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Regional mobility and COVID-19 vaccine hesitancy: Evidence from China☆

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ABSTRACT

China's Zero-COVID Policy imposed stringent restrictions on citizens' mobility to curb the spread of COVID-19. While effective in reducing viral transmission, these measures may have inadvertently delayed or deterred vaccine uptake by fostering a heightened sense of security. This study examines the relationships between intra- and inter-regional travel mobility and individual hesitancy towards COVID-19 vaccines (HCV), leveraging the Baidu Mobility Index and data from a cross-sectional survey of 12,000 participants. Our descriptive analysis reveals that (a) individual attitudes toward COVID-19 vaccines are more polarized across regions with different mobility levels than toward vaccines in general and (b) regions with higher population mobility exhibit lower levels of hesitancy toward COVID-19 vaccines. Our OLS and IV results further demonstrate that a one-standard-deviation increase in inter-provincial travel rates is associated with a decrease of 0.0112–0.0195 standard deviations in HCV, whereas intra-provincial mobility is not correlated. Overall, this paper suggests prioritizing the roll-out of COVID-19 vaccines or similar initiatives in areas with higher mobility levels, where residents perceive greater risks and exhibit a higher likelihood of seeking vaccination.

1. Introduction

The reaction of governments to the COVID-19 pandemic was diverse [1]. At one extreme, were those countries with Zero-COVID policies, of which the People's Republic of China (PRC) was one of the most stringent and of longest duration [2]. As the first country to experience this health shock, the PRC implemented the Zero-COVID policy from January 2020 to December 2022, which severely restricted travel mobility among its citizenry and was largely successful in limiting the spread of the virus compared to other countries. For instance, on one hand, the total number of passenger trips during the 2021 Spring Festival Travel Rush was only 29.2% of that in the same period in 2019.[1] On the other hand, the average number of confirmed cases per month was just 787 in the first half of 2021, with zero deaths for most of that time.

Social distancing, travel restrictions, and lockdown were adopted as the main preventive measures, highlighting the role of human mobility as a key factor in the process of virus spread and thus prevention. Beginning in March 2021, vaccination campaigns emerged as a key strategy to further control virus spread, complementing the Zero-COVID measures already in place. Yet, the limited mobility during restrictions may have led to an elevated sense of security, resulting in vaccine hesitancy; therefore, after the end of the Zero-COVID policy, the lifting of restrictions permitted higher mobility, exposing the unvaccinated populace.

Since vaccination hesitancy contributed to excessive mortality among vulnerable populations after China ceased its Zero-COVID policy [3], it is important to understand whether and how mobility restrictions influenced prompt vaccination, as this knowledge can inform

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[1] Spring Festival Travel Rush, also called "Chunyun," is a period around the Chinese New Year with extremely high travel rates in China. During such periods, family reunions are often the primary driving force behind travels.

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more effective policy responses. Specifically, if individual hesitancy toward COVID-19 vaccines increases with higher regional mobility – defined in our study as the intensity of travel within and across provincial boundaries – governments could prioritize combating misinformation and tailoring vaccine messaging. Conversely, if higher regional mobility reduces hesitancy, governments could establish temporary clinics in high-traffic areas, such as transportation hubs, to further enhance prompt vaccination coverage.

The effectiveness of mobility restrictions in reducing the spread of COVID-19 [4] suggests that areas with high travel mobility, or living in an overcrowded region particularly with considerable population flows moving from and into other regions, can be associated with a relatively higher risk of infection. As evidenced, perceived risk of COVID-19 penetration can mitigate the deterrent to vaccination [5]. Therefore, it is reasonable to assume that people who are at higher risk of exposure to COVID-19 would be more likely to adopt preventive strategies, typically vaccination, to reduce their potential risk. Hence, a refusal or procrastination of uptake leads to larger opportunity costs for them, which, in turn, impose stronger probabilities on them to prefer receiving vaccines. In this vein, human mobility triggers a positive externality for public health by influencing individual perceptions of and reactions to COVID-19 vaccines.

The related literature can be categorized into two strands. The first strand centers on human mobility, investigating either the relationships between viral transmission or containment measures – typically lockdowns – and mobility dynamics (e.g., Kraemer et al. [6], Fang et al. [7], Glaeser et al. [4], Gong et al. [8], Wang-Lu et al. [9]), or the associations between COVID-induced changes in mobility and various socio-economic outcomes, including demographic characteristics, inequities, inequalities, public health, economic growth, consumption patterns, carbon emissions, remote work, and housing prices, among others (e.g., Friedson et al. [10], Glodeanu et al. [11], Campos-Vazquez and Esquivel [12], Chakrabarti et al. [13], Lei et al. [14], Cicala [15], Gamber et al. [16], Wu et al. [17]).

The second strand emphasizes vaccines. Specifically, the speed of drug development and approval stages has contributed to public distrust [18–20]; different governments have implemented diverse incentive schemes to promote vaccine uptake (see Jacobson et al. [21], and references therein); and studies have examined the health and socio-economic impacts of receiving vaccines (e.g., Deb et al. [22], Deb et al. [23]). In addition, factors influencing individual behaviors and attitudes toward vaccination range from religiosity [24,25] to misinformation [26–28], as well as socioeconomic status [29] and demographic characteristics [30]. In particular, Comperchio et al. [31] show that the relationship between neighborhood disadvantage and vaccine uptake becomes statistically insignificant once individual characteristics are included in the analysis.

To date, none of the existing literature investigates the relationship between human mobility and public attitudes toward COVID-19 vaccines. However, this is crucial for policy-makers to make informed decisions about balancing mobility restrictions with vaccine promotion. Therefore, the main objective of this paper is to examine the associations between regional travel intensity and COVID-19 vaccine hesitancy. We conducted an online survey covering 12,000 individuals across 31 Chinese provinces and merged it with provincial statistics and the Baidu Mobility Index. The survey was carried out during the initial phase of the COVID-19 vaccination rollout in China. According to official daily monitoring reports, by the end of our data collection, approximately 23% of the population had received a full vaccination, assuming two doses per person. By leveraging this unique dataset, we study vaccine attitudes among the general population, rather than among patient populations, at a critical juncture, whilst previous literature relied predominantly on patient data.

The remainder of the paper is structured as follows: Section 2 introduces the datasets. Section 3 provides a descriptive analysis. Section 4 presents the regression analyses followed by a discussion and concluding remarks in Section 5.

2. Data sources

2.1. Survey data

The survey was initially designed for a randomized controlled trial, using three storytelling videos to test the effectiveness of video interventions in disseminating health information and changing subjective beliefs [32]. The primary outcomes were individual hesitancy toward COVID-19 vaccines (HCV) and hesitancy towards vaccines in general (HVG), respectively, rating the extent to which participants agree with statements related to perceived safety of vaccination on a scale of 1–5, with the original values being: 1="strongly disagree," 2="disagree," 3="neither agree nor disagree," 4="agree" as well as 5="strongly agree."

Specifically, following Opel et al. [33], Brown et al. [34] and Larson et al. [35], the hesitancy measure summarized 10 survey questions related specifically to COVID-19 vaccines and 12 questions upon attitude toward vaccines in general. Notably, in our survey, the questions about vaccines in general were intentionally presented before the COVID-19 vaccine questions to protect the general measure from being biased by strong feelings about COVID-19 experiences (e.g., Schwarz et al. [36], Tourangeau et al. [37], Lee and Grant [38]). In addition, maintaining a logical flow from general attitudes to specific cases for all participants allowed us to obtain more stable and consistent measurement of attitudes.

The specific questions are listed in Table 1. We adjusted the scale of each question so that higher values indicate higher levels of hesitancy, and then calculated the arithmetic mean and geometric mean of all the ratings to create two composite indicators reflecting overall attitudes. The composite indices ranged from 1.6 to 5 and from 1.43 to 5, respectively, with intervals of 0.1 or smaller. Our descriptive analysis relied mainly on the geometric outcome, while both indicators were used in regressions.

In addition, the questionnaire also collected essential individual characteristics of the participants, such as gender, age, place of residence, education level, household income, behavioral intent to get vaccinated and mental health. The data was collected on the Kurundata platform in May 2021, with participants recruited through its own platform, its partnerships with other websites, and the popular mobile application WeChat. The final dataset comprises 12,000 individuals aged over 18 years old.

2.2. Baidu mobility index

Mobility data, quantifying inter- and intra-regional travel intensity in a given province, were sourced from Baidu Qianxi, a program initiated in 2014 that leverages Baidu Map's location-based services. As one of China's leading web mapping applications, it processes 130 billion real-time location service requests daily, serves over 500 million users with its AI-powered voice assistant, and supports over 500,000 mobile apps in user location tracking. This enables Baidu Qianxi to accurately monitor and map population movements within and between subnational regions every day. Despite the lack of clear explanations for how Baidu normalizes the data to provide indices that are comparable across different regions and periods, Baidu Mobility Index has become a major resource for researching COVID-19 and has seen increased use in recent studies Gibbs et al. [see39], Fang et al. [7], Liu et al. [40], Huang et al. [41], Mu et al. [42], Chen et al. [43]. In Table A.1, we provide descriptive statistics of all the variables used in this study.

2.3. Data representativeness

According to China's 7th Population Census conducted in 2020 and the China Statistical Yearbook (2021), the following demographic and economic characteristics were reported: 51.24% of the population were male; 63.89% were urban residents; the average educational attainment

Table 1
Summary of questions.
Source: Authors' elaboration using Baidu Mobility Index and Chen et al. [32].

Hesitancy toward COVID-19 vaccines	
1	COVID-19 vaccines are important for my health
2	COVID-19 vaccines are effective
3	Having myself vaccinated with a COVID-19 vaccine is important for the health of others in my community
4	All COVID-19 vaccines offered by the government program in my community are beneficial
5	The information I receive about COVID-19 vaccines from the vaccine program is reliable and trustworthy
6	Getting COVID-19 vaccines is a good way to protect myself from COVID-19
7	I am concerned about serious adverse effects of COVID-19 vaccines
8	I do not need COVID-19 vaccines if it is not a pandemic anymore
9	I am concerned that COVID-19 vaccines might not prevent the disease
10	I am concerned that COVID-19 vaccines might not be safe
Hesitancy toward vaccines in general	
1	Vaccines are important for my health
2	Vaccines are effective
3	Having myself vaccinated is important for the health of others in my community
4	All vaccines offered by the government program in my community are beneficial
5	New vaccines carry more risks than older vaccines
6	I trust the information I receive about shots
7	Getting vaccines is a good way to protect myself from disease
8	I am concerned about serious adverse effects of vaccines
9	People do not need vaccines for diseases that are not common anymore
10	I believe that many of the illnesses shots prevent are severe
11	People get more shots than are good for them
12	It is better to develop immunity by getting sick than to get a shot

among individuals aged over 15 was 9.91 years of schooling (equivalent to the completion of the first year of high school); the per capita disposable income reached 32,189 Yuan (equivalent to 4414 USD); and the average household comprised 2.62 persons.[2] In comparison, the participants in our dataset comprised 51.06% males, 60.47% urban residents, an education level approximately equivalent to high school (about two years above the national average), and an annual gross household income primarily falling between 90,000–120,000 Yuan (equivalent to 12,342–16,456 USD) and 120,000–150,000 Yuan (16,456–20,570 USD). Suppose two individuals in the household are engaged in paid jobs, each earning 60,000 Yuan (8,228 USD) per year. The corresponding after-tax household income would be approximately 93,000 Yuan (12,754 USD), which is relatively close to the average disposable household income, calculated as 32,189 × 2.62=84,335 Yuan (11,565 USD). Given all that, we conclude that our dataset is likely to be nationally representative of the adult population in China. Nevertheless, it is worth recapping that our participants were all aged over 18, whereas the national census typically includes individuals aged 15 and above for statistical purposes on years of schooling. As a result, a perfectly comparable census statistic is not available.

3. Descriptive analysis

By dividing intra-provincial travel intensity into tertiles,[3] at first glance, the average level of hesitancy toward COVID-19 vaccines appears very similar across groups, at 2.87, 2.84 and 2.84 in the lower, middle, and upper groups, respectively. To offer a clearer picture of how attitudes are distributed–patterns that may be masked by mean values alone–we classified participants as more hesitant if they selected "strongly agree" or "agree" more frequently than the other response options, and as less hesitant if they more often chose "strongly disagree" or "disagree."

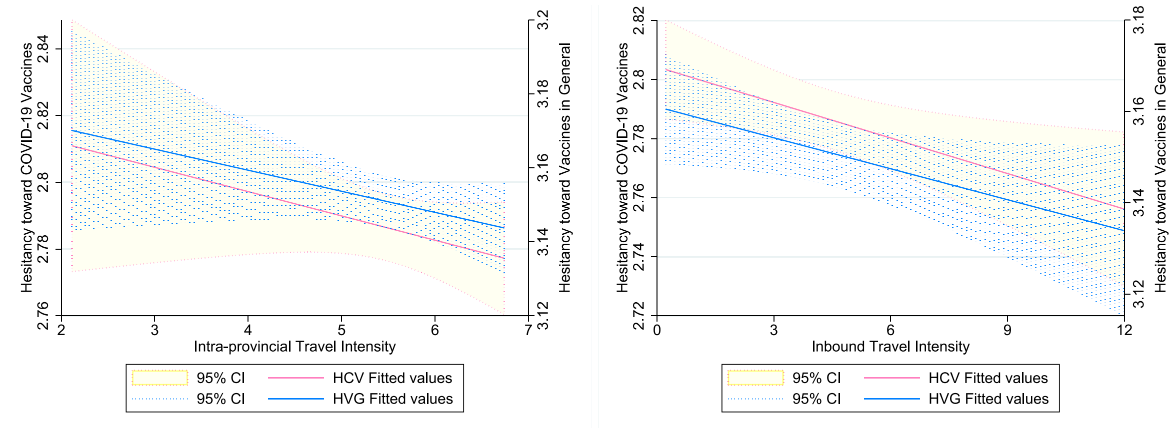
Consequently, 29.81% of participants in the lower group are less hesitant to receive the COVID-19 vaccines, compared to 12.38% who are more hesitant. The percentage of those less hesitant increases to 30.63% in the middle and upper groups, while the percentage of those more hesitant decreases to 9.87%. Interestingly, when considering vaccines in general, participants tend to be neutral much more often. As a result, only 3.9% and 19.74% of participants in the lower group are classified as less or more hesitant, while 4.47% are less hesitant and 18.42% are more hesitant in the middle and upper groups. As shown in Fig. 1(a), there appears to be negative relationships between vaccine hesitancy and intra-regional mobility, with the trend being slightly more pronounced for hesitancy toward COVID vaccines.

Similarly, when examining inter-provincial mobility, our data reveal that 30.07% of participants in the lower inbound travel group are less hesitant, compared to 12.42% who are more hesitant. In contrast, 30.48% of participants in the middle and upper groups are less hesitant, while 9.89% are more hesitant. As mentioned earlier, attitudes toward vaccines in general are much more neutral, with only 3.76% being less hesitant and 19.8% being more hesitant in the lower group. The percentage of less hesitant participants increases to 4.52% in the middle and upper groups, while the percentage of more hesitant participants decreases to 18.42%.

The results based on outbound travel are very similar: 29.62% of participants in the lower group are less hesitant, while 12.45% are more hesitant, compared to 30.7% and 9.9% in the middle and upper groups, respectively. For hesitancy toward vaccines in general, the corresponding statistics are 3.73% and 19.77% in the lower group, and 4.55% and 18.44% in the middle and upper groups, respectively. The fitted lines plotted in Fig. 1(b) further illustrate a slightly stronger negative relationship between individual hesitancy toward COVID-19 vaccines and inter-provincial mobility than between hesitancy toward

[2] Disposable income is the amount of money left after a household's total income has been reduced by personal income taxes, contributions to social security, and any recorded subsidies like housing or childcare benefits.

[3] It is worth noting that, as the Baidu Mobility Index is normalized and proprietary, with Baidu not disclosing the exact method of normalization, the index values cannot be interpreted in absolute terms. Therefore, the tertile categorization here reflects relative mobility levels rather than specific quantitative thresholds. In other words, the Baidu Mobility Index can only be interpreted in a comparative sense, either across time periods (e.g., mobility increased or decreased over time) or across regions (e.g., Region A had more trips than Region B).



(a) Intra-provincial travel intensity. (b) Inter-provincial, inbound travel intensity.

Fig. 1. Plausible relationships between travel intensity and hesitancy toward COVID-19 vaccines or vaccines in general.
Notes: Both sub-figures plot fitted lines with 95% confidence intervals. The results for inter-provincial, outbound travel intensity are almost identical to those in Fig. 1(b) and are therefore not presented here.
Source: Created by authors using Baidu Mobility Index and Chen et al. [32].

vaccines in general and inbound travel rates. In sum, we find that people tend to be less hesitant about vaccination in more travel-intensive regions, and vice versa. To further explore this finding, we developed two econometric models in the next section as a complement to the descriptive analysis presented here.

4. Regression analysis

4.1. Econometric models

The baseline model adopted to estimate the effects of travel intensity on hesitancy toward COVID-19 vaccines is as follows:

$$(g)HCV_{ij} = \alpha + \beta_1 InterMob_{2021,j} + \beta_2 X_i + \beta_3 P_j + \gamma_g + \epsilon_{ij} \quad (1)$$

$$(g)HCV_{ij} = \alpha + \beta_4 IntraMob_{2022,j} + \beta_5 X_i + \beta_6 P_j + \gamma_g + \epsilon_{ij} \quad (2)$$

where $(g)HCV_{ij}$ is the COVID-19 vaccine hesitancy of an individual i living in province j; $InterMob_{2021,j}$ and $IntraMob_{2022,j}$ are the travel intensity indices, reflecting the average intra- or inter-provincial (i.e., inbound or outbound) travel rates in each province j over the three months preceding the completion of data collection. However, since the data available to us does not have information on intra-city travel intensity for March–May 2021, from which our intra-provincial mobility is aggregated,[4] we used the corresponding period in 2022 as a proxy. As China enforced the Zero-COVID policy, travel restrictions remained quite stringent throughout 2021 and into 2022 until the release of the 9th Edition of the Protocol for Prevention and Control of COVID-19 on June 27, 2022. Due to these continued restrictions, mobility patterns from March to May 2022 are likely to resemble those of 2021. For example, the 2021 and 2022 Spring Festival Travel Rushes saw 870 million and 1050 million passenger trips, while the pre-pandemic average was typically around 3 billion.

X_{ij} are individual characteristics, such as gender, age, educational level, urban or rural residence, household annual income, depressive symptoms, and most importantly, HVG; P_j are provincial characteristics, that is, population density, medical resources (the number of hospital beds per 10,000 persons is used as a proxy), general retail price index, living standards (the log of average wages is used as a proxy), and the number of confirmed COVID-19 cases per 10,000 persons; γ_g are treatment group fixed effects as our survey data were collected upon a randomized controlled trial; ϵ_{ij} is an error term.

However, the OLS estimates could be biased mainly for two reasons. Firstly, unobservable characteristics, like occupations (think about if people worked in logistics industries), are hard to measure but may co-evolve with mobility patterns and influence our studied outcomes. Secondly, travel restrictions could deter both population movement and vaccination. Given the potential presence of endogeneity and the uncertain direction of bias, we adopted an instrumental variable (IV) approach to further estimate the mobility effects. Akin to Fruehwirth et al. [44]'s strategy, we utilized the pre-pandemic mobility index, which captured travel intensity in early 2019. This assumes that pre-pandemic mobility is mean independent of unobservable factors associated with COVID-19 vaccine hesitancy, conditional on controls.

One may be concerned about the validity of this IV as population mobility may still affect hesitancy toward COVID-19 vaccines via other factors existing before the pandemic. For instance, provinces with higher mobility are often more economically developed and equipped with better healthcare infrastructure, leading residents to exhibit greater trust in vaccines. Individuals with higher health literacy are more likely to make informed decisions, avoiding irrational panic and misinformation. Additionally, established attitudes toward other vaccines, shaped by factors such as education levels, occupations, subjective health, and previous vaccination experiences, can significantly influence how individuals evaluate COVID-19 vaccines.

To address these concerns, we first included a variety of control variables to largely account for variations across individuals and regions, including education levels, personal attitudes toward vaccines in general, employment in healthcare industries, as well as regional living standards and medical resources. Then, we considered two additional instruments reflecting pre-pandemic mobility: the total volume of passenger traffic per 10,000 persons in 2018 (including railways, highways, waterways, and civil aviation) and the railway passenger

[4] It is worth noting that Baidu provides statistics on intra-regional mobility rates only at the city level, and on inter-regional mobility rates at both the province and city levels.

Table 2
Baseline estimates of intra- and inter-provincial mobility on hesitancy toward COVID-19 vaccines.
Source: Authors' elaboration using Baidu Mobility Index and Chen et al. [32].

	(1) intra-HCV	(2) intra-gHCV	(3) in-HCV	(4) in-gHCV	(5) out-HCV	(6) out-gHCV
DV: Hesitancy toward COVID-19 vaccines						
Mobility	−0.0060	−0.0074	−0.0114**	−0.0160***	−0.0112**	−0.0154***
	(0.0069)	(0.0073)	(0.0045)	(0.0047)	(0.0043)	(0.0048)
HVG	1.8090***	1.7649***	1.8089***	1.7648***	1.8090***	1.7648***
	(0.0199)	(0.0212)	(0.0199)	(0.0212)	(0.0200)	(0.0212)
Constant	−5.5190***	−5.4062***	−6.0246***	−6.0834***	−6.0077***	−6.0495***
	(0.8902)	(1.0083)	(0.7853)	(0.8979)	(0.7801)	(0.8929)
Controls	Y	Y	Y	Y	Y	Y
Adj. R^2	0.5698	0.5222	0.5699	0.5224	0.5699	0.5224
Obs.	12,000	12,000	12,000	12,000	12,000	12,000

Notes: Columns (1), (3) and (5) use the arithmetic mean of the COVID-19 vaccine hesitancy ratings, while Columns (2), (4) and (6) use the geometric mean. Robust standard errors shown in parentheses are clustered at the province level. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

traffic volume per 10,000 persons in 2018. This alternative specification allows us to test the overidentifying restrictions, providing insights into the joint exogeneity of the instruments. Also, a comparison of the results can lend further support to the robustness of our estimates.

Accordingly, our two-stage least squares (2SLS) model can be formulated as follows:

$$\text{1st stage: } InterMob_{2021,j} = \theta + \pi_1 InterMob_{2019,j} + \pi_2 X_i + \pi_3 P_j + \gamma_g + \varepsilon_{ij} \tag{3}$$

$$\text{2nd stage: } (g)HCV_{ij} = \eta + \lambda_1 \widehat{InterMob}_{2021,j} + \lambda_2 X_i + \lambda_3 P_j + \gamma_g + \upsilon_{ij} \tag{4}$$

where $InterMob_{2019,j}$ are the pre-pandemic travel intensity instrumented for $InterMob_{2021,j}$. All other notations have the same meanings as in Eq. (1).

4.2. Main results

Table 2 presents the results corresponding to Eqs. (1) and (2). By employing both arithmetic and geometric means, we provide a more comprehensive evaluation of central tendency, thereby enhancing the robustness of the estimates. Interestingly, Columns (1) and (2) indicate that intra-provincial travel intensity is not correlated with individual hesitancy toward COVID-19 vaccines. In fact, the wider confidence intervals (CIs) shown in Fig. 1(a) suggest that there might be considerable variability in the associations between the two factors. In contrast, as shown in Columns (3)–(6), both inbound and outbound mobility are correlated with individual hesitancy toward COVID-19 vaccines. Specifically, a one-standard-deviation increase in inter-provincial travel rates is associated with a decrease of 0.0112–0.0160 standard deviations in HCV. Moreover, individuals who are more hesitant about vaccines in general exhibit significantly higher levels of hesitancy toward COVID-19 vaccines. Additionally, although not detailed here, we find that the density of confirmed COVID-19 cases is negatively correlated with individual hesitancy toward COVID-19 vaccines, while other provincial controls are all found to have no correlation.

In Table 3, we report both the first-stage and second-stage results of the 2SLS model. Since intra-provincial mobility is not correlated with individual hesitancy toward COVID vaccines, we base our IV analysis here on two inter-provincial travel indicators. All estimates in Panel A are statistically significant at the 1% level. The Kleibergen-Paap Wald F-statistic is 88.46 for inbound travel and 56.86 for outbound travel, confirming that there is no weak instrument problem. Panel B shows that a one-standard-deviation increase in move-in or move-out rates reduces the hesitancy by 0.0123–0.0195 standard deviations. The magnitudes here are slightly larger than those reported in Table 2, suggesting that our OLS estimator is downward biased.

In addition, to gain plausible support (though definitely not a guarantee) for the validity of our identification, we consider two additional instruments: the total volume of passenger traffic per 10,000 persons in 2018 (including railways, highways, waterways, and civil aviation) and the railway passenger traffic volume per 10,000 persons in 2018.[5] Including these two instruments allows us to test the overidentifying restrictions. As shown in Table A.2, the p-values of the Hansen J-test are 0.3838, 0.2258, 0.3548, 0.1976, respectively, indicating no evidence against the joint exogeneity of the instruments. Moreover, the results are almost identical to those in Table 3, with the magnitudes of the effects ranging from −0.0121 to −0.0191. Therefore, we conclude that our estimates are adequately robust.

5. Discussion and concluding remarks

As long as social interactions play an essential role in the transmissibility of respiratory viruses, the level of mobility inevitably carries contagion risks, exposing residents to a higher infection probability (e.g., Buckee et al. [46], Alfaro et al. [47]). Curbing mobility, in this context, is highly meaningful and effective at protecting the masses. However, when the need to travel is minimal, an illusion of safety or a perceived lack of urgency may mislead some individuals to prioritize other potential or even minor health concerns over more immediate threats like COVID-19. In this paper, we investigate the relationships between regional population movement and hesitancy toward COVID-19 vaccines. Our empirical results suggest prioritizing the roll-out of COVID-19 vaccines or similar initiatives to populations residing in areas with higher mobility levels, where residents perceive higher risks and are more likely to seek vaccination. Usually, peer effects and herding behavior can appear after a certain number of "pioneers" are seen (e.g., Sato and Takasaki [48], Kairiza et al. [49]). Thus, a smooth first step is rather important and helpful.

More specifically, by eliciting subjective attitudes from an online survey involving 12,000 individuals and assigning concurrent Baidu Mobility Index to their provinces, we find that (a) individual attitudes are more polarized toward COVID-19 vaccines than toward vaccines in general, and (b) higher levels of population mobility are associated with lower hesitancy in receiving COVID-19 vaccines. Interestingly, while greater inter-provincial mobility tends to reduce individual hesitancy toward receiving COVID-19 vaccines, the intensity of intra-provincial travel does not seem to be correlated. To assess the robustness of our estimates, we calculated the hesitancy measure using both arithmetic and geometric means. In addition, to address potential endogeneity, we employed an IV approach alongside the OLS estimator.

[5] That being said, we consider it a secondary specification here because bias is minimized in a just-identified model, where the number of instruments exactly equals the number of endogenous variables, although weak instruments can still produce considerably imprecise estimates [45].

Table 3
2SLS estimates of inter-provincial mobility on hesitancy toward COVID-19 vaccines.
Source: Authors' elaboration using Baidu Mobility Index and Chen et al. [32].

	(1) in-HCV	(2) in-gHCV	(3) out-HCV	(4) out-gHCV
Panel A: First stage				
DV: 2021 move-in/move-out rates				
$Mobility_{2019}$	0.9359***	0.9359***	0.9397***	0.9397***
	(0.0995)	(0.0995)	(0.1246)	(0.1246)
HVG	−0.0057	−0.0057	−0.0068	−0.0068
	(0.0089)	(0.0089)	(0.0087)	(0.0087)
Constant	4.8650	4.8650	4.9020	4.9020
	(6.5278)	(6.5278)	(6.8831)	(6.8831)
Panel B: Second stage				
DV: Hesitancy toward COVID-19 vaccines				
$\widehat{\text{Mobility}}$	−0.0133**	−0.0195***	−0.0123**	−0.0183***
	(0.0051)	(0.0050)	(0.0046)	(0.0047)
HVG	1.8089***	1.7647***	1.8089***	1.7647***
	(0.0199)	(0.0212)	(0.0200)	(0.0212)
Constant	−6.0658***	−6.1687***	−6.0265***	−6.1166***
	(0.7942)	(0.9033)	(0.7901)	(0.8985)
F statistic	88.46	88.46	56.86	56.86
Controls	Y	Y	Y	Y
R-squared	0.5707	0.5233	0.5707	0.5233
Obs.	12,000	12,000	12,000	12,000

Notes: Columns (1) and (3) use the arithmetic mean of the questions, while Columns (2) and (4) use the geometric mean. F-statistic is the kleibergen–Paap Wald F-statistic for weak instruments. Robust standard errors shown in parentheses are clustered at the province level. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

Nonetheless, it is important to acknowledge that a few limitations remain in this study. Firstly, due to the age of the recruited participants, our dataset is more likely to be nationally representative for the population aged over 18 than for the entire Chinese population. Second, despite the significant population disparities across China, with some provinces being highly populous like Guangdong and others being sparsely populated like Tibet, our dataset has either 360 or 400 participants in each province, municipality, or equivalent administrative region. This may cause an overrepresentation of individuals from less populous regions and an underrepresentation of those from more populous ones, potentially introducing bias into our analysis.

Third, the granularity of geographic data collected from participants limits the investigation of mobility effects at more specific levels, such as cities or communities, where intra-regional mobility may exert stronger impacts on individual perceptions. Lastly, our IV strategy may fail under certain conditions: (a) if regional mobility has lingering effects on personal attitudes toward vaccines that are not fully captured by the control variables we included, (b) if our control variables are susceptible to the pandemic shock, and (c) if there are omitted variables influencing the studied outcome that are correlated with our instrument. Ideally, panel data with pre-pandemic covariates, particularly pre-pandemic HVG, and a mobility instrument that was collected sufficiently earlier than the outbreak of COVID-19, such as in 2010, would be crucial to address these concerns and enable robust causal inference. Unfortunately, such data are unavailable, which constrains the generalizability and causal interpretation of our findings.

In sum, rooted in the co-evolution of mobility dynamics and changing infectious risks, this study adds to the broader body of COVID-19 research on regional mobility and individual responses to vaccines. Future research can consider collecting data on neighborhood or community mobility, as well as subjective perceptions of infectious disease risks, to further elucidate how roll-out policies of similar vaccines can be developed and tailored.

CRediT authorship contribution statement

Huaxin Wang-Lu: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Octasiano Miguel Valerio Mendoza:** Writing – original draft, Validation, Supervision, Software, Project administration, Investigation, Funding acquisition. **Simiao Chen:** Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Data curation. **Pascal Geldsetzer:** Writing – review & editing, Validation, Resources, Methodology, Investigation. **Maya Adam:** Resources, Methodology, Investigation, Data curation.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Simiao CHEN reports financial support was provided by Horizon Europe. Octasiano Miguel VALERIO MENDOZA reports financial support was provided by Horizon Europe. Huaxin WANG-LU reports financial support was provided by Societat Econòmica Barcelonesa d'Amics del País. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix

See Tables A.1 and A.2.

Data availability

Data will be made available on request.

Table A.1
Descriptive statistics.
Source: Authors' elaboration using Baidu Mobility Index and Chen et al. [32].

Variable	Description	Num. of Obs.	Mean	Range/Distribution
move-in	Inbound mobility (z-score) during March–May 2021	12,000	−5.47e−17	Ranges from −1.3605 to 2.4199
move-out	Outbound mobility (z-score) during March–May 2021	12,000	2.16e−16	Ranges from −1.4173 to 2.3205
intra	Intra-provincial mobility (z-score) during March–May 2022	12,000	−1.00e−16	Ranges from −3.6525 to 1.3666
HCV	Arithmetic mean of hesitancy toward COVID-19 vaccines (z-score)	12,000	−1.92e−16	Ranges from −2.4641 to 4.2135
gHCV	Geometric mean of hesitancy toward COVID-19 vaccines (z-score)	12,000	1.81e−16	Ranges from −2.4363 to 3.9787
HVG	Geometric mean of hesitancy toward vaccines in general	12,000	3.15	Ranges from 1.73 to 5
mental	Depressive symptoms	12,000	5.8302	Ranges from 1 to 8
COVID	Diagnosed with COVID-19: yes=1; no=0	12,000	0.0004	0.04%=1; 99.96%=0
contacts	Any relatives, friends or colleagues were diagnosed with COVID-19: none=1; any=0	12,000	0.9918	99.18%=1; 0.82%=0
age	Individual age groups	12,000	40-49	18.95%=18-29; 19.62%=30-39; 19.74%=40-49; 19.08%=50-59; 22.60%=60+
gender	Individual gender: male=1; female=0	12,000	0.5106	51.06%=male; 48.94%=female
ethnicity	Ethnic groups	12,000	1.1138	96.33%=Han; 3.67%=others
residence	Living in urban=0 or rural=1	12,000	0.3953	39.53%=rural; 60.47%=urban
education	Educational levels	12,000	3.93	5.88%=none (1); 6.06%=primary (2); 18.06%=junior secondary (3); 32.07%=high (4); 35.04%=college (5); 2.89%=postgraduate (6)
work	The respondent is a healthcare provider=1 or not=0	12,000	0.0151	1.51%=1; 98.49%=0
income	Household income levels ranging from less than 30,000 to more than 300,000 Yuan	12,000	4.573	Ranges from < 30000 to > 300000
info	Primary source of information on vaccines, e.g., social media, government, friends, etc.	12,000	2.687	26.71%=social media; 23.71%=government; 21.59%=TV; 19.17%=friends, neighbors, or colleagues; 8.82%=others
medical	Number of hospital beds per 10,000 persons	12,000	7.8599	Ranges from 2.3702 to 18.9590
wage	Log of average wages	12,000	11.4782	Ranges from 11.1754 to 12.1283
GRP	General retail price index	12,000	101.461	Ranges from 100.5 to 102.7
case	Number of COVID-19 cases per 10,000 persons	12,000	0.5938	Ranges from 0.0027 to 11.8641
density	Population density	12,000	0.2516	Ranges from 0.0648 to 0.4725
passenger	Total volume of passenger traffic in 2018 (per 10,000 persons)	12,000	12.6180	Ranges from 4.1527 to 27.1463
railway	Railway passenger traffic volume in 2018 (per 10,000 persons)	12,000	2.5923	Ranges from 0.9575 to 6.6133

Table A.2
Supplementary 2SLS estimates of inter-provincial mobility on HCV.
Source: Authors' elaboration using Baidu Mobility Index and Chen et al. [32].

	(1) in-HCV	(2) in-gHCV	(3) out-HCV	(4) out-gHCV
Panel A: First stage				
DV: 2021 move-in/move-out rates				
$Mobility_{2019}$	0.9396***	0.9396***	0.9394***	0.9394***
	(0.1034)	(0.1034)	(0.1277)	(0.1246)
Passenger	0.0701*	0.0701*	0.0674	0.0674
	(0.0413)	(0.0413)	(0.0474)	(0.0474)
Railway	−0.0173**	−0.0173**	−0.0147*	−0.0147*
	(0.0082)	(0.0082)	(0.0086)	(0.0086)
Constant	1.4980	1.4980	1.8027	1.8027
	(5.9861)	(5.9861)	(6.6900)	(6.6900)
Panel B: Second stage				
DV: Hesitancy toward COVID-19 vaccines				
$\widehat{\text{Mobility}}$	−0.0130**	−0.0191***	−0.0121**	−0.0180***
	(0.0049)	(0.0049)	(0.0045)	(0.0047)
Constant	−6.0575***	−6.1574***	−6.0209***	−6.1087***
	(0.7947)	(0.9041)	(0.7911)	(0.8995)
F statistic	63.90	63.90	42.75	42.75
Hansen J stat.	0.3838	0.2258	0.3548	0.1976
Controls	Y	Y	Y	Y
R-squared	0.5707	0.5233	0.5707	0.5233
Obs.	12,000	12,000	12,000	12,000

Notes: Columns (1) and (3) use the arithmetic mean of the questions, while Columns (2) and (4) use the geometric mean. F-statistic is the kleibergen–Paap Wald F-statistic for weak instruments. The p-value of Hansen J statistic is for overidentifying restrictions. Robust standard errors shown in parentheses are clustered at the province level. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

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