shrubs to grow.

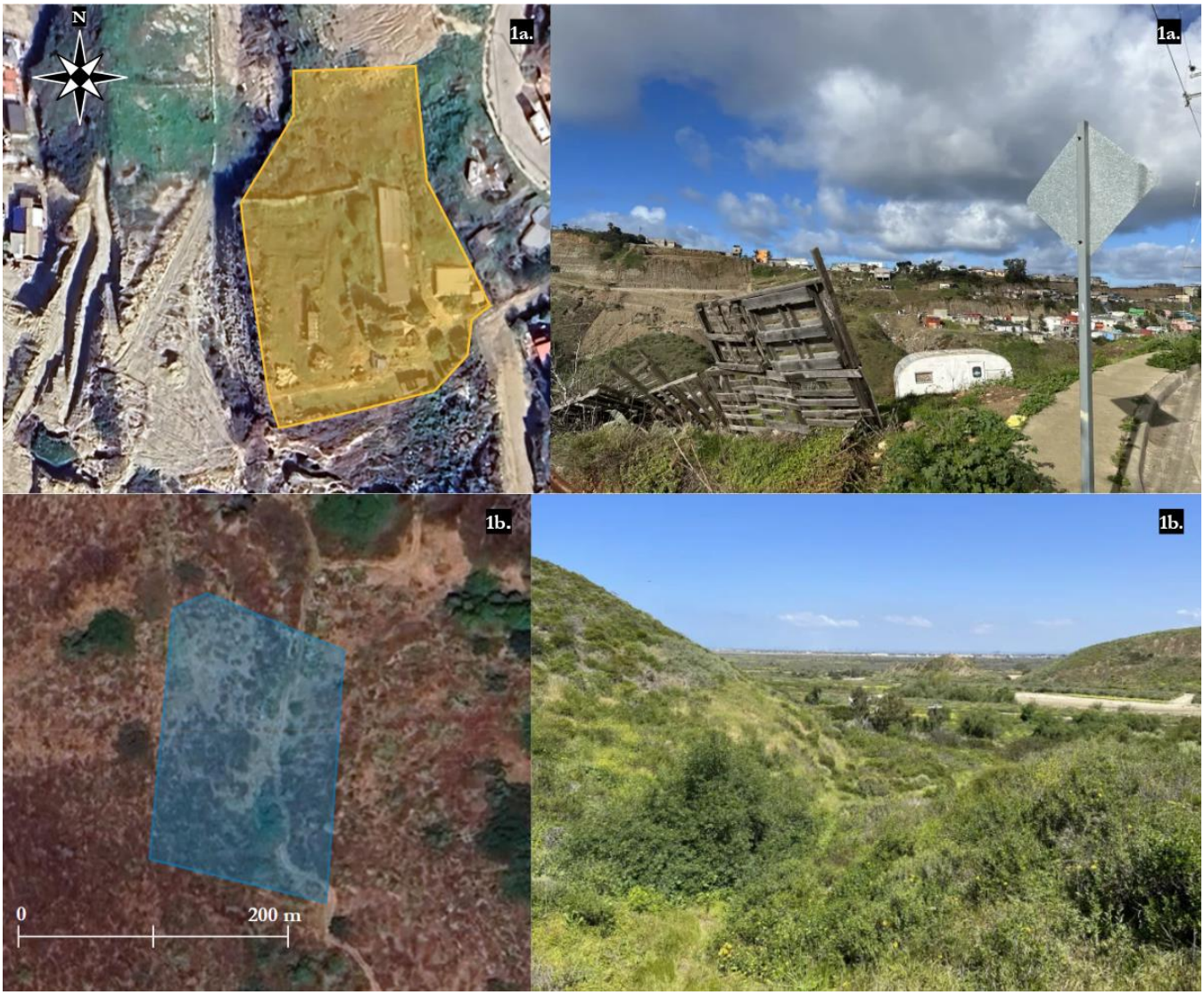

Figure 1. Shows the sampling sites from Tijuana in Vivero Hormiguitas (**1a.**) and from San Diego in Bunker Hill of Border State Field Park (**1b.**) in top view form from satellite image alongside general landscape view captured through camera on the ground.

Sampling method

Pitfall traps were placed flush to the ground using 532 ml plastic cups. The traps were filled with solution composed of 10% salt water and 5% bleach. An orange flag was placed adjacent to the trap to mark the traps (**Figure 2**). Twenty traps were randomly placed at each site by randomly generating coordinates with a computer within the select site. As invasive plants were generally homogenous throughout the sites, this method allowed for the most straightforward randomization. The traps were collected two weeks after placement and invertebrate identification followed. The site in Tijuana was sampled from February 29 to March 14, 2024, and the San Diego site was sampled from April 8 to April 22, 2024. Invertebrates were identified to the most specific taxa possible and by morphospecies. Spiders (Araneae) and beetles (Coleoptera) were heavily focused on due to their abundance, diversity, and functional group representation within terrestrial ecosystems, making them excellent ecosystem indicators.

Morphospecies were used for many spiders and insect larvae. Spiders were mostly identified to family level based on eye positioning, spinnerets, and pedipalps. Beetles, ants, isopods, dermapterans, orthopterans, hemipterans, mantids, scorpions, and cockroaches were mostly able to be identified to species or genus level. Each beetle was also categorized into their respective families for analysis. For individuals in the same family that appeared to be different, they were counted as different morphospecies. Some individuals were not able to be identified and were not the same as the other species morphologically, those individuals were counted as one morphospecies without being assigned to a family and labeled "unidentified". These "unidentified" individuals did not contribute to an additional family level richness count. Hard to identify groups such as Lepidoptera larva, silverfish, centipedes, millipedes and harvestmen that occurred in low abundance used morphospecies.

For the purpose of this study, invasive invertebrate species and other exotic species are all grouped under the label of "non-native", as it can be hard to identify what may be considered invasive, as there is often a lack of research on impacts of some of these exotic invertebrates. However, some of these invertebrates are already considered invasive, such as *Coccinella septempunctata* (seven-spotted lady beetle), *Cornu aspersum* (garden snail), and *Forficula mediterranea* (European earwig). Furthermore, all non-native invertebrates are identified to the species level as it would be almost impossible to know if an invertebrate is non-native without doing so. Due to rain causing mud to slide into and burying some traps on the slope, a total of only 17 traps were collected from the site in Tijuana and a total of 16 traps were collected from the site in San Diego. Permit to sample invertebrates in the Border Field State Park was provided by the California State Parks Department of Parks and Recreation. The permit granted is Scientific Collecting Permit 24-669-03, and is valid from March 19, 2024 to March 19, 2025.

Figure 2. Pitfall trap set up with a plastic cup flush to the ground filled with 10% salt solution + bleach (5%) with an orange flag beside it.

Pooled data analysis

The samples from each site were pooled together so that two samples are obtained, the total SD and total TJ samples. Using these pooled data, a table was created to summarize the raw data findings of the sites. The table reports raw data in both the abundance (how many counts) and richness (how many types) of each category. The categories include the total beetle abundance and richness (Order Coleoptera), Coleoptera families at each site (number of families), including the abundance and richness of species each of those families, the total spider abundance and richness (Order Araneae), Araneae families (number of families at each site), and the abundance and richness of species within each of those families. The table also reports the total abundance and richness of all other invertebrate orders collected from each site, and the total abundance and species richness of non-native invertebrate species, native invertebrate species, and total invertebrates. Centipede and millipede classes were included and counted as an order each because there was no more than one individual of each at each site and identification to order was more difficult for these groups.

From this pooled data, a couple important taxonomic groups of interest are noted, these are: (i) Carabidae, as they are abundant in both sites, and often used as biological indicators for restoration and for biodiversity assessment; they are also a group of predaceous beetles that can be used as one functional group;[60–63] (ii) Tenebrionidae, as they are also abundant within both of the

sites and serve as a good alternative functional group to Carabidae, as they are mostly scavengers and detritivores;[64] (iii) Gnaphosidae, as a highly cursorial ground-dwelling spider that is often used as an environmental indicator due to their particularly sensitive nature to disturbance;[11] and (iv) Isopods, as they show a particularly large change in abundance between sites. Most of the analysis will be focused on spiders (Araneae) and beetles (Coleoptera) as these two groups are very abundant within the samples, can serve as large functional groups, and are used extensively as bioindicators.[7–11]

Statistical analysis

The Shannon diversity index (H') was calculated as a measure for diversity in morphospecies for each individual pitfall trap to conduct t-test analysis—this is termed all-taxa invertebrate H'. It is important to note that "native invertebrates" here are invertebrates excluding the non-native invertebrates identified, as some individuals not identified as non-native due to difficulty of species identification can still be exotic.

Abundance here is measured by the number of individuals sampled within the family, order, or in all-taxa totals. To carry out a t-test for abundance of a specific family or order, the number of individuals in that family or order was counted for each individual pitfall trap. To carry out a t-test for an all-taxa invertebrate abundance, the total count of invertebrates from all taxa for each individual pitfall trap was used. Total abundance for each site was also calculated by combining all pitfall traps within a site together. To carry out a t-test for non-native invertebrate all-taxa abundance, abundance was calculated for each individual pitfall trap. Total non-native invertebrate abundance is the abundance of non-native invertebrates calculated by counting the combined non-native invertebrate taxa for each site. By excluding non-native invertebrates, the all-taxa native invertebrate abundance for each pitfall trap was calculated to perform a t-test and the total native abundance was calculated.

To analyze the data obtained, multiple unequal variance t-tests were conducted after confirming unequal variance using F-test on the following response variables: beetle (Coleoptera) abundance (F-test p-value = 0.00179), spider (Araneae) abundance (F-test p-value = 7.355e-05), all-taxa invertebrate abundance (F-test p-value = 1.45e-12), non-native invertebrate abundance (F-test p-value < 2.2e-16), Carabidae abundance (F-test p-value = 1.172e-05), Isopod (Isopoda) abundance (F-test p-value < 2.2e-16), and Gnaphosidae abundance (F-test p-value = 5.923e-06). Student's t-tests were performed on variables that did not show significant unequal variances, these include: beetle (Coleoptera) H' at the species level (F-test p-value = 0.8822), beetle (Coleoptera) species richness (F-test p-value = 0.7021), spider (Araneae) H' at the species level (F-test p-value =0.4959), spider (Araneae) species richness (F-test p-value = 0.0746), Carabidae H' at the species level (F-test p-value = 0.4762), Tenebrionidae abundance (F-test p-value = 0.2195), all-taxa invertebrate species richness (F-test p-value = 0.8555), non-native invertebrate H' at the species level (F test p-value = 0.52), native invertebrate H' at the species level (F-test p-value = 0.6929), native abundance (F-test p-value = 0.2601), and all taxa H' at the species level (F-test p-value = 0.7072).

Species richness t-tests for Tenebrionidae, Carabidae, Isopoda, and Gnaphosidae were not performed because there were not enough morphospecies and individuals of each morphospecies to result in meaningful robust analysis. A t-test on non-native invertebrate species richness was not performed as the information provided by this test can be easily interpreted through the raw data as most of the same non-native species were present in both sites. A t-test on isopod species H' was not calculated or compared because there were only two non-native species of isopods present. A t-test on Gnaphosidae species H' was not calculated as only two morphospecies of Gnaphosidae were collected. All statistical analysis and data organization was performed using RStudio 2023.09.1+494 with R package ggplot2 (stacked bar graph made using function barplot())and Microsoft Excel.[65, 66]

RESULTS

In total, 923 invertebrates were collected from TJ. These individuals were made up of 766 non-native invertebrates from 10 species, 619 of which were isopods composing of two species, 189 *Armadillidium vulgare* (common pill woodlouse) and 430 *Porcellio laevis* (swift louse). 77 of the non-native individuals were dermapterans, all of which were *Forficula mediterranea* (European earwig), 33 were hymenopterans, all of which were *Linepithema humile* (Argentine ant), 23 of which were Stylommatophora (land snails and slugs), made up of 19 *Rumina decollata (*decollate snail) and four *Cornu aspersum* (garden snail), seven non-native beetles, six of which were *Coccinella septempunctata* (seven-spotted lady beetle) and one which was *Amara aenea* (common sun beetle), four non-native spiders, all of which were *Dysdera crocata* (woodlouse spider), and three non-native hemipterans, all of which were *Bactericera lavaterae* (island mallow psyllid). A total of 47 beetles of 11 morphospecies were collected from four families (also included one "unidentified" beetle larva): Carabiade, Tenebrionidae, Coccinellidae, Histeridae, and Curculionidae. 99 spiders from 10 morphospecies were collected comprising of eight families (also included one "unidentified" spider): Lycosidae, Agelenidae, Salticidae, Thomisidae, Anyphaenidae, Dysderidae, Gnaphosidae, and Theridiidae. The rest of the invertebrates collected were composed from the class of millipedes (Diplopoda) and centipedes (Chilopoda), and other invertebrate orders, including: Orthoptera, Hemiptera, Lepidoptera (larval form), and Opiliones. All individuals from Isopoda, Stylommatophora, Hymenoptera, and Dermaptera were non-native. (**Table 1**).

In total, 207 invertebrates were collected from SD. These individuals were made up of 51 non-native invertebrates from seven species, 30 of which were isopods composed of two species, three *Armadillidium vulgare* (common pill woodlouse) and 27 *Porcellio laevis* (swift louse), one of the non-native individuals was a dermapteran, which is a *Forficula mediterranea* (European earwig), five were hymenopterans, made of four *Linepithema humile* (Argentine ant) and one *Prenolepis imparis* (American winter ant), three were Stylommatophora, all of which were *Cornu aspersum* (garden snail), 12 non-native beetles, all which were *Amara aenea* (common sun beetle). A total of 112 beetles of 18 morphospecies were collected from eight families (also included one "unidentified" beetle): Silphidae, Tenebrionidae, Limnichidae, Carabidae, Scarabaeidae (subfamily Aphodiinae), Latridiidae, Hydraenidae, and Lampyridae. 32 spiders from nine morphospecies were collected from six families (also included one "unidentified" spider): Lycosidae, Salticidae, Thomisidae, Gnaphosidae, Trachelidae, and Theridiidae. The rest of the invertebrates collected were composed from various other invertebrate orders including: Orthroptera, Hemiptera, Lepidoptera (larval form), Hymenoptera, Mantodea, Zygentoma, Blattodea, Lithobiomorpha (stone centipede), Scorpiones, and Opiliones. All invertebrates from Isopoda, Stylommatophora, and Dermaptera were non-native (**Table 1**). Slugs were likely sampled at both sites, but their bodies melted in the solution and could not be identified.

TJ			**SD**		
Taxa	Total Abundance	Total Richness	Taxa	Total Abundance	Total Richness
Order Coleoptera	46	10	Order Coleoptera	112	18
Coleoptera Familes	46	4	Coleoptera Familes	112	8
Family Carabidae	16	5	Family Carabidae	39	5
Family Tenebrionidae	18	3	Family Tenebrionidae	46	7
Family Coccinellidae	8	2	Family Silphidae	13	1
Family Curculionidae	3	1	Family Limnichidae	1	1
Family Histeridae	1	1	Family Scarabaeidae	1	1
			Family Latridiidae	1	1
			Family Hydraenidae	9	1
			Family Lampyridae	1	1
Order Araneae	99	10	Order Araneae	32	9
Araneae Families	99	8	Araneae Families	32	6
Family Lycosidae	17	2	Family Lycosidae	6	2
Family Salticidae	4	1	Family Salticidae	2	1
Family Gnaphosidae	2	1	Family Gnaphosidae	20	2
Family Theridiidae	1	1	Family Theridiidae	1	1
Family Thomisidae	64	1	Family Thomisidae	1	1
Family Dysderidae	4	1	Family Trachelidae	1	1
Family Agelenidae	1	1			
Family Anyphaenidae	5	1			
Order Hemiptera	6	3	Order Hemiptera	2	2
Order Orthoptera	8	2	Order Orthoptera	3	1
Order Lepidoptera	4	4	Order Lepidoptera	3	1

Order Hymenoptera	33	1	Order Hymenoptera	11	3
Order Blattodea	0	0	Order Blattodea	3	1
Order Mantodea	0	0	Order Mantodea	2	1
Order Dermaptera	77	1	Order Dermaptera	1	1
Order Zygentoma	0	0	Order Zygentoma	1	1
Order Opiliones	5	1	Order Opiliones	1	1
Order Scropiones	0	0	Order Scropiones	1	1
Order Isopoda	619	2	Order Isopoda	30	2
Order Stylommatophora	23	2	Order Stylommatophora	3	1
Class Chilopoda	1	1	Class Chilopoda	1	1
Class Diplopoda	1	1	Class Diplopoda	0	0
Non-native Invertebrates	766	10	Non-native Invertebrates	51	7
Invertebrate Orders	917	13	Invertebrate Orders	207	14
Total Invertebrates	917	38	Total Invertebrates	207	45

Table 1. Raw data in number of individuals (abundance) and richness broken down by taxa. Total abundance and richness here is the combined count of each taxa from all pitfall traps within a site. Trends in total abundance and total richness of Order Coleoptera (total beetle species richness and abundance), Coleoptera families (total beetle abundance and number of beetle families), Order Araneae (total spider species richness and abundance), Araneae families (total spider abundance and number of spider families), Invertebrate Orders (number of invertebrates in total and number of invertebrate orders, the class Chilopoda and Diplopoda each count as one order as there is no more than one individual of these per site collected), Total Invertebrates (by species), Non-native invertebrates (by species), and all other Orders of invertebrates, millipedes (Class Diplopoda) and centipedes (Class Chilopoda). SD = Border Field State Park, San Diego and TJ = Vivero Hormiguitas, Tijuana.

Abundance

There was higher all-taxa invertebrate abundance in TJ than in SD (t = -2.2634, df = 16.286, p-value = 0.0376) (**Figure 3a**). This result was mainly due to an increase in non-native taxa, which was significantly higher at TJ than SD (t = -2.2804, df = 16.082, p-value = 0.03656) (**Figure 3b**), with the majority of the increase coming from non-native isopods, *Armadillidium vulgare* (common pill woodlouse) and *Porcellio laevis* (swift louse) (**Figure 3b** and **Figure 5c**). Abundance for the two common invasive isopod species was found to be marginally higher at TJ (t = -1.9693, df = 16.028, p-value = 0.06646) (**Figure 4c**). Native invertebrate abundance did not differ significantly between SD and TJ (t = 0.29028, df = 31, p-value = 0.7735) (**Figure 5d**).

Beetle abundance was found to be significantly higher at SD (t = 2.4618, df = 20.132, p-value = 0.02297) (**Figure 3c**), and spider abundance was found to be significantly higher at TJ (t = -3.0426, df = 19.506, p-value = 0.006557) (**Figure 3d**). The higher beetle abundance in SD comes from the increased prevalence of Tenebrionidae, a slight increase in Carabidae, and the presence of Silphidae beetles (**Figure 5a**). However, only Tenebrionidae showed a significantly higher abundance at SD (t = 2.2352, df = 31, p-value = 0.03275) (**Figure 4b**). There were more Carabidae individuals in the samples from SD, but the trend was not statistically significant (t = 1.1664, df = 17.375, p-value = 0.2592) (**Figure 4a**). The higher spider abundance in TJ is largely attributed to the prevalence of ground crab spiders (Family Thomisidae) in the genus *Xysticus* (**Figure 5b**). There was a significantly higher abundance of Gnaphosidae in SD than in TJ (t = 3.3697, df = 17.09, p-value = 0.003617) (**Figure 4d**).

Shannon Diversity Index (H')

There was no significant difference in the H' value between TJ and SD for beetles species level diversity (Order Coleoptera) (t = 1.5188, df = 31, p-value = 0.139), nor for spiders species level diversity (Order Araneae) (t = -1.7089, df = 31, p-value = 0.09747) (**Figure 6a** and **Figure 6c**). Similarly, Carabidae beetles species level H' values were not significantly different between SD and TJ (t = 0.19983, df = 31, p-value = 0.8429) (**Figure 6f**). While the non-native H' values at TJ was significantly higher than the H' value at SD (t = -5.7711, df = 31, p-value = 2.357e-06) (**Figure 6b**), there was no significant difference for the native H' values between SD and TJ (t = 0.95198, df = 31, p-value = 0.3485) (**Figure 6d**) and the all-taxa H' values between SD and TJ (t = -0.3608, df = 31, p-value = 0.7207) (**Figure 6e**).

Richness

There were significantly higher spider species richness in TJ compared to SD (t = -2.4164, df = 31, p-value = 0.02175) and higher beetle species richness in SD compared to TJ(t = 2.5504, df = 31, p-value = 0.01592) (**Figure 7b** and **Figure 7c**). The all-taxa invertebrate species richness was not found to be significantly different between SD and TJ (t = -5.1698, df = 31. p-value = 0.1266) (**Figure 7a**).

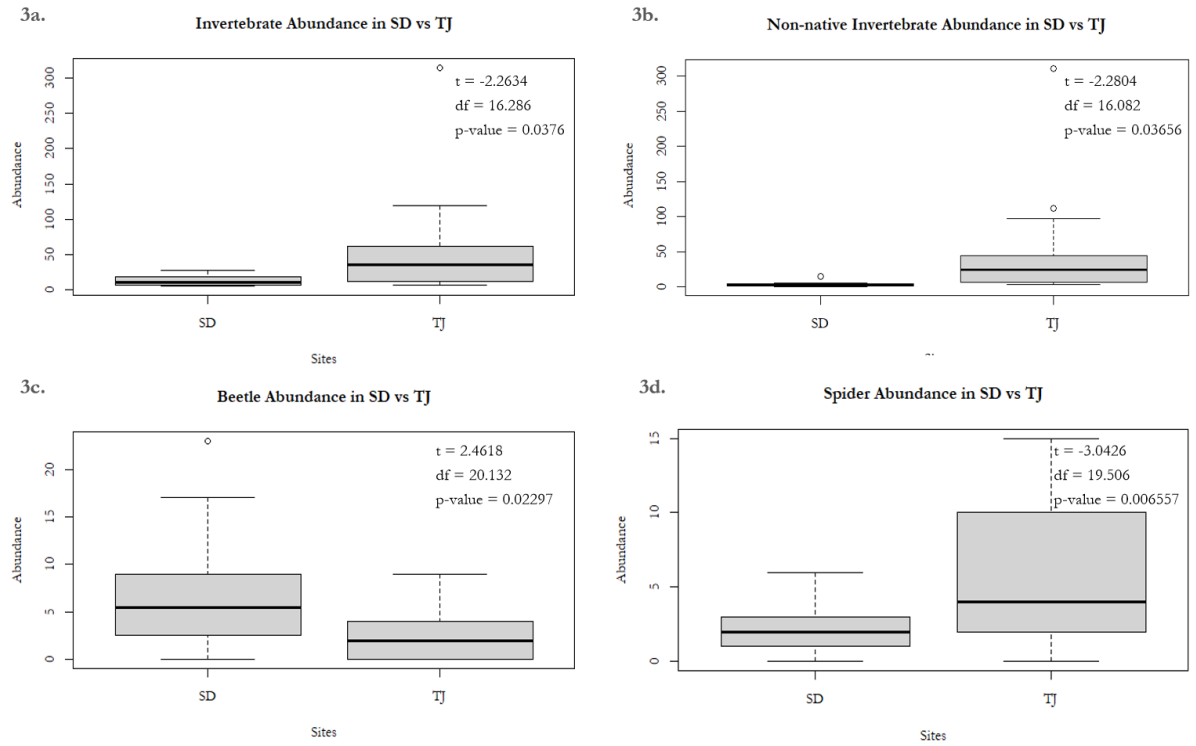

Figure 3. Boxplots depicts the all-taxa abundance of invertebrates (**3a.**), abundance of non-native invertebrates (**3b.**), beetle abundance (**3c.**), and spider abundance (**3d.**) across sites. Abundance is measured in counts of individuals. SD = Border Field State Park, San Diego and TJ = Vivero Hormiguitas, Tijuana. The degrees of freedom, t-statistic, and p-value are displayed in the legend located in the top-right corner. Outliers are represented with a white circle. The median is represented by the bolded line, first to third quartile represented by the box, and the whiskers represent the maximum and minimum values. There are more invertebrates at TJ than SD (**3a.**), more non-native invertebrates at TJ than SD (**3b.**), and more spiders at TJ than SD (**3c.**). There are more beetles in SD than TJ (**3d.**).

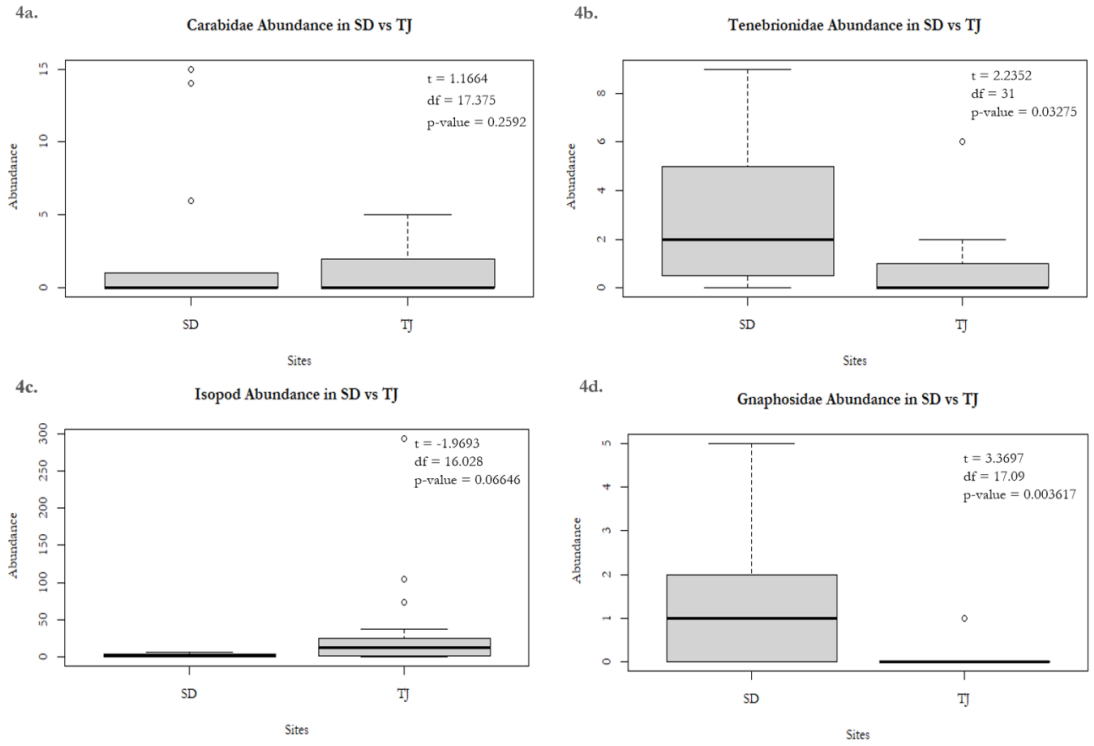

Figure 4. Boxplots of Carabidae (**4a.**), Tenebrionidae (**4b.**), Isopod (**4c.**), and Gnaphosidae (**4d.**) abundances across two sites. Abundance is measured in the count of individuals. SD = Border Field State Park, San Diego and TJ = Vivero Hormiguitas, Tijuana. The degrees of freedom, t-statistic, and p-value are displayed in the legend located in the top-right corner. Outliers are represented with a white circle. The median is represented by the bolded line, first to third quartile represented by the box, and the whiskers represent the maximum and minimum values. Carabidae abundance does not show significant difference between SD and TJ (**4a**.), while Tenebrionidae (**6b.**) and Gnaphosidae (**4d.**) abundance are higher in SD than TJ. Isopods are more abundant in TJ than SD (**4c.**).

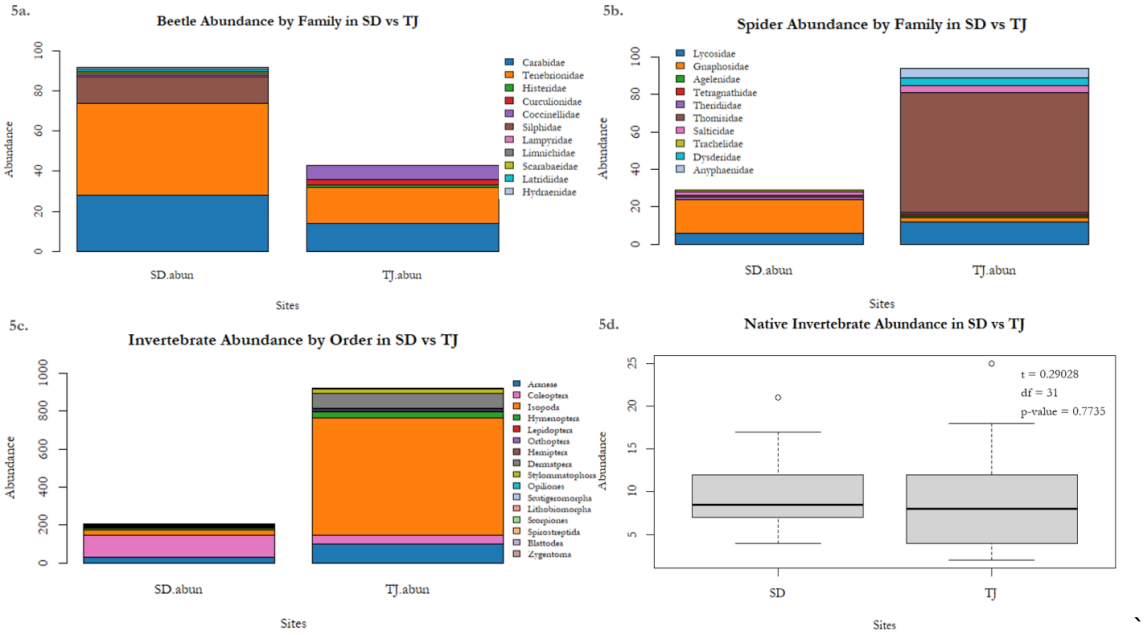

Figure 5. Stacked bar graphs of beetle abundance by family (**5a**.), stacked bar graph of spider abundance by family (**5b.**), a stacked bar graph of invertebrate abundance by order (**5c.**), and a boxplot of native invertebrate abundance (**5d.**). Abundance is measured in counts of individuals. SD = Border Field State Park, San Diego and TJ = Vivero Hormiguitas, Tijuana. The degrees of freedom, t-statistic, and p-value is displayed in the legend located in the top-right corner for **5d.** For **5d.**, Outliers are represented with a white circle. The median is represented by the bolded line, first to third quartile represented by the box, and the whiskers represent the maximum and minimum values. Tenebrionidae and Carabidae raw counts are noticeably more abundant in SD than TJ (**5a**.), Thomisidae is noticeably more abundant in TJ than SD (**5b.**), and Isopods are noticeably more abundant in TJ than SD (**5c.**). No significant difference in native invertebrate abundance between SD and TJ (**5d.**).

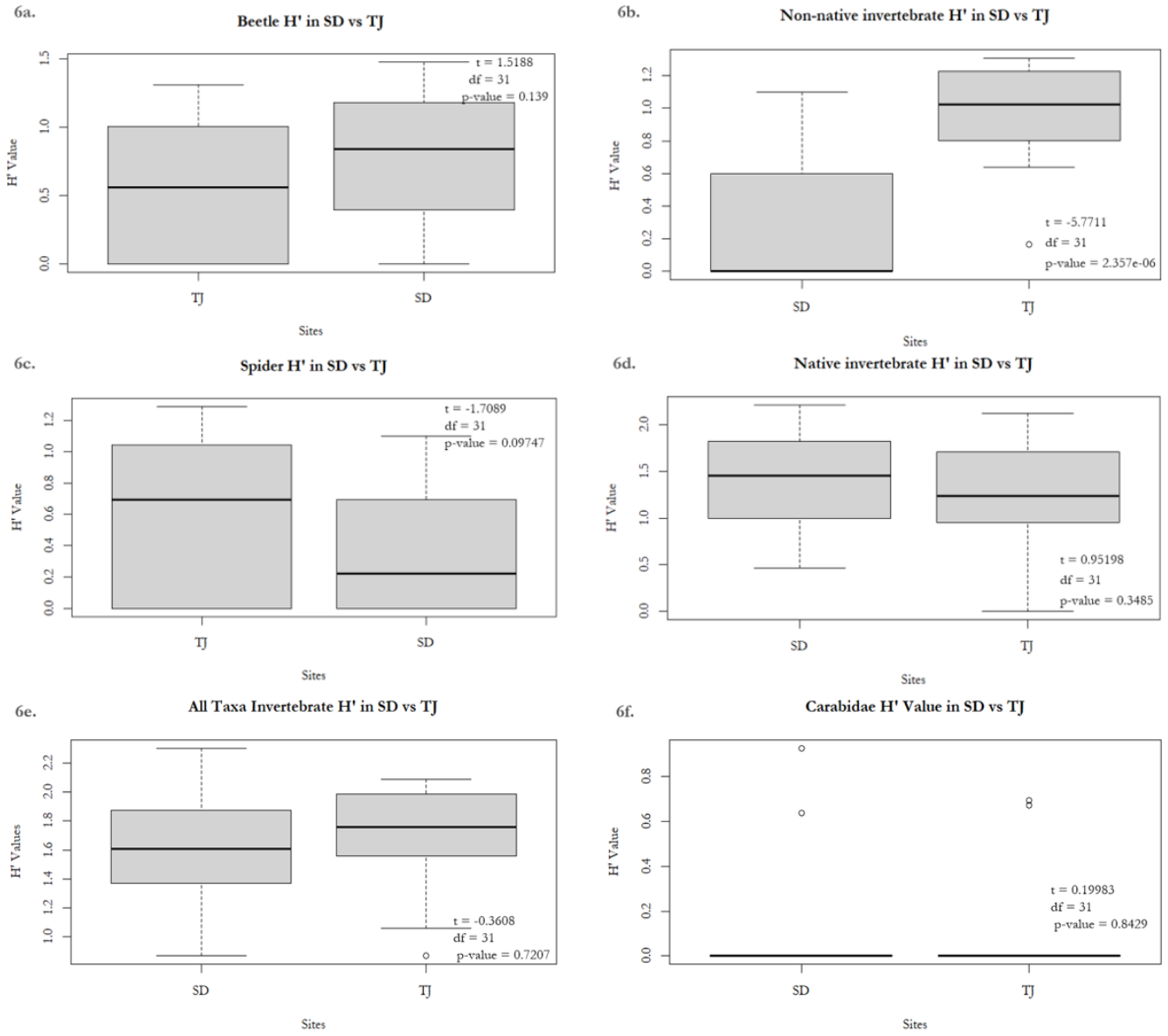

Figure 6. Boxplot of the Shannon diversity index (H') values of beetles from different samples (**6a.**), non-native invertebrate H' values (**6b.**), spider H' values (**6c.**), native invertebrate H' values (**6d.**), all taxa invertebrate H' values (**6e.**), and Carabidae H' values (**6f.**) across the two different sites. SD = Border Field State Park, San Diego and TJ = Vivero Hormiguitas, Tijuana. The degrees of freedom, t-statistic, and p-value are displayed in the legend located in the top-right or bottom-right corner. The median is represented by the bolded line, first to third quartile represented by the box, and the whiskers represents the maximum and minimum values. Beetle H' values (**6a.**), spider H' values (**6c.**), native invertebrate H' values (**6d.**), All taxa invertebrate H' values (**6e.**), and Carabidae H' values (where most samples only had one species) (**6f.**) did not differ significantly between SD and TJ . Non-native invertebrate H' is significantly higher at TJ than SD (**6b.**).

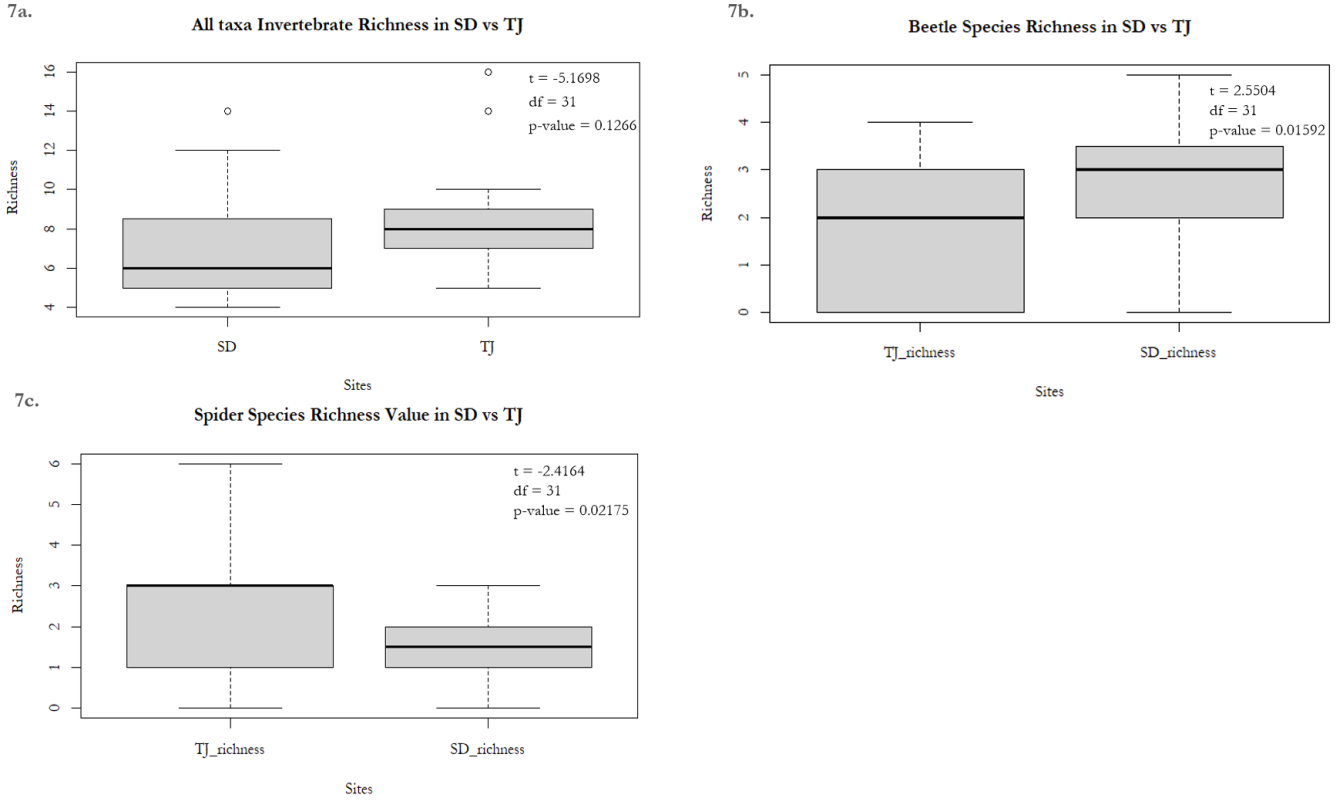

Figure 7. Boxplots of all-taxa invertebrate species richness (**7a.**), beetle species richness (**7b.**), and spider species richness (**7c.**), across two sites. SD = Border Field State Park, San Diego and TJ = Vivero Hormiguitas, Tijuana. The degrees of freedom, t- statistic, and p-value are displayed in the legend located in the top-right corners. Outliers are represented with a white circle. The median is represented by the bolded line, first to third quartile represented by the box, and the whiskers represent the maximum and minimum values. No significant difference in all taxa species richness (**7a.**) and spider species richness (**7c.**) between SD and TJ. There is significantly higher beetle species richness at the SD site compared to the TJ site (**7b.**).

DISCUSSION

The results of the study supported the hypotheses that spider abundance and non-native invertebrate abundance would increase, that all-taxa invertebrate abundance would increase, and that beetle abundance would decrease in urbanized spaces of Vivero Hormiguitas, Tijuana compared to less disturbed protected sites in San Diego Border Field State Park. The results of the study partially supported the hypothesis that beetle biodiversity would decrease in urbanized spaces of TJ compared to SD and spider diversity would increase as the species richness reflected this trend. However, the Shannon diversity index (H') did not show a significant difference between the two sites on beetle and spider diversity, nor did it show a significant difference in the all-taxa invertebrate H' value.

The all-taxa invertebrate abundance was found to be significantly higher in TJ than SD, and much of this increase in invertebrate abundance can be attributed to the non-native invertebrate species, which were significantly more abundant TJ than SD. This can be attributed to the lower abundance of invasive isopods *Armadillidium vulgare* and *Porcellio laevis* in SD. These results follow the opportunistic species hypothesis, which claims that generalist and opportunistic species, such as many non-native invertebrates in urban spaces, would increase with disturbance. These non-native invertebrates are therefore ecological exploiters, by exploiting the change caused by environmental disturbance, they become more successful in urbanized environments. One potential explanation for this finding is the relative differences in aridity of the study sites. Aridity in southern California plays an important role in resisting invasion in southern sage scrub.[67] There are also significantly fewer exotic invertebrates in less urbanized areas with less water subsidies (i.e., more arid regions).[67] One final contributing explanation could be that invasive plants are also facilitating the invasion of exotic invertebrate species.[36, 37] Many of these factors can be working in synthesis, contributing to the significant increase in non-native invertebrate taxa in urbanizing TJ compared to the protected state park in SD.

Interestingly, the native invertebrate abundance did not show a significant change between the two sites. This is potentially due to the variety of taxa and different functional groups included within this categorization. As such, some native invertebrate species

that are generalists, and or ecological exploiters, may increase in abundance while others that are more sensitive to change, and/or are specialists, and are therefore detectors of change, decrease in abundance. Thus, this shifts the community composition but does not change the overall abundance.

The all-taxa invertebrate H' value did not show a significant difference between the sites, nor did the native invertebrate H' value; however, the non-native H' value was significantly higher at TJ than SD. This means that non-native species was not only more abundant in TJ than SD, but more consistently abundant across all samples in TJ compared to the SD samples. There are also a few non-native taxa completely absent in the SD samples. These included *Rumina decollata (*decollate snail), *Coccinella septempunctata* (Seven-spotted lady beetle)*, Dysdera crocata* (woodlouse spider), and *Bactericera lavaterae* (island mallow psyllid). These four species likely contributed to the difference in non-native species H' values between the two sites. It is important to note however, according to citizen-generated data on *iNaturalist*, all of these species except for *Rumina decollata (*decollate snail) have been recorded at the state park near the sample site in SD.[68] But failure to collect them within SD samples may suggest a decrease in abundance for these taxa within the protected site.

We also know from these results that the all-taxa invertebrate richness did not differ significantly between the two sites. From these results alone, it may seem like the only change when comparing the two sites is the non-native species H' and abundance. However, when we break down these broad categories into more specific taxa and categories such as native vs non-native, a different story emerges that can explain these results.

Spiders were found to be in higher abundance and richness in TJ than SD, indicative of an ecological exploiter; the change in habitat may be subsidizing or benefitting them in some way. Being generalists, these ground-dwelling spiders may be matrix species, exploiting the change from a dense shrub habitat to open grassland habitat and increases in invertebrate abundance. Shannon diversity index (H') for spiders showed only a marginally significantly higher value at TJ than SD. These results reflect the trend that generalist predators, such as many spiders, tend to benefit from urbanization. For example, generalist spiders have been found to increase in abundance with fragmentation and urbanization in Hungary.[59] Urban green spaces also tend to have increased spider abundance and richness compared to rural areas, consistent with the results of this study.[59, 69-72] Urbanization and human disturbance had little to no effect on abundance of many habitat generalist spiders.[73] However, some studies have found a reduction in spider diversity.[74] It is likely that taxonomic identity is critical when assessing the effects of human disturbance on the structure of spider communities, as although many spiders are generalist predators, they can differ drastically in hunting strategies and habitats needed to support their lifestyle.[73-75] For instance, invasive plants seem to exhibit effects on the structure of spider communities, notably by increasing preferred habitat for certain spider taxa, such as Thomisidae, Salticidae, and Theridiidae. Many invasive plant species promote spider abundance by providing ideal plant structure for webs and preferred hunting grounds, or directly, by subsidizing prey; for example, in the case of Lycosidae, where some invertebrates who are able to exploit the change in environment caused by invasive plants, such as by providing more shelter, increase in abundance, giving generalists Lycosidae spiders more prey to hunt and their abundance increases.[75-77] Still, others show a mix of effects due to the different urban environments that may occur, such as in Agelenidae.[78] The methods of sampling could influence which groups are more represented in the samples as well, an example of this can be seen from the results, wherein majority of spider taxa sampled are cursorial, such as Lycosidae, Gnaphosidae, Salticidae, and a ground-dwelling genus of Thomisidae. It should also be noted that due to the usage of morphospecies, some spider groups such as Lycosidae may be inflated in richness; however, this should have marginal effects on richness calculations as both sites compared use morphospecies, as most morphospecies are discerned because they are different families, and species richness within each spider family generally only consists of one or two morphospecies.

Gnaphosidae spiders were found to be almost entirely absent in samples from disturbed sites in TJ, while they were abundant in samples from SD. Gnaphosidae are a highly cursorial family, and evidence suggests they are more sensitive to disturbances than other groups.[79, 80] Urbanization has had a negative effect on Gnaphosidae species richness and abundance.[81] The results of this paper also show the high abundance of ground crab spiders in the genus *Xysticus* at TJ. While previous research has indicated negative effects of urbanization and human disturbance on the family to which this genus belongs (Thomisidae), studies on urbanized spaces demonstrate the continued presence of *Xysticus* in those areas.[82, 83] Results from this study and the current body of research confirms that crab spiders in the genus *Xysticus* show a tolerance to human urbanization. Taken together, these results demonstrating changes in spider abundance, richness, and community composition under anthropogenic disturbance suggest that certain taxa such as *Xysticus* may be taking advantage of reduced competition from other species. Further, it is likely that this group benefits from increased prey abundance in disturbed spaces, facilitated by increases in non-native ground-dwelling invertebrate taxa found in samples at TJ, while other taxa such as Gnaphosidae are being negatively affected by the change in habitat. These results indicate that a change in invertebrate predator community structure has occurred in the human-dominated landscape.

Beetles were found in lower abundance and richness in TJ than SD but Shannon diversity index scores (H') for these samples were not significantly different between the two sites. However, Shannon diversity index values (H') in beetles are often found to decrease across urbanized sites, implicating urbanization as a leading threat to beetle diversity.[84] This could be due to many beetle species being specialists within an ecosystem and occupying very specific niches and microhabitats, creating a mosaic of species distribution with high turnover rates at one site. Therefore, calculating H' for each individual site gives us H' values that are lower despite higher species richness, as one site may be a microhabitat that is dominated by a specialist beetle. In an urbanizing landscape such as that in TJ, this ecological complexity is destroyed and replaced with more generalist and monotonous habitat unsuitable for many specialist herbivores, such as many native beetles, so that beetle diversity within TJ is more homogenous and evenly distributed. In conclusion, while the richness and abundance of beetles may be higher in SD than TJ, the beetle species are more evenly distributed in TJ, resulting in finding little difference in H' between the two sites. Another explanation could also be that the sites in TJ were not completely urbanized as the slopes of the canyon still had intact sites with native vegetation, although it is disappearing rapidly.

There was no significant difference in Carabidae abundance between TJ and SD in this study. This can be explained as urbanization often has little effect on abundance of Carabid species as more generalist and tolerant species would increase in abundance in the absence of others.[60-62] However, this study suggests that there is no significant difference in Carabidae H' between the two sites either, which is not consistent with many other works that suggest there is a strong negative effect of urbanization on carabid beetle diversity. This is not entirely unheard of, as other studies have found that Carabidae diversity does not necessarily decrease or homogenize with urbanization, suggesting that composition is more influenced by location.[63] Most of the samples of this study also only had one species of Carabidae, suggesting that species turnover may also play a role in not finding significant differences in the H' values. This is not likely the case as both sites had the same total cumulative species richness for Carabidae. Another factor that can explain these results is the presence of invasive plant species. Invasive plants can also shift the microclimate of an environment to increase abundance of certain taxa of Carabidae while decreasing the abundance of rarer Carabidae species.[85] Human disturbance not only influences Carabidae fauna directly through alteration of landscape and native vegetation but also through the facilitation of invasive species.

There was a significant decrease in Tenebrionidae abundance within the disturbed site of TJ compared to that of SD. Although the total pooled sample count of Tenebrionidae species richness was lower in TJ than SD, there were not enough data points to run a t-test to confirm whether Tenebrionidae species richness was actually lower at TJ. Most species of Tenebrionidae within the samples are detritivores.[86] So a lower abundance in TJ could be explained by the decrease in native plant detritus due to the complete stripping of topsoil along with native plants, creating conditions that are far less hospitable for Tenebrionidae beetles. Presently, there exists little to no research on how urbanization and invasive plants could be influencing the composition of Tenebrionids. The results here suggest that there may be a negative effect on these detritivorous invertebrates, indicating a slower rate of decomposition at the human-dominated site. One other potential explanation for the difference in Tenebrionidae abundance between the two sites could be attributed to individuals within the genus *Eleodes,* which based on *iNaturalist* data suggests that they may be more abundant in May than April, as the SD dataset was sampled in May and the TJ dataset in April.[87]

Silphidae showed a presence at SD, concentrated within one sample due to the presence of a dead rodent within the sample. Dead rodents were also present in two samples in TJ, but no Silphidae beetles were observed. The Silphidae beetles collected from SD were likely attracted to recently deceased rodents that fell into the pitfall trap. Current published research indicates that Silphidae beetles are particularly sensitive to urbanization and have been shown to decrease in abundance and diversity with urbanization.[88, 89] Invasive plant species also have the potential to decrease the abundance of some Silphidae taxa.[90] Although no solid conclusions can be drawn from these samples, the observation suggests a decrease in Silphidae presence, potentially indicative of decreased decomposition rates by carrion beetles. A targeted study should be conducted to fully compare the difference in their presence between the two localities.

Limitations

Due to logistical and permitting constraints, the two locations were sampled at different times, about a month apart. However, temperature conditions were similar in March and April, as spring had already begun in coastal San Diego and Tijuana. Precipitation was slightly lower in the weeks sampling the San Diego site than the weeks sampling the Tijuana sites. However, just days before sampling began in the San Diego site, precipitation conditions were still similar in frequency and intensity. All identifiable beetles within this study's samples should be present in similar abundance in both March and April, with the possible exception of species in the genus *Eleodes.*[87] The method of invertebrate sampling using pitfall traps biases towards ground-dwelling invertebrate taxa. By focusing only on ground-dwelling taxa and only drawing conclusions based on ground-dwelling taxa, we eliminate some biases in comparing community composition. However, for groups that have large taxa in both ground-dwelling and arboreal or aerial lifestyles, such as spiders, it can only provide a limited view of the overall composition of the group. The pitfall traps are known for positive biases for ground-dwelling cursorial spiders that hunt actively, including spider

families such as Salticidae, Gnaphosidae, and Lycosidae. However, differences in cursorial spider taxa among the two study sites can still yield insight into cursorial spider community composition.

The pitfall trap fluid chosen for this study could also influence the sample of ground-dwelling invertebrates.[91] However, while this may influence which invertebrates are more likely to be collected, it would not explain the difference in invertebrate abundance and composition from the different localities as both used the same solution.

CONCLUSIONS

This study is one of the few studies that has considered and characterized the invertebrate composition of a rapidly developing urban space in Tijuana, Mexico. Through the comparison of invertebrate community composition in similar, but far less disturbed habitat at the San Diego border, inferences regarding anticipated shifts in invertebrate community composition in response to the rapid and ongoing urbanization in Tijuana was made. The study found that the ground-dwelling invertebrate communities in urbanizing TJ differed from protected SD sites in a couple of key ways: (i) all-taxa invertebrate abundance was greater at TJ attributed largely to the increase in abundance of non-native invertebrate taxa; (ii) spider community composition changed with an increase in spider abundance in TJ compared to SD attributed to *Xysticus sp.* increasing in abundance, and more sensitive spider taxa such as Gnaphosidae decreased in TJ compared to SD; and (iii) Beetle abundance and richness decreased in TJ compared to SD, partially attributed to a decrease in Tenebrionidae abundance. More research on invertebrate community composition in Tijuana will provide valuable information about how rapid urbanization is changing the invertebrate composition of this area, in addition to providing important records of invertebrates in Tijuana. The Tijuana area is under-sampled, so little is known about the invertebrates there. Understanding the effects of rapid urbanization, coupled with the introduction of exotic plants in southern California coastal sage scrub is important to the continued preservation of sage scrub communities.

Most of the coastal sage scrub in San Diego is fragmented and destroyed, so the majority of intact habitat now lies in the rapidly developing areas of Tijuana, and as such is critically threatened. Future research should focus on long-term sampling of invertebrates in these areas to provide more robust datasets on invertebrate composition. Although outside the scope of this study, future research should also look at the effect of vegetation change and invasive plant species on invertebrate composition within coastal sage scrub in southern California and northwestern Baja California. This study did not sample for taxa that are not ground-dwelling, so future research should also study how aerial and arboreal taxa of this region are being affected by changes in vegetation and increasing human disturbance. The information on invertebrate community composition can be used to provide important ecological indicators to habitat restoration.

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PRESS SUMMARY

Invertebrates such as spiders, beetles, and insects are some of the most diverse and abundant groups of terrestrial animals. This makes them excellent indicators for the health and well-being of an ecosystem. They provide important roles within an ecosystem and can quickly respond to environmental changes such as urbanization. Urbanization, human disturbance, and the introduction of invasive plants affect invertebrates and are changing community composition, structure, diversity, and abundance of them. Some invertebrates can exploit these changes and increase in numbers; others are sensitive and disappear. The San Diego and Tijuana regions have been increasing in urbanizing pressure for decades. Tijuana is now one of the fastest growing municipalities in Mexico and urbanization threatens the integrity of much of the remaining coastal sage scrub, an endangered ecosystem. The invertebrates currently residing in these semi-disturbed landscapes have rarely been sampled and investigated. In this study, one native plant nursery in an urbanizing area of Tijuana at Vivero Hormiguitas and a protected site in Border Field State Park in San Diego are sampled to compare the differences in the invertebrate communities. There were more beetles and beetle species in protected San Diego sites lacking these disturbances while spiders appear to increase in abundance and number of species in the human-disturbed site. Lastly, invasive species, especially pill bugs, showed dramatic increase in abundance in disturbed Tijuana sites, contributing to increased overall invertebrate abundance and decreased biodiversity in Tijuana compared to San Diego protected sites. The results show how the invertebrate communities of Tijuana are currently shifting due to human impacts.

Screen Time, Physical Activity, and Anxiety in Honors College Students during the COVID-19 Pandemic

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ABSTRACT

Background: The COVID-19 pandemic presented a unique opportunity to study the effects of increased screen time on student mental health, due to the transition to virtual learning across colleges and universities in the United States. Current literature suggests that college/university students, particularly those enrolled in Honors programs, are at an increased risk for symptoms of anxiety. Emerging research suggests that increased screen time increases anxiety but never had there been such a marked increase in screen time. **Purpose**: The aim of this pilot study was to observe the relationships between anxiety, screen time, and physical activity in Honors students during the COVID-19 pandemic. **Methods**: A REDCap survey, consisting of the GAD-7 measure of anxiety, screen time questionnaire, physical activity questionnaire, and self-reported impact of the pandemic, was distributed to Honors students. **Results**: Anxiety and screen time increased during the pandemic, while physical activity did not significantly change. Eighty-point-nine percent of respondents met GAD-7 scoring guidelines for mild to severe anxiety and 71.56% self-reported experiencing more anxiety than before the pandemic. Increased screen time was associated with increased GAD-7 score, independent of physical activity or COVID-19 impact. Increased physical activity was associated with decreased GAD-7 score. **Conclusion**: Anxiety and screen time increased in Honors students during COVID-19. Increases in screen time were associated with increased anxiety in Honors students, while physical activity was associated with decreased anxiety. Universities should consider strategies to mitigate negative effects of increased screen time, including the use of physical activity.

KEYWORDS

COVID-19; Pandemic; Screen Time; Physical Activity; Anxiety; College Students; GAD-7; Technology; Media Effects; Children and Media

INTRODUCTION

Anxiety disorders constitute the highest proportion of mental health disorders, with a lifetime prevalence of 31.6% in Americans over 13 years old.[1] Numerous studies have also established a high prevalence of anxiety in college students, ranging from 30-40%.[2–5] In fact, evidence points to a marked increase in anxiety in college students over the past decades.[2,4,6] A significant increase in the prevalence of anxiety in college students has been reported during the Coronavirus Disease 2019 (COVID-19) pandemic,[7–13] with one study reporting that almost one-third of the students in the cohort met criteria for anxiety according to the Diagnostic Statistical Manual – Fifth Edition (DSM-5).[12]

Emerging evidence suggests a relationship between screen time, defined as activities performed using or in conjunction with a digital device featuring a screen,[14] and anxiety. The American Academy of Pediatrics has found adequate evidence to support limiting screen time for children, but no clear guidelines exist for college students.[15] Studies have suggested a causal relationship between screen-based sedentary behavior and anxiety; however, due to an emphasis on television without great consideration to aggregate screen time, further research examining the effect of increased screen time on anxiety is needed.[16–20] Due to an explosion in the number of screen-based devices, it is important to consider screen time as an aggregate value versus focusing on one category of device. Of note, research suggests that emotion plays an important role in this relationship. In fact, regulation of emotion may reduce the suggested increase in anxiety correlated with screen time.[18] Studies conducted during COVID-19 have reported that the pandemic increased screen time and negative mental health symptoms.[21–24] A longitudinal study from Stanford demonstrated that the COVID-19 pandemic increased screen time in college students from 50.2% of their waking hours to 77.6%.[25] Additional research suggests a relationship between increased screen time and poor mental health in the context of the pandemic.[22,26]

There are a variety of ways that can help reduce anxiety, including physical activity, adequate sleep, meditation, connection with others, and lifestyle changes.[27] Of special interest to this present study is the impact of physical activity on anxiety. Multiple studies have demonstrated that exercise is effective in reducing anxiety symptoms in both the short- and long-term.[28–31] Most studies evaluating exercise and anxiety report that exercise reduces both anxiety prevalence and severity in college students, with some studies demonstrating a significant reduction in anxiety and improved mood after regular physical activity over the course of a semester.[32–34] Of note, any and all studied modes of physical activity have proven beneficial.[31] During COVID-19, studies have demonstrated that decreased exercise can lead to increased anxiety.[35–39] A systematic review of physical activity in university students during the COVID-19 pandemic found that nearly every study demonstrated a significant reduction in physical activity, with reductions in "light" physical activity and "high" physical activity of up to 365.5% and 52.8%, respectively.[40] The increased screen time during this time also contributed to reductions in physical activity.[39]

Despite strong evidence of an association between screen time, physical activity, and mental health, there is limited research examining these relationships primarily among college students. In two studies, high screen time was positively correlated with anxiety, independent of physical activity.[41,42] One study found that screen time greater than two hours is a risk factor for anxiety symptomology independent of physical activity, and that a low level of physical activity and a high level of screen time work synergistically to increase the risk for psychological diagnoses.[43] Additional research suggests that screen time greater than four hours influences the prevalence of anxiety disorders in college students.[44,45]

In an environment where college students are already at an increased risk for anxiety, increased screen time and decreased physical activity could antecede additional mental health symptomology.[41] The COVID-19 pandemic presented a unique opportunity to study the association between screen time and mental health at a time when screen time was necessarily increased. The primary objective of this study was to observe symptoms of anxiety, screen time, and physical activity during the COVID-19 pandemic in Honors university students. The secondary objective of this study was to investigate the association between screen time and/or physical activity and anxiety. It was hypothesized that during the COVID-19 pandemic, physical activity mediated the relationship between screen time and anxiety, with increased screen time leading to decreased physical activity, which subsequently contributed to elevated anxiety levels.

METHODS AND PROCEDURES

Design

This Institutional Review Board (IRB)-approved (STUDY00001534) study used a cross-sectional survey design that incorporated both quantitative and qualitative data collection.

Subjects

Nine hundred and fifty-nine students in the Honors college of a medium-sized New England public university were invited to participate in the research survey. This population was selected because Honors students display increased incidence of perfectionism, academic achievement, and social stress.[46–49] Students had varied academic majors. No compensation was provided for participating in the study. See **Table 1** for details below.

Measures

The survey included four separate questionnaires, consisting of demographics, anxiety, screen time, and physical activity, in the order listed. The first questionnaire was demographics, consisting of sex, undergraduate year, and specific college enrolled at the University of Vermont. These served as groups in data analysis and were used to determine the representativity compared to the overall Honors college population at the University of Vermont.

Anxiety. The Generalized Anxiety Disorder Assessment (GAD-7) tool was used to assess anxiety, as this tool provides a short clinical measure for assessing generalized anxiety disorder (GAD).[50] The GAD-7 consists of seven items, each scored on a 4-point Likert scale ranging from 0 ("not at all") to 3 ("nearly every day"). Total scores range from 0 to 21, with higher scores indicating greater anxiety severity. Cut-off points for the GAD-7 categorize anxiety severity as follows: 0–4 (minimal anxiety), 5–9 (mild anxiety), 10–14 (moderate anxiety), and 15–21 (severe anxiety).[50] This tool has satisfactory reliability and criterion, construct, factorial, and procedural validity.[50] In addition, the GAD-7 tool is substantiated for use with populations and as an index of general anxiety severity.[51]

Screen Time. This study used a measure of screen time adapted from Vizcaino.[52] "Mandatory activity screen time" was defined as screen time used for school or work, rather than leisure. "Leisure activity screen time" was defined as screen time used for leisure, rather than school or work. "Weekday" was defined as between the time an individual wakes up until the time they go to bed on Monday through Friday. Finally, "weekend day" was defined as between the time an individual wakes up until the time they go to bed on Saturday and Sunday. The questions themselves were self-reported based on provided brackets of total time, asking the

respondent to report the average time spent on screens over the past two weeks, separated by weekday/weekend and mandatory/leisure activity screen time. This measure was used to obtain an aggregate measure of screen time.

Physical Activity. In the survey, exercise was defined as physical activity that is planned, structured, and repetitive for the purpose of conditioning any part of the body used to improve health and maintain fitness.[53] "Weekday" and "weekend day" were defined as above. The questions themselves were self-reported based on provided brackets of total time, asking the respondent to report the average time exercising over the past two weeks. This questionnaire was used to obtain a measure of physical activity.

For all three questionnaires, questions regarding the impact of the COVID-19 pandemic were included. These questions asked respondents to indicate if the pandemic had subjectively impacted the three variables of interest and were intended to gauge the self-perceived impact of the pandemic.

See Appendix for the survey questions.

Procedures

Study data were collected and managed using Research Electronic Data Capture (REDCap) electronic data capture tools hosted at the University of Vermont.[54,55] REDCap is a secure, web-based software platform designed to support data capture for research studies, providing 1) an intuitive interface for validated data capture; 2) audit trails for tracking data manipulation and export procedures; 3) automated export procedures for seamless data downloads to common statistical packages; and 4) procedures for data integration and interoperability with external sources. The invitation to participate was sent out to all 959 students in the Honors College within one year of the start of the COVID-19 pandemic.

Analyses

After the survey data were collected from the respondents, the anonymized data were downloaded from REDCap for analysis. All analyses were done with Statistical Package for the Social Sciences (SPSS) Version 29.0.2.0. Demographics were compared to the population by the Honors College to determine if the sample was representative. Next, the physical activity and screen time variables were transformed into numeric values using the midpoint of categorical ranges. For screen time, the midpoint values were 0 hours for 0 hours, 1 hour for 0-2 hours, 3 hours for 2-4 hours, 5 hours for 4-6 hours, 7 hours for 6-8 hours, and 8 hours for more than 8 hours. These values were calculated for weekday leisure, weekday mandatory, weekend leisure, and weekend mandatory screen time and summed to determine total screen time. For Physical Activity, the midpoint values were 0 minutes for 0 minutes, 15 minutes for 1-30 minutes, 45 minutes for 31-60 minutes, 75 minutes for 61-90 minutes, and 90 minutes for more than 90 minutes. These values were calculated for both weekday and weekend day physical activity and summed to determine total physical activity. A composite COVID-19 impact variable was then calculated by assigning numerical values to each response category (*more* = 3, *same* = 2, *less* = 1) and computing an average of these variables to create a single composite variable. A mean-split was then performed to split the respondents into "High Impact" (1) and "Low Impact" (0).

For all tests, the significance level used was $p < .05$. After checking for the assumptions of linear regression, linear regression was performed to examine the relationships between total screen time, total exercise time, and anxiety (GAD-7 total score). Moderated mediation analysis using regression was performed to test the hypothesized model that physical activity mediated the relationship between screen time and anxiety symptomology. Finally, moderation analysis using linear regression was performed to determine if the COVID-19 impact variable moderated the results.

RESULTS

A total of 225 out of 959 (23.5%) complete responses were recorded. According to the University of Vermont Honors College, the demographics of the sample were representative of the population. **Table 1** provides key descriptive data. The mean GAD-7 score was 9.62 (SD = 5.26). Eighty-point-nine percent of respondents reported mild to severe anxiety (**Table 1**). For the final question of the GAD-7 ("If you checked off any problems, how difficult have these made it for you to do your work, take care of things at home, or get along with other people?"), 56.0% of respondents reported that their anxiety had made these tasks "somewhat difficult" and a further 24.9% indicated that their anxiety had made these tasks "very difficult." After midpoint value conversion and summation, the mean total physical activity time was 71.67 minutes (SD = 51.05). Mean total screen time was 16.89 hours (SD 4.81).

Sex		
Sex	**Frequency**	**Percent (%)**
Male	57	25.3
Female	155	68.9
Other	12	5.3
Prefer not to Answer	1	0.4
Total	225	100.0

College Year		
College Year	**Frequency**	**Percent (%)**
First year	76	33.8
Second year	61	27.1
Third year	47	20.9
Fourth year	41	18.2
Total	225	100.0

GAD-7 Category		
GAD-7 Category (Score Range)	**Frequency**	**Percent (%)**
Minimal Anxiety (0-4)	43	19.1
Mild Anxiety (5-9)	78	34.7
Moderate Anxiety (10-14)	59	26.2
Severe Anxiety (15-21)	45	20.0
Total	225	100.0

COVID Impact Group		
COVID Impact	**Frequency**	**Percent (%)**
Low Impact	146	64.9
High Impact	79	35.1
Total	225	100.0

Table 1. Key Descriptives. Summary of respondent demographics. Frequencies and relative percentages are reported for all responses to demographic questions, GAD-7 categories, and COVID impact group.

Table 2 provides correlation data between GAD-7 score, total physical activity time, and total screen time. Increased physical activity was associated with lower GAD-7 scores. Increased screen time was associated with increased GAD-7 scores.

Pearson Correlations			
	GAD Total Score	**Total Physical Activity**	**Total Screen Time**
GAD-7 Total Score	1.00	-0.20*	0.27*
Total Physical Activity	-0.20*	1.00	-0.12
Total Screen Time	0.27*	-0.12	1.00

Table 2. Correlation Table. Summary of Pearson correlations between key variables. Statistical significance is determined at the $p < .05$ level and are marked with an asterisk (*).

See **Table 3** for screen time response percentages. Twelve-point-nine percent of respondents reported that they had not exercised in the past two weeks. See **Table 4** for exercise time response percentages.

Mandatory Screen Time Response Percentage (%)						
	0 Hours	**0-2 Hours**	**2-4 Hours**	**4-6 Hours**	**6-8 Hours**	**More than 8 Hours**
Weekday	0.00	2.22	16.89	35.11	33.33	12.44
Weekend	0.44	18.67	37.33	28.00	9.78	5.78
Leisure Screen Time Response Percentage (%)						
	0 Hours	**0-2 Hours**	**2-4 Hours**	**4-6 Hours**	**6-8 Hours**	**More than 8 Hours**
Weekday	0.00	21.33	40.44	26.22	6.67	5.33
Weekend	0.00	20.89	36.89	26.22	11.56	4.44

Table 3. Screen Time Response Percentages. Summary of screen time question response percentages.

Physical Activity Time Response Percentage (%)					
	0 Minutes	**1-30 Minutes**	**31-60 Minutes**	**61-90 Minutes**	**More than 90 Minutes**
Weekday	12.44	32.44	35.56	12.44	7.11
Weekend	20	29.33	28.89	12.89	8.89

Table 4. Physical Activity Time Response Percentages. Significance of Levene's Test is .261, so equal variances are assumed.

Self-report of COVID-19 impact was recorded for anxiety, screen time, and physical activity. Seventy-one-point-fifty-six percent of respondents reported that the COVID-19 pandemic had led to more anxiety than before, while 24.89% of respondents answered that they experienced the same anxiety as before and 3.56% of respondents reported that they experienced less anxiety than before the pandemic. Ninety-eight-point-sixty-seven percent of respondents reported that they spent more time on screens for school and/or work than before the pandemic. Only 0.89% responded that they spent the same time on mandatory screen time as before the pandemic, and 0.44% reported that they spent less time on mandatory screen time than before the pandemic. In addition, 61.33% of respondents reported that they spent more time on screens for leisure use than before the pandemic, while 29.78% responded that their leisure screen time was the same as before and 8.89% answered that they spent less time on leisure screen time than before the pandemic. For physical activity, 38.67% of respondents reported that they spent the same amount of time on physical activity as before the pandemic, 33.78% responded that they spent less time on physical activity than before, and 27.56% of survey respondents reported that they spent more time on physical activity than before the pandemic.

An independent samples *t*-test was conducted to compare GAD-7 scores between individuals who engaged in regular exercise (n = 196) and those who did not (n = 29) (**Table 5**). The assumption of homogeneity of variances was tested using Levene's Test and was not violated ($F = 0.072$, $p = 0.789$). The results showed that individuals who exercise have significantly lower GAD-7 scores (M = 9.17, SD = 5.14) compared to those who do not exercise (M = 12.62, SD = 5.17), $t(223) = 3.37$, $p < .001$, $d = 0.67$. The 95% confidence interval for the mean difference ranged from 1.43 to 5.46, indicating a moderate effect size.

GAD-7 Score and Exercise Status							
	t	**df**	**Sig.**	**Mean Difference**	**95% CI (Lower)**	**95% CI (Upper)**	**Cohen's d**
GAD-7 Total Score	3.37	223	<.001	3.45	1.43	5.46	0.67

Table 5. Independent Samples t-Test Results.

A linear regression was conducted to examine the relationship between total GAD-7 score and total screen time (**Table 6**). The overall model was significant, $F(1,223) = 16.89$, $p < .001$, explaining 7.0% of the variance in GAD-7 score ($R^2 = 0.070$, Adjusted $R^2 = 0.066$). Total screen time significantly predicted GAD-7 score ($B = 0.290$, $SE = 0.071$, $\beta = 0.265$, $t(223) = 4.110$, $p < .001$). Higher screen time levels were associated with higher GAD-7 scores.

GAD-7 Score and Total Screen Time					
	Unstandardized Coefficient		Standardized Coefficient		
	B	Std. Error	Beta	t	Sig.
(Constant)	4.712	1.241		3.797	<.001
Total Screen Time	0.290	0.071	0.265	4.110	<.001

Table 6. Linear Regression Coefficients for Screen Time. Linear regression of GAD-7 score and total screen time.

A linear regression was conducted to examine the relationship between total GAD-7 score and total physical activity (**Table 7**). The overall model was significant, $F(1,223) = 9.10$, $p = .003$, explaining 3.9% of the variance in GAD-7 score ($R^2 = 0.039$, Adjusted $R^2 = 0.035$). Total physical activity significantly predicted GAD-7 score ($B = -0.020$, $SE = 0.007$, $\beta = -0.198$, $t(223) = -3.016$, $p = .003$). Higher physical activity levels were associated with lower GAD-7 scores.

GAD-7 Score and Total Physical Activity					
	Unstandardized Coefficient		Standardized Coefficient		
	B	Std. Error	Beta	t	Sig.
(Constant)	11.080	0.595		18.631	<.001
Total Physical Activity	-0.020	0.007	-0.198	-3.016	0.003

Table 7. Linear Regression Coefficients for Physical Activity. Linear regression of GAD-7 score and total physical activity.

Mediation analysis was conducted to test whether physical activity mediated the relationship between screen time and anxiety. The results showed that screen time did not significantly predict physical activity ($a = -1.295$, $p = 0.068$) (**Table 8**). Physical activity significantly predicted anxiety, controlling for screen time ($b = -0.017$, $p = 0.009$) (**Table 9**). The total effect of screen time on anxiety was significant ($c = 0.290$, $p < .001$) (**Table 6**), but the direct effect was reduced when physical activity was included in the model ($c' = 0.268$, $p < .001$) (**Table 9**). The indirect effect ($a*b = 0.022$) was tested using the Sobel test and found not to be significant ($Z = 1.464$, $p = 0.143$) (**Table 10**). These results suggest that physical activity does not mediate the relationship between screen time and anxiety.

Total Screen Time and Total Physical Activity					
	Unstandardized Coefficient		Standardized Coefficient		
	B	Std. Error	Beta	t	Sig.
(Constant)	93.539	12.398		7.545	<.001
Total Screen Time	-1.295	0.706	-0.122	-1.834	0.068

Table 8. Linear Regression Coefficients for Screen Time and Physical Activity. Linear regression of total screen time and total physical activity.

Total Screen Time, Total Physical Activity, and GAD-7 Score					
	Unstandardized Coefficient		Standardized Coefficient		
	B	Std. Error	Beta	t	Sig.
(Constant)	6.333	1.372		4.614	<.001
Total Physical Activity	-0.017	0.007	-0.168	-2.619	0.009
Total Screen Time	0.268	0.070	0.245	3.813	<.001

Table 9. Linear Regression Coefficients for Screen Time, Physical Activity, and GAD-7 Score. Results of the regression analysis where the mediator and independent variable predict the dependent variable.

Mediated Model Summary			
Effect	**B**	**Std. Error**	**Sig.**
Total Effect (*c*)	0.290	0.071	<.001
Direct Effect (*c'*)	0.268	0.070	<.001
Indirect Effect (*a*b*)	0.022	0.015	0.143

Table 10. Summary of the Mediated Model. Summarizes the direct, indirect, and total effects in one table.

Moderation analysis using linear regression was performed to determine if COVID-19 impact moderated the effect of screen time on GAD-7 score (**Table 11**). The overall model was significant, $F(3,221) = 5.886$, $p < .001$, explaining 7.4% of the variance in GAD-7 score ($R^2 = 0.074$, Adjusted $R^2 = 0.061$). Total screen time significantly predicted GAD-7 score ($B = 0.346$, $SE = 0.097$, $\beta = 0.316$, $t(221) = 3.578$, $p < .001$). COVID impact did not have a significant independent effect on GAD-7 score ($B = 1.613$, $SE = 2.542$, $\beta = 0.147$, $t(221) = 0.634$, $p = .526$). In addition, the interaction between COVID impact and total screen time did not show a moderation effect ($B = -0.114$ $SE = 0.143$, $\beta = -0.195$, $t(221) = -0.798$, $p = 0.426$), meaning the relationship between total screen time and GAD-7 total was consistent across COVID impact group.

Total Screen Time, COVID Impact, and GAD-7 Score					
	Unstandardized Coefficient		**Standardized Coefficient**		
	B	**Std. Error**	**Beta**	**t**	**Sig.**
(Constant)	3.912	1.655		2.364	0.019
Total Screen Time	0.346	0.097	0.316	3.578	<.001
COVID Impact Group	1.613	2.542	0.147	0.634	0.526
Total Screen Time COVID Interaction	-0.114	0.143	-0.195	-0.798	0.426

Table 11. Linear Regression Coefficients for Screen Time, COVID Impact, and GAD-7 Score. Results of the regression analysis evaluating the impact of COVID group on screen time's effect on GAD-7 score.

Moderation analysis using linear regression was performed to determine if COVID-19 impact moderated the effect of physical activity on GAD-7 score (**Table 12**). The overall model was significant, $F(3,221) = 3.327$, $p = .021$, explaining 4.3% of the variance in GAD-7 score ($R^2 = 0.043$, Adjusted $R^2 = 0.030$). Total physical activity significantly predicted GAD-7 score ($B = -0.025$, $SE = 0.009$, $\beta = -0.238$, $t(221) = -2.868$, $p = .005$). COVID impact did not have a significant independent effect on GAD-7 score ($B = -0.028$, $SE = 1.455$, $\beta = -0.003$, $t(221) = -0.019$, $p = .985$). In addition, the interaction between COVID impact and total physical activity did not show a moderation effect ($B = 0.008$ $SE = 0.015$, $\beta = 0.077$, $t(221) = 0.515$, $p = 0.607$), meaning the relationship between total physical activity and GAD-7 total was consistent across COVID impact group.

Total Physical Activity, COVID Impact, and GAD-7 Score					
	Unstandardized Coefficient		**Standardized Coefficient**		
	B	**Std. Error**	**Beta**	**t**	**Sig.**
(Constant)	11.132	0.675		16.489	<.001
Total Physical Activity	-0.025	0.009	-0.238	-2.868	0.005
COVID Impact Group	-0.028	1.455	-0.003	-0.019	0.985
Total Physical Activity COVID Interaction	0.008	0.015	0.077	0.515	0.607

Table 12. Linear Regression Coefficients for Physical Activity, COVID Impact, and GAD-7 Score. Results of the regression analysis evaluating the impact of COVID group on physical activity's effect on GAD-7 score.

DISCUSSION

The COVID-19 pandemic presented challenges to university students on many levels. Anxiety and screen time in Honors university students has increased during the pandemic. Increased screen time was found to be associated with increased anxiety, while increased physical activity was found to be associated with decreased anxiety. The pandemic presented an unprecedented opportunity to look at the effect of both physical activity and screen time on anxiety.[16,17,20,22,34,42,43]

The results of this research suggest the prevalence of anxiety symptomology in college students increased during the COVID-19 pandemic, with 80.9% of respondents having clinically elevated levels of anxiety and 20% having "severe" anxiety, according to the GAD-7 clinical assessment of anxiety.[50] In contrast, studies before the pandemic reported a prevalence of anxiety between 30-40% with a prevalence of "severe" anxiety around 15%.[2,3,5,34] In addition, 71.56% of survey respondents reported that the COVID-19 pandemic had led to them experiencing more anxiety than before the pandemic. This statistic was similar to the findings of other studies conducted during this time.[7,10] Notably, the majority of respondents reported that anxiety made everyday tasks difficult or very difficult. This could be due to increased stress during the pandemic, such as worrying about illness, the future, financial stress, or other factors related to COVID-19. An interview study reported that the factors that impacted mental health were concerns regarding health and academic performance, disrupted sleep, financial difficulties, and other similar themes.[7]

Screen time was a primary focus of this study. The results of this study are in line with what is to be expected when colleges shifted to primarily remote learning, corroborating other studies conducted during the COVID-19 pandemic.[22–26,56] The results of the survey indicated that 98.67% of respondents reported that they spent more time on screens for school and/or work and 61.33% of respondents reported that they spent more time on screens for leisure than before the pandemic. These results are in line with other findings during the COVID-19 pandemic, with one study showing that 94.7% of students reported increased screen use, with two-thirds increasing their usage by over 51%.[22] This study also indicated that 28.7% of the respondents believed their increase in emotional issues were due to increased screen time.[22] Self-reported impact of COVID-19 on screen time is also in line with prior findings demonstrating that screen time has increased during the pandemic.[22–26] This study discovered that increases in both mandatory and recreational screen time occurred during the pandemic, a significant additive that impacted the mental health of the cohort. These increases may be due to increased social isolation, increased leisure time, or a desire to increase social connectiveness due to isolation.[57]

Pearson correlation analysis and linear regression both suggest that increased screen time is significantly associated with total GAD-7 score. These results support previous research surrounding anxiety and screen time, with other research suggesting that high screen time is correlated with anxiety.[20,41–45,56] Previous research focused on specific devices, such as television or smart phones, rather than aggregate screen time.[20,42] Furthermore, these findings are in line with current research which has suggested that increases in screen time during COVID-19 have led to more mental health symptomology in college students, including anxiety.[22,23,26] In addition, the results of this study suggest that COVID-19 impact group did not mediate this relationship, meaning that increases in screen time were associated with increased anxiety independent of reported COVID-19 impact. The hypothesis that physical activity mediated the relationship between screen time and anxiety, with increased screen time leading to decreased physical activity, which subsequently contributed to elevated anxiety levels was rejected in this study. Instead, increases in screen time were independently associated with increased GAD-7 score, regardless of physical activity. During a time when mandatory screen time was necessarily increased, studying the association between screen time and anxiety led to results that lend evidence to the current literature.

Most respondents reported engaging in physical activity, these results indicate that the sample studied exercised more than other college student cohorts noted in prior literature who demonstrated a marked decrease in exercise.[36,37,40,58] Both Pearson correlation and linear regression suggested that increased physical activity was associated with decreased GAD-7 score. In addition, exercise status in the past 2 weeks was significantly correlated with total GAD-7 score, with those who had exercise displaying a lower average GAD-7 score. These findings suggest that increased physical activity is associated with decreased anxiety. Prior literature corroborates this finding, demonstrating that increasing exercise can help decrease feelings of anxiety.[28–33,39,43] COVID-19 impact group did not mediate this relationship, meaning that the observed relationship was independent of COVID impact. During COVID-19, other studies demonstrated that decreased exercise and increased sedentary time have led to greater anxiety in college students.[35–38,58] These are important findings to disseminate among colleges and universities to support the development of programs that promote exercise opportunities for students.

The results of the survey question regarding self-reported impact of the COVID-19 pandemic on physical activity supported findings that the aggregate exercise time of students at the University of Vermont Honors College had not significantly decreased during the pandemic, as compared to similar studies conducted elsewhere. This is in contrast to the dramatic decrease in exercise reported from other studies conducted on college students during the pandemic.[36,37,40,58] One hypothesis that could explain the difference in findings is that the University of Vermont has a strong commitment to physical activity and was able to keep the

university's fitness center open during the school year, while other areas may not have had the same access to gyms. Another hypothesis is proximity to the university fitness center, as the students in the survey were part of the Honors College at University of Vermont. The housing provided for honors students is next to the fitness center, making access easier than other parts of the college campus. Finally, the University of Vermont is in a state with great access to outdoor recreation and physical activities, promoting activity and providing an expansive outdoor space to recreate.

Some hypotheses can be used to better understand these results. Emotion regulation, defined as a "process by which individuals regulate their emotions based on the environment," is essential for one's experience of emotion.[18] It has been hypothesized that low levels of emotion regulation can lead to less "flexibility" in regulating one's emotions while utilizing screens, which can increase the experience of negative emotions.[18] As it is influenced by both internal and external factors, it is possible that the COVID-19 pandemic increased negative emotions, which, exacerbated by elevated screen time, increased the prevalence of anxiety symptomology. Emotion regulation and emotional reactivity are also influenced by physical activity. Another study conducted during the pandemic illuminated that physical activity may act as a mediating mechanism between regulation of emotion levels and "emotion reactivity," concluding that physical activity can improve emotion regulation levels.[39]

Another hypothesis that could explain the correlations between screen time, anxiety, and physical activity is sedentary behavior.[16,18,19,56,59,60] It is important to note that physical activity did not mediate the observed relationship between screen time and GAD-7 score in this study. However, a prior study among South Korean college students demonstrated that increased sedentary behavior elevated stress, anxiety, and depression.[59] It is reasonable to assume that the increased screen time observed in this study led to increased sedentary behavior, which in turn increased anxiety. This can also impact time spent socially, yet another factor that influences anxiety.[59] Additionally, time spent alone was found to attenuate the association between screen time and anxiety in a longitudinal study performed in the United Kingdom.[19]

Sleep offers another hypothesis, as inadequate sleep can worsen, or even spark, anxiety.[61] Functional magnetic resonance imaging studies have demonstrated that sleep loss increases electrical activity within the limbic system and salience network (the "fear network"); sleep loss also impairs "medial prefrontal cortex activity and associated connectivity with extended limbic regions."[61] In addition, the adenosinergic system, which underlies sleep-arousal regulation, may be involved in the molecular basis of anxiety.[61] Clearly, sleep, and lack thereof, plays a key role in anxiety; inversely, anxiety can also decrease sleep quality. Sleep disturbance was quite common during the pandemic, with one study reporting that 33% of higher education students experienced poor sleep.[13] Increased screen time could displace time normally spent sleeping, increasing, and even causing, anxiety. One review sums these sentiments: "excessive screen time… may delay bedtime…[and] blue light from digital devices could suppress melatonin and lead to circadian rhythm disorder, which ultimately causes poor sleep outcomes."[56] A study conducted during the COVID-19 pandemic noted that participants with worse sleep quality experienced more anxiety symptomology, and the effect of sleep was more pronounced than screen time and physical activity.[56] Finally, the authors also mention the impact of the pandemic on delayed sleep patterns, as individuals did not need to wake up early to go to work or school. This can increase anxiety through circadian rhythm disruptions.[56]

CONCLUSIONS

This study did have some limitations. First, the population studied was Honors students at one university, which means the results cannot be applied to all students. No data was collected for non-Honors students, limiting comparisons and preventing analysis of the attenuated effect of Honors status. Future research should be conducted to follow up with students during the COVID-19 pandemic to quantify the long-term effects of the pandemic on both mental and physical health. It will be important to use any future findings to address the mental health impacts on students who were in college during this unique time in history. Second, the measure of physical activity did not line up with other measures in previous research, making comparisons difficult. Future research should work to determine a dose-response relationship between physical activity and anxiety. Another limitation of the study was the use of self-reported measures rather than objective measurement techniques. It is possible that individuals with high screen time were predisposed to high anxiety, or vice versa. It is noted that screens can aid in avoidance-coping in high-stress individuals through distraction and relaxation.[62] Perhaps individuals with high anxiety were using high screen time to cope with mental health symptoms, confounding results. During the pandemic, screens became ubiquitous for social connection. Individuals predisposed to high anxiety may have used screens more to communicate with others to cope with their stress. In addition, because of the lack of quantitative values, a dose-response relationship was not able to be determined for screen time versus anxiety. Therefore, further research attempting to quantify a dose-response relationship should be conducted.

In conclusion, this study provides novel findings regarding the association between screen time and anxiety in Honors university students during a time when screen time was necessarily increased to prevent the spread of COVID-19. The significant increases in screen time observed in this cohort were associated with increases in anxiety. In addition, this study found an association between physical activity and anxiety, a relationship that is important to discuss as screen time increases due to changes in the

world around us. Additional research should be conducted to further support these findings and investigate strategies to support mental health for student populations spending great amounts of time behind a screen.

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PRESS SUMMARY

Due to mandates during the COVID-19 pandemic, screen time in Honors college students increased. This presented an opportunity to study the effects of increased screen time on student mental health. The pandemic also impacted the physical activity of students, which is known to impact mental health.

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