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Understanding regional mobility resilience and its relationship with regional culture during the COVID-19 pandemic: A pathogen-stress theory perspective

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ARTICLE INFO

Handling Editor: Cecilia Maria Villas Bôas de Almeida

Keywords:
- Mobility
- Resilience
- Cities
- COVID-19
- Regional culture
- Pathogen-stress theory

ABSTRACT

The global COVID-19 pandemic has severely impacted the passenger flow. Facing the same pandemic, various regions differ in the resilience of population mobility due to differences in the regional cultural. This study uses mobile big data to quantifies regional mobility resilience of 358 cities in China. Study results reveal the differences in regional mobility resilience of cities through spatial autocorrelation analysis, and verify the effects of regional culture on mobility resilience using a panel logit regression model based on pathogen-stress theory. Spatial heterogeneity and autocorrelation in the regional mobility resilience of Chinese cities are identified through spatial analysis, which are manifested by various hot spots over time. Moreover, the panel regression results indicate that the COVID-19 pandemic has a significant negative effect on regional mobility resilience; and that the negative effect of COVID-19 on regional mobility resilience is amplified in the cities with high degrees of dialect diversity, while it is weakened in the cities with high degrees of cultural tightness (which have strict norms and punishments for deviance). This study provides theoretical implications for mobility resilience in the context of COVID-19 and advances the pathogen-stress theory. Study findings also provide practical recommendations for regions to enhance regional mobility resilience under the challenges of future public health crisis events.

1. Introduction

Population mobility reflects the economic and social connections among regions. Population mobility is an important indicator of regional vitality and plays an important role in sustainable development of regional economy (Pan and Lai, 2019). Population mobility, however, is vulnerable to public crisis events and natural disasters (Jiang et al., 2021; Tong et al., 2020). In the context of the COVID-19 global pandemic, there is a dramatic decline in population mobility (Nundy et al., 2021). Until now, the non-pharmacological intervention (NPI) is still the common method to prevent virus, including unprecedented global travel bans and stay-at-home measures (Gössling et al., 2020), travelers are also cutting back on their trips to reduce the probability of exposure to the virus (Neuberger and Egger, 2020). The International Civil Aviation Organization (ICAO) estimates that in 2020, aviation seats reduced by 50% overall, and air passenger traffic dropped by 2.699 billion (ICAO, 2020). The reduction in regional mobility has also impacted industries such as transportation (ACI, 2021) and tourism (UNWTO, 2021), and has reduced overall global economic dynamism (IMF, 2020). However, there are regional differences in the extent of the impact of the crisis on passenger flow (Dobruszkes and Van Hamme, 2011; Hu and Chen, 2021). For example, it can be seen from the ICAO report that the impact on domestic mobility in the Asia-Pacific region is reduced by almost ten percent compared with other regions (ICAO, 2020). This is not only because of the different levels of impact or recovery of the epidemic, but also reflects regional differences in mobility resilience. Evaluating the impact of COVID-19 epidemic on regional mobility and assessing its resilience can provide valuable information.
about spatial variances of mobility resilience across different cities. In addition, this line of research is meaningful to evaluate urban mobility emergency policies and provide strategic decisions for urban traffic recovery.

Although a few pilot studies have measured the mobility resilience under epidemic, most of these studies examine the mobile resilience from the temporal perspective, very few studies have measured the mobility resilience from the spatial and regional perspective (Tong et al., 2020). Quantifying regional mobility resilience can effectively reveal regional differences in mobility resilience (Martin and Sunley, 2015). Resilience is the ability of a system to recover to its original functional structure in the face of external shocks (Martin and Sunley, 2015). In the face of sudden external changes, some regional passenger flow has shown a certain degree of stability in the face of the impact of the epidemic (Gonçalves and Ribeiro, 2020; Hu and Chen, 2021). The regional differences in mobility resilience under the influence of the epidemic have enlightening value for strengthening the response to the crisis and the recovery of the global epidemic (Tong et al., 2020). Therefore, how to measure regional mobility resilience and identifying the regional differences have both theoretical implications and managerial relevance.

In previous studies, social, economic, and demographic factors are often considered as factors associated with mobility (Galeazzi et al., 2021), however, regional culture has rarely been included in the studies on mobility (da Mata Martins et al., 2019). Regional culture is increasingly valued in studies related to regional resilience and considered as one of the “foundational factors” along with regional history, geography, and other factors (Spolaore and Wacziarg, 2013). Verifying the influence of regional culture on regional mobility resilience will reveal the deep-seated factors that shape regional mobility resilience. Regional culture studies have long focused on the behavioral schema of groups in the face of external threats such as pathogens (Chen et al., 2020). Pathogen-stress theory suggests that when people face the pressure of pathogens, they tend to choose to move within the identified group (Fincher et al., 2008), that is, to choose areas that are culturally aligned with them. This theory explains the patterns of regional mobility under epidemics, however, research on this theory in regional research in still in nascent stage (Chen et al., 2020). More research is needed to explain the mechanism of movements of groups under challenges of public crisis events through the pathogen-stress theory.

Regional culture serves as an ideal objective to explore the implications of the pathogen-stress theory. In previous studies of mobility, cultural differences have been suggested to possibly lead to barriers, prejudice, lack of trust, and communication barriers between groups that hinder social and economic exchange between groups (Guiso et al., 2009; Spolaore and Wacziarg, 2009). Moreover, a number of studies have demonstrated the effect of cultural distance on mobility (Yang et al., 2019). Thus, cultural distance may provide an explanation for the pathogen-stress theory, as well as being a factor influencing regional mobility resilience. There are many measurements of cultural distance, of which dialect distance is a widely agreed variable (Li et al., 2018). In addition, social norms may also provide an understanding of pathogen-stress theory. Psychology considers social norms as implicit or explicit rules that constrain behavior, which have the power to effectively coordinate the actions of groups in response to external threats (Cialdini and Trost, 1990). Cultural tightness-looseness is the variable that characterizes social norms (Gelfand et al., 2006). Under the threat of an epidemic, people in tight culture are more likely to comply with social norms. As a result, the regional community is able to coordinate social action more quickly for a holistic response and reduce the negative impact of epidemic (Gelfand et al., 2021). Accordingly, it can be further assumed that cultural tightness-looseness may be a factor that weakens the epidemic shock and enhances mobility resilience. Yet, the existing studies have not examined the impacts of these factors on regional mobility. It is possible to acknowledge that examining the impacts of cultural tightness on regional mobility resilience will help the managers and decision-makers understand the mechanisms of pathogen-stress theory in terms of epidemic mobility. The introduction of these two regional cultural variables will validate and advance the pathogen-stress theory and provide a valid theoretical framework for understanding the mobility of people in the face of the COVID-19 pandemic.

To fill up these gaps, this study aims to investigate the following research questions:

a. How to measure regional mobility resilience? What is the pattern of its distribution at the regional level?
b. How does regional culture affect regional mobility resilience? Specifically, how cultural distance (i.e., linguistic distance) and social norms (i.e., cultural tightness-looseness) affect the regional mobility resilience under the threat of pathogens?

We conducted a panel data econometric analysis on selected data to find answers to these questions. The breakout of COVID-19 in China in early 2020 and was largely contained within several months (Tian et al., 2020; Wang and Zhang, 2021). The process caused a significant reduction in people’s mobility, but the reduction in mobility varied across cities in the face of the epidemic (Chen et al., 2021). Therefore, we explored the spatial characteristics of regional mobility resilience and its regional cultural factors under COVID-19, using Chinese cities as examples.

The rest of the paper is structured as follows. First, we review the existing literature related to regional mobility resilience (section 2). Section 3 explains the study methodology, including the data and its collection and analysis. In section 4, the empirical results were discussed explicitly. Finally, in section 5, the primary research findings, theoretical contributions, and practical implications were summarized.

2. Literature review and hypothesis

2.1. Regional mobility resilience

There are many definitions of resilience, and scholars tend to define the concept in terms of three domains, namely: engineering resilience (Pimm, 1984), ecological resilience (Holling, 1973), and evolutionary (adaptive) resilience (Metcalfe et al., 2006). In the field of regional economic research, resilience is mostly defined from the perspective of system evolution (Simmie and Martin, 2010), where resilience is the ability of a system to change its structure to minimize disturbances and to renew and adjust itself (Pendall et al., 2010). The topic of regional resilience, a concept used to describe the characteristics of resilience at the regional level, has been widely studied (Gowell, 2013). In particular, there have been many studies of regional economic resilience, which is a hot topic in the field of economic geography (Tan et al., 2020; Wang and Wei, 2021). Regional economic resilience is the ability of a regional or local economy to resist, recover, and restructure in the face of market, competitive, and environmental shocks to its development and growth path (Martin and Sunley, 2015). Similarly, population mobility can be resilient to external shocks (da Mata Martins et al., 2019). And from the perspective of system evolution, economy and mobility represent two major parts of society, i.e., wealth and population (Liang et al., 2021), the resilience of them are also the common features of social systems in the face of external shocks (Osth et al., 2018). Moreover, under the impact of the epidemic, mobility shows a certain degree of resilience and heterogeneity at different scales of space (Kang et al., 2020; Mu et al., 2020). Thus, similar to regional economic resilience, regional mobility resilience is an objective phenomenon with research value under COVID-19. And the definition of the concept of regional mobility resilience can also be referred to regional economic resilience. Drawing on relevant research (i.e., Giannakis and Bruggeman (2020) and Martin and Sunley (2015)), we define regional mobility resilience as the capacity of a regional or local passenger flow to withstand, recover from, and
In the studies of and regional resilience, the measurement of resilience is one of the most important issues (Bristow and Healy, 2020). In general, there are two basic measurement strategies, one using multiple indicators to construct a resilience index (Sharma et al., 2020), and the other using a single indicator to measure resilience (Tupy et al., 2021). Multi-dimensional resilience measurement generally uses multiple socio-economic system indicators related to resilience to yield an overall resilience index value through dimensionality reduction (for example, Chacon-Hurtado et al. (2020); Cheng and Zhang (2020)). In the literature on measurement of regional economic resilience, there is a growing trend toward single-dimensional measures (Giamakis and Bruggeman, 2020), and the relevant literature suggests that regional economic resilience can be measured by calculating what proportion of economic indicators (such as employment or output) is lost during the financial turmoil (Martin and Sunley, 2015; Senser et al., 2016). Especially after Martin et al. (2016) used employment as a single measure of regional economic resilience, a large number of articles adopted a similar approach. Single-dimensional measures do not require as much socio-economic data as multidimensional ones, which is particularly appropriate for the current epidemic situation because the variability of the epidemic requires highly frequent data, such as weekly data, and it is difficult to ensure that the multiple data sources are found with a weekly frequency. However, a single dimension approach requires that the selected indicators are highly representative. Since the regional economic resilience can be greatly manifested in the employment rates, regional mobility resilience can be measured by calculating what portion of passenger flow indicators is lost during the crisis correspondently. The loss of passenger flow indicators can be obtained using big data on passenger flows.

2.2. Pandemic and regional mobility resilience

Urban and metropolitan are vulnerable to risks such as infectious diseases (Okeke et al., 2020). The pandemic has a serious impact on urban passenger flow, especially NPI is considered to be one of the most effective epidemic prevention measures (Tian et al., 2020) and is widely implemented worldwide. Whether it is quarantine or border closures, these tough measures result in restricted transportation conditions (Chen et al., 2021). In addition, the global panic caused by the pandemic far outweighs the actual danger of the virus (Novelli et al., 2018). Fear of epidemics has expedited the development of the home-based economy such as food delivery (Puriwat and Triposakul, 2021), and it has also severely affected the willingness to travel (Neuburger and Egger, 2020). Wang (2009) compared the effects of earthquakes, 9/11, the financial crisis, and SARS on Taiwan’s inbound tourism and found that SARS triggered the greatest decline in passenger flow. In addition, there are regional differences in the impact of the epidemic. Mao et al. (2010), based on the mutation theory, found that there were significant differences in travel flows between Japan, Hong Kong, and the United States in the post-SARS period. Although exposed to crisis events, the transportation system has a certain degree of resilience (Kim et al., 2019). In the aftermath of previous disasters such as 9/11, Severe Acute Respiratory Syndrome (SARS), and other global disasters, the mobility of transportation passengers has been impacted, but has gradually returned to an orderly state due to the resilience of the system (Adey et al., 2014). In the process, however, the impact of the crisis on passenger flows has been characterized by regional heterogeneity (Dobruszkes and Van Hamme, 2011), with some regions being able to withstand the shock and recover from the crisis quite quickly, while others have shown less resilience. In addition, many resilience research papers have identified epidemics as a major influencing factor (Chen et al., 2021). In summary, this study proposes the following hypothesis:

\[ H_1 \] An increase in confirmed cases of COVID-19 results in lower regional mobility resilience.

2.3. Regional culture and regional mobility resilience

Regional culture have the characteristics of spatial differentiation and stability in time and space. Culture is considered the map for behavior (Peterson, 1979), which is transferred by the social environment and influences, shapes, and determines the behavior of people in social context (Brons, 2006). Hardware facilities, such as engineering and organization of facilities are often considered to be an important force in achieving sustainable development (Floricic, 2020). However, culture as the “fundamental factors” is deeper explanations of socioeconomic phenomena than traditional institutional and engineering factors (Spolaore and Wacziarg, 2013) and have a profound impact on resilience. Research by Huggins and Thompson (2015) demonstrates that local socio-cultural values play an important role in fostering firm resilience. Obschonka et al. (2016) compared the impact of regional Big Five personality on regional economic resilience with regional macro-industrial variables, and found that the former makes a higher contribution. Thus, regional culture can have an impact on regional resilience, but there are many measurements about regional culture, for example, Hofstede’s cultural dimensions (Hofstede, 2001), Schwartz’s cultural dimensions (Schwartz, 1994) et al. Finding the effective variables of regional culture which influence regional mobility resilience under the epidemic is one of the key tasks of this study.

The pathogen-stress theory can help us better understand the relationship between regional mobility and culture under the current pandemic. It suggests that people in areas with higher prevalence of infectious diseases adapt collectivistic coping strategies, such as ingroup assortative sociality, outgroup avoidance, and less dispersal or travel over shorter distances to manage external environment threats (Fincher et al., 2008). In the context of the COVID-19 pandemic, groups may also move between culturally similar sub-regions in the majority. Among the many variables that characterize cultural distance, dialect is representative of ethnicity and culture, and dialect gaps can affect psychological distance in interpersonal interactions (Easterly and Levine, 1997). Individuals are more likely to interact with individuals of similar cultures (McPherson et al., 2001). Language affects communication, social identity, and skill exchange, and thus influences immigrants’ decisions to move (Liu et al., 2020). In areas with diverse dialects, cultural heterogeneity is greater, which may create certain communication barriers for incoming passengers and a sense of cultural alienation in incoming passengers. Therefore, when faced with the threaten of an epidemic, people may tend to move to regions with less difference in dialects. This study proposes the following hypothesis:

\[ H_2 \] Dialect distance moderates the negative impact of COVID-19 on regional mobility resilience. Cities with a high dialect density are affected more than cities with a low dialect density.

Cultural tightness-looseness is also closely related to the pathogen-stress theory, as it is often associated with regional responses to external threats (e.g., natural disasters, invasions, pathogens)(Gelfand et al., 2011). This theory suggests that people adopt stronger social norms to coordinate social behavior in the face of greater external threats and thereby gain group survival (Elster and Gelfand, 2021; Harrington and Gelfand, 2014). The meaning of cultural looseness consists of two parts, namely, “how clear and pervasive norms are within societies” and “how much tolerance there is for deviance from norms within societies” (Gelfand et al., 2006). In a tight culture, people learn from childhood to comply with social norms and adapt their behavior to the existing rules (Gelfand et al., 2017). While people in a loose culture tend to emphasize personal attributes and make decisions with more consideration for the individual (Tam and Chan, 2017). Cultural tightness-looseness has been widely used as a dimension to represent regional cultural differences in anthropology, sociology and psychology (Tang et al., 2019). Some scholars have measured regional cultural tightness-looseness (Harrington and Gelfand, 2014). Gelfand et al. (2011) measured the differences in cultural tightness-looseness in 33
countries around the world. Chua et al. (2019) mapped cultural tightness and looseness across 31 provinces in China.

Cultural tightness-looseness arises in relation to regional exposure to pathogen (Harrington and Gelfand, 2014). This kind of regional cultural schema that developed throughout history allows the region to function with a certain resilience in the face of epidemics. A study by Gelfand et al. (2021) showed that regions with high levels of loose culture (e.g., Italy, Spain, Brazil, etc.) had 4.99 times the number of COVID-19 cases and 8.71 times the number of deaths than regions with high level of tight culture (e.g., Japan, Singapore, China, etc.). Regions with high level of tight culture have higher social norms that allow for more rapid coordination of social behavior and enhanced cooperation to unify the response to the threat of an outbreak, resulting in higher survival rates. Similarly, under the stress of epidemics, the function of regional resilience index.

behavior through social norms and better guarantee the resilience of regional mobility functions. Accordingly, the following assumptions are made:

**H3.** Cultural tightness moderates the negative impact of COVID-19 on regional mobility resilience. Cities with high cultural tightness are affected less than cities with low cultural tightness.

3. Research design

3.1. Measurement of the regional mobility resilience

Building upon on the conceptual framework that discussed in the Section 2.1, this study used a single-dimensional approach to measure regional mobility resilience. In passenger flow research, the number of passenger arrivals at a destination is a commonly used indicator to examine regional passenger flow. Similarly, in this study, destination passenger arrival data is also used to measure mobility resilience. With reference to Martin et al. (2016) and Giannakis and Bruggeman (2020), this study derived the following formula for a regional mobility resilience index.

\[
    RES_i = \frac{(T_i^c - T_{i-1}^c)}{(T_i^o - T_{i-1}^o)} \times \frac{|(T_i^o - T_{i-1}^o) / T_{i-1}^o|}{|T_i^c - T_{i-1}^c| / T_{i-1}^c} \quad (1)
\]

\(T^c\) represents the intensity of passenger arrivals at the city level, while \(T^o\) represents the average intensity of passenger arrivals at the national level, and \(t - 1\) represents the same week the preceding year, which is used in order to match the data in comparable periods. Specifically, data for the same period over two years can minimize differences in passenger flows due to holidays and the Spring Festival, back-to-work and back-to-school waves, etc. \(t\) is the number of weeks in the study period. In general, a positive regional mobility index indicates that the city is more resilient than the national average.

3.2. Research model and variables

In this study, the dependent variable, regional resilience, is a dichotomous variable:

\[
    DRES_i = \begin{cases} 
    1 & \text{if } RES_i \geq 0 \\ 
    0 & \text{if } RES_i < 0 
    \end{cases} \quad (2)
\]

Because the dependent variable is a dichotomous variable, a panel logit model is set up by referring to Giannakis and Bruggeman (2020). In addition, because of the use of panel data, the double fixed effects of time and region were used for the model in this study. Referring to the common form of the panel logit model with double fixed effects (Yang et al., 2020), the basic model takes the following form:

\[
    DRES_i = a_0 + a_1 \cdot \text{Total case}_i + a_2 \cdot X_i + \tau_t + \gamma_r + \epsilon_i \quad (3)
\]

where \(i\) and \(t\) stand for city level and time, respectively, and \(RES_i\) stands for the regional mobility resilience of city \(i\) in week \(t\), \(\tau_t\) and \(\gamma_r\) stand for area fixed effects and time fixed effects, respectively, and \(\epsilon_i\) is a random perturbation term. \(\text{Total case}_i\) is the logarithm of the cumulative number of confirmed cases for city \(i\) in week \(t\). \(X_i\) is the control variables that may affect mobility resilience, mainly including the following:

(1) Measures such as lockdowns and quarantines that correspond to a first-level response to a security incident will have a significant impact on passenger flow (Gosling et al., 2020). This study used the first-level response to a security incident in each region as a significant control variable (noted as emergency level). (2) The frequency of HSR can have a significant impact on destination passenger traffic (Jin et al., 2020). During the pandemic, some cities took measures to reduce HSR frequencies, which affected the resilience of urban passenger flow. The HSR index for each city is one of the control variables (noted as HSR_index). (3) Media coverage is widely used to characterize the level of social attention, which can have a significant impact on customer flow (Narangajavana et al., 2017). This study uses media_index to represent the impact of media coverage. (4) Temperature is an important factor affecting mobility (Wilkins et al., 2018). Some studies have shown that the effect of temperature on passenger flow is curvilinear (Yang et al., 2020), so this study also included a quadratic temperature term into the control variable. (5) Weather conditions have an important impact on passenger flow (Böcker et al., 2019), and rainy days can cause many inconveniences to travel. This study used the proportion of sunny and almost sunny days of the weeks in a city as a control variable (noted as sunny). (6) Air quality is often considered an important variable that affects mobility flow (Gao and Zhang, 2019), PM2.5 was used as a control variable reflecting air quality in this study.

In addition, in order to explore the influence of regional culture on the resilience of passenger flows, this study adds regional culture as a moderating variable to model (3) and construct the following model (time and city double fixed effect):

\[
    Y_i = a_0 + a_1 \cdot \text{Total case}_i + \mu_1 Y_i \cdot \text{Total case}_i + a_2 \cdot X_i + \tau_t + \gamma_r + \epsilon_i \quad (4)
\]

\(Y_i\) is a regional cultural variable that does not change over time. \(Y_i \cdot \text{Total case}_i\) is its interaction term with \(\text{Total case}_i\). In this study, the regional cultural variable interacts with the confirmed cases of COVID-19 to allow us to examine its moderating effect on the main causal relationship. Based on the literature review and research hypotheses, this study considers two main moderating variables: first, this study takes into account the dialectal diversity of each destination city to analyze the resilience of passenger flow in the pandemic, which is noted as dialect diversity. Second, this study explores the impact of cultural tightness-looseness on the resilience of passenger flow during pandemic. These two variables are separately interacted with the number of confirmed cases in the model.

3.3. Research data

The data of passenger arrives used in this study was derived from a Python crawler of Baidu’s migration data (available through the url “https://qianxi.baidu.com/”). The migration intensity data was crawled from January 1 to March 15, 2020, for each of the 358 cities in China, and converted them to the lunar calendar. The migration intensity data of each city in the same period in 2019 were also crawled, and were aggregated into weekly data in this study. The research period selected here is a typical cycle from outbreak to control of the pandemic in China. COVID-19 broke out at the end of December 2019, became pandemic from January to February, and had already begun to decay by mid-March. Weekly time scales are used to overcome the volatility of daily data and the weakness of coarse-grained monthly data, and to better reflect the changing characteristics of passenger flow in an epidemic. In addition, for the independent variables, we integrated the epidemic data...
The control variables of this study include important factors associated with regional mobility resilience: emergency_level_1 is a dummy variable and the data are obtained from the Ministry of Justice of the PRC (http://www.moj.gov.cn/subject/content/2020-05/08/1451_324820.html). HSR_index in this study uses data compiled by the Harvard Dataverse from the 12306 train ticket website (https://dataverse.harvard.edu/dataset.xhtml?persistentId=doi:10.7910/DVN/JUBLGB). Media_index in this study is based on the media index of Baidu Big Data. By using Python crawlers, we obtained the weekly media index for each of the 358 cities in China during the study period to reflect the level of media attention each city received. Temperature data were compiled from the China Meteorological Administration (http://data.cma.cn/). The average value of the weekly temperature and its quadratic were selected and put into the model. The data of sunny also come from the China Meteorological Administration. In this study, PM2.5 was derived from the data published by the China Environmental Monitoring Station (http://www.cnemc.cn/sssj/).

As for moderating variables, the date of dialect diversity index of the cities used is from the research of Xianxiang et al. (2015). As for tightness, this study used the scores of China’s cultural tightness-looseness measured by Chua et al. (2019).

Table 1 lists the descriptive statistics of dependent variables, independent variables, control variables, and moderating variables. There are many negative values for temperature, for which no logarithm is taken. Resilience (binarization processing was carried out later) and emergency level are binary variables, and no logarithm is taken of either.

4. Empirical results

4.1. Descriptive analysis

Fig. 1 presents the nationwide weekly passenger flow intensity from 1 to 11 weeks in 2020 and the raw data for the same period the preceding year. As shown in the time series diagram, the first three weeks of 2020 are the early stage of the outbreak, with no significant change in passenger flow. The intensity of passenger flow is higher than in previous years. After the pandemic started, in the fourth week, the intensity of passenger flow declined sharply. It was not until the ninth week that the epidemic slowed down and the passenger flow showed a tendency to rebound.

As regional mobility resilience involves continuous panel data, here we intercept the first, sixth, and eleventh week data for cross-sectional presentation. As shown in Fig. 2, in the first week of the initial germination of the epidemic, the mobility resilience of the south was significantly higher than that of the north, the south regions showed better resilience after the impact of the epidemic because of its relatively developed economy and infrastructure. In the 6th week, it was lower in the center and higher in the southwest and northeast. In the middle of the epidemic, the epidemic developed mainly in the central region centered on Wuhan, Hubei, and spread to its eastern region, thus having a huge impact on mobility of these cities. In the 11th week, mobility resilience was higher in the south, northwest, and southwest, and lower in the center and northeast. This is because in the late stage of the epidemic, Wuhan and the central region of Hubei still implement strict control measures, and mobility continues to be affected. The south has a high level of mobility resilience and a faster recovery rate of mobility. The southwestern region was relatively unaffected by the outbreak and its mobility recovered relatively quickly. And the northeast is still experiencing epidemic that have impacted mobility.

In order to investigate the spatial correlation characteristics of the regional resilience index, the global and local Moran’s I indices are used to calculate the global spatial autocorrelation of resilience and local hot spots at three time points. As Table 2 shows, the results of Moran’s I are significant and positive at the three weeks, indicating a positive autocorrelation of resilience. From Fig. 3 we can see that the first week is characterized by high value clustering of resilience values in the southeast-central cities and low value clustering in the north. Initially, the epidemic broke out in Hubei Province, but the infection rates of COVID-19 outside the Hubei province was not high. The central and southern cities are mostly labor-exporting cities, which have greater population mobility during the Spring Festival, so the overall performance is characterized by higher mobility and resilience. The northern region has a lower population density and is inherently less mobile and relatively less resilient. In the sixth week, the resilience values in the southwestern and southern regions are characterized by high-value clusters, and by low-value clusters in the central and southeastern regions. In the middle of the epidemic, the epidemic continued to affect and spread centered on Wuhan. The central and southeastern regions were impacted by the epidemic and showed low mobility and resilience. The southwest and part of the south, which were less affected by the epidemic, had higher population mobility and showed a high-value agglomeration of mobility resilience. In the eleventh week, the south was characterized by high-value agglomeration, while the cities in the northeast and near Hubei showed low-value agglomeration. As the overall epidemic eased in the later period, the mobility of southern cities recovered, and mobility resilience showed a high-value agglomeration. Hubei is still affected by the long-tail effect of the epidemic, while the epidemic situation in northeast China has intensified. Therefore, the mobility resilience of the two regions has shown low-value agglomeration of mobility resilience.

4.2. Influencing factors of regional mobility resilience

Table 3 shows the estimated results of the logit model on the regional
mobility resilience index. Model 1 is the baseline model. In addition to the control variables, \( \ln(\text{total_cases}) \) (the logarithm of the cumulative number of confirmed COVID-19 cases per week) is included in the baseline model. Model 2 adds \( \ln(\text{total_cases}) \times \ln(\text{tightness}) \) (the interaction item of cumulative confirmed COVID-19 cases and cultural tightness), while model 3 adds \( \ln(\text{total_cases}) \times \ln(\text{dialect diversity index}) \) (the interaction item between the cumulative number of confirmed COVID-19 cases per week and dialect diversity index).

Basic coefficient estimates can be obtained from Model 1. \( \ln(\text{total_cases}) \) has an estimated coefficient of 0.4435, which is statistically significant at the 0.01 level. This result shows that the increase in the cumulative weekly number of confirmed COVID-19 cases in cities will reduce the probability of regional mobility resilience. This result provides support for H1. This result is in line with the results of previous studies about the impact of the epidemic on mobility (Galeazzi et al., 2021; Jiang et al., 2021). Due to restrictions on travel conditions and the panic of the masses in severely epidemic cities, the degree of mobility has been greatly reduced compared with the past, that is, mobility

Table 2
| Moran’s I | 1st week | 6th week | 11th week |
|-----------|----------|----------|-----------|
| Z value   | 0.5360   | 0.5045   | 0.6523    |
|           | 15.8612  | 15.2736  | 19.7990   |

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Table 3
Logit model regression results.

| Variable                  | Model 1          | Model 2          | Model 3          |
|---------------------------|------------------|------------------|------------------|
| lnHSR_index               | 5.3549***        | 5.2968***        | 5.7690***        |
| (1.445)                   | (1.4232)         | (1.4371)         |                  |
| emergency_level_1         | −1.0009***       | −1.0283***       | −1.0359***       |
| (0.1909)                  | (0.1902)         | (0.1919)         |                  |
| lnmedia_index             | 0.1956*          | 0.1928*          | 0.2061*          |
| (0.1112)                  | (0.1112)         | (0.1123)         |                  |
| temperature               | −0.0969***       | −0.0887***       | −0.0952***       |
| (0.0222)                  | (0.0225)         | (0.0225)         |                  |
| temperature2              | 0.0073***        | 0.0074***        | 0.0071***        |
| (0.0088)                  | (0.0088)         | (0.0090)         |                  |
| lnPM 2.5                  | −0.2046          | −0.1175          | −0.2278          |
| (0.327)                   | (0.3295)         | (0.3287)         |                  |
| Insunny                   | 0.2475           | 0.2697*          | 0.2369           |
| (0.158)                   | (0.1587)         | (0.1586)         |                  |
| lntotal_cases             | −0.4435***       | −0.9526***       | −0.5850***       |
| (0.0863)                  | (0.167)          | (0.099)          |                  |
| lntotal_cases*Insunny     | 0.9850***        |                   |                  |
| (0.2747)                  |                  |                  |                  |
| lnlnotal_cases*ln dialect_diversity | −0.1998***  |                  |                  |
| (0.0473)                  |                  |                  |                  |
| week-specific effects     | Yes              | Yes              | Yes              |
| city-specific effects     | Yes              | Yes              | Yes              |
| Sample size               | 3718             | 3718             | 3696             |
| Cities                    | 338              | 338              | 336              |
| Pseudo R-squared          | 0.0791           | 0.0830           | 0.0827           |

legend: *p < 0.1; **p < 0.05; ***p < 0.01.

5. Discussions

5.1. Theoretical implications

We exploratively apply the regional resilience theory to mobility study. And this study has creatively developed a regional mobility resilience index, which helps to better understand the spatial heterogeneity of the impact of the COVID-19 pandemic on regional passenger flows. First of all, compared with the existing research on mobility resilience under the epidemic (da Mata Martins et al., 2019; Galeazzi et al., 2021; Tong et al., 2020), this research adopts the method of regional resilience, which measures the mobility resilience by highlighting the regional differences, and verifies that it has a good measurement effect; On the other hand, compared to traditional regional resilience research (Bristow and Healy, 2020; Martin and Sunley, 2015; Wang and Wei, 2021), this research build upon the research framework based on regional resilience and expands it to mobility measurement. In general, the results of this study provide useful insights into mobility resilience under the COVID-19 pandemic, and contributes to regional passenger flow forecasting and resilience literature.

A more important research contribution is that, applying the assumptions of pathogen-stress theory, we propose and confirm that the regional culture moderate the negative impact of COVID-19. Pathogen-stress theory proposed by Fincher et al. (2008) helps us to understand the underlying factors and mobility patterns that underlie spatial differences in the resilience under external threats. But the applications of the theory in regional studies stay at the stage of conceptualization of the phenomenon, and have not described the internal mechanism underlying the theory. By integrating two variables of regional culture: dialect diversity and cultural tightness-looseness, our research results reveal in more detail about how Pathogen-stress theory can affect group movement under the threats of the COVID-19 pandemic.

As manifested in the results, dialectal diversity can moderate the negative effect of pandemics on mobility. This is consistent with the view of Liu et al. (2020), which suggested that the cultural distance behind dialects diversity will affect the migrants’ choice of destination and hinder passenger flow. This finding echoes the connotation of pathogen stress theory, which states that people tend to congregate in culturally similar groups (or regions) under the external threats. Secondly, based on pathogen-press theory, this study exploratively
introduced cultural tightness-looseness into mobility research. Although there is research revealed that cultural tightness-looseness can effectively reduce the negative impact of the epidemic (Gelfand et al., 2021), the findings of this study further demonstrate the role of cultural tightness-looseness as a potential schema for ensuring the function of regional mobility resilience under the epidemic. People in regions with tight culture have higher social norms, and social norms are thought to contribute to higher levels of pro-social behavior (Krupka and Weber, 2009). Under the threat of epidemic, tight cultural societies can more quickly coordinate overall social behavior and take efficient measures such as transportation inspection, quarantine of suspected passengers, and information sharing on epidemic prevention. Local people are also more likely to cooperate and follow the social order by actively wearing masks, disinfecting, sharing trip information, cooperating with security checks, etc. As a result, areas with high level of tight culture are able to guarantee the operation of transportation functions more effectively, passengers will travel to those destinations with greater confidence.

The results of the study can be further conceptualized as a theoretical framework of the expanded pathogen-stress theory under the epidemic, as shown in Fig. 4. Pathogen-stress theory describe the people’s collective coordinated behavior in the face of external threats at the conceptual level, while cultural tightness-looseness implicitly explains the coordinating role of social norms on social behavior in the face of threats (Gelfand et al., 2021), further explaining the mechanism of the pathogen-stress theory. The cultural distance represented by dialect diversity intensifies the impact of the epidemic on regional mobility resilience, and reflects the core of the pathogen-stress theory, that is, people tend to move within groups with similar cultures in the face of the epidemic. These two regional cultural variables amplify or reduce the effect of the epidemic on regional mobility resilience, verifying the role of pathogen-stress theory as a cultural schema in explaining people’s mobility under the epidemic, and provide a more detailed explanation for the theory.

5.2. Practical implications

Our results provide important managerial implications. First of all, the level of mobility resilience of each city to COVID-19 can be obtained through the regional mobility resilience calculation method. This index has insightful implications for local governments and other stakeholders. In preparing for later waves of COVID-19 and future pandemics, societies can learn from what regions with higher mobility resilience have done to help them succeed. Our results show that models of regional mobility resilience will be improved by integrating regional cultural factors. Regions should reduce cultural distance and elevate social norms to ensure the stability of mobility functions in the face of external threats of epidemics. To reduce cultural distance, the region should strengthen acceptance of general culture and enhance cultural openness. Specifically, measures should be taken to reduce dialect barriers, promote general language, and create an inclusive cultural environment. On the other hand, cultural tightness-looseness is shaped by long history and cannot be changed rapidly, but social norms can be enhanced through intensive interventions (Hiselius and Rosqvist, 2016; Matias, 2019). For example, tightening social norms on behaviors such as social distancing, wearing masks, and temperature testing at traffic entrances, tightened interventions are conducive to mobility resilience. However, the interventions in each region should be adapted to its particular situation, because people in regions with loose culture are resistant to social constraints, and too strong interventions may have counterproductive effects. Lastly, it is important to emphasize that not all loose cultures do not perform well, and not all tight cultures can guarantee regional mobility resilience. However, it is really a responsibility to follow social norms during collective threats.

5.3. Limitations and future research

There are several limitations to this study. First, we used single data source—Baidu mobility index to measure the intensity of passenger flow, which may be subject to unexamined measurement bias. Future research should concern itself with the application of multiple data sources. Second, since this is a panel regression of weekly data, there are many other control variables not included in the model for lack of weekly data. We have tried to control for as many social and environmental variables as possible, but there are still many variables that affect the resilience of passenger flow. Third, we used data only from China, further testing is needed to see whether the extended pathogen-stress theory proposed by this study can be generalized to other countries. Subsequent studies may compare the differences between different cultural zones based on a global comparison, such as the differences between East countries and Western countries in controlling the pandemic. In addition, future studies can consider using other regional cultural variables to further refine the theoretical mechanisms of pathogen-stress theory, or to study the differences in pathogen-stress theory under different external threats.

6. Conclusions

This study examined the impact of the COVID-19 pandemic on the regional mobility resilience of Chinese cities during the 11 weeks from January 1 to March 15, 2020, the cycle from outbreak to pandemic and finally to control. We borrowed the commonly used regional resilience measurement equations to obtain the regional mobility resilience index of cities across the country in 11 weeks. The index shows spatial auto-correlation and has different hotspots over time. After controlling for high-speed rail, emergency level, media index, weather, air quality, and other factors, this study tested the effect of COVID-19 cases on mobility resilience. Moreover, this study verified the influence of regional culture on regional mobility resilience based on pathogen-stress theory. The detailed findings are as follows:

a. In the first week of the epidemic, the overall regional mobility resilience of the southern region was higher than that of the north, and the south-central regions were agglomerated with high values, while the northern cities were agglomerated with low values. In the sixth week of the epidemic, regional mobility resilience values in the central region were low and agglomerated at low values, while regional mobility resilience values in the southwest and northeast regions were high and agglomerated at high values. In the eleventh week of the epidemic, Hubei and northeast regions showed low-value agglomerations, while southern regions showed high-value agglomerations.

b. The number of confirmed cases of COVID-19 epidemics has a significant negative impact on regional mobility resilience. The increase
in the cumulative weekly number of confirmed COVID-19 cases in cities will reduce the probability of regional mobility resilience. c. Regional culture of a city plays a moderate role in the impact of the epidemic on regional mobility resilience. Specifically, cultural tightness-looseness can weaken the negative effects of the epidemic, indicating that in areas with high level of cultural tightness, regional mobility resilience is less affected by COVID-19. Dialect diversity can magnify the negative impact of the epidemic, that is, the shock of COVID-19 on regional mobility in cities with diverse dialects is more severe. d. This research validates and advances the pathogen-stress theory. Findings of this research suggest that the characteristics of regional mobility under epidemic can be understood through pathogen-stress theory. People are willing to move within culturally similar groups when facing epidemic threats (e.g., low level of dialect diversity). In addition, social norms (e.g., high level of regional cultural tightness-looseness) may potentially guarantee an organized movement pattern of people under the impacts of the COVID-19 pandemic.

CRediT authorship contribution statement

You-Hai Lu: Conceptualization, Formal analysis, Writing – original draft. Honglei Zhang: Supervision, Project administration. Min Zhuang: Writing – original draft, Writing – review & editing. Meng Hu: Resources, Data curation, Writing – original draft. Chi Zhang: Methodology, Writing – review & editing. Jingxian Pan: Visualization, Writing – review & editing. Peixue Liu: Methodology, Data curation. Jie Zhang: Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

We are grateful to the National Natural Science Foundation of China for NSFC projects (No. 41771153 and No. 41971173); the program B for Outstanding PhD candidate of Nanjing University (No. 202101B036).

Nomenclature

cases The cumulative number of confirmed COVID-19 cases per week in each city

highway index The frequency of HSR per week in each city media_index Media coverage index from Baidu Index, reflecting media attention

emergency level_1 the first-level response to a security incident in each city

temperature The weekly temperature for each city

PM2.5 The PM2.5 value that reflects the air quality of each city

sunny The percentage of sunny and almost sunny days per week in a city

tightness The value of cultural tightness-looseness of each city

dialect The value of the dialectal diversity of each city

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