




Linking physical violence to women's mobility in Chile

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Abstract

Despite increased global attention on violence against women, understanding the factors that lead to women becoming victims remains a critical challenge. Notably, the impact of domestic violence on women's mobility—a critical determinant of their social and economic independence—has remained largely unexplored. This study bridges this gap, employing police records to quantify physical and psychological domestic violence, while leveraging mobile phone data to proxy women's mobility. Our analyses reveal a negative correlation between physical violence and female mobility, an association that withstands robustness checks, including controls for economic independence variables like education, employment, and occupational segregation, bootstrapping of the data set, and applying a generalized propensity score matching identification strategy. The study emphasizes the potential causal role of physical violence on decreased female mobility, asserting the value of interdisciplinary research in exploring such multifaceted social phenomena to open avenues for preventive measures. The implications of this research extend into the realm of public policy and intervention development, offering new strategies to combat and ultimately eradicate domestic violence against women, thereby contributing to wider efforts toward gender equity.

Keywords: Mobility; Violence; Domestic violence; Women

1 Introduction

Global trends in violence against women reveal a distressing pattern: in 2018, one in every seven women worldwide experienced physical or sexual violence by their partners. By 2019, considering the entirety of a woman's lifespan, this ratio increased alarmingly: one in three women reported enduring such violence at some point in their lives [53, 54]. Zooming into Chile, the Undersecretary of Crime Prevention reported an increase of 7.5% in 2019 compared to the preceding year. This surge underscores the need to take action on violence against women, which is now regarded as a pressing public health crisis and a flagrant violation of women's human rights [18].

Violence against women influences not only women's physical and mental health but also their urban mobility [10, 35]. Mobility patterns are shaped by various factors, from transportation systems to traditional gender roles that often restrict women's movement

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[16, 23]. This constraint can arise from a controlling partner behavior or self-imposed limitations, impacting women's independence and their exposure to domestic violence [16, 38, 45].

This study explores the relationship between female mobility and domestic violence in Santiago, Chile. By analyzing digital traces from mobile devices, we can examine this relationship at a detailed level [7, 23]. Incorporating geolocalized police case reports, we consider the impact of domestic violence on female mobility.

Our work is guided by the hypothesis that domestic violence disrupts women's daily routines and mobility patterns. Following an overview of our methods, we present the results and the identification strategy. We conclude by discussing our findings, evaluating our study's limitations, and potential directions for future research.

2 Violence against women

Literature explores the intricacies of violence against women, a complex social phenomenon with multiple dimensions, through evolutionary, social, and ecological lenses. The World Health Organization (WHO) identifies violence against women as a pressing public health issue and an egregious violation of their basic human rights, a concern that has seen a disturbing escalation in the last decade [18]. Various forms of violence inflicted upon women, encompassing physical, psychological, sexual, and economic abuse, intensifying their susceptibility to harm and exploitation [62, 63].

Violence against women often yields profound psychological repercussions, instilling feelings of vulnerability and a pervasive sense of insecurity. This apprehension may precipitate alterations in behavior, potentially restricting daily activities, notably urban mobility—the act of moving from one place to another [10, 35].

The dynamics of female mobility are intricate and multifaceted, influenced not solely by transportation systems [16, 23], but also shaped by variables at the community, household, and individual levels. For instance, traditional role assignments, such as that of a housewife, frequently curtail women's mobility [16]. The increased time dedicated to domestic tasks and child-rearing often results in women making shorter trips [16, 23, 55], and consequently visiting fewer destinations than men [23, 48].

The restrictions imposed on female mobility can be viewed through two lenses: control exerted by the partner and self-imposed control by the woman herself. Negative attitudes and controlling behavior from partners can constrain a woman's employment outside the household and, in extreme cases, may escalate into domestic violence if a woman resists altering her occupational choices [16, 38]. Conversely, by the woman herself and under an agency-based perspective, women have the autonomy to make decisions and strive towards their life aspirations, including freedom from domestic violence and physical mobility [16, 38]. Domestic violence can significantly impede a woman's choice to relocate and pursue improved economic opportunities [16, 38, 45]. Within this context, "agency" is synonymous with "empowerment" [38]. Thus, a woman's economic independence is intricately linked with her mobility and the likelihood of becoming a victim of violence [6].

Adopting an economic independence perspective, violence against women and its triggers can be evaluated based on the victim's and the perpetrator's personal, psychological, and socioeconomic attributes. Personal characteristics of women, such as educational attainment and employment status, serve as key factors influencing the incidence of violence

against them [6, 33]. For instance, the United Nations International Children's Emergency Fund (UNICEF) underlines that limited access to education for women enhances the probability of violence exposure [37]. Education is thus deemed a protective buffer against such adversities [21, 40, 60, 65].

The relationship between employment and violence experienced by women, however, is less clear-cut. The literature lacks consensus on how a woman's ingress into the workforce impacts her experience of violence [13, 30, 60]. It is proposed that women's gainful employment might mitigate the risk of domestic violence, but this potential benefit appears to be heavily contingent upon the employment status of their partners [5]. For instance, women's participation in the labor force diminishes the risk of domestic violence when their partners are also employed, but inversely amplifies the risk if their partners are unemployed [30]. Employment for women, thereby, confers economic autonomy and independence, serving as a protective factor by reducing isolation and the time spent at home [5, 14, 20, 22]. Additionally, it provides women with the resources necessary to escape abusive situations, further strengthening their resilience against violence.

Mobile devices serve as a gateway to examine aggregate human behavior within a specific territory by giving insights into the locations individuals visit, thereby bypassing potential biases from origin-destination surveys (e.g., due to self-reporting), a traditional tool in mobility studies [23]. Our paper explores the relationship between female mobility and domestic violence against women in Santiago, Chile. The uniqueness of our study lies in its use of granular, large-scale mobility measures derived from digital traces left by mobile devices supplied by a highly representative telephone company. Such an approach enables us to delve deep into human behavior and interactions [7], providing us with the ability to inspect human movement patterns across a broad scale with remarkable temporal and spatial precision [4, 9, 25, 26].

To assess the impact of domestic violence on female mobility, we extracted two dimensions from geolocalized police case reports: physical and psychological violence. In Chile, violence against women predominantly manifests within the family environment, as physical or psychological abuse. As per the Chilean National Service for Women and Gender Equity (SernamEG), physical violence encompasses any physical aggression inflicted upon women. Psychological violence includes actions aimed at dominating women, leading them to feel insecure and devoid of control over their own lives and decisions.

Interestingly, the spatio-temporal distribution of domestic violence against women in Santiago reveals a starkly defined pattern, with higher concentrations noted in the lower-income southwest sector of the city [11]. This pattern resembles the results of Gauvin *et al.* [23], who also observed a larger gender mobility gap in these economically disadvantaged areas. This convergence signals the crucial need to control for employment and education, which serve as effective proxies for income.

3 Data and method

3.1 Data

This study used three data sources: police case records, mobile phone records, and the national census. The indicators of domestic violence against women were generated using police case records obtained from the Center for the Study and Analysis of Crime (Undersecretary of Crime Prevention, Chile). These records included complaints and arrests in flagrancy for domestic violence against women. Mobility was measured using anonymized

and aggregated mobile phone records from Telefónica Chile. Finally, we used the Population and Housing Census of Chile (National Statistics Institute, INE, Chile) to obtain socio-economic and demographic information about the country's residents.

As detailed below, our sources correspond to two different years, 2016 for mobility and 2017 for violence against women and Census data. While this is a limitation due to the data at our disposal, this issue is significantly alleviated by the fact that crime events tend to be persistent over time. The concentration of crime patterns presents temporal stability in different years and these concentrations persist across time. Several studies have examined the distribution of crime at microgeographic places using longitudinal incident-level data and found that the phenomenon persists over observation periods stretching nearly 30 years in some cases [8, 12, 57–59]. Based on this, several works have used data sources from different dates.

Although our work analyzes domestic violence against women and not crime, upon close examination of the domestic violence data across the years surrounding our study period, we observed that the patterns of violence reported at the commune level exhibit a remarkable degree of stability. Specifically, we have conducted a year-over-year comparison which reveals a high correlation in the patterns of reported violence, with a correlation coefficient of 0.953 between the years 2016 and 2017. This stability extends beyond these years, suggesting that the trends we have observed are not anomalous but reflective of a representative pattern.

This study's geographical area of analysis was the commune, the smallest administrative unit in Chile. The country has 346 communes in 16 regions. Our research and analysis were conducted in the city of Santiago, the capital city located in the Metropolitan Region, which comprises 34 communes.¹

3.1.1 Domestic violence

We analyzed domestic violence records against women in the urban area of Santiago for 2017. Among 20,750 geolocated records, 10,237 (49%) represented physical domestic violence, and 10,513 (51%) represented psychological violence. We only included violence against women within their homes, as approximately 5% of cases take place elsewhere. We established two indicators to assess domestic violence against women: physical and psychological violence. To facilitate comparison, we normalized the number of cases of domestic violence against women per 100,000 adult women in a given geographical area. We used demographic data from the Chilean Population and Housing Census for normalization.

3.1.2 Mobility

We assessed mobility based on the indicators described by Gauvin *et al.* [23], derived from anonymized and aggregated mobile phone records from May to July 2016. This dataset of anonymized call detail records (CDRs) includes information on gender, nationality, socioeconomic status, and the number of telephone lines registered to a given phone number. Using an identifiable home antenna [41] we analyzed 418,624 unique users, of whom

¹Cerrillos, Cerro Navia, Conchalí, El Bosque, Estación Central, Huechuraba, Independencia, La Cisterna, La Florida, La Granja, La Pintana, La Reina, Las Condes, Lo Barnechea, Lo Espejo, Lo Prado, Macul, Maipú, Ñuñoa, Pedro Aguirre Cerda, Peñalolén, Providencia, Pudahuel, Puente Alto, Quilicura, Quinta Normal, Recoleta, Renca, San Bernardo, San Joaquín, San Miguel, San Ramón, Santiago and Vitacura.

51% were women. We employed two individual-level mobility metrics differentiated by gender: the number of trips and the entropy [23, 32].

Our central mobility measure is the number of trips. We used mobile phone records to define a trip as the movement between two different antennas. Thus, to estimate the number of trips between two geographic communes, A and B, we sum the number of trips among antennas within commune A and those within commune B. We note that these records do not provide the exact location of the devices but rather the antenna to which they are connected.

As a robustness check, we used entropy which measures the diversity of an individual's mobility. This measure calculates Shannon's entropy of a user's trajectories as follows:

$$S_i = - \sum_{l \in L} p_l \ln p_l, \quad (1)$$

where L represents all of the locations visited by user i , and p_l represents the probability of observing user i at the location l . The probability p_l is calculated as the fraction of calls made by the user at that location [23]. Thus, a user with high entropy distributes their trips among many different locations with approximately the same probability, whereas a user with lower entropy exhibits higher regularity in their mobility patterns, consistently visiting a smaller set of locations [23, 32, 50].

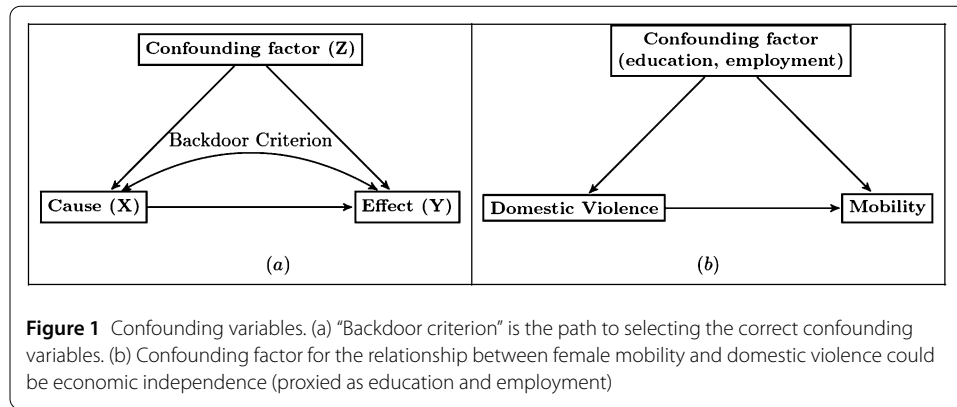
3.1.3 Economic independence

In an agency approach, the relationship between domestic violence and female mobility may be linked to the economic independence of women [16, 38]. To measure economic independence or autonomy, we use female employment, occupational segregation, and female education from the Chilean Census as proxies [2, 19, 39]. Female employment is defined as the percentage of women working out of the female population aged 15 years and older. Female labor force participation provides insight into how women contribute to economic growth, access economic resources, and improve their well-being. Occupational segregation measures the extent of change the employed population requires to achieve gender equity in economic participation by occupation [17]. This indicator helps determine how much progress must be made to achieve gender equality in the labor market. Finally, female education is defined as the average years of schooling for the female population aged 15 years and older. Education can improve access to information and increase independence from partners [13, 20, 30].

Negative partner attitudes and controlling behaviors are also associated with domestic violence against women. Thus, we define an indicator for male education as the average years of schooling for the male population aged 15 years and older and an indicator for male employment as the percentage of working men relative to the male population aged 15 years and older.

3.2 Method

We used descriptive and inferential bivariate analyses to evaluate the relationship between mobility and domestic violence. We employed a t-test to compare means by type of violence and characteristics by gender. Pearson's linear correlation coefficient was used as the indicator to evaluate the relationship between mobility and domestic violence.



Understanding the concept of confounding is pivotal in determining causal relationships. Specifically, the relationship between female mobility and domestic violence could be misleading due to the presence of overlooked confounding variables. A confounding variable is one that independently correlates with both the explanatory (or exposure) variable and the outcome (or response) variable.

The procedure for selecting the appropriate confounding variables is described as the “backdoor criterion” (Fig. 1a). This criterion suggests that the confounding factor Z must block or intercept every pathway between X and Y that comprises an arrow directing towards X [24, 43, 44, 56]. This mechanism ensures that the effect we observe is solely between X and Y , eliminating the influence of external variables that might distort the relationship.

Our hypothesis states a relationship between female mobility and economic independence (proxied as education and employment). However, these variables could also influence violence against women, and thus, they serve as confounding factors (Fig. 1b).

We employed multiple regression analysis and Propensity Score Matching (PSM) to manage confounding factors and aid identification.

In the context of multiple regression, we controlled for confounders by incorporating them as independent or explanatory variables. This technique allows us to examine the direction and size of the relationship between relevant variables, both before and after adjusting for potential confounders. To elucidate this relationship and scrutinize causality, we modeled the functional connection between female mobility (denoted as Y) and physical domestic violence (denoted as X) using linear regression (equation 2 and equation 3) [27, 28]. To ensure that no essential variables were excluded from our model, which could potentially result in omitted variable bias, we deployed Ramsey’s RESET test [46] before introducing any potential confounders into the multivariate model. 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 [36].

Next, we implemented Propensity Score Matching (PSM) as our identification strategy. PSM is a robust technique to estimate the causal effect of a treatment, intervention, or policy by accounting for the covariates that predict receiving the treatment. By comparing subjects with similar propensity scores but different treatment status, we could isolate the effect of the treatment, which in this study is domestic violence. This approach offers us a quasi-experimental design when random assignment is not feasible, thus increasing the

robustness of our causal inferences.

$$y_i = \beta_0 + \beta_1 x_i + \varepsilon_i, \quad (2)$$

$$\text{Mobility}_i = \beta_0 + \beta_1 \text{Violence}_i + \varepsilon_i,$$

$$y_i = \beta_0 + \beta_1 x_{1i} + \beta_2 x_{2i} + \varepsilon_{ij}, \quad (3)$$

$$\text{Mobility}_i = \beta_0 + \beta_1 \text{Violence}_i + \beta_2 \text{Confounding}_i + \varepsilon_{ij}.$$

Propensity Score Matching is a robust statistical technique that effectively manages multiple confounding factors while minimizing random errors. This method has particular utility in quasi-experimental design as it compares observations that are exposed and unexposed to a treatment. The unexposed group serves as the counterfactual scenario, enabling an evaluation of the treatment or exposure impact on the outcome of interest. PSM operates by selecting and pairing units—striving for a balanced distribution of experimental participants (one treated unit with one untreated unit)—according to their likelihood of receiving treatment or being subjected to a condition [3, 29, 47]. This likelihood, termed the Propensity Score, is derived from the confounding factors. Units are matched based on their Propensity Score similarity, following which the average treatment or exposure effect on an outcome variable is assessed.

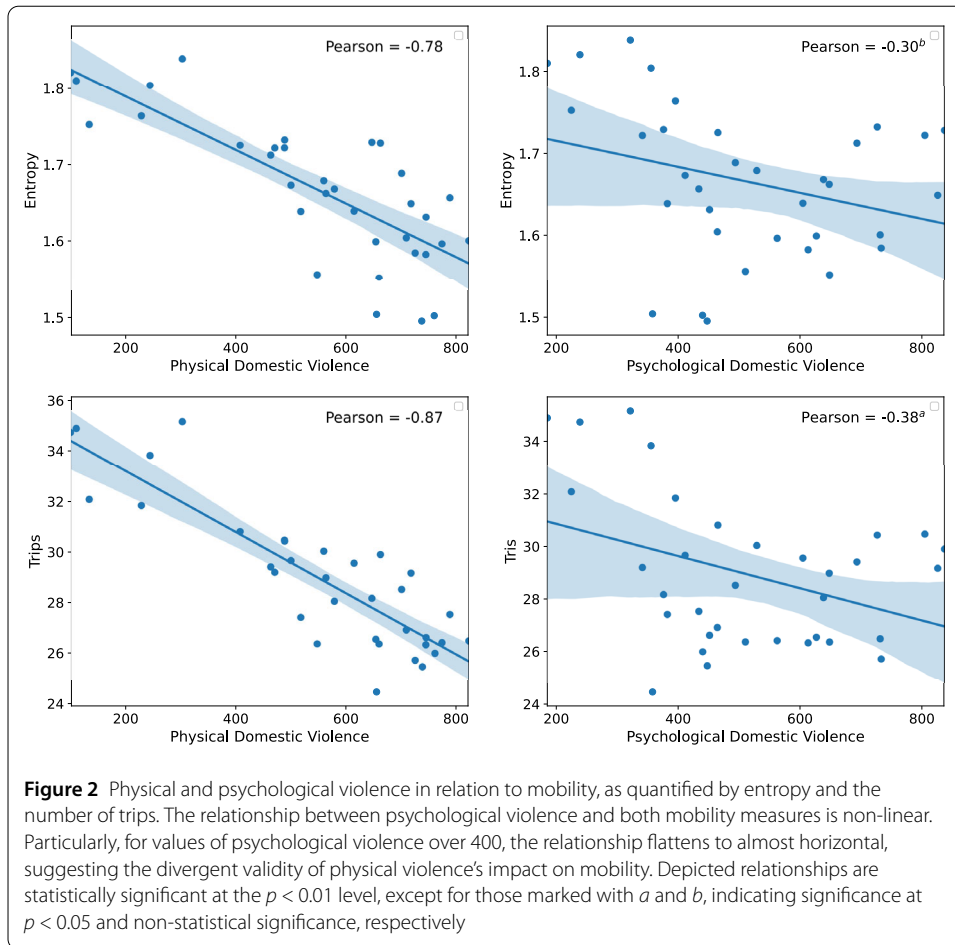
While traditional matching methods typically employ binary exposure variables (treated or untreated), the exposure variable in this study—domestic violence—is continuous. Consequently, we utilized a Generalized Propensity Score (GPS), computed using Generalized Boosted Models (GBM), to estimate causal effects [31, 34, 64, 66]. The GPS allowed us to treat domestic violence against women as a continuous exposure variable, control for confounding factors, and evaluate its impact on female mobility. The GPS was computed using the “twangContinuous” package in R.

4 Results

In the assessment of female mobility, measured as entropy and number of trips, the mean values are found to be 1.67 ± 0.03 and 28.94 ± 0.99 , respectively, within a 95% confidence interval. When examining the incidences of physical and psychological domestic violence, the corresponding mean values are reported as 553.7 ± 71.03 and 515 ± 61.05 per 100,000 women, according to police case data, within a 95% confidence interval. The t-test indicates no statistically significant differences between these average values (for more details see the Descriptive Statistics section in the Additional file 1).

With respect to education, the data reveals an average of 14.80 ± 0.40 and 15.07 ± 0.44 years of schooling for females and males, respectively, within a 95% confidence interval, implying no substantial gender disparities. In terms of employment, 74% of males report being employed, as compared to 58% of females. This data signifies a pronounced gender disparity in employment ($p < 0.01$). Moreover, the mean value for occupational segregation is measured at -0.08 , suggesting a widespread occupational segregation disadvantaging women (with positive values denoting segregation favoring women and negative values favoring men).

In relation to mobility and violence, only physical violence shows a substantial correlation ($p < 0.01$) with female mobility, denoting a Pearson’s correlation coefficient of -0.78



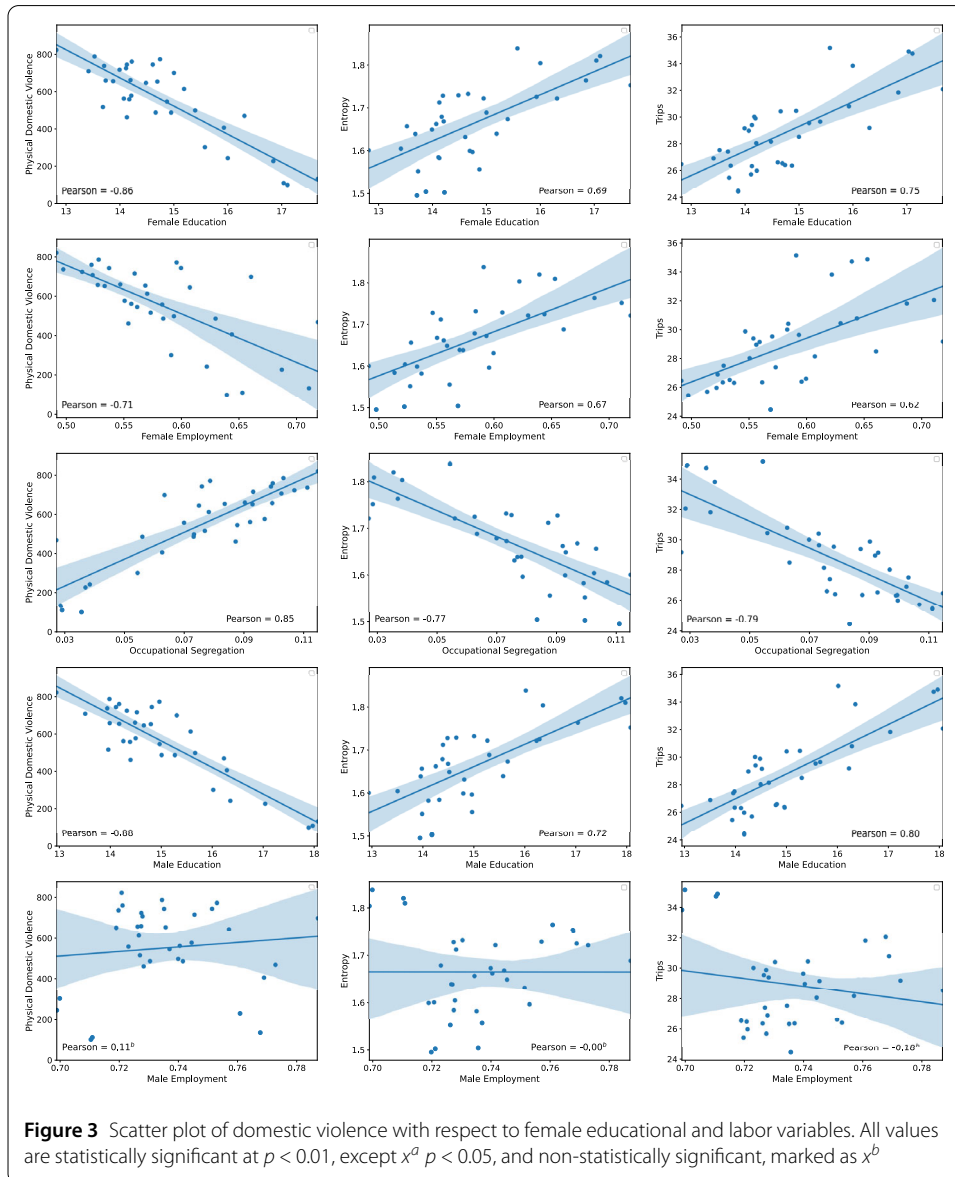
for entropy and -0.87 for the number of trips. The negative correlation with entropy suggests that as women's visits to diverse locations increase, the incidence of physical violence they encounter decreases. Similarly, the number of trips demonstrates that an increase in women's mobility correlates with a decrease in the physical violence they face.

The relationship between psychological violence and both metrics of mobility—entropy and the number of trips—is non-linear. Intriguingly, for instances where psychological violence exceeds 400, the relationship appears to plateau, essentially becoming horizontal. This pattern underscores the divergent validity of the impact of physical violence, as opposed to psychological violence, on women's mobility. Concretely, psychological violence shows only a weak, albeit statistically significant, correlation with the number of trips taken by women ($-0.38, p < 0.05$). Conversely, the correlation with entropy is weak and not statistically significant (-0.30), further illustrating the nuanced impact of different types of violence on mobility. Visual representations of these relationships are illustrated in Fig. 2.

Table 1 and Fig. 3 present the correlations between domestic violence against women, female mobility, education, employment, and occupational segregation. With the exception of male employment (see row 5, Fig. 3), all variables demonstrate a significant correlation with both domestic violence and female mobility ($p < 0.01$). Notably, the comparatively flatter relationship observed between male education and violence, and mobility, underscores the divergent validity of our findings related to female employment.

Table 1 Pearson’s correlation between domestic violence/mobility and educational and labor variables. Relationships are statistically significant at the $p < 0.01$ level, except for those marked with *a* and *b*, indicating significance at $p < 0.05$ and non-statistical significance, respectively

	Physical violence	Psychological violence	Entropy	Trips
Male education	-0.88	-0.59	0.72	0.80
Female education	-0.86	-0.60	0.69	0.75
Male employment	0.11 ^b	-0.01 ^b	-0.00 ^b	-0.18 ^b
Female employment	-0.71	-0.53	0.67	0.62
Occupational segregation	0.85	0.61	-0.77	-0.79



Both male and female education show a strong negative correlation with physical violence (column 1, row 1 and row 4, Fig. 3), with coefficients of -0.88 and -0.86 , respectively. Psychological violence also negatively correlates with education, albeit less strongly, with coefficients of -0.59 and -0.60 for males and females, respectively (Table 1). These re-

sults suggest that higher education levels correspond to lower rates of domestic violence against women.

Female employment is inversely related to both forms of domestic violence (Table 1), showing a stronger correlation with physical violence (-0.71) than with psychological violence (-0.53). Consequently, an increase in female employment could contribute to reducing physical and psychological violence against women. Occupational segregation also shows a strong positive correlation with domestic violence (Table 1), more prominently with physical violence (0.85) than with psychological violence (0.61). This suggests that greater gender disparities in labor are associated with higher instances of domestic violence against women, particularly physical violence (row 3, Fig. 3).

Turning our attention to mobility, both female (columns 2 and 3, row 1, Fig. 3) and male education levels (columns 2 and 3, row 4, Fig. 3) positively correlate with entropy (0.72 and 0.69 , respectively), suggesting that increased education levels are associated with higher mobility. Female employment also shows a positive correlation with entropy (0.67), implying that higher female employment rates are associated with higher mobility. However, the correlation with occupational segregation is negative (-0.77), suggesting that increased labor disparities favoring men are associated with reduced female mobility.

Regarding the number of trips, both male and female education exhibit positive correlations of 0.80 and 0.75 , respectively, suggesting that female trips increase with rising education levels. Similarly, female employment shows a positive correlation (0.62), indicating that greater female labor participation is related to increased mobility. Meanwhile, occupational segregation presents a negative correlation (-0.79), implying that increased gender disparities in labor are associated with fewer female trips.

4.1 Identification strategy

Our study revealed a significant negative correlation between physical violence and female mobility (Fig. 2). As such, our ensuing identification strategy analysis was targeted specifically towards the physical violence category. However, it's crucial to note that this significant relationship shows divergent validity, further underscoring the differentiated impact of physical violence, as opposed to other forms of violence, on women's mobility.

Our analysis, using a univariate regression model, underscores a strong dependency relationship (model 1, Table 2), suggesting that female mobility might be influenced by the extent of physical violence against women in the community ($p < 0.01$).

In the subsequent multiple linear regression models, we incorporated variables related to economic independence—such as female education, female employment, and occupational segregation—which have been identified in the literature as potential confounders of the relationship between domestic violence and mobility [16, 38]. In constructing these models, we adhered to five distinct specifications.

In all of these specifications, domestic violence consistently displayed a negative and significant impact on mobility ($p < 0.01$), even after accounting for confounders that were found to be significantly correlated with the number of female trips (Table 1). This result suggests that an increase in domestic violence rates would be accompanied by a decrease in the number of trips undertaken by women. Visual representations of the marginal effects of these predictions can be found in the Model Robustness section of the Additional file 1.

Of note, due to significant collinearity issues, we refrained from constructing a model that incorporated both female employment and occupational segregation as these vari-

Table 2 Linear models (dependent variable: number of trips, independent variable: physical domestic violence). Standard errors in parentheses, x^a parameters statistically significant $p < 0.01$ and x^b statistically significant at $p < 0.05$

	Number of trips					
	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6
Intercept	35.6420 ^a (0.7143)	34.7498 ^a (7.4781)	35.0685 ^a (4.2967)	35.9671 ^a (0.7862)	34.8500 ^a (7.7316)	43.3223 ^a (10.2498)
Domestic violence	-0.0121 ^a (0.0012)	-0.0119 ^a (0.0024)	-0.0119 ^a (0.0017)	-0.0101 ^a (0.0023)	-0.0119 ^a (0.0025)	-0.0108 ^a (0.0025)
Female education		0.0509 (0.4248)			0.0208 (0.6065)	-0.4076 (0.5664)
Female employment			0.8254 (6.0953)		0.6162 (8.7023)	
Occupational segregation				18.6096 (18.7756)		30.8245 (25.4187)
R-squared	0.7569	0.7570	0.7570	0.7644	0.7571	0.7684
R-squared Adj.	0.7493	0.7413	0.7414	0.7492	0.7328	0.7452
N	34	34	34	34	34	34

Table 3 Matching estimates (dependent variable: trips, independent variable: physical domestic violence). Note that the estimations consider all confounders. Standard errors in parentheses, x^a parameters statistically significant $p < 0.01$ and x^b statistically significant at $p < 0.05$

	Model 2	Model 3	Model 4	Model 5	Model 6
Intercept	35.2250 ^a (0.7082)	35.9267 ^a (1.2335)	34.0335 ^a (0.7975)	35.2270 ^a (0.7260)	34.6722 ^a (0.7429)
Domestic violence	-0.0108 ^a (0.0013)	-0.0118 ^a (0.0020)	-0.0082 ^a (0.0013)	-0.0111 ^a (0.0012)	-0.0104 ^a (0.0014)

ables exhibited a strong correlation (Pearson’s index of 0.93, $p < 0.01$), which could undermine the robustness of the model.

In order to address concerns about potential omitted variables in our models, we employed the Ramsey RESET test, which is designed to detect any missing explanatory variables. Under the null hypothesis, the model is deemed well-specified and inclusive of the necessary variables, whereas the alternative hypothesis suggests the presence of omitted variables that could potentially influence the model’s interpretation and generate bias.

Strong statistical evidence from the Ramsey RESET test does not allow us to reject the null hypothesis, indicating no relevant variables were excluded from our models (Additional file 1, Model Robustness section). This outcome underpins the robustness of our models in explaining entropy (p-value=0.588) and the number of trips (p-value=0.585) as influenced by physical domestic violence, alleviating the concern of omitted variable bias.

The Ramsey test provides robustness to our models, even when we control for variables linked to economic independence, as these factors significantly contribute to explaining female mobility.

To further ensure the robustness of our findings, we applied Generalized Propensity Score Matching (GPS) to the number of trips data (Table 3). This technique was employed on the same five specifications utilized in the multiple linear regression models (Table 2).

The outcomes underpinned the initial results, underscoring a substantial negative correlation between female mobility and physical domestic violence, while controlling for factors such as female education, employment, and occupational segregation. Notably, both

the number of trips and entropy demonstrated substantial and statistically significant impacts ($p < 0.01$).

Given that we've adjusted for potential confounding variables associated with economic independence, this robustness check further solidifies the linkage between female mobility and physical violence. The marginal effects of these correlations are elaborated upon in the Model Robustness section of the Additional file 1.

As an additional validation step, we conducted the same analysis using entropy, a measure of an individual's mobility diversity. These alternative models are presented in the Entropy Models section in the Additional file 1. The outcomes further reinforced our original findings drawn from the number of trips, suggesting that our results aren't a product of the chosen measure for female mobility.

Considering the scope of our data set, with observations drawn from a specific set of communes, we have employed bootstrapping as a supplemental measure of robustness. When comparing interval estimates obtained with and without bootstrapping, no substantial differences emerge in terms of parameters and their statistical significance. This lends further credence to the robustness of our findings. For additional details on this process, please consult the Bootstrapping Models Section in the Additional file 1. Our analyses, therefore, hold steadfast regardless of the particular scale of our data set.

5 Discussion and conclusions

Our study provides empirical support for the proposed hypothesis, illustrating a negative correlation between female mobility and domestic violence against women. This relationship is significantly stronger in the case of physical violence. A rise in domestic violence levels leads to a noticeable decrease in female mobility, predominantly when physical violence is involved, as indicated by Pearson's correlation of -0.78 with entropy and -0.87 with the number of trips.

Our findings, derived from the multivariate and matched models, suggest a potential causal link between female mobility and physical domestic violence. Specifically, as physical violence against women escalates, their mobility diminishes. Interestingly, this correlation does not appear to be directly tied to agency factors linked with economic independence, such as education or female employment. However, when examining entropy, we found an association with the gender labor gap emerging from occupational segregation.

The absence of a strong relationship between psychological domestic violence and mobility may suggest that this form of violence is more insidious, exerting less impact on mobility among victims. This lack of correlation warrants further research, particularly given the high rates of unreported psychological violence cases in Chile. A substantial number of incidents are not captured in official records, with only 22.8% of psychological violence cases reported in 2017 and an even lower figure of 19% in 2020 according to the National Survey of Domestic Violence against Women conducted by the Center for Crime Studies and Analysis (CEAD, Chile). This underreporting may stem from a lack of awareness about the nature or specifics of psychological aggression against women. Moreover, psychological violence often coincides with physical violence, which is more likely to be reported or identified in authorities' records. Thus, the relative invisibility of psychological violence may mask its effects on female mobility.

Economic autonomy serves as a crucial element in gender equality, potentially acting as a buffer against violence towards women. Both women's employment and educational

attainment are known to shape their mobility, thereby indirectly affecting gender violence [61]. However, existing research presents a complex picture, with no definitive consensus on the relationship between female employment and violence against women [13, 30, 60]. In our study, while we identified a significant correlation between female employment, mobility, and domestic violence against women, this factor did not serve as a primary determinant of women's mobility. Likewise, the impact of female education on domestic violence remains ambiguous [21, 40, 60, 65]. Despite our findings indicating a significant association between female education, mobility, and violence, we did not identify a direct causal link. Therefore, our study does not provide evidence to suggest that female employment and education act as protective factors against domestic violence against women.

Interestingly, we observed a strong, negative, and significant correlation between female mobility and occupational segregation. Although this gender labor gap fails to explain women's mobility, it merits attention given that female labor participation and mobility offer valuable insights into women's contribution to economic growth, access to economic resources, and overall well-being.

Turning to the issue of negative partner attitudes and controlling behaviors impacting female mobility and employment, our analysis indicates a positive correlation between male education and female mobility, with an inverse relationship to physical domestic violence. This observation suggests that higher male education levels correspond with decreased violence against women and increased mobility, lending support to the perspective that male education promotes access to information and augments women's independence [13, 20, 30]. Contrastingly, our study found no significant relationship between male employment and either female mobility or domestic violence against women, providing no evidence to suggest that women's independence is influenced by men's employment status [13].

The scholarly discourse around urban mobility has yet to incorporate a comprehensive gender-focused lens. An exploratory study investigating mobility in Santiago highlighted discernable gender differences in frequently visited locations [23]. In parallel, the territorial distribution of domestic violence against women in Santiago reveals notable concentration patterns,² associated with areas of limited mobility. Consequently, it becomes vital to scrutinize these phenomena through a gendered lens, given that mobility serves as a proxy for the dynamic behavior of individuals [49], and violence against women is inevitably intertwined with this relationship.

Violence against women is a multidimensional phenomenon, due to the personal, psychological, or socioeconomic characteristics of both, the victim and the aggressor. Therefore, future research endeavors should further elucidate the variables influencing domestic violence against women and its repercussions. Also, other types of violence exist, such as economic and labor violence, and they could also affect female mobility. Economic violence, which manifests itself in a domestic context, occurs when the woman is economically dependent on her partner. And workplace violence occurs in the workplace with psychological or emotional aggression by an authority.

This paper employs mobility measures gleaned from digital traces of mobile devices to elucidate the crime of domestic violence committed against women. This evidence of-

²<https://n9.cl/tugn>.

fers valuable insights that could empower policymakers to devise and implement targeted strategies to mitigate or eradicate this pervasive issue.

The intricate relationship between domestic violence and female mobility is further complicated when considering the diverse socio-economic backgrounds and the individual circumstances of women. Education and employment do not operate in isolation but are part of a broader socio-cultural fabric that influences female autonomy. For instance, while higher education provides women with greater mobility and economic independence, it's crucial to also weigh cultural norms and power dynamics in relationships. A woman's decision to mobilize or seek employment is not solely a matter of economic need or opportunity but is also influenced by partner dynamics, familial expectations, and societal roles that may either facilitate or restrict her movement [1, 42, 51, 52].

Furthermore, partner dynamics can either exacerbate or mitigate the effects of domestic violence on women's mobility. Controlling behaviors by partners may impose limitations on women's access to employment or education, effectively curtailing their mobility and reinforcing their vulnerability to further violence. On the other hand, supportive partners can play a pivotal role in promoting women's mobility and access to resources, acting as a buffer against the impacts of violence [15]. Hence, the consequences of domestic violence on female mobility can only be fully understood by examining these interdependencies within the context of individual and societal structures that govern women's lives.

Our analysis suggests that while the direct causal links between female education, employment, and domestic violence remain ambiguous, the association between these factors and female mobility is significant. It is this mobility, or lack thereof, that may serve as a key indicator of a woman's ability to navigate through and potentially escape from abusive circumstances. Occupational segregation, which reflects broader societal gender biases, indirectly contributes to the complexities of domestic violence by influencing the spaces women occupy and their relative freedom within them. These insights highlight the need for multi-dimensional policy approaches that address not only the symptoms of domestic violence but also its socio-economic determinants, supporting women's mobility and autonomy as essential components of such strategies.

In closing, the research presented in this paper underscores the importance of a nuanced understanding of the various factors influencing domestic violence against women. We advocate for the necessity of an integrated approach that considers the individual, relational, and societal dimensions shaping female mobility. By doing so, we contribute to the critical discourse on violence against women and provide actionable insights for stakeholders aiming to foster safer, more equitable environments for women to move freely and without fear.

6 Limitations

While our study provides valuable insights into the complex relationship between female mobility and domestic violence, it is subject to certain limitations. The first limitation pertains to the level of aggregation of our data. Our analyses are anchored in commune-level data from Santiago, Chile. Hereby, extrapolating the results to individual behaviors or differing geographical contexts should be undertaken with caution [49]. Yet, acquiring individual-level data on violence is inherently challenging due to privacy and ethical concerns, and it is particularly difficult to match such data with mobility data. For more details on representativeness and privacy issues of the mobility measure, see subsection S1.1.2 of the Additional file 1.

Our current analysis is constrained by the granularity of our data, which is at the tower level. Preliminary investigations revealed that the signal degrades substantially at more granular levels, such as neighborhoods or city blocks, resulting in a loss of correlation. This issue is compounded by factors like the non-proximity-based connections of individuals to antennas due to the necessity of a direct line of sight and the sparse distribution of antennas in residential areas, which necessitate a certain level of data aggregation to maintain analytical robustness.

Second, while the asynchrony of the data could be a limitation, as noted in the Data subsection, the data on domestic violence against women over the last decade shows stability. Particularly, a correlation of 0.953 is observed between 2016 and 2017, reflecting a representative pattern.

Third, the measure of female mobility used in our study can be potentially biased due to its dependence on data from a single mobile service provider with about 40% market share and the spatial granularity of cellphone antennas. Yet, it remains the most viable option for this type of research currently available. The data may not capture the full scope of female mobility, especially considering those without mobile devices or who choose not to use them regularly. However, despite these limitations, mobile device data provides us with the most comprehensive and accessible method of capturing mobility patterns, as it is the state-of-the-art data source for studying mobility.

Fourth, our study relies on officially reported instances of domestic violence. This is an important limitation, as it is widely acknowledged that many instances of domestic violence go unreported. Despite this, reported cases currently represent the most reliable and accessible data for such analyses. Therefore, while our analysis might not capture the totality of instances of domestic violence, it does provide a robust representation of the patterns and prevalence of the officially recognized situation.

Finally, despite our efforts to control for a range of potential confounding factors identified in the existing literature, we recognize that domestic violence is multi-dimensional and influenced by various socio-cultural, economic, and individual factors that may not have been considered in our models. While the Ramsey RESET test supported our model specification, indicating no omitted variables, it is important to remember that this does not eliminate the possibility of unmeasured or unobserved confounding variables influencing our results.

Despite these limitations, we believe our study contributes significantly to understanding the relationship between female mobility and domestic violence, and we hope that it will inspire further research in this crucial area.

Supplementary information

Supplementary information accompanies this paper at <https://doi.org/10.1140/epjds/s13688-023-00430-5>.

[Additional file 1.](#) (PDF 2.3 MB)

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Abbreviations

INE, National Institute of Statistics, in Spanish Instituto Nacional de Estadística; CEAD, Center for Crime Studies and Analysis, in Spanish Centro de Estudios y Análisis del Delito; SernamEG, Chilean National Service for Women and Gender Equity, in Spanish Servicio Nacional de la Mujer y Equidad de Género; GPS, Generalized Propensity Score.

Availability of data and materials

The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

Declarations

Competing interests

The authors declare that they have no competing interests.

Author contributions

HC conceived and led the research project. HC, BL, and LF collaborated on the mobility analysis design. HC and RT worked on the econometric analysis design. HC was responsible for collecting, processing, and analyzing violence data, while LF handled the mobility data. All authors contributed to the data interpretation and results. CC wrote the manuscript in collaboration with CRS, HC, LB, LF, and RT. Finally, all authors thoroughly reviewed and approved the manuscript.

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