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Feelings of insecurity as a gender-specific constraint on urban mobility

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Abstract

Crime and violence shape psychological and sociological perceptions, fostering a sense of insecurity, especially in urban settings. This perception significantly alters lifestyles, routines, and social interactions. In this study, it is conducted an empirical analysis of the relationship between personal feelings of insecurity and the way individuals move in their daily lives, with a particular focus on differences between genders. The methodology used combines subjective data gathered from individuals' reported perceptions of insecurity with objective data derived from digital mobile phone tracking, providing a comprehensive view of how these fears affect people's daily routines and mobility patterns. The results highlight that perceived insecurity is significantly related to a lower mobility of individuals of both genders. This effect is more pronounced in women, reflecting significant gender-based differences in the impact of perceived insecurity on daily mobility. The findings, revealing higher levels of insecurity and fear of crime among women, require policy action. Public policy must prioritize making urban spaces, such as bus stops, squares, parks, sports courts, and streets, safer and more welcoming for women. This approach is essential to create an urban environment that is inclusive, secure, and conducive to the well-being of all its inhabitants.

Keywords: Insecurity; Fear; Crime; Mobility; Gender

1 Introduction

Urban environments are shaped by both physical infrastructure and the social dynamics that govern how individuals navigate public spaces. Crime and violence, as persistent urban challenges, influence psychological and sociological perceptions, fostering a sense of insecurity that extends beyond direct victimization [10, 33]. This perception of insecurity plays a crucial role in shaping daily routines, limiting access to opportunities, and altering mobility patterns. While prior research has established that safety concerns affect mobility, particularly for women, a comprehensive understanding of how perceived insecurity constrains movement across gender lines remains incomplete.

This study examines how perceived insecurity, shaped by fear of crime, constrains urban mobility, a critical public policy issue influencing access to essential services and opportunities [24, 51]. The extent to which mobility is restricted is closely linked to individuals'

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perceptions of insecurity, which are shaped by a combination of personal factors, prior victimization experiences, awareness of crime within the community, and actual crime levels [10, 33]. However, this relationship is not uniform across populations; gender differences play a crucial role in shaping how perceived insecurity affects mobility. To examine these gender disparities, we analyze how the relationship between perceived insecurity and mobility differs between men and women in Santiago, Chile. To quantify perceived insecurity, we use data from the National Urban Survey on Citizen Security (ENUSC), a nationally representative survey conducted by Chile's National Institute of Statistics (INE). Specifically, we construct a gender-specific measure of emotional insecurity based on responses to questions about perceived safety in seven key urban locations: buses, collective taxis, subways, neighborhood squares and parks, neighborhood sports courts, bus stops, and streets. Respondents classified their sense of security in each location on a four-point scale (very insecure, insecure, secure, very secure), which we operationalized as the proportion of individuals reporting insecurity in a given location at the commune level, the smallest administrative unit in Chile, equivalent to a municipality. We also generate an aggregate insecurity index by averaging insecurity levels across all locations.

Mobility is assessed using anonymized and aggregated mobile phone records from Telefónica Chile, tracking the locations of users based on cellular tower connections over a three-month period. Following established methodologies [12, 19, 30], we measure mobility through two primary indicators: (i) number of locations, defined as the count of distinct locations where a user initiated or received a call, and (ii) entropy, which quantifies the diversity of visited locations using Shannon's entropy formula.

We hypothesize that higher levels of perceived insecurity are associated with reduced mobility, with a stronger effect observed among women. This disparity can be attributed to multiple factors. First, women generally report higher levels of fear related to crime, particularly concerning the risk of sexual violence, reinforcing behavioral restrictions aimed at minimizing exposure to potential threats [18, 29, 49, 52]. Second, beyond direct victimization, the anticipation of sexual harassment or assault—captured by the shadow of sexual assault hypothesis—has been shown to significantly shape women's mobility patterns, leading to route modifications, avoidance of certain areas, and in some cases, self-imposed restrictions on movement [9–11]. Third, environmental factors, such as inadequate urban infrastructure, poor lighting, and the presence of incivilities, amplify perceptions of insecurity and exacerbate gendered mobility constraints [8, 37, 42, 43]. Lastly, structural inequalities—such as socioeconomic vulnerability and intersectional discrimination—further compound mobility limitations for women in urban environments, shaping their access to essential services and economic opportunities [14, 50, 59].

Prior research has documented gender disparities in mobility, showing that women exhibit more constrained travel patterns due to safety concerns and structural inequalities [9–11, 26, 47, 63]. These studies rely on self-reported behavioral changes from surveys. The use of digital traces has transformed the study of urban mobility by enabling large-scale, high-resolution analyses that reduce biases inherent in self-reported data [1, 2, 5, 12, 19, 21, 30, 55]. While studies using mobile phone data have provided insights into mobility, only Gauvin et al. [19] differences between men and women. Our study builds on this literature by combining subjective measures of perceived insecurity with objective mobility indicators at the commune level, allowing us to assess how gender moderates the relationship between insecurity and movement patterns. This approach

provides a novel empirical framework to evaluate how urban environments shape mobility constraints and to inform policies aimed at mitigating gender restrictions on access to public spaces.

1.1 Literature review

The emotional, cognitive, and evaluative dimensions of insecurity are crucial components in understanding the perception of crime as a social problem [38]. The feeling of insecurity, in an emotional dimension, refers to the fear of dangerous situations or places [38]. The interaction between the feeling of insecurity and exposure to crime-prone locations can increase fear levels. Therefore, studying the relationship between insecurity and mobility, especially in the context of gender differences, has been of interest to both academics and policy makers.

Insecurity, as a social problem, refers to society's fear of crime [45, 57, 64, 66]. The role of individual factors in determining risk perception and victimization is well-documented. Individual factors play an important role in defining the risk of victimization, as well as in the overall perception of safety [10]. Previous victimization, or awareness of others victimization, is often considered a determining factor in a person's fear, despite some contradictory research findings, as in more vulnerable groups, the victimization rate can be lower [63]. For example, while women may be more vulnerable to victimization, they present a lower victimization rate compared to men [24, 51].

The individual dimension of fear is often related to the hypothesis of vulnerability, that is, those who perceive themselves as vulnerable are likely to be more fearful. Traditionally, women are portrayed as more fearful than men about their personal safety [4, 10, 41, 46]. This applies similarly to older and disabled individuals [32, 40], those belonging to the LGTBIQ community and those who are socially or economically disadvantaged [4, 51, 53].

The influence of individual factors on risk perception and victimization is well-documented within criminological research. In the case of women this heightened fear, which significantly restricts their travel behavior, can be attributed to both the fear of potential sexual victimization (rape or harassment) and actual experiences of crime. The "shadow of sexual assault hypothesis" [18, 29, 49, 52] effectively encapsulates this phenomenon, suggesting that women's mobility is constrained not only by direct experiences of victimization but also by the pervasive fear of potential assaults or harassments. This hypothesis underscores that anticipatory fear alone, even in the absence of actual victimization, can lead to significant behavioral modifications such as restricted mobility. By exploring both the perceived risks and the lived experiences of crime, we can better understand the complex dynamics that govern women's mobility decisions in urban environments. However, and contrary to this perception, there is also evidence that public space could be a protector against the risk of sexual assault, since being outdoors would not necessarily be riskier for women compared to closed public environments [8]. A vehicle or even the home itself in some cases can be more dangerous than any outdoor environment [17].

The impact of environmental characteristics on perceived insecurity is another critical aspect. Visible deterioration, disorder, property damage, and neglect are seen as indicators of potential crime, linking to the theory of incivilities or broken windows [37, 42, 43]. Associations between security perceptions and various physical and socioeconomic variables have been studied [25, 28, 36, 39, 44, 67] and its relationship with individual factors, such

as age or gender [36]. In this context, studies reflect the security feelings of the respondents provoked by their visual perception of the environment and neighborhoods [58], illustrating how an urban landscape image, where these perceptions can be influenced by the situational context. Studies such as [35, 36, 67, 68] assess the perception of insecurity based on the observation of images of urban environments, however, these methods often lack a gender perspective. Sociodemographic factors, in a context of social vulnerability, such as income and age, also influence women's perception of insecurity and fear of crime, further limiting their interactions with their surroundings.

In examining women's experiences of insecurity, it is crucial to adopt an intersectional perspective, acknowledging that factors such as age, economic status, ethnicity, and physical and cognitive abilities do not operate independently but interact in complex ways to shape individual experiences. This intersectionality, a concept pioneered by Kimberlé Crenshaw [14], highlights that fear and victimization are not solely influenced by singular aspects of identity such as age or gender but are the cumulative result of various intersecting factors. For instance, women of color, transgender women, and women from lower socioeconomic backgrounds often face heightened risks and unique safety concerns due to systemic inequalities like racial profiling and economic disparity. These intersecting vulnerabilities can significantly enhance the perception of insecurity, consequently restricting their mobility patterns more severely than those of their counterparts. This complexity must be acknowledged to fully understand and address the diverse impacts of insecurity on women's mobility in public spaces. For more recent approximations and case studies associated with this phenomenon, see Cecatto [8], Santoro et al. [59] and Nourani et al. [50].

The mobility of individuals depends on a variety of contexts [16, 57]. A significant body of literature examines the behavioral adaptations in response to insecurity and fear of crime. If fear is a reflection of everyday life experiences, the feeling of fear and insecurity has the power to modify behavior and possibly restrict people's activities in their daily life [10, 33]. In situations of insecurity, adaptations in behavior are observed. This behavior may vary according to the time of day or, more specifically, according to daylight and lighting conditions. The strategies to manage predicted threats vary, including spatial and temporal distancing from potential aggressors, modifying travel patterns, destinations, or routes, and in extreme cases, self-confinement [9–12, 26, 47, 63].

In transit environments in different countries, women present higher frequencies of harassment in transportation (buses and train systems), affecting their perceptions of security [8, 48]. Studies on safety in public spaces have shown that men's and women's everyday geographies differ in terms of lifestyles, mobility, and behavior in the city. It has been observed that women restrict their movements around the city to minimize their perception of insecurity and fear in public spaces [9, 11, 57, 63], avoiding certain destinations or routes and modes of travel. Therefore, the fear of being a crime victim, thus, generally restricts women's travel behavior more than men [7, 10, 13, 27, 60, 63].

There is evidence that a majority of women avoid certain routes, destinations, and modes of travel due to fear. This response to fear is seen in cities like Vienna and Stockholm, where previous victimization, especially of sexual offenses, triggers precautionary behavior in public transport systems [10, 63]. Studies assessing gender-differentiated responses to feelings of insecurity rely on self-reported behavioral changes. For example, respondents may report changes in routes, destinations, or modes of transportation, but

these studies do not have an objective measure of mobility. Ceccato et al. [9] conducted a systematic review of the literature about crime and safety in transit environments (245 articles between 1970 and 2020). The authors recommend a multidisciplinary approach to the problem, including computer science, as well as greater use of technologies to measure mobility (e.g. information from travel smart cards or apps). This paper contributes to filling gaps in the literature in two ways: (i) using an objective measure of mobility to assess the effect of feelings of insecurity on behavior, and (ii) differentiating by gender the measure of mobility based on digital traces. To the best of our knowledge, there is no previous work that has related feelings of insecurity distinguishing by gender using digital traces from mobile phones.

We hypothesize that higher levels of insecurity will result in lower levels of mobility due to the impact on routines and lifestyles. Furthermore, given women's higher level of vulnerability, we hypothesize a stronger relationship between insecurity with mobility in women. This relationship may be further amplified in places where the perception of insecurity concerning sexual crimes could be greater.

2 Data and methods

2.1 Data

This study integrates data from two distinct sources to construct a comprehensive analysis of insecurity and mobility in urban areas. First, the 2017 National Urban Survey on Citizen Security (ENUSC), conducted by Chile's National Institute of Statistics (INE), offers insights into the public's feeling of insecurity, reactions to crime, and experiences of victimization in individuals and households. This survey, representative of urban areas nationally and regionally, forms the foundation of our insecurity indicators.

In parallel, anonymized and aggregated mobile telephone records from Telefónica Chile provide a rich perspective on mobility patterns. These mobile phone records, which serve as a novel source of data in this context, enable an in-depth analysis of how individuals navigate urban spaces in response to feeling of insecurity.

A critical aspect of our methodology is the independence and anonymity of the data sources. It is not possible to link at the individual level the ENUSC survey and the telephone records of Chile, but they can be analyzed at the aggregate level at the commune level, the smallest administrative unit in Chile. This convergence allows for a robust, aggregated analysis of insecurity and mobility within these units.

It is worth noting that both in the ENUSC survey and in the telephone records we have information on the gender of the respondent and the telephone user.

Santiago, located in Chile's Metropolitan Region and comprising 34 distinct communes, serves as our study's focal point. These communes, representing a diverse urban landscape, offer a rich dataset for examining the interplay between feeling of insecurity and mobility patterns.

2.1.1 Feeling of insecurity

The National Urban Survey on Citizen Security (ENUSC) was conducted from September to December 2017, targeting households and individuals aged 15 and older in urban areas. With a sample of 27,616 households, the survey has a national absolute error rate of 0.8% and an average regional error rate of 2.91%. Focusing on Santiago, the study utilized data from 18,191 respondents, comprising 8599 men and 9592 women [31].

Our analysis developed a gender-specific indicator of emotional insecurity and fear of crime based on the ENUSC survey. This measure comes from responses to questions about feelings of insecurity in various urban places that are associated with behavioural changes during daytime mobility. Notice that the definition of urban place in the survey does not refer to their geographic location, but to a characterization as an urban space. Respondents were asked if: "in the last 12 months, based on your experience how did you feel in the following locations?" and then the respondent was presented with a series of locations (urban spaces). This question has four response categories: very insecure, insecure, safe and very safe. We classified as insecure observations whose response was very insecure or insecure, and we operationalized a specific measure as the percentage of people who feel insecure in a specific urban space at the commune level. Key urban spaces for this assessment included buses, collective taxis, subways, neighborhood squares and parks, neighborhood sports courts, bus stops and streets. Besides, we operationalized a general insecurity index as an aggregate of feeling of insecurity across these seven urban spaces. Thus, the formulation of our two primary study variables is as follows:

1. Insecurity: For each commune, the proportion of urban spaces where individuals of each gender are feeling insecure.
2. Space-Specific Insecurity: For each commune, the proportion of individuals of each gender feeling insecure in a specified urban space category i (encompassing buses, collective taxis, subway, neighborhood squares and parks, neighborhood sports courts, bus stops, and streets).

2.1.2 Mobility

Mobility was assessed using the methodologies established by Gauvin et al. [19]. We utilized anonymized and aggregated mobile phone records from May to July 2016, featuring call detail records (CDRs) that include demographic information such as gender, nationality, socioeconomic status, and number of telephone lines per user. This dataset encompasses 418,624 unique users, with a 51% female representation, based on their home antenna location [54].

Mobility patterns were inferred from the locations of each call made or received. By having the geolocation of the towers in the urban area of Santiago, we can know the commune in which they are located. From this geolocation, each home location is determined based on their calling activity. A home location to each user is defined as the cell phone tower most visited during the time interval from 7 p.m. to 8 a.m. during the data collection period [19, 65].

The method for constructing mobility measures was inspired by the principles set forth in de Montjoye *et al.* [15]. It places a high priority on the anonymization of data to address privacy issues in CDR data research. To this end, mobile phone numbers were anonymized using the SHA-3 algorithm, an internal procedure conducted by the operator. This anonymization process was complemented by keeping the CDR data strictly within the operator's infrastructure, ensuring that all analysis occurred on their systems, thereby reinforcing data security.

In addition, we implemented a policy of not reporting data from towers that registered fewer than three unique numbers. Instead, we aggregated data at the tower level rather than examining data from individual antennas, where each tower can have more than one antenna. This approach was based on the understanding that the nature of CDR data itself

offers some level of privacy protection. Due to factors such as time and usage patterns, mobile devices do not consistently connect to the same antenna. This inherent variability in the connection patterns of devices adds a layer of complexity to any attempt to identify individuals based on the location data derived from CDR analysis.

Our primary measure of mobility is the number of locations. In addition, as a robustness analysis, we also use entropy as a measure of mobility, as defined by Gauvin et al., Hong et al. and Song et al. [19, 30, 62]. It's noteworthy that these records reflect the connected antenna, not the precise location of the device.

To measure the number of locations, a two-dimensional spatial grid of 0.01 degree steps long both the latitude and longitude coordinates was defined and the towers were aggregated within each grid cell. The number of locations for each individual was determined by the number of grid cells in which a user initiates or receives a call during the three-month observation period. Finally, the number of locations was averaged by commune according to the individual's place of residence, distinguishing between men and women. It is worth noting that our definition is different from that of origin-destination surveys, in which a trip corresponds to the physical displacement between an origin and a destination for a specific reason.

There are two aspects to consider in our definition of the number of locations as a mobility metric. One is that, unlike the previously defined insecurity and space-specific insecurity measures, locations now refer to a geographic place in the city and not to a category of urban space. The second aspect is that towers are not evenly distributed throughout the city and often reflect user density. The use of a grid of locations of equal size, and not the specific position of a tower, prevents a higher density from being taken as a greater number of locations. Instead, a greater number of visited cells in the grid will reflect more mobility.

Our second measure of mobility is entropy, which is also based on locations, but also reflects the diversity of mobility. We calculate the Shannon entropy for each individual by the formula:

$$S_i = -\sum_{l \in L} p_l, \ln, p_l, \tag{1}$$

where L represents the set of locations visited by user i and p_l the probability of encountering user i at location l, based on relative call frequency [19]. High entropy indicates a diverse mobility pattern, while low entropy suggests more regular, location-specific movements [19, 30, 62]. Entropy quantifies the variability in an individual's movement patterns across different locations. High entropy suggests a person visits a wide variety of locations, indicating less predictability and more complex movement patterns. Conversely, low entropy implies more regular visits to fewer, specific locations, reflecting a more predictable and constrained pattern of movement. In extreme cases, the entropy takes the value "0" when a single location has 100% probability, and takes the value "1" when all locations have identical probability.

2.2 Methodology

Our analysis employed both descriptive and inferential bivariate techniques to scrutinize the relationship between mobility and feeling of insecurity, with a specific focus on gender disparities. The t-test was used for comparing mean values across genders. To assess the

strength and direction of the relationship between our variables, we used Pearson's linear correlation index (we also used Spearman's and Kendall's correlation indexes for robustness analysis). To calculate the standard errors of the sample correlation coefficients we use the estimator proposed by Bonett [3], which has the least bias for small samples [20]. Although mean tests, as well as sample correlations, are simple characterizations of the data, they have the advantage of being robust to assumptions about functional forms or the nature of the phenomenon studied.

To further explore the functional relationship between mobility and insecurity, linear regression models were employed, as outlined in standard econometric literature [22, 23]. Initially, we considered a simple linear model where Y represents mobility by gender and X represents insecurity and space-specific insecurities:

$$Y = \beta_0 + \beta_1 X \tag{2}$$

While this model allows for an assessment of dependency, it does not capture potential gender-based discrepancies. To address this, we introduced a dummy variable, D, indicating gender (with $D = 1$ for females and $D = 0$ for males):

$$Y = \beta_0 + \beta_1 X + \beta_2 D + \beta_3 XD \tag{3}$$

$$Y = \beta_0 + \beta_2 D + (\beta_1 + \beta_3 D)X \tag{4}$$

In this expanded model, the coefficient of X has two components, $\beta_1 + \beta_3 D$. For males ($D = 0$), the coefficient is β_1, and for females ($D = 1$), it is the sum $\beta_1 + \beta_3$. This allows us to analyze the gender differences in the mobility-feeling of insecurity relationship. For women:

$$Y = (\beta_0 + \beta_2) + (\beta_1 + \beta_3)X_1 \tag{5}$$

And for men:

$$Y = \beta_0 + \beta_1 X_1 \tag{6}$$

Here, β_2 represents the difference in average mobility between women and men at a baseline level of insecurity, and β_3 signifies the difference in mobility change per percentage point increase in insecurity for women compared to men. A null hypothesis of no gender influence on mobility (i.e., $\beta_2 = \beta_3 = 0$) was tested against an alternative hypothesis of a gender-dependent relationship. Rejecting the null hypothesis would signify that gender plays a significant role in how mobility correlates with feeling of insecurity. Notice that estimating equation (3) by pooling the data for males and females is equivalent to estimating equation (2) separately by gender.

For reasons of parsimony and to avoid excessive loss of degrees of freedom, we do not include other socioeconomic or demographic control variables in equation (4). To verify that no essential variables were excluded from our model, which could potentially result in omitted variables or confounding bias, we implemented Ramsey's RESET test [56]. Although the Ramsey's RESET test is commonly used to detect omitted variables, the rejection of the null hypothesis can also be due to an incorrect specification of the functional form [34].

Table 1 Means difference in feeling of insecurity by urban space and gender. x^a differences statistically significant $p < 0.01$ and x^b statistically significant at $p < 0.05$

	Male	Female	Differences
Insecurity	0.50	0.59	0.09^a
Insecurity in buses	0.70	0.83	0.12^a
Insecurity in collective taxis	0.32	0.43	0.11^a
Insecurity in subway	0.44	0.56	0.12^a
Insecurity in neighborhood squares and parks	0.47	0.53	0.06
Insecurity in neighborhood sports courts	0.38	0.50	0.12^a
Insecurity in bus stops	0.58	0.67	0.09^b
Insecurity in streets	0.45	0.51	0.06

Table 2 Means difference in mobility by gender. x^a differences statistically significant $p < 0.01$ and x^b statistically significant at $p < 0.05$

	Male	Female	Differences	Difference rate
Locations	38.64	28.94	9.70^a	33.52%
Entropy	1.95	1.67	0.28^a	16.77%

A joint hypothesis test was conducted to assess the statistical significance of the gender variable and its interaction with insecurity [6, 22]. The significance of both parameters would indicate that gender indeed modulates the relationship between mobility and feeling of insecurity.

We estimate equation (4) using Ordinary Least Squares (OLS). According to the Gauss-Markov theorem OLS estimation, under certain assumptions, provides the best linear unbiased estimators (BLUE). Furthermore, we perform robustness analyzes for the standard errors of the estimators using bootstrapping and the Bayesian Model (presented in the supplementary material), to confirm our main findings.

The statistical analysis was performed with Python 3, using the scipy and statsmodels packages. The joint hypothesis test was performed with STATA 15 software.

3 Results

Significant differences are observed in average insecurity by gender ($p < 0.01$). Women report a larger proportion of places feeling insecure, 0.59 ± 0.03, as opposed to men, where only 0.50 ± 0.03 report it ($\pm$ Margin of Error within a 0.95 confidence interval). Our analysis revealed distinct gender disparities in feeling of insecurity across various urban spaces. Table 1 presents the mean differences in perceived insecurity across various urban spaces, segregated by gender. Statistically significant higher levels of insecurity were observed among females compared to males in buses, collective taxis, subways, neighborhood sports courts, and bus stops (all $p < 0.01$). In contrast, differences in neighborhood squares and parks, and streets, were not statistically significant. Summary statistics of insecurity and space-specific insecurities by gender are presented in Tables S2 and S3 of the Supplementary Material, while Figures S2 and S3 show box plots of the variables.

Mobility metrics revealed notable gender differences. Males exhibited higher mobility than females, with a mean entropy of 1.95 ± 0.02 compared to 1.67 ± 0.03 and an average of 38.64 ± 0.73 locations versus 28.94 ± 0.99 for females (Table 2). These differences were statistically significant ($p < 0.01$). The discrepancy in number el locations was particularly pronounced, with males exhibiting a 33.5% higher average than females, compared to a 16% difference in entropy. Figure S1 in Supplementary Material shows distributions for

Table 3 Pearson's correlation between mobility and feeling of insecurity by urban space (standard error in parentheses by approximation of Bonett (2008)) x^a correlations are statistically significant at $p < 0.01$ and x^b statistically significant at $p < 0.05$

	Male locations	Female locations	Male entropy	Female entropy
Insecurity	-0.46^a (0.14)	-0.70^a (0.09)	-0.38^b (0.15)	-0.67^a (0.10)
Insecurity in buses	-0.43^b (0.15)	-0.68^a (0.10)	-0.35^b (0.16)	-0.64^a (0.11)
Insecurity in collective taxis	−0.17 (0.17)	0.02 (0.18)	−0.20 (0.17)	0.02 (0.18)
Insecurity in subway	-0.35^b (0.16)	-0.35^b (0.16)	−0.26 (0.17)	−0.30 (0.16)
Insecurity in neighborhood squares and parks	-0.49^a (0.14)	-0.83^a (0.05)	-0.42^b (0.15)	-0.78^a (0.07)
Insecurity in neighborhood sports courts	-0.37^b (0.16)	-0.79^a (0.07)	−0.28 (0.17)	-0.68^a (0.10)
Insecurity in bus stops	-0.45^a (0.14)	-0.82^a (0.06)	−0.34 (0.16)	-0.78^a (0.07)
Insecurity in streets	-0.47^a (0.14)	-0.67^a (0.10)	-0.37^b (0.15)	-0.64^a (0.11)

both mobility metrics. Summary statistics of mobility measures by gender are presented in Table S1 of the Supplementary Material, while Figure S1 show a box plot of the variables.

Moreover, our analysis found a negative and significant correlation between mobility and feeling of insecurity for both genders. Men showed a correlation of −0.38 with entropy ($p < 0.05$) and −0.46 with number of locations ($p < 0.01$), whereas women exhibited stronger correlations of −0.67 with entropy and −0.70 with number of locations (both $p < 0.01$). This indicates a significant, linear association between decreased mobility and increased feeling of insecurity, especially pronounced among women.

Table 3 details the Pearson's correlations of insecurity in specific urban spaces with mobility metrics (Tables S4 and S5 of the Supplementary Material show the Spearman's and Kendall's correlations). For men, significant correlations were observed predominantly with the number of locations, though these showed low adjustment. In contrast, women demonstrated negative and significant correlations in both mobility measures across all evaluated urban spaces, most notably in neighborhood squares and parks, sports courts, bus stops, and streets. The results suggest a substantial reduction in women's mobility in response to heightened feeling of insecurity (Fig. 1 and Fig. 2).

3.1 Identification strategy

Building on the observed disparities in mobility patterns influenced by gender and feeling of insecurity, our identification strategy further examines the nuances of this relationship. Table 4 presents the estimates of equation (3) for each variable X: insecurity and space-specific insecurities. We assess how gender differentially moderates the link between mobility and feeling of insecurity, considering various urban environments. This deeper analysis, outlined in Table 4 (and Table S6 in the Supplementary Material for entropy), provides a clearer understanding of the gender-specific impacts on mobility in response to feeling of insecurity in distinct urban contexts.

All the estimated parameters of the interaction between feeling of insecurity and gender have the expected signs, in accordance with previous literature. This implies that a greater feeling of insecurity is related to a greater decrease in mobility in women than in men. Notice that a greater feeling of insecurity corresponds to a higher proportion of people per commune reporting feeling insecure. However, the interaction coefficients in the context of collective taxis and in the subway were not statistically significant. On the other hand, the parameters corresponding to buses, bus stops, neighborhood squares and parks, neighborhood sports courts, and streets were significant. Notably, the negative and significant coefficients for the gender dummy variable indicate that women, on average,

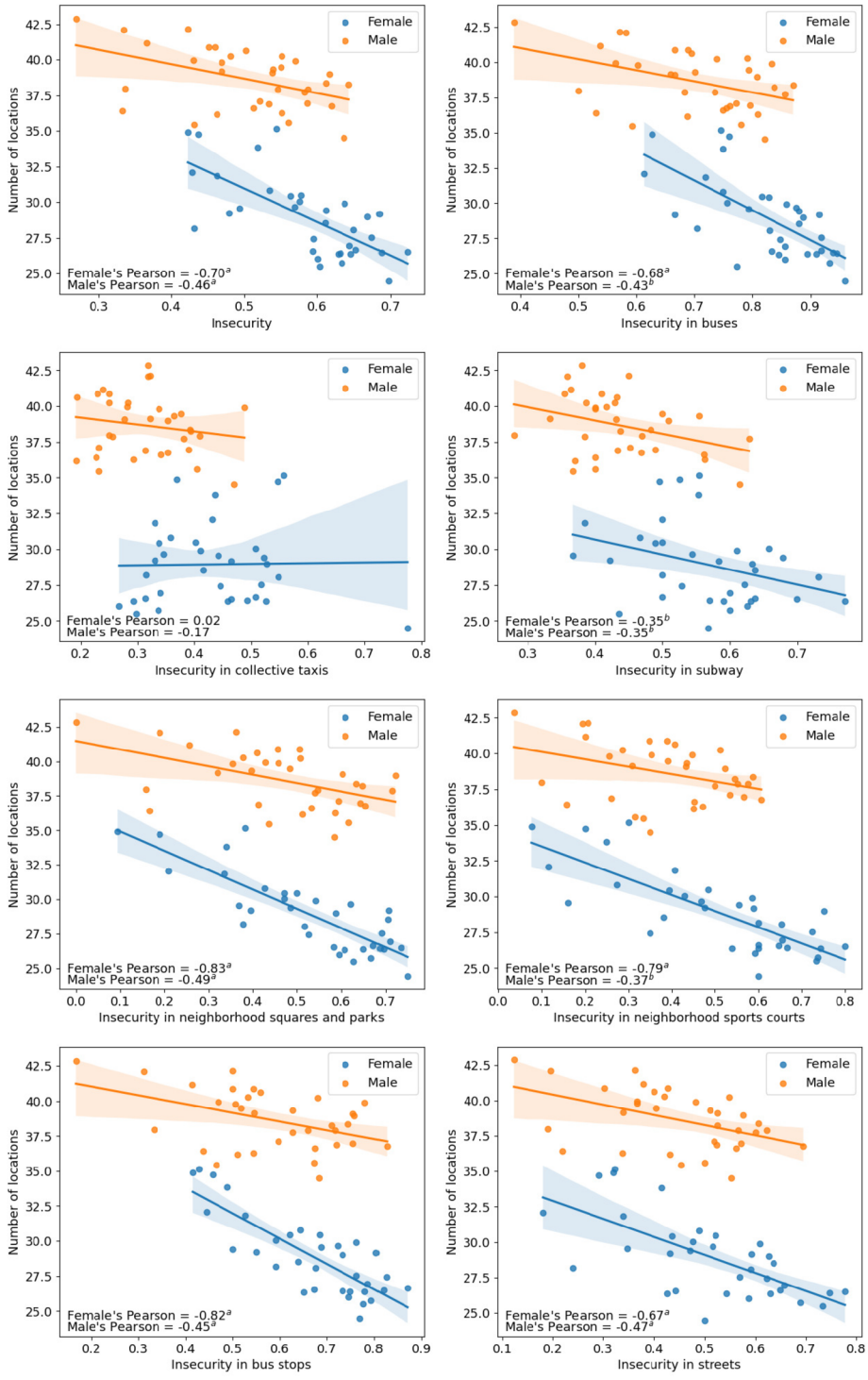

Figure 1 Scatter plot of number of locations with respect feeling of insecurity by urban space. x^a correlation are statistically significant $p < 0.01$ and x^b statistically significant at $p < 0.05$

exhibit lower mobility than men. Visual representations of these effects are available in the Model Robustness section of the Supplementary Material (Fig. 4 and Fig. 5), offering further insights into the marginal effects of these relationships.

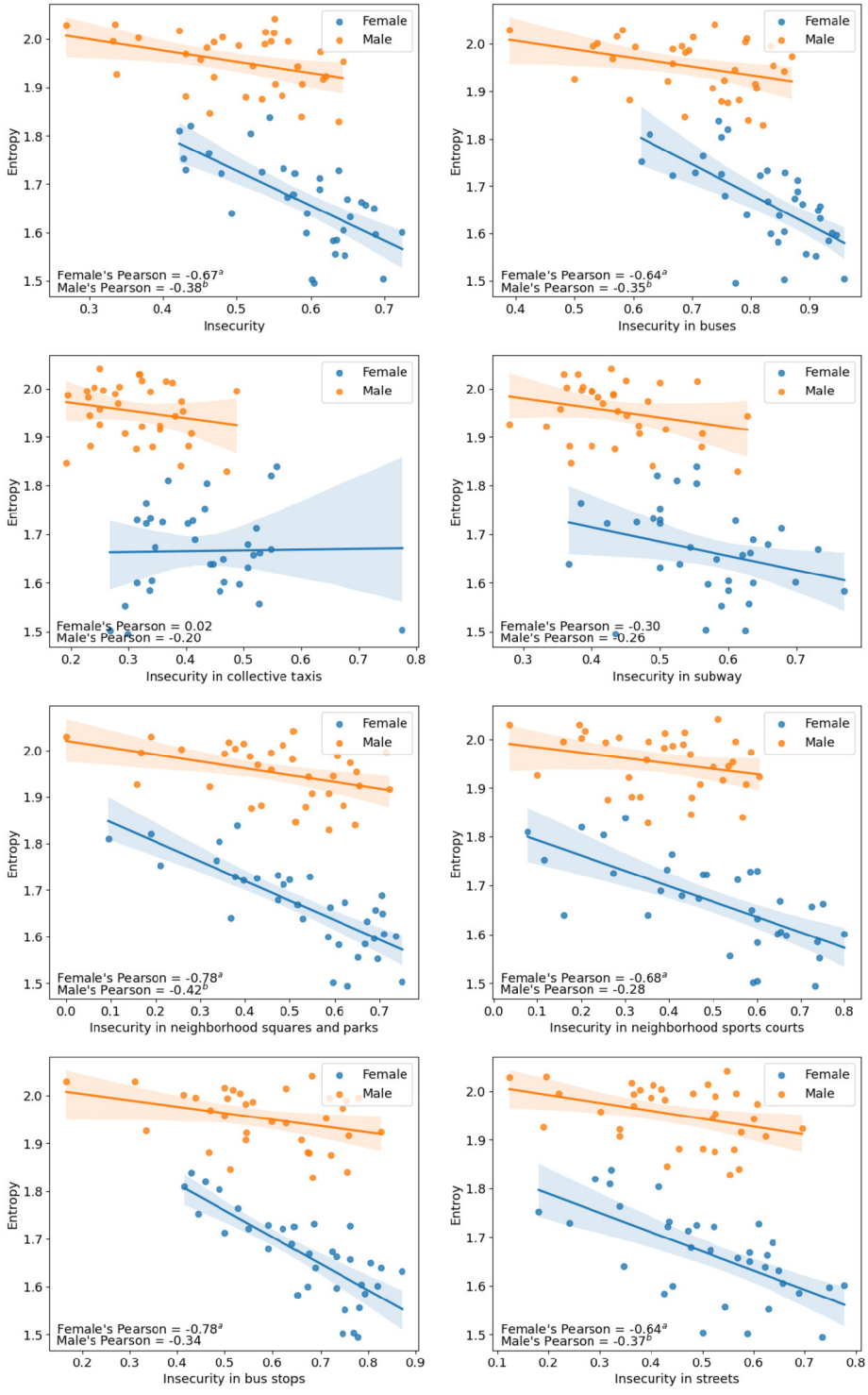

Figure 2 Scatter plot of entropy with respect feeling of insecurity by urban space. x^a correlation are statistically significant $p < 0.01$ and x^b statistically significant at $p < 0.05$

Regarding the Ramsey RESET tests (Table S6), the null hypothesis of correct specification is not rejected for any of the regressions of Table 4 at the 1% level of significance and is only rejected in one case at the 5% level of significance.

Table 4 Modeling by urban space, dependent variable: number of locations. Standard errors in parentheses, x^a parameters statistically significant $p < 0.01$ and x^b statistically significant at $p < 0.05$

	Insecurity	Insecurity in buses	Insecurity in bus stops	Insecurity in sports courts	Insecurity in squares and parks	Insecurity in streets	Insecurity in subway	Insecurity in collective taxis
Intercept	43.73^a	44.14^a	42.29^a	40.63^a	41.47^a	41.85^a	42.73^a	40.16^a
	(1.83)	(2.15)	(1.25)	(0.91)	(0.88)	(1.20)	(2.32)	(1.88)
Female	−1.01	2.26	−1.26	−6.00^a	−5.15^a	−6.39^a	−7.86^b	−11.43^a
	(3.02)	(3.84)	(2.08)	(1.28)	(1.32)	(1.74)	(3.43)	(2.63)
Insecurity	−10.15^a							
	(3.59)							
Insecurity x Female	−13.38^b							
	(5.42)							
Insecurity in buses		−7.86^b						
		(3.02)						
Insecurity in buses × Female		−13.28^a						
		(4.88)						
Insecurity in bus stops			−6.25^a					
			(2.08)					
Insecurity in bus stops × Female			−11.84^a					
			(3.20)					
Insecurity in neighborhood sports courts				−5.19^b				
				(2.21)				
Insecurity in neighborhood sports courts × Female				−6.10^b				
				(2.77)				
Insecurity in neighborhood squares and parks					−6.09^a			
					(1.77)			
Insecurity in neighborhood squares and parks × Female					−7.90^a			
					(2.51)			
Insecurity in streets						−7.18^a		
						(2.57)		
Insecurity in streets × Female						−5.54		
						(3.49)		
Insecurity in subway							−9.34	
							(5.22)	
Insecurity in subway × Female							−1.16	
							(6.83)	
Insecurity in collective taxis								−4.81
								(5.80)
Insecurity in collective taxis × Female								5.30
								(7.13)
R-squared	0.88	0.87	0.90	0.89	0.90	0.87	0.82	0.80
R-squared Adj.	0.87	0.86	0.89	0.88	0.90	0.86	0.81	0.79
N	68	68	68	68	68	68	68	68

Joint hypothesis testing results, as shown in Table 5, evaluate the significance of gender's marginal effect on mobility in relation to feeling of insecurity. Under the null hypothesis that gender does not influence this relationship ($\beta_2 = \beta_3 = 0$), the observed p-values provide strong statistical evidence ($p < 0.01$) that gender is significantly associated with the relationship between mobility and feeling of insecurity, suggesting a gender-specific disparity.

Table S9 and Table S10 of the Supplementary Material compare the estimation of 95% confidence intervals of the parameters by OLS, bootstrapping and the Bayesian approach.

Table 5 Joint significance test by urban space, dependent variable: number of locations

Model	Null hypothesis	p-value
Insecurity	$\beta_{\text{Female}} = 0$ $\beta_{\text{Insecurity * Female}} = 0$	0.000
Insecurity in buses	$\beta_{\text{Female}} = 0$ $\beta_{\text{Insecurity in buses * Female}} = 0$	0.000
Insecurity in bus stops	$\beta_{\text{Female}} = 0$ $\beta_{\text{Insecurity in bus stops * Female}} = 0$	0.000
Insecurity in neighborhood sports courts	$\beta_{\text{Female}} = 0$ $\beta_{\text{Insecurity in neighborhood sports courts * Female}} = 0$	0.000
Insecurity in neighborhood squares and parks	$\beta_{\text{Female}} = 0$ $\beta_{\text{Insecurity in neighborhood squares and parks * Female}} = 0$	0.000
Insecurity in streets	$\beta_{\text{Female}} = 0$ $\beta_{\text{Insecurity in streets * Female}} = 0$	0.000
Insecurity in subway	$\beta_{\text{Female}} = 0$ $\beta_{\text{Insecurity in subway * Female}} = 0$	0.000
Insecurity in collective taxis	$\beta_{\text{Female}} = 0$ $\beta_{\text{Insecurity in collective taxis * Female}} = 0$	0.000

In general terms, the confidence intervals are similar and confirm our main findings. Only in the case of the bootstrapping estimate of the interaction term between feeling of insecurity and gender for the number of locations (Table S9), the estimate becomes marginally significant at the 5% level.

The analysis concludes that gender, together with the feeling of insecurity, is related with different patterns of mobility. This mobility gap increases significantly with the aggregate measure of insecurity, as well as in the specific contexts of buses, bus stops, neighborhood squares and parks, neighborhood sports courts, and streets. However, this increase in the mobility gap was not significant in the context of collective taxis and the subway.

4 Discussion and conclusions

The use of mobile device data offers a large-scale, detailed view of urban mobility patterns, overcoming some limitations of traditional origin-destination surveys. It provides insights into the aggregate behavior of individuals within a territory and avoids biases inherent in survey methods. The ENUSC survey, although not measuring specific travel routes, inquires about avoidance of certain areas due to fear of crime, reflecting significant gender differences in behavior related to mobility and feeling of insecurity.

Building on the findings that both men and women experience feelings of insecurity, with women exhibiting a greater feeling (Table 1), we delve into the relationship between this feeling of insecurity and mobility. Our analysis reveals a negative and significant relationship between feeling of insecurity and mobility for both genders, with women showing a stronger correlation. This indicates a more pronounced reduction in women's mobility in response to the same level of insecurity, particularly in buses, bus stops, neighborhood squares and parks, neighborhood sports courts, and streets. Men, while showing a relationship with the number of trips, have a lower association as indicated by Pearson's correlation index. Women, in contrast, demonstrate a significant correlation across both mobility measures in almost all locations, except collective taxis and subways (Table 3).

Although we did not identify the factors that would explain this difference in behavior by gender, one possible explanation is the "shadow of sexual assault hypothesis". The "shadow of sexual assault hypothesis" posits that women's feeling of insecurity and mobility restrictions are linked not only to actual victimization but also to the fear of potential sexual assault [18, 29, 49, 52]. This hypothesis is supported by data from the Observatory Against Harassment in Chile and the National Women's and Equity Gender Service (SernamEG), which highlights the prevalence of street sexual harassment in various urban settings. For the city of Santiago, SernamEG indicates that between 40% and 50% of sexual assaults against women occur on buses, between 20% and 30% on the street, and between 15% and 20% on the subway. Meanwhile, the Observatory against Harassment in Chile states that the most common scenarios of street sexual harassment occur on the street (50%), on buses (15%), on the subway (11%), in a square or park (6%), and in other means of transportation and public places (18%).

Our modeling of the relationship between mobility and feeling of insecurity underscores a gender gap. Greater feelings of insecurity are related to greater decreases in mobility among women than men, particularly in buses, bus stops, neighborhood squares and parks, neighborhood sports courts, and streets (Tables 4 and 5, and Tables S7, S8, S9 and S10 of the Supplementary Material).

The findings indicate that women's number of locations, as well as their measure of entropy, are significantly correlated with feelings of insecurity, with a stronger association for the number of locations. This could imply that as women feel more insecure, they may limit their mobility to fewer locations, thus decreasing the entropy of their mobility patterns [19, 30, 62]. They likely avoid areas perceived as less safe, reducing both the diversity of their visited locations and the overall number of locations. For men, the lack of significant correlation between entropy and feeling of insecurity might suggest that their diversity of locations visited is less affected by feelings of insecurity. This could be due to several reasons, including societal norms and perceptions of risk which often affect men and women differently [16]. Men might feel less threatened in varied environments or may not modify their routine locations despite feelings of insecurity. Women often experience higher levels of fear of crime, especially in urban environments, which can significantly influence their movement patterns. The "shadow sexual assault hypothesis" could explain part of this phenomenon, where the fear of potential sexual assault impacts women's mobility decisions more acutely than men. Thus, in contexts of high insecurity, women might choose to frequent a smaller set of familiar and perceived safe locations, leading to lower entropy in their mobility patterns.

In conclusion, this study supports the hypothesis that an increase in feeling of insecurity correlates with reduced mobility, with a more substantial impact observed among women. This gender-specific response is particularly pronounced in places associated with higher perceived risks of sexual crimes. These findings contribute to the ongoing discourse on urban feeling of security, mobility and gender, by using an objective measure of mobility to assess the impact of feelings of insecurity on behavior and also differentiating the mobility measure based on digital traces by gender.

4.1 Public policy implications

Gender disparities and mobility constraints significantly impact women, affecting both time management and overall well-being. Venturing outside their homes exposes women

to persistent security risks, instilling fear and stress during their journeys, thereby compromising their emotional health. In regions marked by elevated crime and violence rates, women often opt for safer travel alternatives, even if it means longer commute times. Inequalities between men and women significantly influence mobility [16].

Diminished mobility has far-reaching consequences for the personal and professional development of women. If accessibility is defined as "the ease with which an individual can access opportunities within the space of the city" [16], then safety concerns and crime victimization curtail mobility, restricting the geographic scope of women's trips [16].

The freedom to move unrestrictedly is a fundamental human right that facilitates participation in social and economic life. Therefore, public policy design must encompass all social phenomena capable of modifying behavior and constraining daily habits and activities [10, 33]. Effective policies require well-designed and implemented social programs and projects that consider their impact on people's mobility. Infrastructure design in social projects, such as public transport, can enhance the perception of insecurity and fear of crime and, consequently, female mobility.

Our findings suggest that in Santiago, there is a gender gap in mobility that is related to feelings of insecurity. The primary challenge for policymakers is to formulate comprehensive interventions that tackle the various factors affecting female mobility, such as the feeling of insecurity. Therefore, interventions designed to reduce or eliminate phenomena like crime and insecurity must prioritize and account for their differential impact on gender-specific mobility.

5 Limitations

This study, while illuminating the complex interplay between mobility, feeling of insecurity, and fear of crime, has certain limitations that warrant consideration. Firstly, the data is aggregated at the commune level in Santiago, Chile, making extrapolation to individual behaviors or other geographical areas less straightforward [61]. Privacy and ethical constraints limit the accessibility to individual-level data on mobility and feeling of insecurity, and aligning such data with mobility patterns remains challenging.

Secondly, our mobility measures may be susceptible to bias, as it relies on data sourced from a sole mobile service provider holding approximately 40% market share, alongside the spatial resolution of cellphone antenna. Due to the difficulty in obtaining this type of information, it is common to work with records from a single company. While this is the most feasible approach in the current research landscape, it might not fully encapsulate the breadth of female mobility, especially for those not using mobile devices frequently or not using them at all. Nevertheless, mobile device data is a leading source for studying mobility, offering valuable insights despite its inherent limitations.

Thirdly, we are aware that the feeling of insecurity has the power to alter behavior and restrict people's activities in their daily lives, changes that may vary depending on the time of day and lighting conditions. Therefore, evaluating the relationship between feeling of insecurity and mobility considering the temporality of the information would be most appropriate. However, the available information for mobility and insecurity measures does not allow us to differentiate by day and hour, thus making it impossible for us to construct measures differentiated by these characteristics. While in the case of our mobility measures, it is not possible for us to distinguish by socioeconomic or demographic characteristics.

Fourthly, the multifaceted nature of mobility, influenced by socio-cultural, economic, and individual factors, is not fully captured in our models. Moreover, we do not know people's need to visit a location, even if they feel insecure. Likewise, we do not know what mobility patterns would be like in the absence of crime, and therefore of insecurity.

Fifthly, care must be taken with the interpretation of mobility measures, since the number of locations and entropy reflect the diversity of places visited by users and not the number of times they visit each of these places or the distances traveled.

Lastly, it is possible that the point value of the parameters we estimate change over time, either due to changes in crime levels, as well as changes in the mobility measure resulting from technological changes.

Despite these challenges, our research makes a substantial contribution to the understanding of mobility and feeling of insecurity, paving the way for further studies in this field.

Abbreviations
BLUE, Best Linear Unbiased Estimators; ENUSC, National Urban Survey on Citizen Security, in Spanish Encuesta Nacional Urbana de Seguridad Ciudadana; INE, National Institute of Statistics, in Spanish Instituto Nacional de Estadística; SernamEG, National Women's and Equity Gender Service, in Spanish Servicio Nacional de la Mujer y Equidad de Género; OLS, Ordinary Least Squares.

Supplementary information

Supplementary information accompanies this paper at https://doi.org/10.1140/epjds/s13688-025-00589-z.

Additional file 1. (PDF 2.3 MB)

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Data availability
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Declarations

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The authors declare no competing interests.

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