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Using mobile phone data to explore gender and age gaps in urban mobility. Revealing the changes after COVID-19 in the metropolitan region of Madrid (Spain)☆

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A B S T R A C T

Gender differences in mobility are common in cities but analyzing them using data from travel surveys is limited by the sample size and the lack of detailed spatial and temporal patterns for different population groups. Big data sources, such as mobile phone data, offer almost ubiquitous data of daily mobility patterns and their changes while including basic socio-demographic characteristics. This paper studies differences in urban mobility from a gender and age perspective following the COVID-19 pandemic, comparing daily patterns of February 2020 and 2023 for the metropolitan region of Madrid. Urban activity, changes in mobility, and the gender gap are analyzed using different temporal and spatial aggregations based on Transport Analysis Zones (TAZ) and travel flows. The results reflect that the gender gap in trips decreases while remaining for the distance travelled for all age groups after COVID-19. Temporal patterns changed with more trips in the daytime and fewer at night, while the distance travelled evolves towards shorter journeys. Although women still make fewer trips and shorter distances, young women have reversed the gender gap between 2020 and 2023. This paper highlights how gender and age are longitudinal and transversal factors shaping mobility over an individual's life course and how COVID-19 seems to have accelerated pre-existing changing trends in urban mobility. Understanding the nature and relevance of the social dynamics and the differences between each population group is essential for supporting the study of urban segregation and helping authorities manage mobility in the territory.

1. Introduction

Urban mobility patterns have a high spatial and temporal regularity (González et al., 2008) that reflects the lifestyle of the population and its different social groups. Mobility research enables the study of human behavior through its relationship with the territory, how people move around the city and their differences, attributed to both individual capabilities and spatial and sociocultural factors (Israel and Frenkel, 2018; Kaufmann et al., 2004; Randal et al., 2020; Vecchio and Martens, 2021). These global factors create population groups with specific mobility constraints that may negatively affect their opportunities and social interactions, like the case with women, resulting in the gender gap concept.

Urban mobility patterns have been mainly studied using household travel surveys, which offer detailed information on people's characteristics (gender, age, ethnicity, etc.), capabilities (transport options, income, attitudes, etc.) and travel details (purpose, origin-destination, etc.). However, they present some limitations when analyzing detailed spatial and temporal patterns, which might affect the analysis, including study of the gender gap. Firstly, there are technical issues in obtaining a large volume of data and with all socio-demographic groups equally represented. Secondly, people create data themselves with the associated human limitations, as surveys capture *"what people say they do"*. Surveys may also be biased and focus on, or forget about, specific questions that may underrepresent social and gender-based realities from non-dominant groups (Buvinic and Levine, 2016). Thirdly, replicating a survey over time requires a great effort in real-time tracking and verifying the data's representativeness and compatibility in the long-term period. All these issues make it necessary to apply careful data treatment when exploring specific socio-

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demographic contexts (Wang et al., 2022).

Since the 2010s, the application of geolocated Big Data sources in urban mobility studies has spread (Steenbruggen et al., 2015), and the use of mobile phone data in particular stands out (Blondel et al., 2015; Wang et al., 2018), with kind of a homogeneous data structure. The mobile phone has greater penetration, frequency and reliability in recording real mobility actively (call detail records, CDR) and passively. These characteristics make it almost ubiquitous in every social group, space and time, especially in urban contexts. Of course, this data has some weaknesses: data gaps can be solved by enriching data with external sources, for instance, to include household structure data or the probable transport mode; others are related to bias, technical difficulties, and ethical concerns (Calabrese et al., 2014; Järv et al., 2017), but the use of mobile phone records has significantly increased in recent years. In this vein, Wu and Zhou (2023) analyzed the main fields where Big Data sources are being applied to urban mobility. Of the six fields detected, half ("Human dynamics in spaces", "Travel behaviors and mobility patterns", "Socio-demographic heterogeneity") are closely related to mobility differences in the population.

This paper explores how the gender gap in mobility changed because of the COVID-19 pandemic, analyzing hourly detailed spatiotemporal dynamics from mobile phone records based on gender and age population groups. The study case covers the daily activity comparison of February 2020 and 2023 in the metropolitan region of Madrid (Spain). The rest of the paper is structured as follows. Section 2 provides a literature review and defines the analysis approach of the paper. Section 3 details the study area and the data used. Section 4 describes the methodology applied. Section 5 presents the results divided into two thematic blocks, and Section 6 develops the discussion and conclusions of the paper.

2. Literature review

Gender-based differences in mobility, defined as the gender gap, are a well-known topic in social sciences (Buvinic and Levine, 2016; Law, 1999). The gender gap has been traditionally studied using trip diary surveys from multiple approaches, such as events and everyday activities (Best and Lanzendorf, 2005), commuting trips (Crane, 2007; Sandow, 2008), household structure (Chidambaram and Scheiner, 2020; Tilley and Houston, 2016), urban structure (Ta et al., 2022) or transport choice (Scheiner, 2014). As Hanson (2010) pointed out, most of them agree with the "Big Generalization" that women present lower mobility rates in trips and distance travelled and demonstrate that gender gap is a common phenomenon in cities, shaped by spatial, sociocultural and individual contexts. Hanson also collected the main findings made in literature, such as women's spatial footprint is smaller than men's, they travel less by car, their working patterns are less mobile and more diurnal, they make more trip chains, they depend more on public transport, and they undertake disproportionate household and dependents care duties. Gender differences in mobility are also known to vary significantly with age groups. One interesting approach is centered on people's life stage and the life course of generations (Elder Jr. et al., 2007). This theory highlights that "events" (such us COVID-19) have different effects on people, based on their life stage as they bring different realities and capabilities for adapting to new conditions. Hence, gender gap studies are frequently formulated through population groups that includes age as a relevant variable.

Some cultural changes, such as the inclusion of women in the labor force, a higher economic independence or the consequent growth of women's motorization, have notably reduced the gender gap in recent decades. However, important gender-based roles still arise at specific events, especially the birth of children (Best and Lanzendorf, 2005), while activities and travel purposes are very similar for young and childless men and women in Germany. Similar results were described by Scheiner (2014), which categorized important events conditioning people's transport choice into household and family, employment context and residential location. Considering changes over time, Scheiner also found trends in driving patterns towards gender convergence, as well as a constant reduction in the use of cars between young male cohorts, compared with the same cohorts in the 1960s. This decline has been reported in other studies in developed economies, known as 'peak car' (Tilley and Houston, 2016; Cubells et al., 2020), which is leading to lower mobility in distance travelled and car use rates. Interestingly, it is different in gender; while young women maintain or slightly reduce the distance they travel, young men drastically reduce it. This way, young women may experience higher mobility values in some cities, showing a gender turnaround in recent years. On the other hand, older cohorts seem to maintain their gender gap in non-commuting (Tilley and Houston, 2016) and commuting trips (Sandow, 2008) in different European contexts.

Mobile phone data and similar sources have offered more spatial and temporal detail in urban mobility studies with a gender perspective. For example, women in Seoul have shown more activity in residential areas and easily accessible spaces (Jo et al., 2020), mainly related to household and family duties. At the same time, women usually maintain greater contact with their natal family and close friends based on individuals' social networks, although they face more mobility restrictions than men (Puura et al., 2022). Regarding land use, women's mobility in Santiago (Chile) is usually concentrated in urban spaces such as shopping centers, hospitals and transport hubs (Gauvin et al., 2020), and smaller cities in Italy tend to present a higher gender gap as the urban vibrancy shrinks and the car use grows (Collins et al., 2023). These studies confirm that women tend to be more active in social-related environments, while men are more dynamic in the labor market, commuting greater distances. When combining gender and age, Cubells et al. (2023) studied the behavior of micro-mobility users in Barcelona and found that users change their speed as they age depending on the transport mode and reduce their speed when they have a child, but both trends happen later to men compared to women. Younger people have a lower risk perception, while women seem to be more sensitive to harassment, choosing fewer shared lanes and riding faster at night. Considering travel purposes and consumption patterns in Barcelona and Madrid, differences between men and women peak in middle age, as pointed out in (Lenormand et al., 2015). Women tend to travel shorter distances and engage in more non-working activities as their consumption patterns are spatially different. In fact, they clustered two representative groups of consumption, distinguishing "men, young individuals and active people" against "women, old individuals and inactive people".

Mobile phone data has also been crucial in the study of disruptive events such as the COVID-19 pandemic and its consequences on mobility (Lee and Eom, 2024), analyzing changes and new patterns in the population both at the national (Caselli et al., 2022) and the metropolitan level (Liu et al., 2023; Romanillos et al., 2021). Thanks to its massive coverage and real-time tracking, policymakers and health authorities have measured and contained the spread of the disease by imposing mobility restrictions. This way, global mobility rates dropped by more than 80 % during the peak of the pandemic all around the world; public transport modes decreased the most due to risk perception; high-income groups had more facilities to keep working remotely (Lee and Eom, 2024); and even residential relocation trends were measured in some cities (Al-Akioui and Monzon, 2023). Once again, differences by gender and age were measured in many cities. For example, as men are more enrolled in high mobility basic services, their mobility rates remained higher during stay-at-home and mobility restrictions. Working people and students experienced lower mobility rates than older and retired people, as they used to make more daily trips, and those activities tend to happen in places with a high concentration of people. Similarly, women reduced their mobility more, as it was highly related to academic activity restrictions, especially for women aged 25–44 (Caselli et al., 2022). The risk perception was differently experienced among population groups, where older people and women were more conscious than young people and low-income groups, who also faced higher unemployment rates. The COVID-19 pandemic was found to affect population unevenly, depending on their mobility patterns and their capabilities to modify them, which increased urban mobility inequalities through gender, age and income, and its long-term changes still need to be further analyzed (Lee and Eom, 2024).

The existing literature on urban mobility and the gender gap covers a vast research field using different sources of information (surveys, Big Data, etc.), socio-demographic factors (gender, age, income, etc.), indicators (median travel distance, users' behavior, travel choice, etc.), temporal approaches (everyday activity, disruptive events, etc.) and spatial contexts (metropolitan areas, land use, countries, etc.). However, we find that hourly urban mobility patterns after the COVID-19 pandemic need further analysis, as most of the literature focuses only on changes in mobility during the first year since the disease spread worldwide. The interest in the effects of COVID-19 seems to be waning rapidly, but determining changes in the long-term (new normality since 2023) and comparing it with previous trends will shed light on what to expect in the years to come. With this aim, we conduct a detailed spatial and temporal analysis in Madrid (Spain). This country was severely hit by the COVID-19, experiencing strict and lasting restrictions (Romanillos et al., 2021), making Madrid a relevant case study to explore its spatiotemporal effects on mobility. To do so, this paper measures hourly people's trips and travelled distance based on gender and age groups using phone data from 2020 and 2023.

3. Study area and dataset

The case study is the metropolitan region of Madrid (Fig. 1), where more than 6.2 million people lived in 2020 (Instituto de estadística. Comunidad de Madrid, 2024). Madrid city, with 3.3 million inhabitants, is divided into large areas of the City Center (1 million inhabitants) and Outer Madrid (2.3 million inhabitants), which are territorially differentiated by a ring highway (M-30) and the Manzanares riverbed in most of its perimeter. The Metropolitan Area comprises a network of medium-sized cities with 200,000 inhabitants each and other smaller towns, totaling a population of 2.9 million. The region presents a polycentric structure with many transport options and a high land use mixture, supporting complex mobility relations among all urban areas. However, the City Center remains the major area for shopping, working and leisure purposes.

The population is ageing rapidly (1.1 children per woman), and people over 45 are the majority in most of the city areas. However, the region also attracts many students and working-aged people from the rest of Spain and the world, with rising problems about housing affordability. Frequently, new families must move to Outer Madrid or the Metropolitan Area looking for better housing prices and benefits, increasing the younger population. Although concentration-segregation dynamics of minorities are not of special concern in Madrid, some areas, like the historic center, may present different gender and age patterns due to ethnic or LGBT communities. By gender, even considering that women are more numerous than men in the region, many spaces in the City Center concentrate a higher female population, while the gender balance switches to a male majority in some distant areas.

Between 2020 and 2023, the population of the studied areas dropped by 0.72 % (45,000 people). In the City Center, the population fell by 2.17 % (22,000 people), and in Outer Madrid, it fell by 1.38 % (32,000 people), but it increased by 0.30 % (8900 people) in the Metropolitan Area. At the gender level, the pattern is shared by both genders, but women experienced greater absolute and relative falls throughout the city of Madrid and a greater increase in population in the Metropolitan Area.

The dataset available for the study is composed of Origin-Destination matrices of travel flows aggregated into 1034 Transport Analysis Zones (TAZ),[1] totaling more than 160 million trips in the region. These flows were defined using mobile phone data composed of event-driven data (CDR on voice calls, text messages and internet connection) and network-driven data (passive interaction with the telephone network), ensuring a greater coverage of mobility patterns. Matrices record mobility patterns for the entire population with a minimum duration of 20 min from a sample of national users of one of the three largest Mobile Network Operators in Spain ($>$ 20 % market share) (NOMMON, 2024). This dataset contains data on hourly mobility, number of trips and distance in a straight line between TAZs for working days (excluding Friday because it evolves into weekend patterns) from 17 to 20 February 2020 and from 13 to 16 February 2023.

All users are anonymized and aggregated by gender and four age groups ($<$ 25; 25–45; 45–65; $\geq$ 65), which totals eight population groups for the study. Therefore, the dataset lacks the individual longitudinal component of users; that is, it is impossible to associate two simultaneous trips with the same user and know how many trips are made in one day nor their travel purpose. The user's TAZ of residence associated with each trip is also unknown. This way, only travel flows by population groups are known, guaranteeing the protection of the users' privacy, their activities, and the places they frequently visit. To estimate the mean number of trips per person, the volume of trips by population group in the dataset was assigned to the corresponding population group defined by the official census, which matches the spatial division into TAZs. This approach does not substantially differ from the actual mean number of trips per person, as daily travel routines tend to be highly consistent across population groups, and annual variations in trips per person remain meaningful when population sizes are stable.

No extraordinary events that could cause a change in regular mobility patterns occurred during the weeks studied. However, it should be remembered that the week of 2020 refers to a typical week before the lockdowns caused by the COVID-19 pandemic, while the week of 2023 is a normal post-pandemic week. The aggregated mobile phone records were stored in PostgreSQL datasets and processed in several Python scripts explicitly created for this study. The resulting cartography was created in ArcGIS Pro.

4. Methods

This research analyzes hourly geolocated travel flows regarding the number of trips per person and average distance to explore changes in urban mobility from a gender and age perspective. Every trip is completely anonymized and aggregated, creating travel flows by TAZs where the available variables are origin-destination, hour, gender, age, number of trips and distance. Despite being limited in terms of descriptive variables, the dataset offers a high spatial and temporal granularity of people's mobility patterns in 2020 and 2023. Thus, the analysis is structured in two study blocks (Table 1). Block I addresses regional differences with higher temporal detail, while Block II explores the spatial differences reaching higher detail at the TAZ level.

In each study block, daily urban mobility is progressively analyzed using a three-step approach composed of urban activity, changes in mobility and the gender gap.

- Urban activity summarizes the daily mobility rhythm in terms of the number of trips and average distance. Thus, Fig. 2 reflects when more trips and/or intercity trips occur hour by hour, while Table 3 (fourth and fifth columns) summarizes the daily travel relations among the three large areas in the region. These results are the starting point for

[1] Transport Analysis Zones available at: *https://gestiona.comunidad.madrid/nomecalles_web/#/inicio*

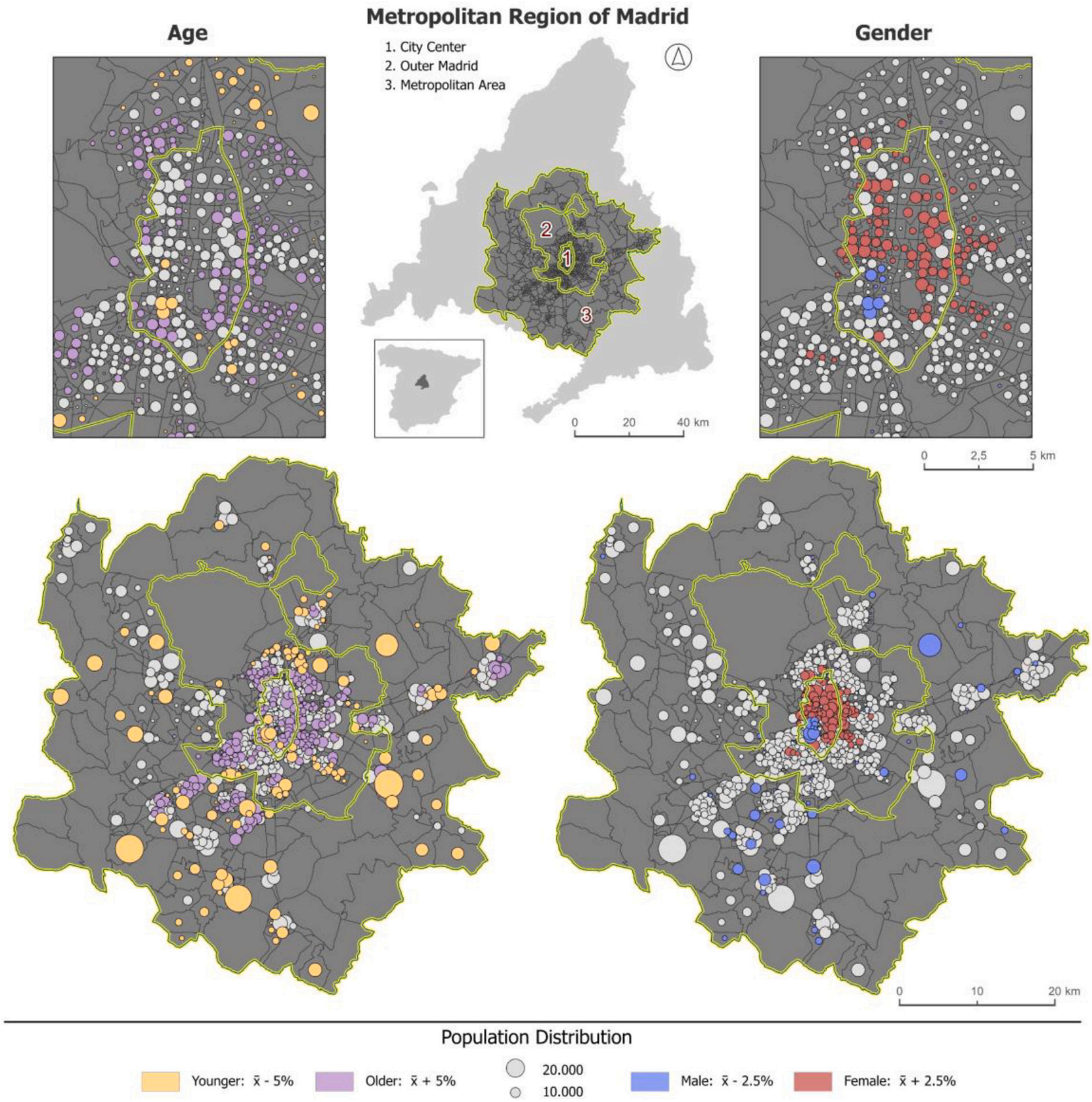

Fig. 1. Study area. The metropolitan region of Madrid (Spain).

Table 1
Structure, variables and level of detail of the results.

	Analysis 20–23	Age Group	Frequency	Comparison	Spatial Unit	Measure	Representation
	Urban Activity		Hour	Study period		Trips/person Average travel distance	Fig. 2
Block I (Section 5.1)	Changes in Mobility Gender Gap	Yes	Hour	2023. Based on 2020 Women. Based on Men	Aggregated	Trips/person [%] Average travel distance [%]	Fig. 3 Fig. 4
	Summary		Day	Study period		Trips/person and % Average travel distance and %	Table 2
	Urban Activity	Yes		2020	Large Areas	Trips/h Average travel distance	Table 3
Block II (Section 5.2)	Changes in Mobility	No	Day	2023. Based on 2020	TAZ	75th percentile Population and Trips-hour/km^2	Fig. 5
		Yes		2023. Based on 2020	Large Areas	Trips [%] Average travel distance [%]	Table 3
	Gender Gap		Time Slots	2020 and 2023 Differences	TAZ	Main travel flows	Fig. 6

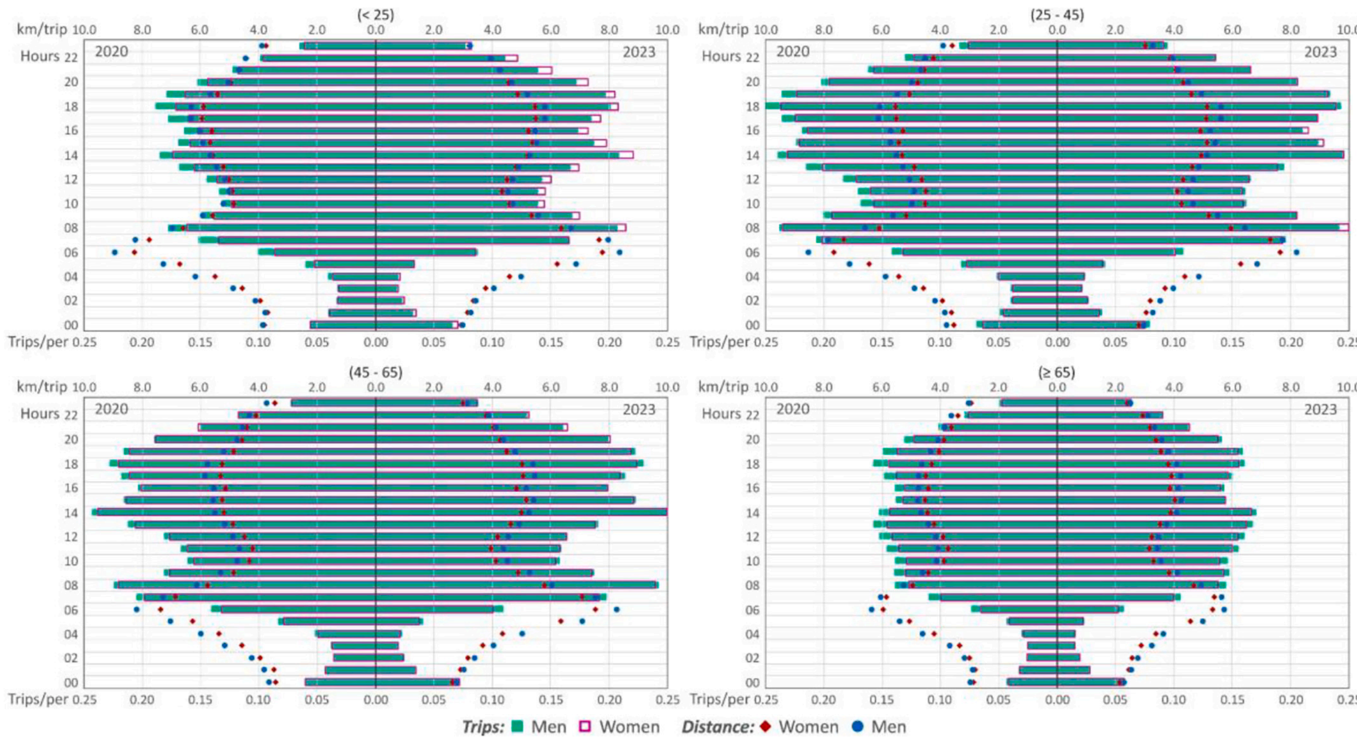

Fig. 2. Urban activity in trips/person (bars) and average travel distance (dots).

analyzing the changes in mobility and the gender gap, which are measured as a percentage of the urban activity.

- Changes in mobility highlight how urban activity evolves during the study period relative to each population group (1). It compares the 2023 urban activity (UA) of each group using their 2020 values as a reference. Thus, a negative value implies a reduction in trips or average distance compared to 2020 and vice versa (Fig. 3 and Table 3).

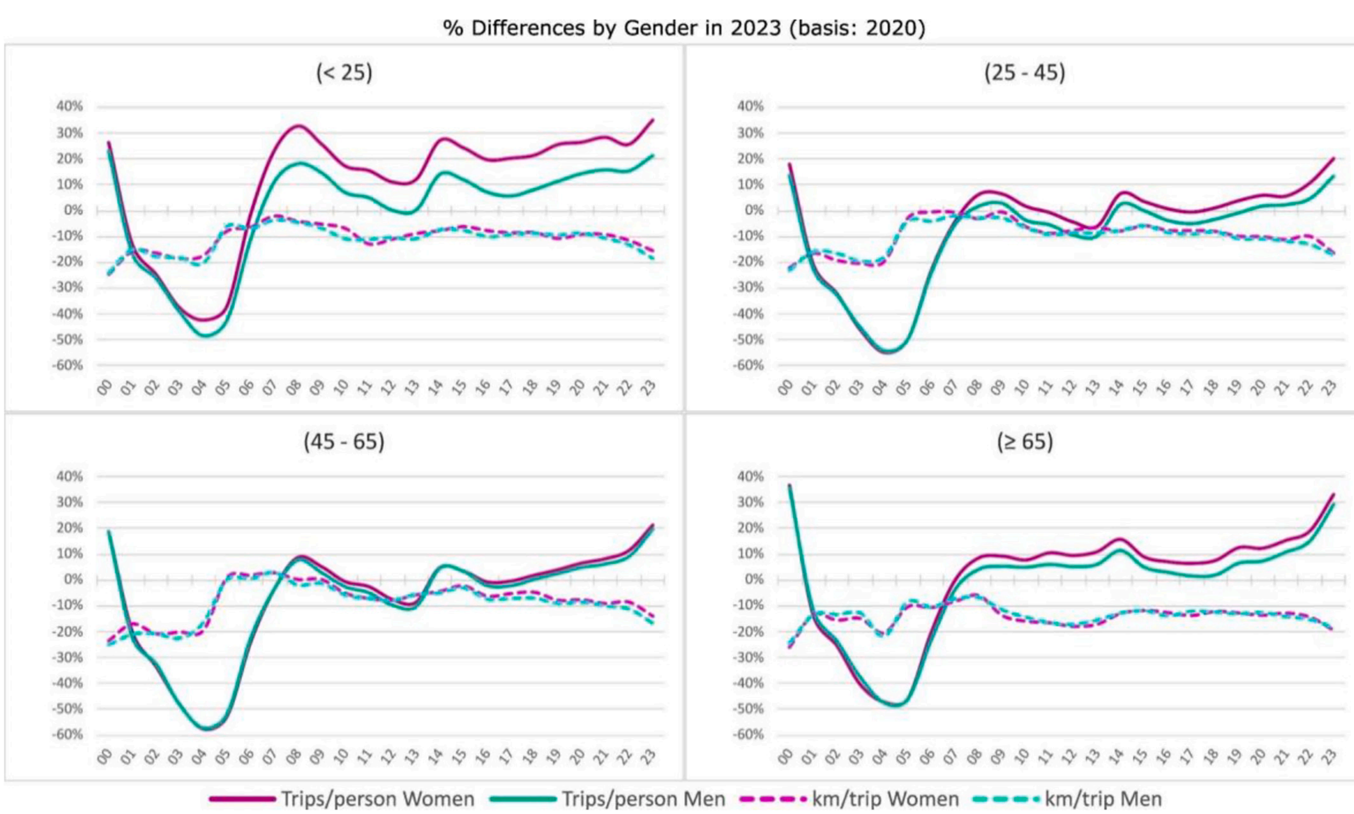

Fig. 3. Changes in urban mobility by age group.

$$Changes\ in\ mobility_{ij} = \frac{UA_{2023ij}}{UA_{2020ij}} * 100 - 100 \forall i \in Gender, \forall j \in Age \quad (1)$$

Natural trends in housing may also cause changes in urban activity without a real change in people's behavior. Fig. 5 addresses this possible effect by comparing changes in the residential distribution and urban activity by TAZ.

- The gender gap captures the differences between men and women for each age group over time (2). As women usually have lower mobility and male patterns are historically used to analyze human behavior, we took male values as a reference line to represent the gap. Thus, a positive gap implies that women travel more or longer distances in the year analyzed and vice versa (Fig. 5).

$$Gender\ Gap_{ij} = \frac{UA_{Femaleij}}{UA_{Maleij}} * 100 - 100 \forall i \in Year, \forall j \in Age \quad (2)$$

The representation of the gender gap in the territory has been aggregated using four time slots adapted to the urban rhythm of the case study (06:00–09:59), (10:00–14:59), (15:00–20:59), (21:00–23:59) (Fig. 6). The travel flows represent spatial relationships with at least 10 trips/h on average and show the existing gender gap in 2020 using colors in each flow. These flows also include the changing trend of the gender gap between 2020 and 2023 by varying the color intensity, regardless of the reason or magnitude of the change recorded. Travel flows between TAZs tend to create mesh structures that outline urban areas with a relevant gender gap and their evolution, thus reflecting changes in social dynamics by gender and age.

Annual changes reveal underlying trends in mobility patterns due to demographic changes, events or culture (e.g. disruptive events, new technologies, ageing population, etc.). Thus, by using Big Data, differences in human behavior can be studied for daily and annual periods simultaneously. This methodology is easily replicable for gender gap research in any metropolitan region, with sufficient knowledge of the local gender roles, demographic characteristics, time slot culture (peak hour, lunch, restaurant closing time, etc.) and general land use distribution. At the same time, it may be modified to attend ethnic or income-related differences if population groups are properly defined.

5. Results

5.1. Mobility differences by gender and age group (block I)

a. Urban activity and changes in mobility

As a starting point, the urban activity profiles were determined for each population group based on trips per person (bars) and average travel distance (dots). These profiles reflect hourly levels of mobility over a regular working day for 2020 (left) and 2023 (right).

Various well-known patterns such as commuting trips, night-time activity or time periods with longer average distances, are noticeable. In line with other studies in literature, the activity profiles reflect that women tend to travel less and shorter distances than men in 2020, while some hours with more trips for women are detected in 2023, especially for the youngest. However, the hourly profile remains generally symmetric for both genders in all age groups. People under $<$25 have experienced more changes in the number of trips because their jobs, housing locations, and social dynamics are usually more fragile and flexible. Working-age groups (25–45; 45–65) are the groups which travel more on average, although younger people travel longer distances. Working-age groups show two peaks in the number of trips, one in the morning (07:00–08:00) and another after midday (14:00–15:00), giving way to a few hours of high activity until the end of the afternoon. Older people ($\geq$ 65) do not show a clear peak in their trips, but rather a constant level of activity in the morning and afternoon due to a lack of commuting trips and more free time. In contrast, the average travel distance for all age groups presents a single peak of greater distance in the morning (06:00–07:00), maintaining a smooth variation of distances for the rest of the day. This pattern indicates a greater variety of destinations in the afternoon and a greater presence of intermediate stops on trips back home compared to commuting trips.

Changes in mobility come from comparing the urban activity profiles of 2023 to those of 2020 as a baseline by population group, number of trips, and average distance. This way, hourly positive values mean higher rates in 2023 than 2020 and vice versa (Fig. 3).

Among the years analyzed, the number of trips for both genders in all age groups dropped in the early morning (01:00–06:00), but it generally increased for the rest of the day, even in the early hours at night. Positive maximum values match peak hours in the urban activity profiles (06:00 and 14:00) and the afternoon until midnight. These trends may show higher hybrid or part-time jobs for peaks at commuting hours. The increase in trips in the afternoon might also show changes in commuting. Also, higher values at night (21:00–00:00) followed by a sharp decline suggest an intention to finish activities earlier, concentrating their trips back home before 00:00, while activities in the early morning have drastically reduced by half.

Both genders show similar changes, but the intensity for women tend towards positive values more noticeably than for men. This tendency indicates that women have increased their number of trips to a greater extent, especially young women, with maximum relative increases of 30 % and nearly doubling the growth compared to men. Contrary to the number of trips, the average travel distance hardly differs by gender but shows a clear trend towards reduction throughout the day and for all groups, with a marked decline in the early morning. Despite recording changes in travel patterns to more or fewer trips, all these changes evolve towards closer activities or more trip chains.

When comparing changes between age groups, the less labor-active groups ($<$ 25; $\geq$ 65) show a greater growth in the number of trips, while the most labor-active groups show a smaller reduction in their average travel distance. In fact, 25–45 and 45–65 cohorts barely show a variation in the distance between 05:00 and 07:00, reflecting trips to work, although a lower number of trips was recorded for the same hours without a clear difference by gender.

b. Gender gap

The gender gap compares changes between the gender profiles from Fig. 3 by taking male values as a base line in both years. This way, hourly positive values mean higher activity (trips/distance) for women and vice versa, so the closer it is to zero, the smaller the gender gap is, both in positive and negative gap values (Fig. 4).

The results reaffirm the continuity of a gender gap in favor of men, both in the number of trips and average distance. However, the gap in the number of trips has reduced between 2020 and 2023 for the entire population. Generally, the gap in 2023 is smaller throughout the day, and unlike in 2020, it is possible to see bands of positive gap, that is, times when women make a greater number of trips; for instance, younger women have positive travel gap values for 2023 for most of the day. The rest of the population also reduced their gap, but the older the age group, the greater their gap in trips towards negative values. These results coincide with mobility trends highlighted in other studies, where women become more active and even turn around gap values in younger cohorts. It is noteworthy that the smallest gap in trips for 2020 was presented by the 45–65 cohort, reflecting a developed working life and greater independence for their potential older children, but it also changed the least in 2023, showing a more settled lifestyle. At the hourly level, the most significant negative gap is concentrated in the early morning, while the largest positive gap happens during commuting and early night hours. This change may reflect the differences in the labor

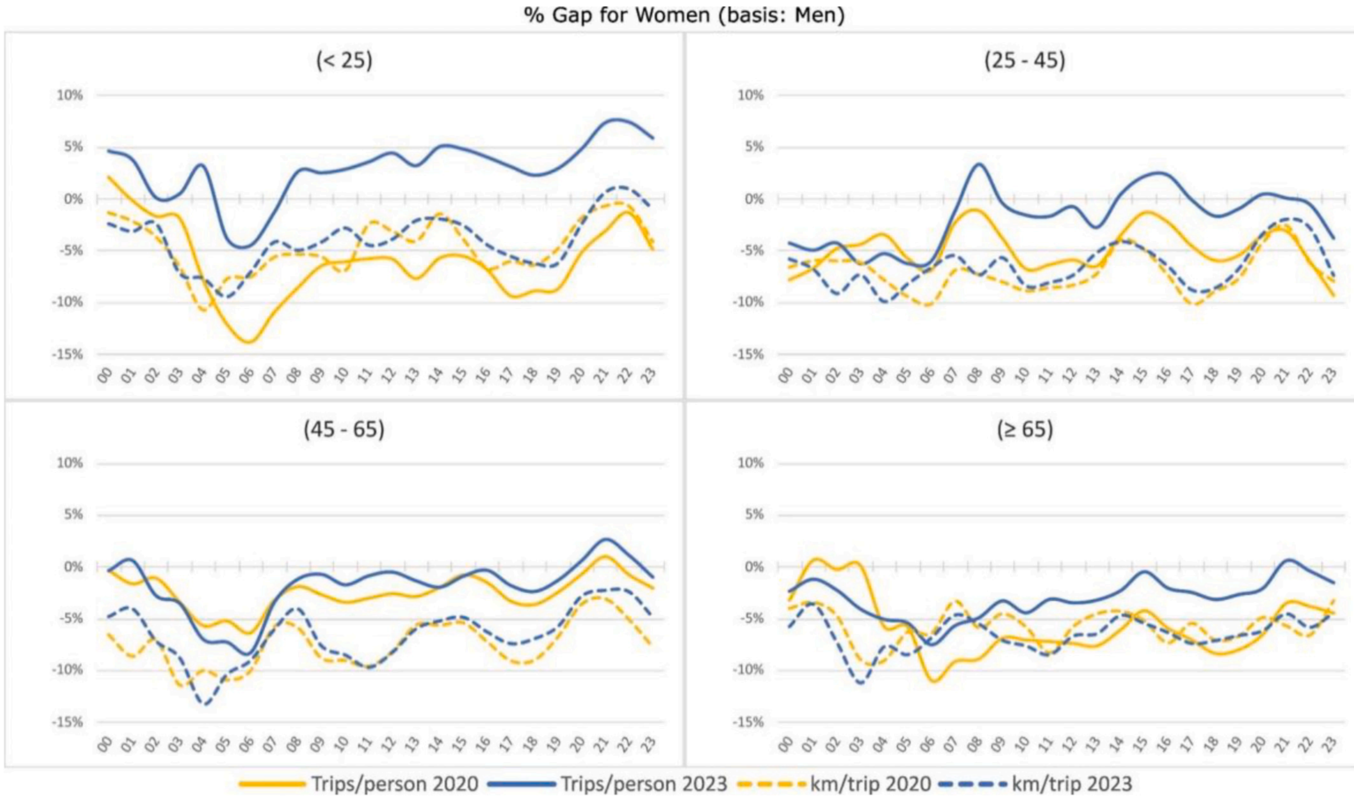

Fig. 4. The gender gap in urban mobility by age group.

market between genders, as women tend to do less night work and interact more with customers.

Unlike the number of trips, the gap in average distance has remained negative in both years, and changes have been small for all age groups. Trip distance gap also presents a time pattern, greater in negative values during the early morning and troughs between commuting hours, while being smaller during the early hours of night. Thus, women keep undertaking smaller distances than men, although the gap decreases in commuting hours. As changes in mobility by gender are nearly the same, the gender gap for distance remains in 2020 and 2023.

Table 2 shows the aggregated results of this section in global mean values to highlight changes and differences over the years considered. Globally, women have increased the number of trips per person while men have barely maintained theirs, creating a gender convergence during the study period. On the contrary, both genders have reduced the average distance travelled per trip, where the greater fall among men has led to a modest reduction in the gender gap. These results suggest that women's mobility may be more resilient after severe mobility restrictions, as they have recovered and even increased their number of trips. On the other hand, distance travelled has experienced a similar decrease by age group, where COVID-19 may have played an active role or just accelerated a previous trend (e.g. remote working, electronic shopping, etc.).

Over the years, the increase in the number of trips among the elderly and especially young people stands out, with changes that up to triple the evolution of men and even cause a positive global gap. Nevertheless, they also present the greatest reduction in their trip distance, showing the most flexible/fragile mobility. However, the moderate changes experienced by adults are more relevant and they smooth the global gaps because of the greater number of trips per person and greater population weight.

Table 2
Global urban mobility statistics.

Age Group	(Mean Population %)	Trips/person	2020	2023	Diff. 23/20	Age Group	Average Travel Distance (km)	2020	2023	Diff. 23/20
(< 25)	(12.1 %)	Women	2.71	3.20	18.0 %	(< 25)	Women	5.56	5.09	−8.5 %
	(12.7 %)	Men	2.91	3.09	6.4 %		Men	5.86	5.32	−9.3 %
		Gender Gap	−6.8 %	3.3 %			Gender Gap	−5.1 %	−4.3 %	
(25–45)	(14.4 %)	Women	3.67	3.62	−1.3 %	(25–45)	Women	5.28	4.88	−7.6 %
	(13.7 %)	Men	3.84	3.65	−5.1 %		Men	5.68	5.20	−8.5 %
		Gender Gap	−4.5 %	−0.6 %			Gender Gap	−7.1 %	−6.2 %	
(45–65)	(15.1 %)	Women	3.56	3.50	−1.8 %	(45–65)	Women	5.08	4.78	−5.8 %
	(13.8 %)	Men	3.65	3.54	−2.9 %		Men	5.48	5.11	−6.8 %
		Gender Gap	−2.4 %	−1.3 %			Gender Gap	−7.3 %	−6.4 %	
(≥ 65)	(10.7 %)	Women	2.34	2.51	7.2 %	(≥ 65)	Women	4.25	3.65	−14.1 %
	(7.5 %)	Men	2.51	2.58	3.0 %		Men	4.51	3.90	−13.6 %
		Gender Gap	−6.6 %	−2.8 %			Gender Gap	−5.9 %	−6.5 %	
Global	(52.3 %)	Women	3.15	3.26	3.5 %	Global	Women	5.12	4.70	−8.2 %
	(47.7 %)	Men	3.33	3.30	−0.9 %		Men	5.52	5.04	−8.8 %
		Gender Gap	−5.5 %	−1.3 %			Gender Gap	−7.4 %	−6.7 %	

5.2. Territorial differences in mobility by gender and age (block II)

a. Urban activity and changes in mobility

Mobility differences by gender and age also manifest differently across the territory, reflecting the use given to each area of the city (Fig. 5). Starting from a reduction of population in Madrid city and an increase in its Metropolitan Area (upper maps), urban activity has registered greater changes in the number of trips per TAZ without necessarily sharing the same trend of residential changes (lower maps).

This phenomenon is clearly seen in the City Center, where some TAZs have registered even less activity than loss of population, while other TAZs present more activity while reducing their population. On the contrary, many TAZs in Outer Madrid and the Metropolitan Area gain activity, confirming that the population tends to do more activities in their home neighborhoods and cities. Some unpopulated areas, like big urban green parks, business areas and industrial clusters, also present changes; in some cases, they lost more than 15 % of their 2020 activity. These results confirm that people's mobility patterns have changed and are not exclusively related to housing trends. Overall, urban activity increased by 3.73 % for women and decreased by 0.65 % for men in densely populated TAZs (75th percentile), while activity decreased by 3.11 % for women and 7.20 % for men in less populated areas.

Table 3 presents the changes in travel flows relations (trips and distance) by large areas and considers three levels of population group combinations. The first level disaggregates gender and age; the second one only disaggregates gender; and the third one presents travel flows for all residents together.

Beginning with results for all residents, trips between large areas have been reduced in favor of internal trips in Outer Madrid and the Metropolitan Area (trips to and from the same large area). This change causes a greater activity distribution in the territory, increasing with the distance to the City Center. On the contrary, the City Center decreased its activity even internally, which may reflect fewer trips among residents and visitors from other large areas apart from commuting. These results explain the reduction in the average trip distance (Table 2), but the internal distance in all large areas also fell, showing that shorter trips go beyond mobility among large areas and evolve towards activities of greater proximity.

Disaggregated by gender, women present greater internal activity

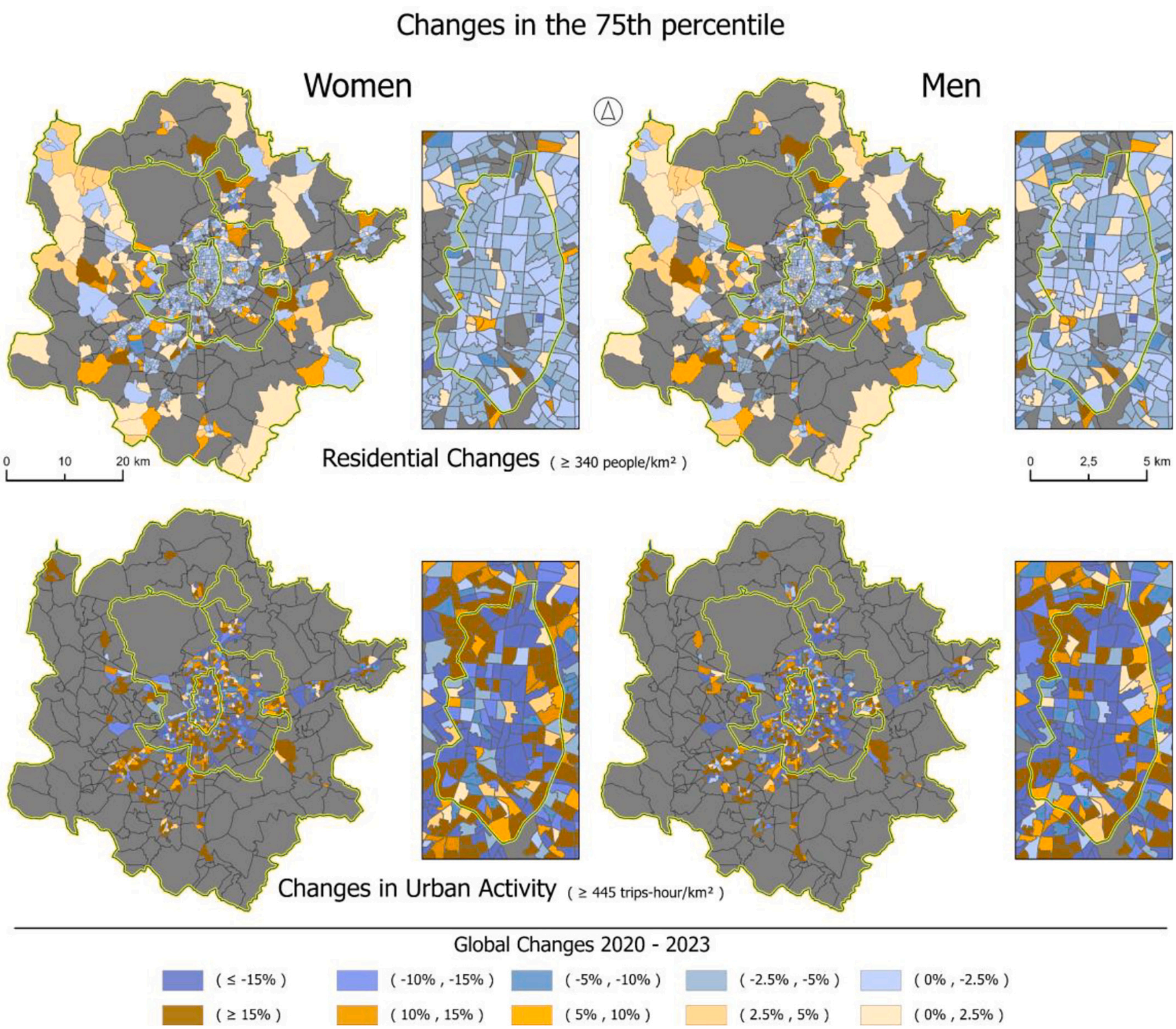

Fig. 5. Changes in population (upper maps) and urban activity (lower maps) by TAZ.

Table 3
Average daily changes in the Origin-Destination travel matrix by large areas.

< 25		City Center	Outer Madrid	Metrop. Area	Trips/h (flows share %) /	Average Travel Distance (km)	Global Change
		Trips / Distance	Trips / Distance	Trips / Distance	(2020)		Trips / Distance
City Center	F	3.7% / -6.4%	4.7% / -5.5%	0.2% / 1.9%	17,900 (59.9; 28.9; 11.2) /	4.2	3.6% / -3.5%
	M	-5.9% / -7.1%	-7.6% / -5.9%	-9.0% / 1.3%	19,300 (58.7; 29.1; 12.1) /	4.4	-6.8% / -4.0%
Outer Madrid	F	5.0% / -5.2%	19.7% / -9.3%	7.9% / -3.6%	29,700 (17.5; 65.8; 16.7) /	5.1	15.1% / -8.7%
	M	-7.1% / -5.4%	10.7% / -10.3%	-6.0% / -2.3%	33,200 (17.0; 64.8; 18.2) /	5.3	4.6% / -10.1%
Metrop. Area	F	1.2% / 1.5%	7.8% / -3.5%	25.3% / -11.3%	39,000 (5.2; 12.7; 82.1) /	6.5	21.8% / -11.2%
	M	-9.2% / 1.5%	-5.9% / -2.9%	14.1% / -11.4%	44,200 (5.3; 13.7; 81.0) /	6.9	10.1% / -11.6%
25-45		**City Center**	**Outer Madrid**	**Metrop. Area**	**Trips/h (flows share %) /**	**Average Travel Distance (km)**	**Global Change**
		Trips / Distance	Trips / Distance	Trips / Distance	(2020)		Trips / Distance
City Center	F	-14.5% / -7.6%	-17.4% / -3.5%	-20.8% / 0.7%	35,000 (63.9; 26.8; 9.3) /	3.8	-15.9% / -5.4%
	M	-17.8% / -6.3%	-17.4% / -4.0%	-23.5% / 0.3%	33,600 (63.9; 25.8; 10.3) /	4.0	-18.3% / -5.0%
Outer Madrid	F	-17.3% / -2.9%	-2.1% / -6.6%	-13.4% / -0.9%	48,900 (19.4; 65.4; 15.2) /	4.9	-6.7% / -6.7%
	M	-17.2% / -3.4%	-4.1% / -7.3%	-18.3% / -2.0%	47,300 (18.4; 63.9; 17.7) /	5.3	-9.0% / -8.3%
Metrop. Area	F	-20.4% / 0.4%	-13.4% / -1.3%	1.8% / -10.7%	57,600 (5.7; 12.9; 81.4) /	6.5	-1.5% / -10.8%
	M	-23.6% / 0.2%	-18.1% / -2.1%	-3.6% / -11.5%	60,600 (5.7; 13.8; 80.5) /	7.0	-6.7% / -11.3%
45-65		**City Center**	**Outer Madrid**	**Metrop. Area**	**Trips/h (flows share %) /**	**Average Travel Distance (km)**	**Global Change**
		Trips / Distance	Trips / Distance	Trips / Distance	(2020)		Trips / Distance
City Center	F	-11.5% / -6.9%	-14.2% / -3.5%	-13.5% / 1.1%	32,800 (61.7; 28.8; 9.4) /	3.9	-12.5% / -3.3%
	M	-11.1% / -7.0%	-13.2% / -3.5%	-12.9% / 0.2%	28,600 (61.2; 28.4; 10.4) /	4.1	-11.9% / -3.4%
Outer Madrid	F	-14.2% / -2.7%	4.4% / -5.1%	-5.3% / -0.1%	49,900 (19.0; 66.6; 14.4) /	4.6	-0.1% / -5.2%
	M	-13.2% / -3.1%	3.3% / -6.8%	-7.6% / -0.2%	45,800 (17.8; 65.8; 16.4) /	5.0	-1.4% / -6.3%
Metrop. Area	F	-12.6% / 0.8%	-5.4% / -0.4%	14.7% / -8.1%	55,600 (5.6; 12.9; 81.5) /	6.2	10.6% / -9.7%
	M	-12.3% / 0.2%	-7.7% / -0.5%	13.4% / -9.8%	54,400 (5.5; 13.8; 80.7) /	6.6	9.1% / -10.7%
≥ 65		**City Center**	**Outer Madrid**	**Metrop. Area**	**Trips/h (flows share %) /**	**Average Travel Distance (km)**	**Global Change**
		Trips / Distance	Trips / Distance	Trips / Distance	(2020)		Trips / Distance
City Center	F	5.8% / -7.7%	-3.3% / -9.2%	-12.7% / 0.4%	17,000 (67.4; 26.2; 6.4) /	3.1	2.1% / -11.4%
	M	1.2% / -9.6%	-8.7% / -7.8%	-16.1% / 1.4%	11,300 (64.8; 27.3; 7.9) /	3.4	-2.9% / -11.1%
Outer Madrid	F	-3.5% / -9.0%	12.3% / -12.5%	-9.5% / -4.2%	25,000 (17.9; 70.7; 11.4) /	3.9	7.0% / -13.8%
	M	-9.0% / -7.6%	6.8% / -12.5%	-13.1% / -3.7%	18,100 (17.1; 69.9; 13.0) /	4.1	1.5% / -13.1%
Metrop. Area	F	-12.4% / -0.1%	-9.7% / -4.6%	24.3% / -15.2%	22,800 (4.8; 12.5; 82.7) /	5.5	18.3% / -17.4%
	M	-15.6% / 1.1%	-13.4% / -4.3%	17.3% / -14.6%	19,400 (4.6; 12.1; 83.2) /	5.5	12.1% / -16.5%
Gender Groups		**City Center**	**Outer Madrid**	**Metrop. Area**	**Trips/h (flows share %) /**	**Average Travel Distance (km)**	**Global Change**
		Trips / Distance	Trips / Distance	Trips / Distance	(2020)		Trips / Distance
City Center	F	-7.0% / -7.1%	-10.1% / -4.8%	-13.0% / 1.1%	102,800 (63.1; 27.7; 9.2) /	3.8	-8.4% / -5.3%
	M	-11.0% / -7.1%	-12.9% / -4.9%	-16.0% / 0.7%	92,700 (62.1; 27.5; 10.4) /	4.0	-12.0% / -5.0%
Outer Madrid	F	-10.0% / -4.4%	6.7% / -7.8%	-5.6% / -1.6%	153,400 (18.7; 66.7; 14.6) /	4.7	1.8% / -7.7%
	M	-12.7% / -4.5%	3.1% / -8.5%	-11.5% / -1.7%	144,400 (17.7; 65.5; 16.8) /	5.0	-2.2% / -8.7%
Metrop. Area	F	-12.3% / 0.7%	-5.7% / -1.8%	14.0% / -10.7%	175,000 (5.4; 12.8; 81.8) /	6.3	10.1% / -11.5%
	M	-15.9% / 0.7%	-11.4% / -1.9%	8.3% / -11.7%	178,600 (5.4; 13.6; 81.0) /	6.7	4.3% / -11.9%
All Residents		**City Center**	**Outer Madrid**	**Metrop. Area**	**Trips/h (flows share %) /**	**Average Travel Distance (km)**	**Global Change**
		Trips / Distance	Trips / Distance	Trips / Distance	(2020)		Trips / Distance
City Center		-8.9% / -7.1%	-11.4% / -4.7%	-14.6% / 0.9%	195,500 (62.6; 27.6; 9.8) /	3.9	-10.1% / -5.1%
Outer Madrid		-11.3% / -4.3%	4.9% / -8.0%	-8.7% / -1.7%	297,800 (18.2; 66.1; 15.7) /	4.9	-0.1% / -8.4%
Metrop. Area		-14.1% / 0.7%	-8.7% / -1.9%	11.2% / -11.3%	353,600 (5.4; 13.2; 81.4) /	6.5	7.2% / -11.9%

than men (Trips/h), and their flows between large areas tend to concentrate in the City Center, where more shops and restaurants are located for both shopping and working. In addition, the changes in women's travel flows among large areas decreased less or grew more than those for men in all large areas.

Disaggregated by gender and age, the share of travel flows for working-age groups is more concentrated in the City Center, although their changes in trips between large areas has also decreased the most (especially from/to the City Center). This fall has been greater for the 25–45 cohort, including their internal trips, while 45–65 cohort generally has no changes. This tendency may be related to greater possibilities for 25–45 cohort to assume remote work, change their place of residence and have fewer secondary activities in the City Center in favor of their home areas. Unlike adults, young people present different trends by

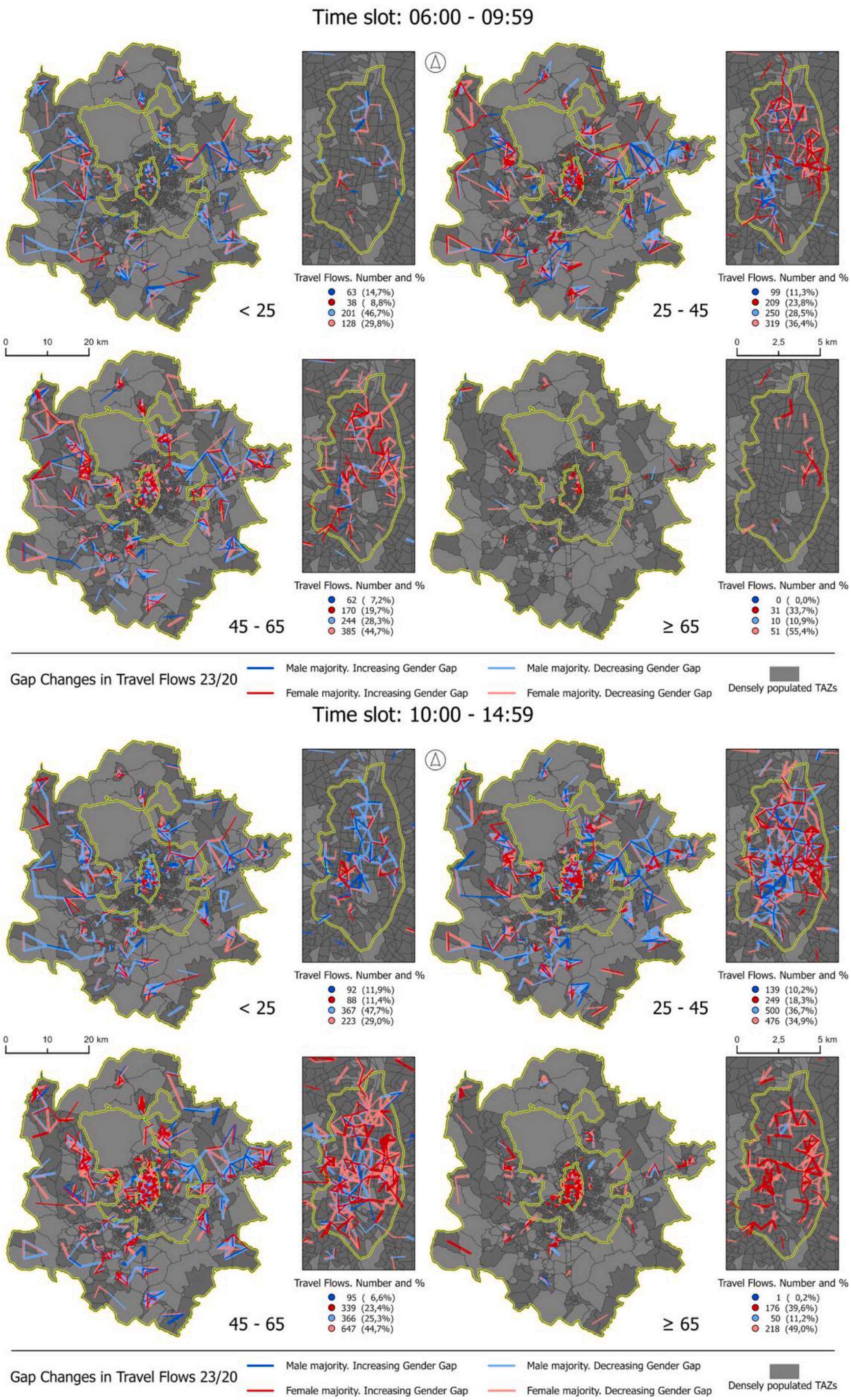

Fig. 6. Gender gap and changes in the main travel flows by TAZ.

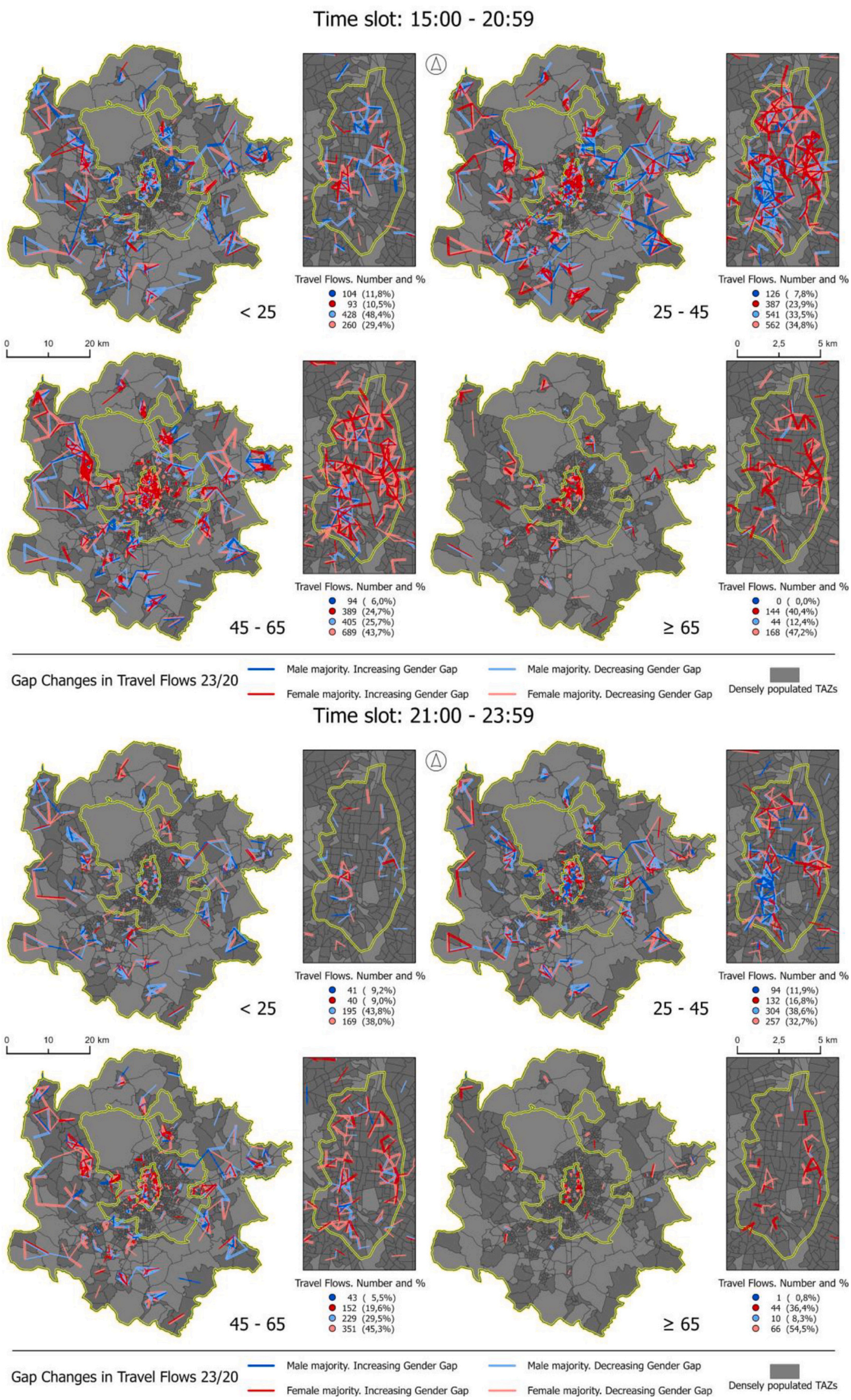

Fig. 6. (*continued*).

gender and higher travel flow shares from the City Center and Outer Madrid to the rest of the region. This dispersed activity is consistent with longer travel distances, which could be related to less residential flexibility and concentrated locations of interest, like universities and the historic center. By contrast, people over 65 have the highest distribution of internal travel in all areas, and although their number of trips is growing, it only does so internally, drastically reducing their travel distance.

b. Gender gap

Finally, the main travel flows are represented by gender and time slot (10 trips/h), where each color indicates the existing gender gap in 2020, and the color's intensity indicates the trend from 2020 to 2023 (Fig. 6). The main travel flows reflect that TAZs of the City Center and the Metropolitan Area present more concentrated relationships in each time slot. The gender gap in these flows shows that women (red colors) make more trips between highly populated TAZs with shorter travel distances, while men (blue colors) account for more flows in the less populated areas of the Metropolitan Area. However, specific time slots and population groups show clusters with higher concentrations of men in urban areas. For example, people under 25 years old in the 10:00–14:59 period show a greater concentration on the north-south axis of offices and restaurants in the City Center, while the 25–45 cohort shows a male predominance for flows in the historic center of Madrid during all time slots. These clusters may be due to a concentration of jobs with high mobility, such as different types of services and riders, where the presence of men is greater.

Changes recorded in the gender gap reflect an apparent reduction in spatial differences, with a predominance of light colors that exceed 65 % of the flows in most groups and time slots. When differentiating travel flows that reduce the gap (light colors), they are noticeably more numerous among flows where women are the majority for people over 45. Among young people, the case is the opposite, and in the 25–45 cohort, there is a balance in both genders for travel flows reducing the gap. At the same time, flows with a female majority that increase the gap (dark red) are also more numerous among those over 45 and the 25–45 cohort. However, younger people do not present a clear gendered pattern for travel flows increasing the gap.

Although travel flows only reflect the pattern of change at the spatial level, the working-age population (25–45; 45–65) have a much higher number of travel flows than young people and the elderly. This observation is not only due to greater individual mobility and population weight, but it also indicates a greater distribution of activity areas with a certain number of trips in the territory. The phenomenon of dispersion in origins and destinations is appreciable through the absence of travel flows for the threshold used, as happens with TAZs of Outer Madrid. Despite being densely populated, this area does not present as many travel flows between adjacent TAZs as the City Center. A similar effect may happen for young women who present a positive gap at night, possibly caused by closing shops and restaurants, but it is not reflected in large flows because of very dispersed destinations. Analyzing this phenomenon in more detail requires the use of different thresholds (people/h by flow, time slot and travel distance), or analyzing specific TAZs of interest, which exceeds the object of the research, but it would help for a better understanding in how the gender gap develops at the spatial level.

The results of this study confirm different mobility patterns between men and women in the spatial and temporal dimensions. However, at the same time, similar mobility patterns have been recorded in both genders for each age group. Consequently, these patterns reflect how an individual's life stage is a transversal factor, while gender is a longitudinal factor that interacts and shapes their daily capabilities and limitations in urban mobility (Fig. 7).

The influence of these factors is visible both in the number of trips per person and the average travel distance. Thus, gender determines that women travel less and over shorter distances, while age establishes an increase in mobility during personal development, followed by a decline in trip distances as people grow older.

6. Discussion and conclusions

This paper analyzes the spatial and temporal changes of the gender gap in mobility after the disruptive event of COVID-19, exploring how gender plays a longitudinal factor while age plays a transversal factor. Analyzing phone data covering three years in the metropolitan region of Madrid shows a reduction in the gap for the number of trips and stability for the distance travelled, confirming that the global gender gap keeps reducing after COVID-19. However, women still make fewer and shorter trips than men. Globally, urban activity has evolved towards shorter distances and considerably reduced the number of trips in the early morning (Romanillos et al., 2021) as a direct consequence of the pandemic and mobility restrictions. However, the population have increased their trips in other time slots, which has led to maintaining or even increasing their mobility. This increase stands out at night-time, possibly caused by a reconfiguration of social activities to return home earlier, as a remaining change in the recovery of nightlife during COVID-19 (Santiago-Iglesias et al., 2024).

The City Center has significantly reduced its internal and external trips, coinciding with a reduction in the population and a greater trend of remote working, as shown in Al-Akioui and Monzon (2023). On the contrary, the Metropolitan Area has increased its internal activity, even considering its growing population since 2020. Global urban activity presents a reduction of the gender gap from −5,5 % to −1.3 % and is observed with light-colored travel flows in all large areas. However,

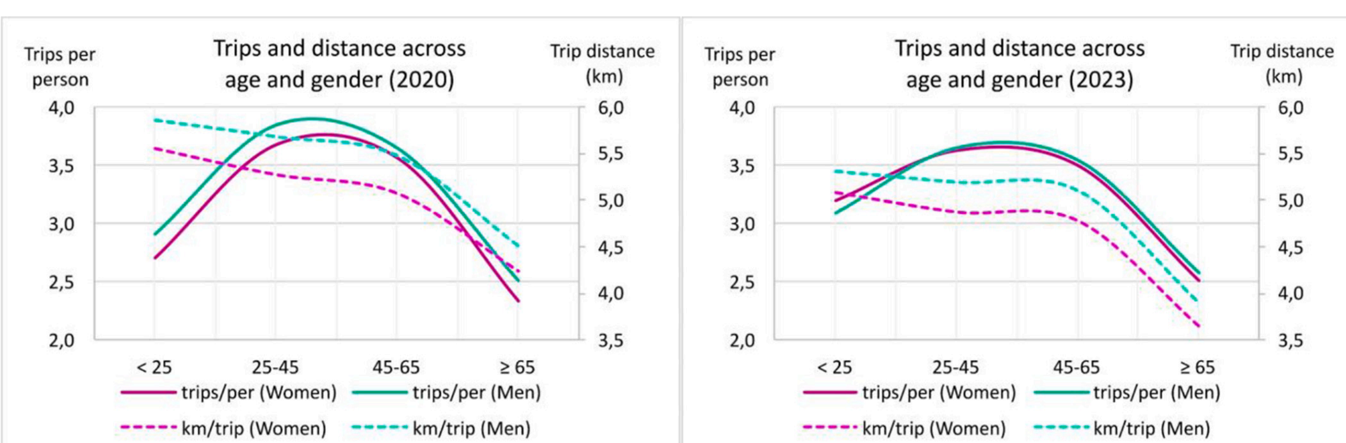

Fig. 7. Changes in urban mobility across gender and age.

spatial differences by gender persist, such as higher mobility for men in business areas or the historic center and more female activity in residential areas or local commerce (Jo et al., 2020; Lenormand et al., 2015).

Reducing the gender gap in mobility was already observed in prepandemic scenarios. The results obtained seem to reflect an opposite long-term trend compared to that recorded in the early stages of the pandemic based on gender and age (Caselli et al., 2022; Liu et al., 2023). This observation suggests a greater inertia of the long-term changes in mobility, where the disease may have accelerated (and/or modified, but not eliminated) these previous trends after its disruptive effects. For example, the evolution experienced by young women is noteworthy, as they have increased and even reversed their proportion of trips towards a positive gap. This gender turnaround was already described by Tilley and Houston (2016), but noting some differences as young men also increased their mobility. A reduction in mobility was also expected among the elderly in the long-term period, but our results now show an increase in both genders that could be related to grandchildren care activities (Tilley and Houston, 2016), but also to cultural changes as new generations age over 65 (Scheiner, 2014). Analyzing the gender gap in relation to age helps to understand how different groups face distinct realities and have varying capabilities and limitations when they are forced to adapt their daily activities (Elder Jr. et al., 2007). However, future research could include other factors, such as socio-demographic characteristics (ethnicity, origin), socio-economic characteristics (education, income, employment), spatial characteristics (place of residence, territorial structure), or the purpose of travel and weekend activities, among others. To this end, more detailed household travel surveys and geolocated data could be used.

While our results show a smaller gender gap for trips and stability in the gap for distance, it is also necessary to provide a critical view on the real implications of the recorded changes. For example, although women have reduced their travel and distance to a lesser extent, they already started from lower values than men in 2020. Therefore, the margin available to reduce their mobility was smaller. In addition, short-distance travel tends to be related to household duties with more women involved (Best and Lanzendorf, 2005), which is more difficult to modify than commuting after increased remote work. On the contrary, those contexts where the number of trips has increased, women have also done so more than men in all age groups, assuming in these cases, a real reduction in the gender gap between the years analyzed.

Mobile phone data has proven to be a more accurate source of information for analyzing urban mobility. On average, there were 3.15 trips per person for women and 3.33 for men in 2020, while the 2018 Mobility Survey of the Community of Madrid recorded an average of 2.44 trips per person (Consorcio de Transportes de Madrid, 2018). While they are not directly comparable, there is a 30 % difference between these sources. Part of this increase is necessarily due to a better measurement of mobility on short-distance trips where women have a greater presence, which reduces the gender gap associated with measurement biases (Buvinic and Levine, 2016). However, there are still technical limitations, such as errors in trip detection, the minimum time threshold for recording a trip, or the limitations derived from the modifiable spatial unit. On the other hand, the data used is completely anonymous and aggregated, eliminating the individual longitudinal component (activity spaces), which has a high potential in studies of segregation and urban inequalities (Müürisepp et al., 2022). Being aware of the limitations and considerations made in the paper, we believe that they do not affect the representativeness of the results as the stability while processing data is guaranteed by coming from a single dataset.

We trust this research will not only provide information on urban mobility changes after COVID-19 in Madrid but will also support a methodological approach to urban activity and activity spaces to analyze the gender gap in mobility. The paper's results show the relative changes between 2020 and 2023, so continuous and comparable monitoring is necessary to isolate specific phenomena from the global trend in the gender gap. Finally, we want to highlight the importance of analyzing urban and social dynamics as a necessary contextualization to address urban segregation and inequality studies. The mobility differences detected do not necessarily imply segregation or inequality that negatively affect society, but they help to develop indicators for cultural changes and warn of possible imbalances (Scheiner, 2014). Thus, urban mobility over time helps to understand each population group's capacity to modify their mobility patterns, whether due to flexibility, rigidity, resilience or vulnerability to changing realities in cities.

CRediT authorship contribution statement

Yeray Cara-Santana: Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Conceptualization. **Borja Moya-Gómez:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Juan Carlos García-Palomares:** Writing – review & editing, Supervision, Project administration, Methodology, Conceptualization.

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Declaration of competing interest

We declare that there is no conflict of interest in the writing of this manuscript.

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Data availability

The authors do not have permission to share data.

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