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Research on the Evolution of Population Distribution and Influencing Factors in Xi'an During the COVID-19 Epidemic Control Period: Based on a Perspective of Multi-source Spatio-Temporal Big Data

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Abstract. Under the "ultra-conventional" control measures of the COVID-19 period, urban population distribution is different from usual time. Studying its evolution laws has a certain reference effect for the judgment of urban population aggregations, the division of precise control zoning, and the differentiated management of places during the COVID-19 control period. Based on the data of Baidu heat maps and points of interest (POIs), this paper uses three models of the population density index (PDI), the exploratory spatial data analysis (ESDA) and the geological detector (Geodetector) to analyze the characteristics and the influencing factors of the evolution of population distribution of Xi'an in three stages which are closed control stage, unsealed control stage and slack control stage. The results show that: in the three stages, 1) The value of the PDI and the range of the PDI change in Xi'an continue to increase. The single-day PDI curve shows "low-high-low" changing characteristics from morning to night in and within the third ring zone, and "high-low-high" in the suburb. And, by comparison, it is found that the social vitality of the first and second ring zone is more strongly impacted because of COVID-19 control measures. 2) The overall population density in Xi'an is gradually increasing, this is represented by gradual increase of the very high- and the high-density areas, and continuous decrease of the low- and the very low-density areas. And the centripetal distribution of population density, which is high inside the city and low outside the city, is becoming more and more obvious. 3) The spatial distribution of population density represents obvious high-value clusters or low-value clusters in the three stages, ESDA shows a circle structure of inner heat and outer cold, and this trend continues to be reinforced. 4) The intensity order of influencing factors of the 7 types of facilities on population distribution is: residential communities > catering facilities > living service facilities > healthy facilities > commercial facilities > office places >

green spaces and squares, and the influencing factor intensities show a continuous increasing or a continuous decreasing process in the three stages.

Keywords: COVID-19 epidemic, population distribution, influencing factors, spatio-temporal big data, Xi'an.

1. Introduction
At the end of 2019, the outbreak of Coronavirus Disease 2019 (COVID-19) spread rapidly throughout China and the world. Its high contagion and high morbidity posed a serious threat to the safety of masses and social stability. In theory, a densely populated urban area is more conducive to the spread of the epidemic, and relevant studies have also shown that there is a strong correlation between the population mobility and the number of infected people [1]. During the period of China's COVID-19, the measures taken to stop people's gathering and people's moving, such as stop working, stop producing and shut down schools, and isolate people at home, have indeed played a good effect to the epidemic control, which has attracted attention and imitation of other countries and regions. In fact, the essence of COVID-19 control is the control of people's movement. Thus, compared with normal period, the laws of population distribution in the COVID-19 control period are more needed to be focused on and discussed. Under the "ultra-conventional" epidemic control measures, what are the temporal and spatial characteristics of urban population distribution? And what are the influencing factors? These conclusions are conducive to judging the trend of population aggregations during the epidemic control period, and for more accurate zoning control and place control. This is of great significance to current COVID-19 managements in other countries and similar social crisis managements in China. At present, relevant research have studied the characteristics of people's migration on a national scale during the COVID-19 control period [2], the impact of population migration on the COVID-19 spread [3-6], and the impact of COVID-19 control on population flows [7], etc., but there is less research on the population distribution within a city during the COVID-19 control period.

In recent years, spatio-temporal big data have become an important method for urban population research. Researchers use Baidu heat maps to study urban population vitality [8] and jobs-housing relationships [9], use Baidu heat maps and points of interest (POIs) to study spatio-temporal distribution of urban population [10], population flows and population aggregations during the day and night [11]. And researchers use mobile phone signaling data to study spatio-temporal distribution of urban population [12,13], employed person's flows [14], population dynamic distribution [15,16], etc. Therefore, this paper also takes Baidu heat maps and POIs to focus on the population distribution laws during the COVID-19 control period. Based on the population density index (PDI), the exploratory spatial data analysis (ESDA) and the geographic detector (Geodetector), this paper will do in-depth research on the population distribution and the influencing factors of Xi'an city from an urban block scale. It can provide reference effect for expanding the field of urban population research and urban population managements under similar social crisis.

2. Models and methods

2.1. Research area
Xi'an is a typical big city in northwest China. At the end of 2018, the residents in the city were 10,003,700 and the residents in the main urban areas was 5,926,000. Since February, 2020, Xi'an has implemented strict COVID-19 control managements, including the traffic control inside and outside the city, the suspension of factories, schools and commercial places, the closed-off managements of communities at an early stage, and the "passing QR code" registration and the urban grid managements in a later stage. These control measures were gradually loosened after March when the epidemic situation has been gradually stabilizing and the people's flows were greatly affected during this special period. Considering the availability of data and the typicality of the study area, this paper focuses on the

main built-up areas in Xi'an, and these areas are divided into 801 blocks as research units according to the urban trunk road network (Figure 1).

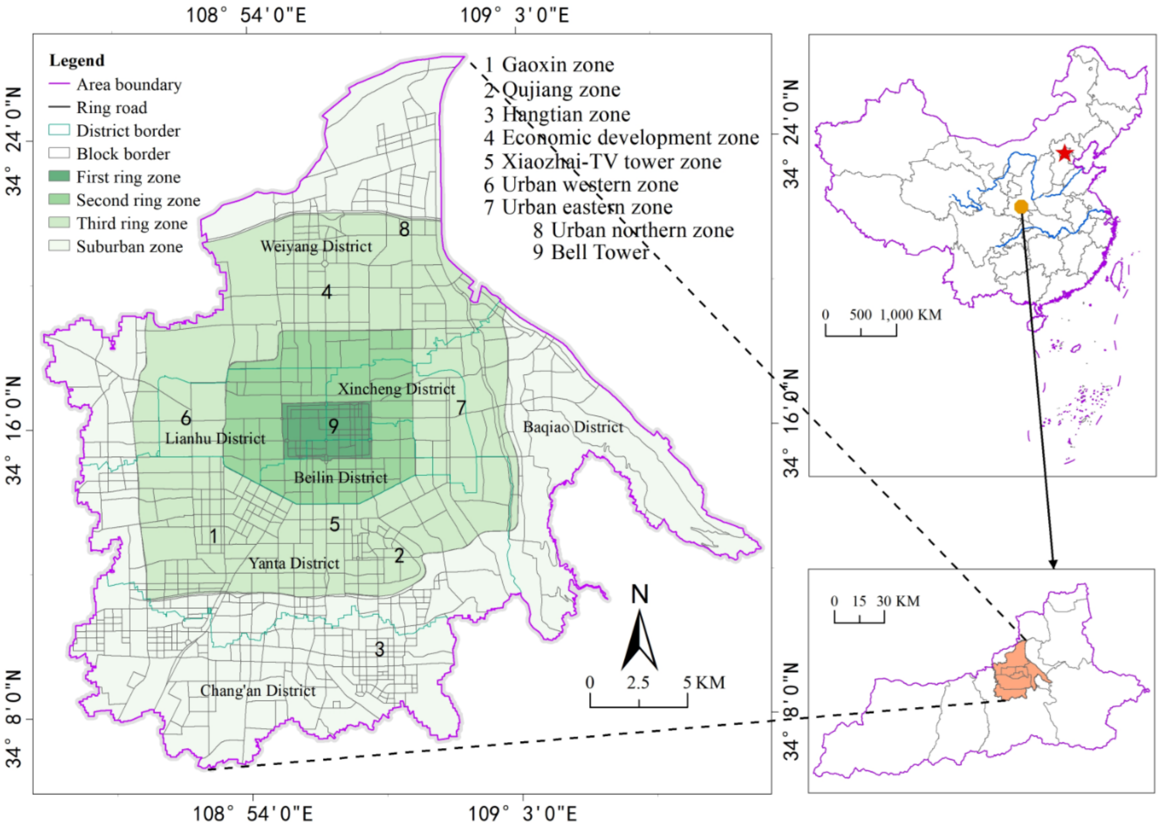

Figure 1. Research area and its location

2.2. Data

Combined with the author's living experience during the COVID-19 control period in Xi'an and the White Paper "China's Action against COVID-19" issued by the State Council Information Office of China. In this paper, the epidemic control period in Xi'an is divided into three stages: from 20 January to 23 February, it was the closed control stage, with strict control managements; from 24 February to middle and late March, it was the unsealed control stage, with differentiated control managements and resumption of production gradually; since the beginning of April, it has been the slack control stage, with local infection has been blocked basically and producing and living activities have returned to normal gradually. Considering that from the late April, except schools and entertainment places, the most social and economic activities in Xi'an are closed to return to normal, and the population distribution is relatively stable. Therefore, no any stage subdivision will be done after the third stage.

Based on the above preparations, this paper collects Baidu heat maps from 7: 00 to 24: 00 on the weekdays (3 Feb., 11 Mar., 16 Apr.) and the weekends (16 Feb., 15 Mar., 11 Apr.)1 of the three stages of Xi'an. At the same time, Baidu heat maps on the weeday (25 Apr., 2019) and the weekend (28 Apr., 2019) during a non-epidemic stage are collected for comparison. So, 144 Baidu heat maps for 8 days are collected totally in this paper. It should be emphasized that, 1) the above-mentioned times do not

① The Baidu heat map is a big data visualization product based on the geographic location data of mobile phone users whose phone is installed a Baidu's application. When a smartphone accesses any Baidu's application, location information is recorded and a location footprint is f ormed, which can reflect the aggregation of human beings in various regions. Baidu heat maps are updated every 15 minutes, so it has a strong timeliness.

include any extreme weather, thus avoid the influence of extreme weather on residents' activities [17]. 2) Although Baidu heat maps are based on huge Baidu application users, it is still difficult to accurately represent real total population, and only reflects the relative gathering trend of population distribution [18]. Meanwhile, the data of POIs in Xi'an in April, 2019 are collected through the Baidu map API, which included 14 categories, 96 subcategories and 446,182 items. Then, all the data are put into Arcgis 10.2, and uniformly georeferenced to the CGCS2000_3_Degree_GK_Zone_36 coordinate system.

2.3. Methods

(1) PDI. The model of the population density index (PDI) reflects population density distribution based on thermal value of Baidu heat maps [10,11]. Considering that netizens have the dynamic characteristics of "going online" and "going offline" constantly, extracted thermal information has great fluctuation in different times on the same day, so it is impossible to compare them [19]. Therefore, the ratio of thermal value of a certain block to all study areas' thermal value in a certain time is adopted to eliminate this influence, and then PDI is calculated by dividing the ratio by the area of the block. The formula is as follows:

$$\rho_i = (Q_{ti} / \sum_{j=1}^{k} Q_{tj} \times 10^9)/S_i \tag{1}$$

ρ_i is the population density index of block i, Q_{ti} represents the Baidu thermal value of block i at t time, $\sum_{j=1}^{k} Q_{tj}$ is the sum of thermal value of all blocks at t time, k is the total number of block samples in study area, and S_i is the land area of block i, which unit is a square meter. The larger ρ_i is, the higher PDI is, the bigger the number of populations is, and vice versa.

(2) ESDA and Geodetector. The model of the exploratory spatial data analysis (ESDA) explores spatial data distribution rules based on a spatial weight matrix to reflect spatial dependence or heterogeneity of geographical phenomena [20]. In this paper, the global coefficient Moran's I and the local hot spot coefficient G_i^* are used to study the global and local spatial aggregation of population distribution. The model of the geological detector (Geodetector) is used to detect spatial heterogeneity of a phenomenon and driving factors behind it. It can be used to test spatial heterogeneity of a single variable, and also to detect a possible causal relationship between two variables by testing the consistency of spatial distribution [21]. In this paper, we use the factor detection of Geodetector to analyze the causes of population distribution in Xi'an. At present, ESDA and Geodetector are relatively mature and common analysis methods. Due to limited space of this paper, the calculating formulas are no longer listed respectively.

3. Results and analyses

3.1. Temporal characteristics of population Distribution

Figure 2 reflects the temporal characteristics of the population distribution in Xi'an from 7:00 to 24:00 in the three stages. For the whole tendency, with gradual relaxation of COVID-19 epidemic control, the PDI and its fluctuation range in Xi'an have been increasing continuously, and the difference between the weekdays and the weekends has become more and more significant. For the single day's tendency, the PDI in and within the third ring zone shows the characteristics of "low-high-low" change from morning to night, while it shows the characteristics of "high-low-high" change in the suburb. In detail, during the weekdays, before 7 o'clock, people are mainly distributed in the suburb, and the population density in and within the third ring zone is relatively low. From 7:00 to 10:00, due to commuting from home to work, the population density in and within the third ring zone increases rapidly, while that in the suburb decreases rapidly. From 10:00 to 18:00, it is work time, high moility of people causes a great change on the population density. From 18:00 to 22:00, due to commuting from work to home, the population density in and within the third ring zone decreases, while that in the suburb increases to a certain extent. However, people still have some leisure activities during this time, so the population density fluctuation range in this period is less than that from 7:00 to 10:00. After 22:00, leisure activities are over, the population density in and within the third ring zone further decreases, and that in the suburb further increases. On the weekends, demands for leisure activities increase, but leisure places gather inside the city mostly. Therefore, from 7:00 to 11:00, the population density in and within the third ring zone gradually increases, that in the suburb gradually decreses, but the magnitude of the change is smaller than that on the weekdays. From 11:00 to 22:00, people's movements cause the change of the population density, but the magnitude of this change is much less than that on the weekdays, and the change in and within the third ring zone is also more intense than that in the suburb. After 22:00, leisure activities are over, the population density in and within the third ring zone decreases slightly, and that in the suburb increases slightly.

It is worth emphasizing that, due to the different management intensity, the fluctuation range of the single-day's population density curve in different stages is quite different, but the changing trend still shows some similarities, and this is similar to the changing trend in the non-epidemic period. It shows that even during the epidemic control period, people's activity habits did not change greatly. At the same time, through the comparion of the population density in different stages, the population density in the first and the second ring zone are more seriously affected by the epidemic control than that in the third ring zone and in the suburb, and the relevant difference between different stages is stronger. It shows that the social vitality of the first and the second ring zone is more seriously affected by the epidemic control than that in the third ring zone and in the suburb.

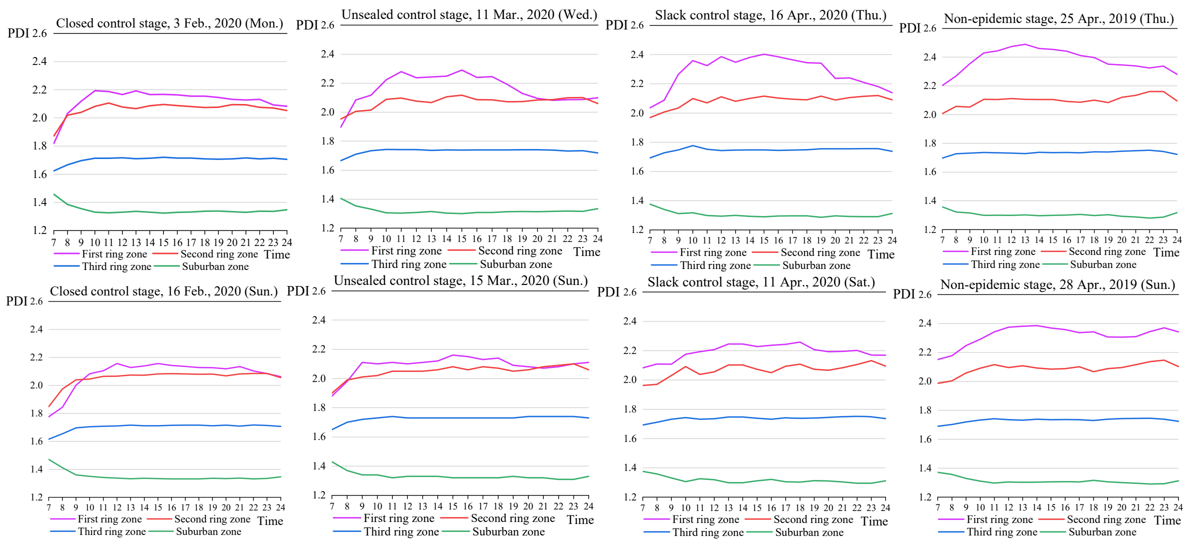

Figure 2. Temporal curves of population distribution

3.2. Spatial characteristics of population Distribution

(1) Spatial distribution characteristics of population density. Figure 3 reflects the spatial areas of the daily average population density of Xi'an in the three stages, and these areas are uniformly divided into very high-density areas, high density areas, low density areas, and very low-density areas by the method of the natural breakpoint in Arcgis 10.22. In the three stages, the very high- and the high-density areas gradually increase, while the low- and the very low-density areas continue to decrease. Affected by the single-center structure of Xi'an [22], the very high- and the high-density areas are mainly distributed inside the city, the low- and the very low-density areas are mainly distributed on the periphery of the city, and the centripetal spatial distribution characteristic, which is high inside the city and low outside the city, is more and more significant. It can be found that, with the gradual relaxation of the epidemic

2 Taking the research need into account, the natural breakpoint method is used to divide the population density on 16 February into four levels and determine the grading standard, and this standard is used to divide the population density on other dates.

control, the population density in Xi'an gradually increases, the population density in the first and second ring zone, the Xiaozhai-TV tower zone and the Economic development zone is relatively high, while that on the periphery of the city is relatively low, and the Gaoxin zone, the Qujiang zone, the Hangtian zone, the Urban northern zone and the Urban eastern zone are the main growing areas of the population density. It can be speculated that these growing areas are also the main gathering areas of migrants whom return to Xi'an after Spring Festival, and the risk of the epidemic infection is relatively higher than other areas3. At the same time, it can be found that, with the relaxation of the epidemic control, the population distribution in Xi'an on the weekdays gradually return to normal, but it has not recovered yet on the weekends, and the population distribution on the weekends is more dispersed.

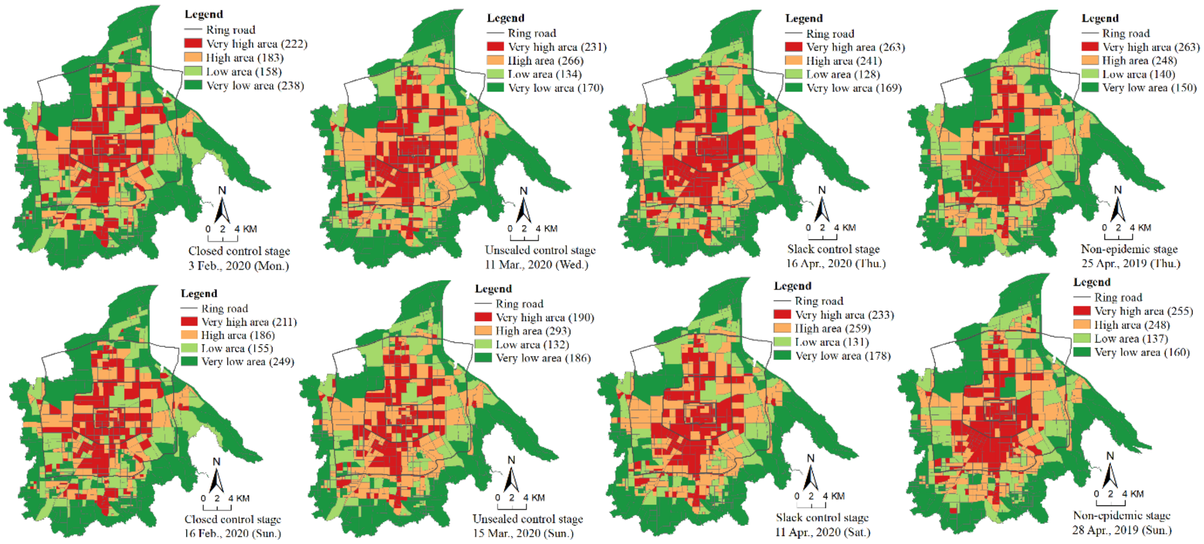

Figure 3. Spatial maps of population distribution

(2) Spatial agglomeration characteristics of population density. The global coefficient Moran's I (Table 1) of the daily average population density in Xi'an is calculated by GeoDa 1.12. On the weekdays, the global Moran's I increase continuously from 0.623 at the closed control stage to 0.692 at the relaxed control stage, and that increases continuously from 0.598 to 0.667 on the weekends, which reflects the population density in Xi'an shows significant high-value clusters or low-value clusters during the epidemic control period. The cluster characteristic is more obvious on the weekdays than on the weekends, and the cluster characteristic in the three stages continues to be reinforced, but it is still weaker than that in the non-epidemic stage.

Table 1. Moran'I of population distribution

Date		Moran's I	Date		Moran's I
Weekdays	3 Feb. (Mon.)	0.622***	Weekends	16 Feb. (Sun.)	0.598***
	11 Mar. (Wed.)	0.662***		15 Mar. (Sun.)	0.630***
	16 Apr. (Thu.)	0.691***		11 Apr. (Sat.)	0.667***
	25 Apr. (Thu., NP)	0.728***		28 Apr. (Sun., NP)	0.710***

Notes: ① *, ** and *** indicate significance levels at 90%, 95% and 99% respectively. ② Marking NP represents that it is a control group during the non-epidemic stage in 2019, the same as below.

(3) Characteristics of hot and cold spots of population density. Figure 4 is the spatial hot and cold spot maps of the daily average population density in Xi'an in the three stages, which is also calculated

3 Actually, about 62% of the COVID-19 infected communities in Xi'an are located in these mentioned areas.

by GeoDa 1.12, and all of them have passed a significance level test at 95%. It can be found that the hot spot areas of the population density in Xi'an are mainly distributed in the first and second ring zone, the Gaoxin zone, the Economic development zone and the Xiaozhai-TV tower zone, etc., while the cold spot areas of the population density of Xi'an are mainly distributed in the suburb, showing a circle structure of inner heat and outer cold, with little difference on the weekdays and weekends. These aggregation characteristics of the three stages gradually tend to be stable, however, compared with the non-epidemic stage, they have not returned to normal yet. According to the strong correlation between population density and the epidemic infection, it can be inferred that the risk of the epidemic infection in hot spot areas is relatively big, while that in cold spot areas is relatively small. For the urban epidemic control zoning, this can be used as a reference basis for accurate epidemic control zoning in different stages.

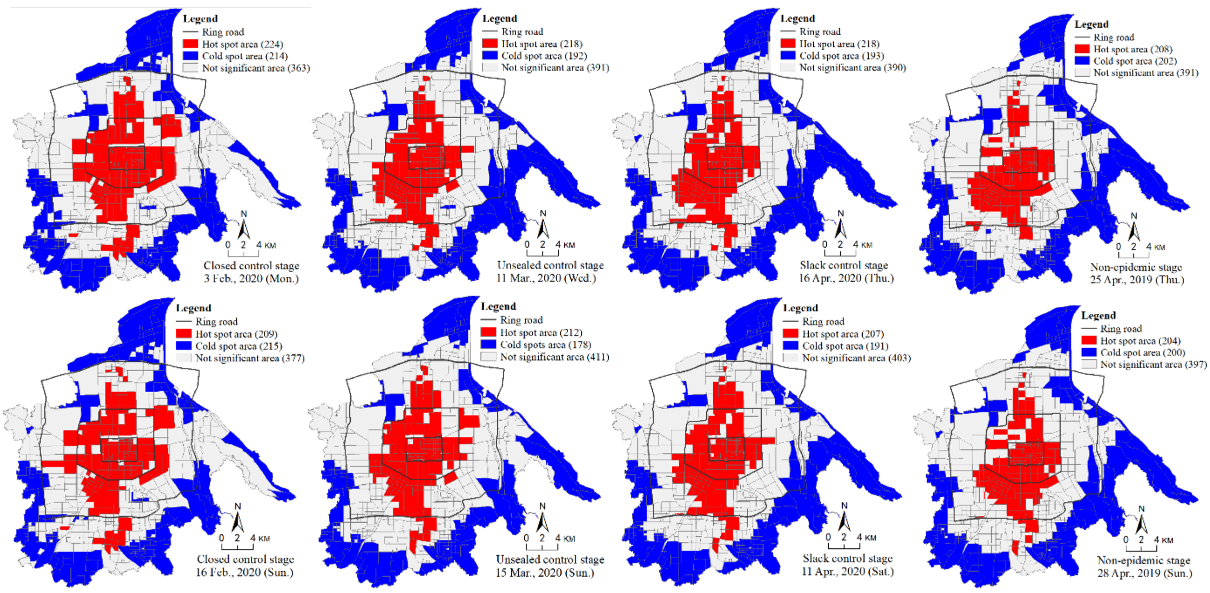

Figure 4. Hot and cold spot maps of population distribution

3.3. Influencing factors

The complexity of urban functions determines the diversity of influencing factors of population distribution. Relevant studies have been done from the aspects of industry, income, transportation, education, medical care, social economy [23,24] and natural condition [25]. Li (2019), based on the data of POIs, studied the supporting facilities such as facilities of residence, commerce, transportation, office, science, educational and medical care, urban parks [10]. This provides a good reference for this paper. Many public places in Xi'an have not opened before 16 April, so residential communities (RPOI), catering facilities (CPOI), living service facilities (LPOI), healthy facilities (HPOI), commercial facilities (COPOI), office places (OPOI), green spaces and squares (GSPOI) are selected, cleaned and analyzed. Meanwhile, considering that short-term activities have no any impacts on Baidu heat maps, facilities in which people don not stay more than 15 minutes obviously are selected and deleted, such as pastry shops, laundry shops, convenience stores, etc., while other facilities are reserved. Then, the number of the 7 type facilities is classified and counted into 801 research units by the zonal statistics tool of Arcgis 10.2 (some empty values are replaced by 0.001). Then, the facility density of each block is calculated, and the facility density of each type is reclassified into 20 zones by the natural breakpoint method. Finally, taking the daily average population density in different stages of Xi'an as the dependent variables and taking the natural breakpoint zones of the density of the 7 type facilities as the independent variables, all data are put into the formula (1) to calculate the driving factors by Geodetector.

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It can be found from Table 2 that, 1) Residential communities have the biggest impact on population distribution, but with the relaxation of the epidemic control, the people's mobility becomes stronger, the population dependence on residential communities gradually decreases, and its influence intensity gradually weakens. At the same time, during the epidemic control period, less people go out on the weekends than weekdays, and most of them gather around their communities [26]. Therefore, the impact of the residential facilities on the population distribution is slightly stronger on the weekdays than that on the weekends. 2) Considering that catering facilities, living service facilities and healthy facilities are mostly located near residential communities4, the intensity of these three factors on population distribution is greatly influenced by the effect of the residential communities on people's aggregation, so the changing tendency of the influence intensity of these three factors on population distribution is similar to that of the residential communities. At the same time, the frequency of people's use of catering facilities and living service facilities is relatively high, so the impact on the population distribution is still relatively high in the unsealed control stage and the relaxed control stage, and the impact on the weekends is slightly greater than that on the weekdays. However, healthy facilities are different. In order to reduce the risk of possible cross infection, people avoid these these healthy facilities deliberately. Therefore, the impact of the healthy facilities on population distribution shows a significant decline in the two later stages, and there is little difference between the weekdays and weekends. 3) Commercial facilities and office places have strong attraction for people's flows, however, in the closed control stage, the attraction is greatly weakened due to the city's shutdown. Then, with recovery of people's flows and opening of places, the intensity of these two facilities gradually increases. In addition, due to shopping demands and shopping time of residents on the weekends are generally more than these on the weekdays [27], the impact of the commercial facilities on population distribution is stronger on the weekends than that on the weekdays, whileas that of the office places is opposite. 4) The number of green spaces and squares in a city is small, and most users are middle-aged and elderly adults [28], this causes that the attraction of green spaces and squares is limited, so the impact of the green spaces and squares is the lowest. But with the relaxation of the epidemic control, people's outdoor activities increase, and the impact of the green spaces and squares gradually increases.

Table 2. Driving factors of population distribution

ID	Type	Weekdays				Weekends			
		3 Feb.	11 Mar.	16 Apr.	25 Apr. (NP)	16 Feb.	15 Mar.	11 Apr.	28 Apr. (NP)
x1	RPOI	0.647***	0.535***	0.500***	0.462***	0.653***	0.541***	0.514***	0.466***
x2	CPOI	0.527***	0.482***	0.490***	0.473***	0.528***	0.494***	0.502***	0.480***
x3	LPOI	0.545***	0.462***	0.459***	0.447***	0.551***	0.479***	0.475***	0.462***
x4	HPOI	0.523***	0.431***	0.418***	0.404***	0.521***	0.440***	0.424***	0.409***
x5	COPOI	0.382***	0.391***	0.409***	0.421***	0.381***	0.398***	0.419***	0.433***
x6	OPOI	0.235***	0.335***	0.346***	0.349***	0.245***	0.264***	0.295***	0.297***
x7	GSPOI	0.075	0.088	0.102	0.141**	0.074	0.083	0.097	0.135**

To sum up, in the three stages of the epidemic control in Xi'an, the influencing intensity of the 7 types of facilities on population distribution is: residential communities > catering facilities > living service facilities > healthy facilities > commercial facilities > office places > green spaces and squares. At the same time, the impact of residential communities, catering facilities, living service facilities and healthy facilities on the population distribution shows a continuous decreasing trend, and the impact of commercial facilities, office places and green spaces and squares shows a continuous increasing trend. This indicates that the epidemic control policy greatly affectes the coupling relationship between

4 In this paper, the pearson correlation coefficients of the spatial distribution between residential communities and living service facilities, catering facilities, healthy facilities, commercial facilities, office spaces, green spaces and squares are 0.72, 0.73, 0.67, 0.59, 0.56, -0.1, respectively.

population and facilities. This is helpful to guide implementation of differentiated managements and control in different places at different control stages.

4. Conclusion

The essence of the COVID-19 epidemic control is the control of people's activities. Based on Baidu heat maps and POIs, this article studies the characteristics of the population distribution evolution in Xi'an during the epidemic control and its influencing factors, this put forward to one of the methods for urban population dynamic monitoring and this also has a certain reference effect for the judgment of urban population aggregation, the division of precise control zoning, and the differentiated management of places during the epidemic control period. The main conclusions are as follows: 1) From the perspective of temporal distribution, with the relaxation of the epidemic control, the PDI and the fluctuation range of the PDI in Xi'an continue to increase, and the difference between the weekdays and weekends has become more and more significant. The single-day change curve of population density presents "low-high-low" changing characteristics from morning to night in and within the third ring zone, and "high-low-high" changing characteristics in the suburb. By the comparison of different stages, it is found that the social vitality of the first and second ring zone is more strongly impacted by the epidemic control. 2) From the perspective of spatial distribution, with the relaxation of the epidemic control and the resumption of production, the overall population density of Xi'an is gradually recovering, this is represented by the gradual increase of the very high- and the high-density areas, and continuous decrease of the low- and the very low-density areas. At the same time, the centripetal distribution of population density, which is high inside the city and low outside the city, is becoming more and more significant. Moreover, these zones of the Gaoxin zone, the Qujiang zone, the Hangtian zone, the Urban northern zone and the Urban eastern zone are the main gathering areas of migrants, the risk of the epidemic infection is relatively bigger than other areas. 3) From the perspective of ESDA, even during the COVID-19 control period, the population distribution in Xi'an still shows significant high-value clusters or low-value clusters. And the aggregation trend in the three stages continues to be reinforced, the circle structure of inner heat and outer cold is also becoming more and more obvious. This can be used as a reference basis for the division of precise control zoning. 4) From the perspective of influencing factors, during the epidemic control period, the intensity order of influencing factors of the 7 types of facilities on population distribution is: residential communities > catering facilities > living service facilities > healthy facilities > commercial facilities > office places > green spaces and squares. In the three stages, the influencing factor intensities of residential communities, catering facilities, living service facilities and healthy facilities represent a gradual declining processs, and the influencing factor intensities of commercial facilities, office places, green spaces and squares represent a gradual increasing process. This is helpful to the differentiated management of different places at different control stages.

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