Methods and Applications

Estimating Changes in Contact Patterns in China Over the First Year of the COVID-19 Pandemic: Implications for SARS-CoV-2 Spread — Four Cities, China, 2020

Yuxia Liang[1]; Cheng Peng[1]; Qian You[1]; Maria Litvinova[2]; Marco Ajelli[2]; Juanjuan Zhang[1,#]; Hongjie Yu[1,3,#]

ABSTRACT

Introduction: Previous studies have demonstrated significant changes in social contacts during the first-wave coronavirus disease 2019 (COVID-19) in Chinese mainland. The purpose of this study was to quantify the time-varying contact patterns by age in Chinese mainland in 2020 and evaluate their impact on the transmission of severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2).

Methods: Diary-based contact surveys were performed for four periods: baseline (prior to 2020), outbreak (February 2020), post-lockdown (March–May 2020), and post-epidemic (September–November 2020). We built a Susceptible-Infected-Recovered (SIR) model to evaluate the effect of reducing contacts on transmission.

Results: During the post-epidemic period, daily contacts resumed to 26.7%, 14.8%, 46.8%, and 44.2% of the pre-COVID levels in Wuhan, Shanghai, Shenzhen, and Changsha, respectively. This suggests a moderate risk of resurgence in Changsha, Shenzhen, and Wuhan, and a low risk in Shanghai. School closure alone was not enough to interrupt transmission of SARS-CoV-2 Omicron BA.5, but with the addition of a 75% reduction of contacts at the workplace, it could lead to a 16.8% reduction of the attack rate. To control an outbreak, concerted strategies that target schools, workplaces, and community contacts are needed.

Discussion: Monitoring contact patterns by age is key to quantifying the risk of COVID-19 outbreaks and evaluating the impact of intervention strategies.

After the first wave of coronavirus disease 2019 (COVID-19) in China in early 2020, social distancing policies were gradually relaxed. A series of studies were conducted to quantify the changes in contact patterns under different interventions, whose intensity and type varied over time, and to estimate their impact on the epidemic spread (*1*–*3*). Previous studies have shown a dramatic decrease in the number of social interactions in China during the early phase of the pandemic (*1*). This was followed by a moderate increase in social contacts after strict non-pharmaceutical interventions (NPIs) were relaxed from March to May 2020 (*2*–*3*). As of the fourth quarter of 2020, almost all schools and workplaces had been opened (*4*–*5*), and daily life had gradually resumed to a normal status. It is still unknown to what extent social interactions had resumed by the end of 2020 and how age-specific contact patterns had affected severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) transmission in China. The purpose of this study was to estimate changes in contact patterns by age in Chinese mainland over the course of the first year of the COVID-19 pandemic. This study aimed to provide valuable information about the risk of transmission and transmission patterns by age in a post-COVID-19-intervention context.

METHODS

To estimate changes in contact patterns by age in the post-epidemic period, we conducted diary-based contact surveys in Wuhan, Shanghai, Shenzhen, and Changsha between September 16 and November 8, 2020 (Figure 1). The design of the survey (Supplementary Material, available in https://weekly.chinacdc.cn/) was similar to that of our previous work (*1*–*2*,*6*), where contact patterns during the pre-pandemic (prior to 2020), outbreak (February 2020), and post-lockdown (March to May 2020) periods were investigated (Figure 1). A contact was defined as either a two-way conversation involving three or more words in the physical presence of another person or direct physical contact (e.g., a handshake). We further divided direct interpersonal contact into three types: 1)

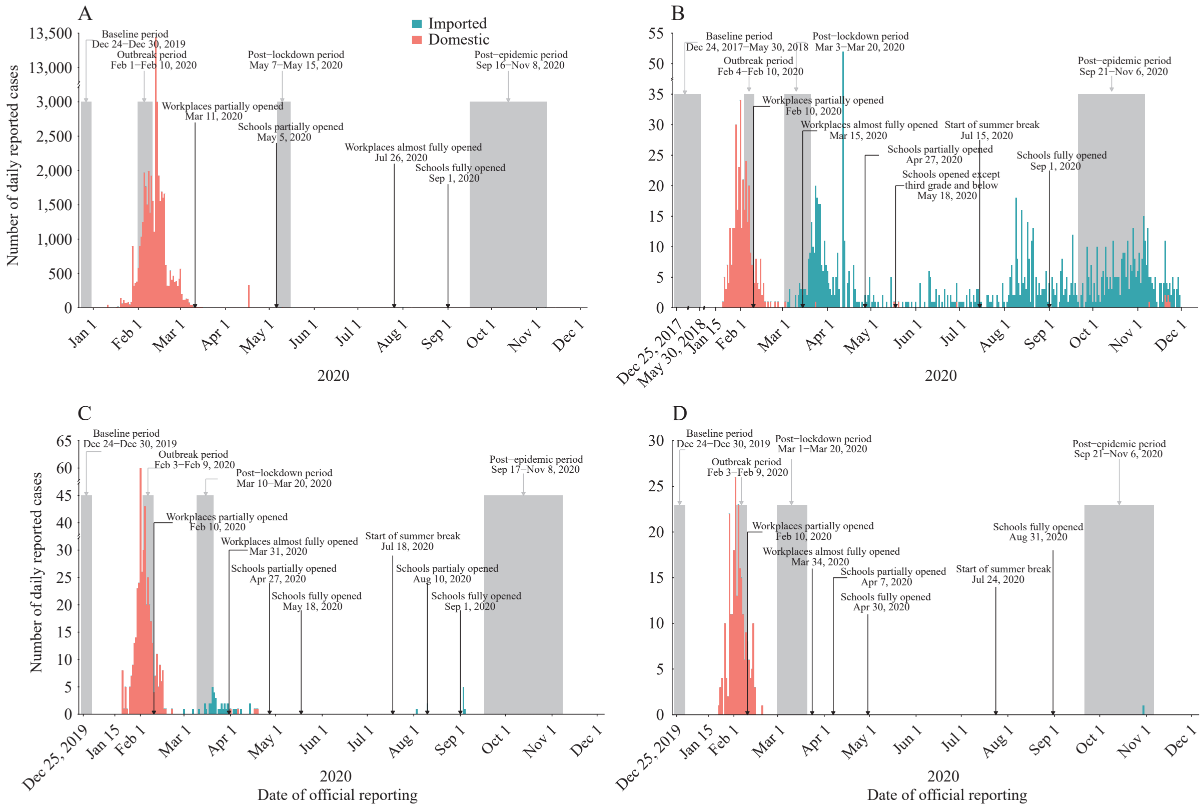

FIGURE 1. Number of reported locally transmitted (red) and imported (green) COVID-19 cases, summary of the main interventions performed over time, and timeline of the surveys in Wuhan (A), Shanghai (B), Shenzhen (C), and Changsha (D).

physical contact, 2) non-physical contact at a distance of 1 meter or less, and 3) non-physical contact at a distance of more than 1 meter. We also recorded whether the participant and contact were wearing face masks (i.e., both wore, neither wore, or one wore), and the contact environment (i.e., indoor, outdoor, or both).

We estimated contact matrices by age, dividing participants into 16 age groups (0–4 years, 5–9 years, ... , 70–74 years, and 75 years and older). We relied on data collected from this survey and three other surveys conducted during the pre-pandemic, outbreak, and post-lockdown periods to estimate contact matrices representing mixing patterns for the four cities (*1*–*2*,*6*).

We estimated the impact of daily life resumption on the potential reproduction number (*R*) of a COVID-19 outbreak by relying on the mixing patterns estimated in contact surveys. The next-generation matrix approach was used to estimate *R*. To evaluate the impact on transmission dynamics of reducing school, workplace, and community contacts, we simulated a possible outbreak of SARS-CoV-2 Omicron BA.5 or another highly transmissible variant using an ordinary differential equation Susceptible-Infectious-Removed (SIR) model (Supplementary Material, available in https://weekly.chinacdc.cn/). We used Shanghai as a case study, based on the baseline contact matrix by setting. We assumed that eliminating contacts in a certain setting while keeping the contacts in other settings the same as the baseline period would indicate closure of that setting. We designed four scenarios to estimate the effect of different social distancing strategies: 1) Baseline scenario (no interventions): workplace, school, and community contacts were at pre-COVID levels; 2) Scenario 1: no contacts at school, while all other contacts were at pre-COVID levels; 3) Scenario 2: no contacts at school and a 75% reduction of contacts at the workplace, while all other contacts were at pre-COVID levels; and 4) Scenario 3: no contacts at school, a 75% reduction of contacts at the workplace, and a 90% reduction of contacts in the community. Scenarios 2 and 3 simulated a 75% and 90% reduction of contacts in the workplace and community, respectively. During the first COVID-19 lockdown in Shanghai, we estimated a nearly 90% reduction of workplace contacts and a 95% reduction of contacts in the community (*1*). As achieving such a high level of reduction may be difficult without imposing a strict lockdown, we used more conservative estimates of a 75% and 90% reduction of workplace and community contacts, respectively.

All the analyses were performed in R (version 4.0.3, R Foundation for Statistical Computing, Vienna, Austria).

RESULTS

A total of 3,281 participants (858 from Wuhan, 832 from Shanghai, 797 from Shenzhen, and 794 from Changsha) were recruited for the post-epidemic survey, and 16,533 contacts were recorded in total. Compared with the outbreak period, the average number of contacts during the post-epidemic period significantly increased by a factor of 1.9 (P<0.001), 0.5 (P<0.001), 1.5 (P<0.001), and 2.0 (P<0.001) in Wuhan, Shanghai, Shenzhen, and Changsha, respectively (Supplementary Table S1, available in https://weekly.chinacdc.cn/). The largest resumption of contacts was observed for school-age individuals (Supplementary Figure S1, available in https://weekly.chinacdc.cn/). In Wuhan, 18.9% of contacts were non-physical contacts at a distance of at least 1 meter, 39.6% of contacts occurred with both or either the participant or the contactee wearing a face mask, and 9.6% of contacts occurred outdoors. Similar contact patterns were observed in Shanghai, Shenzhen, and Changsha (Supplementary Figure S2, available in https://weekly.chinacdc.cn/).

The pre-pandemic (baseline) contact matrices revealed the typical age-mixing patterns observed in

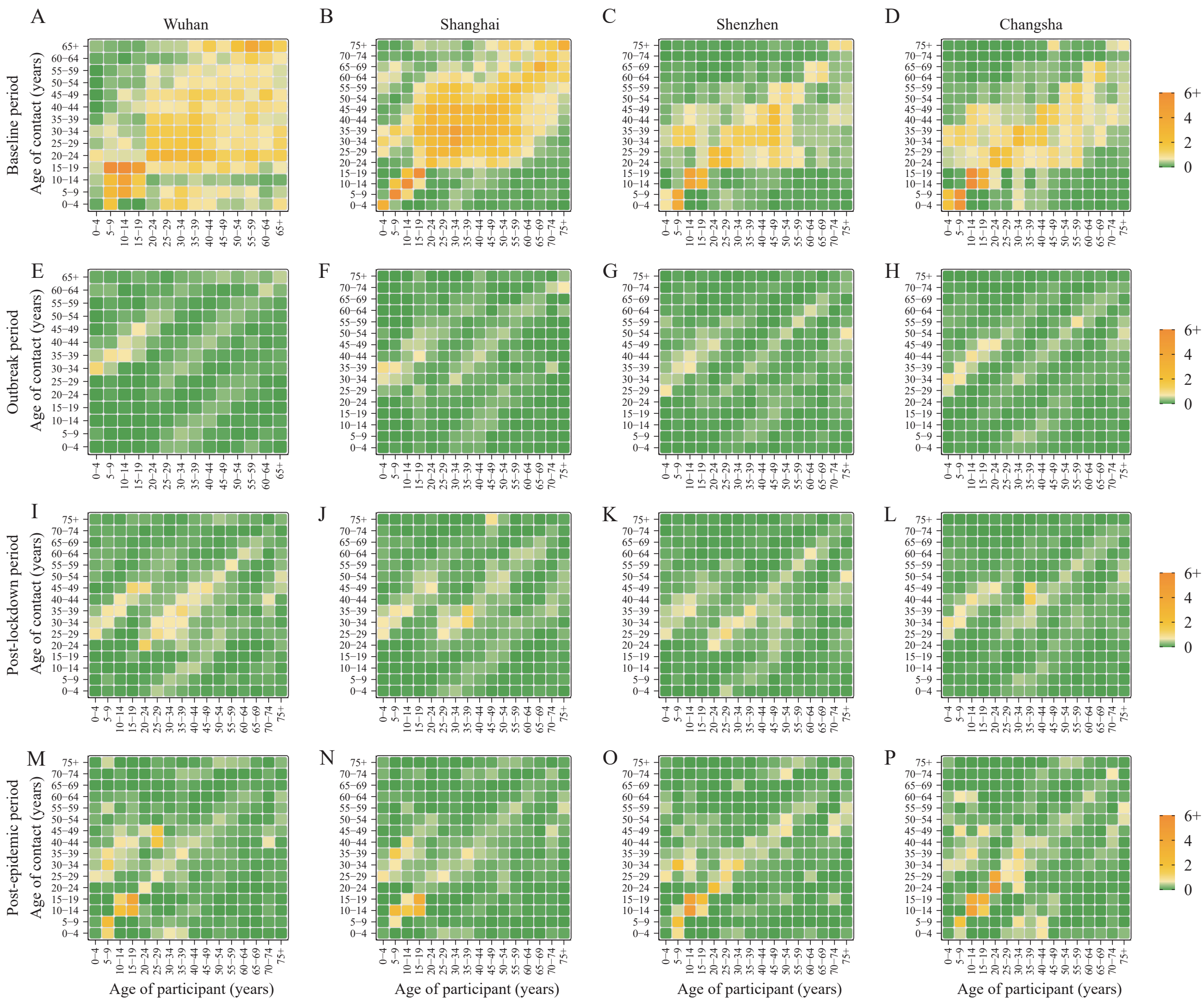

FIGURE 2. Contact matrices by age group for the four study locations for the baseline period in (A–D), outbreak period (E–H), post-lockdown period (I–L), and post-epidemic period (M–P). Each cell of the matrix represents the mean number of contacts that an individual in a given age group has with other individuals, stratified by age groups. The color intensity represents the number of contacts.

previous studies (*7*) (Figure 2A–2D). During the lockdown, most of the classic age-specific features were absent, as the main contributor to contact patterns was the mixing between household members (Figure 2E–2H). Compared to the outbreak period, more contacts gradually occurred among school-age and working-age individuals during the post-lockdown and post-epidemic periods (Figure 2I–2P). During the post-epidemic period, the proportion of household contacts was still remarkably high compared to the pre-COVID era (Figure 2), with household contacts representing approximately half of the total number of recorded contacts (i.e., 48.7% in Wuhan, 53.6% in Shanghai, 43.2% in Shenzhen, and 47.6% in Changsha); the proportion of community contacts was still lower than 20% in the four study locations (i.e., 7.7% in Wuhan, 10.7% in Shanghai, 18.9% in Shenzhen, and 9.5% in Changsha) (Supplementary Table S2, available in https://weekly.chinacdc.cn/).

Assuming a baseline reproduction number of between 1.5 and 3.5 for SARS-CoV-2 considering pre-COVID contact patterns, we used the next-generation matrix approach to investigate the risk of a new epidemic outbreak under the estimated contact patterns during different epidemic phases. Our results show that in the post-epidemic phase, contacts had increased to an extent that would have allowed the emergence of new epidemic outbreaks in fully susceptible populations (as was the case in China at the time of the last survey — November 2020) for R_0 values around 2.5 in Wuhan, Shenzhen, and Changsha, while the risk of resurgence would have been low in Shanghai (Figure 3).

To estimate the effect of social distancing on a possible outbreak of SARS-CoV-2 Omicron BA.5 or another highly transmissible variant, we considered the Shanghai population and assumed an effective reproduction number of 4 [about 20% larger than what was estimated at the onset of the 2022 Omicron BA.2 outbreak in Shanghai (*8*)]. Compared with the baseline scenario considering baseline (pre-COVID) contact patterns, we found that a combination of school closures with a 75% reduction of contacts at the workplace could reduce the infection attack rate by

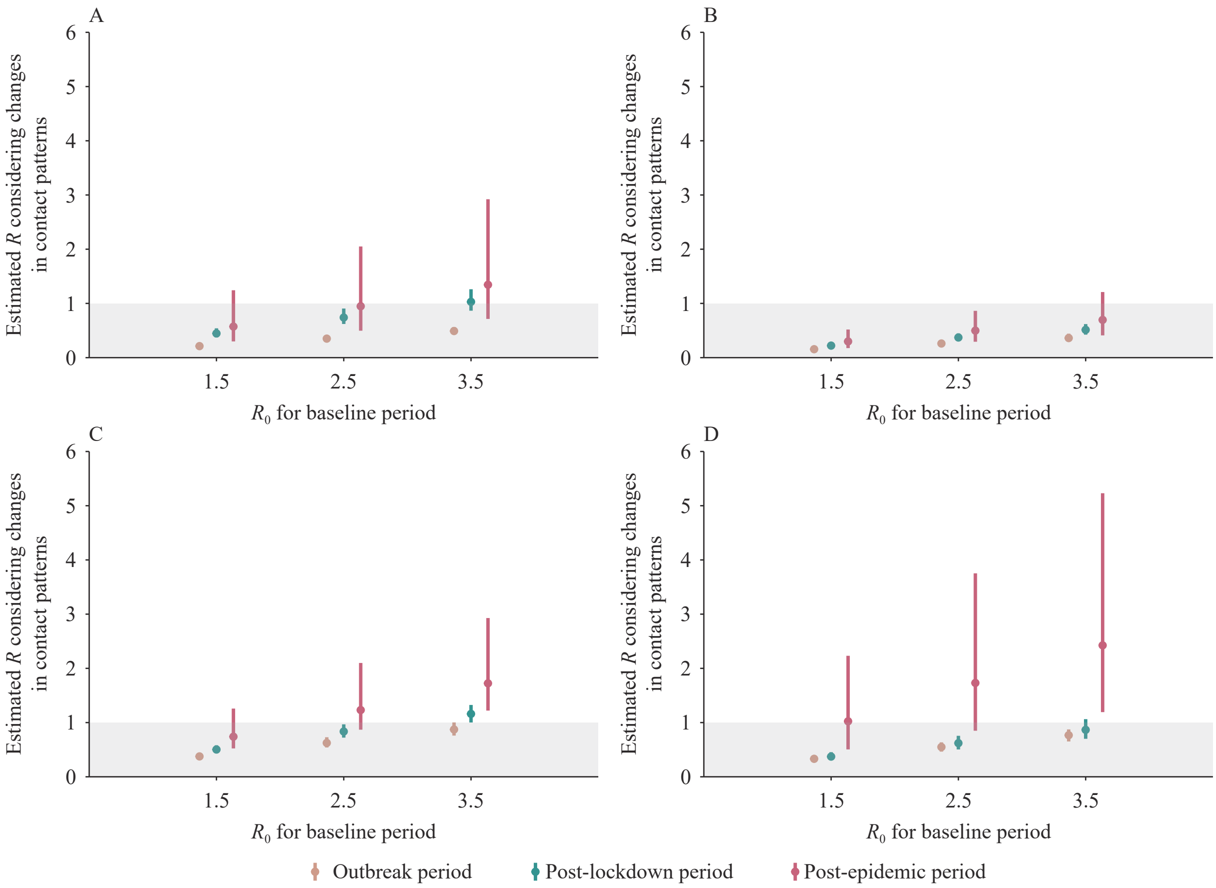

FIGURE 3. Changes in the reproduction number (mean and 95% confidence interval) considering the estimated contact patterns in the different periods in Wuhan (A), Shanghai (B), Shenzhen (C), and Changsha (D).

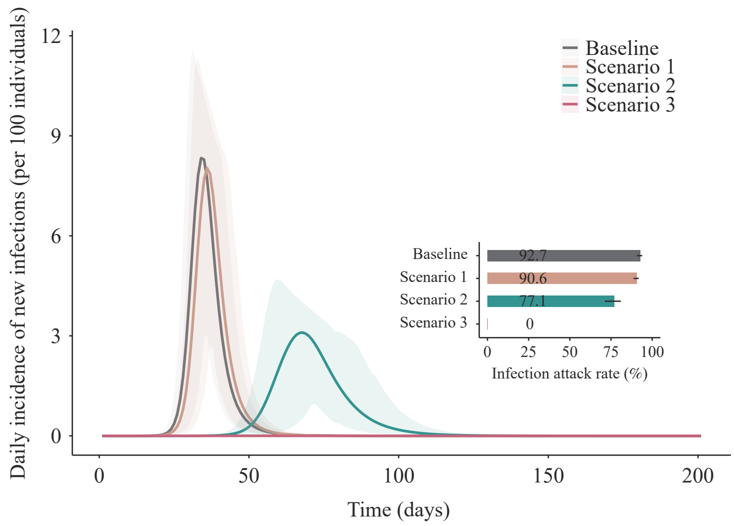

FIGURE 4. The effect of social distancing on the spread of SARS-CoV-2 in Shanghai was examined, assuming an effective reproduction number of 4 and considering baseline (pre-COVID) contact patterns.

Note: The curves show the daily incidence of new infections per 100 individuals (mean and 95% confidence interval) under different social distancing policies. The inset curve shows the infection attack rate (mean and 95% confidence interval) 200 days after the first COVID-19 case. Baseline scenario (no interventions): workplace, school, and community contacts are back to the pre-COVID era; Scenario 1: no contacts at school, while all other contacts are back to the pre-COVID era; Scenario 2: no contacts at school and 75% reduction of contacts at the workplace, while all other contacts are back to the pre-COVID era; Scenario 3: no contacts at school, 75% reduction of contacts at the workplace, and 90% reduction of contacts in the community.

16.8%; an additional 90% reduction of contacts in the community was estimated to be sufficient to control an outbreak (Figure 4).

DISCUSSION

In this study, we quantitatively estimated how human contact patterns by age changed in four Chinese cities during the first year of the COVID-19 pandemic. We found that, although the number of contacts increased in the post-epidemic period (approximately six months after the end of the first COVID-19 wave), the average number of contacts per day remained far from the baseline (pre-COVID) level. In addition to the marked reduction in the mean number of contacts per day, the age of the contacted individuals had markedly changed, highlighting a drop in social interactions with work colleagues and in the community. However, we estimated that the increase in mixing patterns was not sufficient to sustain local transmission in Shanghai, while the risk of an epidemic recurrence in the other three cities remained moderate as of November 2020. During the period of our post-epidemic survey (September 16 to November 8, 2020), fewer than 100 local cases were reported in Chinese mainland, and no local cases were reported in the four study locations, which is consistent with our estimates of the potential reproduction number. Finally, we performed a modeling analysis to evaluate the impact of social distancing in the event of a new SARS-CoV-2 outbreak of Omicron BA.5 or another highly transmissible variant. Our findings support that, although vaccination campaigns conducted in China with current vaccine products (as of 2022) are key to mitigating COVID-19 burden, if policymakers aim to prevent SARS-CoV-2 transmission altogether, social distancing measures are still essential.

Although workplaces, schools, and other public places gradually reopened from February to November 2020, many restrictions were still in place to prevent the resurgence of COVID-19. For example, 1) masks were mandated and body temperature was measured to enter indoor public places (*9*–*10*); 2) indoor mass gatherings were limited in schools (*11*); and 3) cinemas and theaters were operating at 75% or lower capacity, with the audience required to wear face masks and maintain a distance of at least one meter (*12*). From April to August 2020, China experienced several small-scale local outbreaks (*13*). The interventions adopted as well as the fear of infection may explain the slow resumption of contacts highlighted by our surveys in 2020.

Our results are comparable to those obtained in other studies that have assessed changes in contact patterns linked to the relaxation of COVID-19 control measures (*2*,*14*–*17*). After lifting stay-at-home orders and reopening workplaces in China, the United States, and several European countries, the mean number of contacts varied from two to nine per day, which is consistently higher than the number of contacts during lockdowns but significantly lower than the pre-pandemic level. Moreover, similar to Jarvis et al. (*14*), we found a larger proportion of indoor contacts than what was observed in the pre-COVID era.

Our study suffers from the traditional limitations of self-reported contact surveys, including recall, self-reporting, and selection biases, which may have affected our results. Although we explained the anonymity and confidentiality of the survey to study participants, we cannot rule out that the number of contacts may have been underreported during the post-epidemic period, when social distancing and other precautions were still in place. Our modeling analysis is intended to provide only general insights and is based on a set of approximations. For instance, the model does not explicitly consider symptomatic and asymptomatic individuals, pre-symptomatic transmission, the effect of individual-level interventions (e.g., test-trace-isolate, mask wearing), or the level of immunity provided by the primary vaccination cycle. Instead, we combine the effects of all these aspects into a single indicator: the effective reproduction number. Although this allowed us to provide a first-level approximation of the reduction of social contacts, more refined analyses are needed to identify the proper interventions required to contain a novel SARS-CoV-2 outbreak and/or mitigate the COVID-19 burden and pressure on the healthcare system.

Our study quantified contact patterns at different time points during the first year of the COVID-19 pandemic in Chinese mainland and provided evidence of a gradual recovery of contact patterns while social distancing measures were gradually relaxed. Moving forward, monitoring mixing patterns could inform authorities about the risk of resurgence of novel outbreaks caused by highly transmissible SARS-CoV-2 variants, and, in the event of an outbreak, social distancing is likely to play a key role in limiting SARS-CoV-2 transmission and mitigating the burden of COVID-19.

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Corresponding authors: Juanjuan Zhang, zhangjuan@fudan.edu.cn; Hongjie Yu, yhj@fudan.edu.cn.

[1] School of Public Health, Fudan University, Key Laboratory of Public Health Safety, Ministry of Education, Shanghai Municipality, China; [2] Laboratory for Computational Epidemiology and Public Health, Department of Epidemiology and Biostatistics, Indiana University School of Public Health, Bloomington, IN, USA; [3] Shanghai Institute of Infectious Disease and Biosecurity, Fudan University, Shanghai Municipality, China.

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SUPPLEMENTARY MATERIAL

Inclusion Criteria

Individuals were eligible to participate if they met the following criteria: 1) being a local resident of Wuhan, Shanghai, Shenzhen, or Changsha; 2) having lived in the selected city for more than 6 months in the past year; and 3) being present in the selected city at the time of the interview.

Survey Sampling

We planned to recruit 800 participants for each city, with equal sampling by age groups (0–9 years, 10–19 years, 20–29 years, 30–39 years, 40–49 years, 50–59 years, 60–69 years, 70 years and above) and sex. The survey was conducted through computer-assisted telephone interviews based on a well-established platform (*1*–*3*), which used a computerized random digital dialing system to randomly generate mobile phone numbers from the selected cities and automatically dial to connect with the users. Calls were placed three times on the same day before being classified as invalid. All calls were recorded and spot-checked for quality control of data collection. The person who completed the questionnaire depended on the participant's age and accessibility to mobile phone users, as follows: 1) self-completion and informed consent for participants aged 19–69 years; and 2) guardian-proxy completion for individuals aged 0–18 years or 70 years and above. Participants aged 18 years and below or 70 years and above, especially those without a telephone, were recruited through adults aged 19–69 years living in the same household. Specifically, after a participant aged 19–69 years old finished their own questionnaire, the interviewer asked whether there was a household member under 18 or over 70 years old in their household, and the participant could complete a questionnaire on their behalf or not. When the phone call was answered, well-trained staff asked participants to complete a questionnaire describing their contact behavior. Briefly, participants were asked to record their contact behavior on two different days: the most recent weekday and weekend day.

Data Processing

We recruited participants with roughly equal sample sizes in eight age groups (0–9 years, 10–19 years, ..., 60–69 years, 70 years and above) and by sex. To obtain a representative sample of the general population, we resampled the original data using multiple-stage bootstrapping, adjusting for age, sex, household size, day type (i.e., weekdays and weekends), and the probability of being a student or worker by age group.

Modeling SARS-CoV-2 Transmission Estimation of the Reproduction Number

The reproduction number, R, was estimated using a next-generation matrix approach based on the age-specific contact matrix for the COVID-19 outbreak period, the post-lockdown period, and the post-epidemic period, as estimated from our survey in Wuhan, Shanghai, Shenzhen, and Changsha, according to the following equation:

$$R_0 = \frac{\beta}{\gamma}\rho(M)$$

Where,

β is the transmission rate;

γ is the recovery rate. In an SIR model, the recovery rate is equivalent to the inverse of the duration of the generation time.

$\rho(M)$ is the spectral radius of matrix M and whose element Mij represents the average number of contacts between individuals in age group i with individuals in age group j.

Impact of Social Distancing and Vaccination Strategies on the SARS-CoV-2 Transmission

To estimate the impact of social distancing and vaccination strategies on the transmission dynamics of SARS-CoV-2, we implemented a classic age-structured Susceptible-Infectious-Removed (SIR) model for the Shanghai population. Briefly, susceptible and partially protected individuals (i.e., individuals who were previously infected or

SUPPLEMENTARY TABLE S1. Mean number and 95% *CI* of reported contacts by respondent characteristics and locations in the baseline, outbreak and post-epidemic periods.

Characteristics	Wuhan, mean (95% *CI*)			Shanghai, mean (95% *CI*)			Shenzhen, mean (95% *CI*)			Changsha, mean (95% *CI*)		
	Baseline†	Outbreak†	Post-epidemic§	Baseline†	Outbreak†	Post-epidemic§	Baseline†	Outbreak†	Post-epidemic§	Baseline†	Outbreak†	Post-epidemic§
Overall	14.6 (13.3, 16.1)	2 (1.9, 2.1)	3.9 (3, 5.3)***	18.9 (17.7, 20.1)	2.3 (2.0, 2.8)	2.8 (2.4, 3.1)***	7.9 (7.3, 8.7)	2.2 (2.1, 2.3)	3.7 (2.8, 4.6)***	9.5 (8.7, 10.4)	2.2 (2.0, 2.3)	4.2 (3.3, 5.3)***
Sex												
Female	14.7 (12.9, 16.5)	2.1 (2.0, 2.3)	4.1 (2.8, 6.0)***	18.6 (16.9, 20.2)	2.6 (2.1, 3.4)	2.4 (2.1, 2.8)***	7.2 (6.5, 8.2)	2.1 (2.0, 2.2)	3 (2.3, 3.8)***	9.3 (8, 10.7)	2.1 (1.9, 2.2)	4.7 (3.4, 6.3)***
Male	14.5 (12.2, 17.1)	1.8 (1.7, 2.0)	3.8 (2.6, 6.1)***	19.2 (17.6, 20.5)	2.1 (1.9, 2.4)	3.2 (2.6, 3.9)***	8.6 (7.8, 9.5)	2.2 (2.0, 2.4)	4.3 (3.1, 6)***	9.8 (8.8, 10.9)	2.3 (2.1, 2.5)	3.8 (3.1, 4.6)***
Age group (years)												
0–6	8.4 (2.8, 18.5)	2.2 (1.7, 2.7)	3.3 (2.3, 4.3)***	11.5 (9.4, 14)	1.9 (1.6, 2.2)	2.7 (2.2, 3.5)***	7 (4.9, 9.5)	2.6 (2.3, 2.9)	3.1 (2.5, 3.8)***	11.1 (8.3, 14)	2.7 (2.3, 3.0)	3.4 (2.7, 4.1)***
7–19	16.1 (13.4, 20.2)	2.1 (2.0, 2.2)	9 (4.8, 16.1)***	26.9 (23.7, 30.3)	2.6 (2.0, 3.5)	7.9 (4.7, 11.7)***	11.6 (9.9, 14.1)	2.5 (2.2, 2.8)	7.2 (3.8, 11.4)***	16.6 (13.9, 19.6)	2.2 (2.1, 2.4)	8.7 (5.9, 12.2)***
20–39	15.2 (13.1, 17.7)	2.1 (1.9, 2.3)	4.7 (2.8, 7.5)***	22.4 (19.4, 25.7)	2.2 (2.0, 2.5)	2.5 (2.2, 2.8)***	8.0 (7.2, 9.0)	1.8 (1.6, 1.9)	3.4 (2.4, 4.7)***	9.0 (7.6, 11.1)	2.2 (1.9, 2.5)	4.9 (3.1, 7.6)***
40–59	13.8 (10.8, 16.3)	2.0 (1.9, 2.1)	2.3 (2.0, 2.7)***	19.9 (17.1, 22.8)	2.9 (2.0, 4.1)	2.5 (2.0, 3.1)***	8.5 (6.9, 10)	2 (1.8, 2.3)	2.6 (2.1, 3.1)***	9.3 (7.8, 11.3)	2.1 (1.9, 2.3)	2.9 (2, 4.7)***
≥60	14.0 (8.1, 20.2)	1.4 (1.2, 1.7)	1.7 (1.4, 1.9)***	12.7 (10.9, 14.3)	1.5 (1.3, 1.8)	1.7 (1.4, 2)***	5 (4.4, 5.7)	2.3 (2.1, 2.5)	2.2 (1.7, 2.9)**	5.4 (4.6, 6.2)	2.0 (1.8, 2.2)	2.3 (1.9, 2.7)***
Type of profession												
Pre-school	8.4 (2.8, 18.5)	2.2 (1.7, 2.7)	2.6 (2.2, 3.3)***	10.5 (8.3, 13)	1.9 (1.6, 2.2)	2.7 (2.2, 3.5)	5.0 (3.1, 7.5)	2.6 (2.2, 2.9)	3.1 (2.5, 3.8)***	8.6 (6, 11.9)	2.7 (2.3, 3.2)	3.0 (2.5, 3.6)***
Students	14.7 (11.8, 18.2)	2.1 (2.0, 2.3)	8.9 (5.1, 15.3)***	26.1 (23.2, 29.1)	2.5 (2.1, 3.3)	8.7 (5.2, 13.2)***	11.9 (10.4, 13.8)	2.6 (2.3, 2.8)	7.7 (4.6, 11.6)***	16.7 (14.5, 19)	2.3 (2.2, 2.5)	9.6 (6.1, 14.3)***
Employed	15.3 (13.6, 16.9)	2.1 (1.9, 2.2)	4.0 (2.7, 6.0)***	22.4 (20.6, 24.3)	2.6 (2.1, 3.2)	2.7 (2.4, 3.2)***	9.3 (8.5, 10.2)	2.0 (1.8, 2.2)	3.2 (2.4, 4.4)***	10.3 (8.9, 11.7)	2.2 (2.0, 2.4)	3.8 (2.8, 5.3)***
Working-age not in the labor force	13.9 (6.0, 21.6)	1.8 (1.4, 2.4)	2.2 (1.9, 2.6)***	15.4 (7.4, 24.5)	1.8 (1.3, 2.3)	2.0 (1.6, 2.4)***	5.8 (3.6, 9.4)	1.7 (1.4, 2.1)	2.1 (1.8, 2.6)***	5.5 (4.1, 7.4)	2.1 (1.8, 2.4)	2.5 (2, 3.2)***
Retired	12.3 (8, 18.6)	1.5 (1.4, 1.8)	1.8 (1.6, 2)***	11.8 (10.4, 13.4)	1.6 (1.3, 1.8)	1.7 (1.5, 1.9)***	4.8 (4.1, 5.4)	2.2 (2.0, 2.3)	2.1 (1.6, 2.7)*	5.1 (4.4, 5.8)	1.9 (1.7, 2.1)	2.1 (1.8, 2.4)***
Household size												
1	10.8 (5.7, 18.2)	0.6 (0.1, 1.5)	1.0 (0.5, 1.9)***	15.2 (10.5, 21.1)	0.3 (0.2, 0.5)	1.0 (0.8, 1.5)***	5.5 (4.2, 6.9)	0.8 (0.6, 1.0)	2.3 (1.1, 4.2)***	5.6 (4.0, 7.6)	0.9 (0.4, 1.7)	1 (0.5, 1.9)
2	12.5 (7.4, 16.3)	1.1 (0.9, 1.3)	2.7 (1.4, 6.5)***	14.6 (12.8, 16.9)	1.4 (1.1, 1.8)	2.1 (1.6, 2.8)***	6.4 (4.9, 8.0)	1.3 (1.1, 1.4)	3.3 (1.5, 7.1)***	6.4 (5.4, 7.7)	1.4 (1.2, 1.6)	2.7 (1.7, 4.4)***
3	14.7 (13, 16.5)	1.9 (1.8, 2.0)	3.9 (2.9, 6.1)***	20.3 (18.6, 21.9)	2.2 (2.0, 2.3)	3.4 (2.7, 4.4)***	8.8 (8.0, 9.8)	2.3 (2.2, 2.5)	4.8 (3.2, 6.7)***	11.4 (9.8, 13.0)	2.2 (2.1, 2.3)	4.1 (2.8, 5.9)***
4	11.9 (9.1, 15.3)	2.3 (2.2, 2.5)	3.7 (3.3, 4.2)***	20.2 (16.9, 23.7)	3.0 (2.8, 3.2)	4.9 (3.3, 7.7)***	8.3 (7.3, 9.4)	3.1 (2.9, 3.2)	4.3 (3.5, 5.4)***	10.9 (8.5, 13.4)	3.0 (2.8, 3.1)	6.6 (4.4, 10.1)***
≥5	21.7 (16.9, 25.5)	3.2 (2.8, 3.4)	11.0 (5.3, 20.6)***	21.5 (18.1, 24.2)	6.0 (3.9, 8.9)	5.6 (4.8, 6.5)	10.1 (8.3, 12.4)	4.3 (4.1, 4.5)	4.5 (2.7, 6.1)**	11.3 (8.8, 14.2)	3.9 (3.7, 4.1)	6.0 (4.1, 8.2)***

TABLE S1. (Continued)

Characteristics	Wuhan, mean (95% *CI*)			Shanghai, mean (95% *CI*)			Shenzhen, mean (95% *CI*)			Changsha, mean (95% *CI*)		
	Baseline†	**Outbreak†**	**Post-epidemic§**	**Baseline†**	**Outbreak†**	**Post-epidemic§**	**Baseline†**	**Outbreak†**	**Post-epidemic§**	**Baseline†**	**Outbreak†**	**Post-epidemic§**
Day type¶												
Weekday	14.6 (13.3, 16.1)	–	4.5 (3.3, 6.0)	20.3 (18.9, 21.8)	–	3.2 (2.7, 3.6)	7.9 (7.3, 8.7)	–	4.2 (3.2, 5.5)	9.5 (8.7, 10.4)	–	4.9 (3.8, 6.2)
Weekend	–	–	2.7 (2.0, 5.4)	14.6 (12.8, 16.7)	–	1.8 (1.6, 2.1)	–	–	2.4 (1.5, 4.0)	–	–	2.6 (2.0, 3.6)

* P<0.05, ** P<0.01, *** P<0.001. *P*-values are taken from a bootstrap one sample *t* test distinguishing the post-epidemic period from the outbreak period.

† The 95% confidence interval (*CI*) on mean for baseline and outbreak periods were calculated by bootstrap sampling. Specifically, the 95% *CI* are 2.5% quantiles and 97.5% quantiles of 100 means calculated from 100 representative samples.

§ The mean of contacts and 95% confidence interval on mean for post-epidemic period are calculated based on bootstrap-adjusted samples. Specifically, the 95% *CI* are 2.5% quantiles and 97.5% quantiles of 100 means calculated from 100 representative samples.

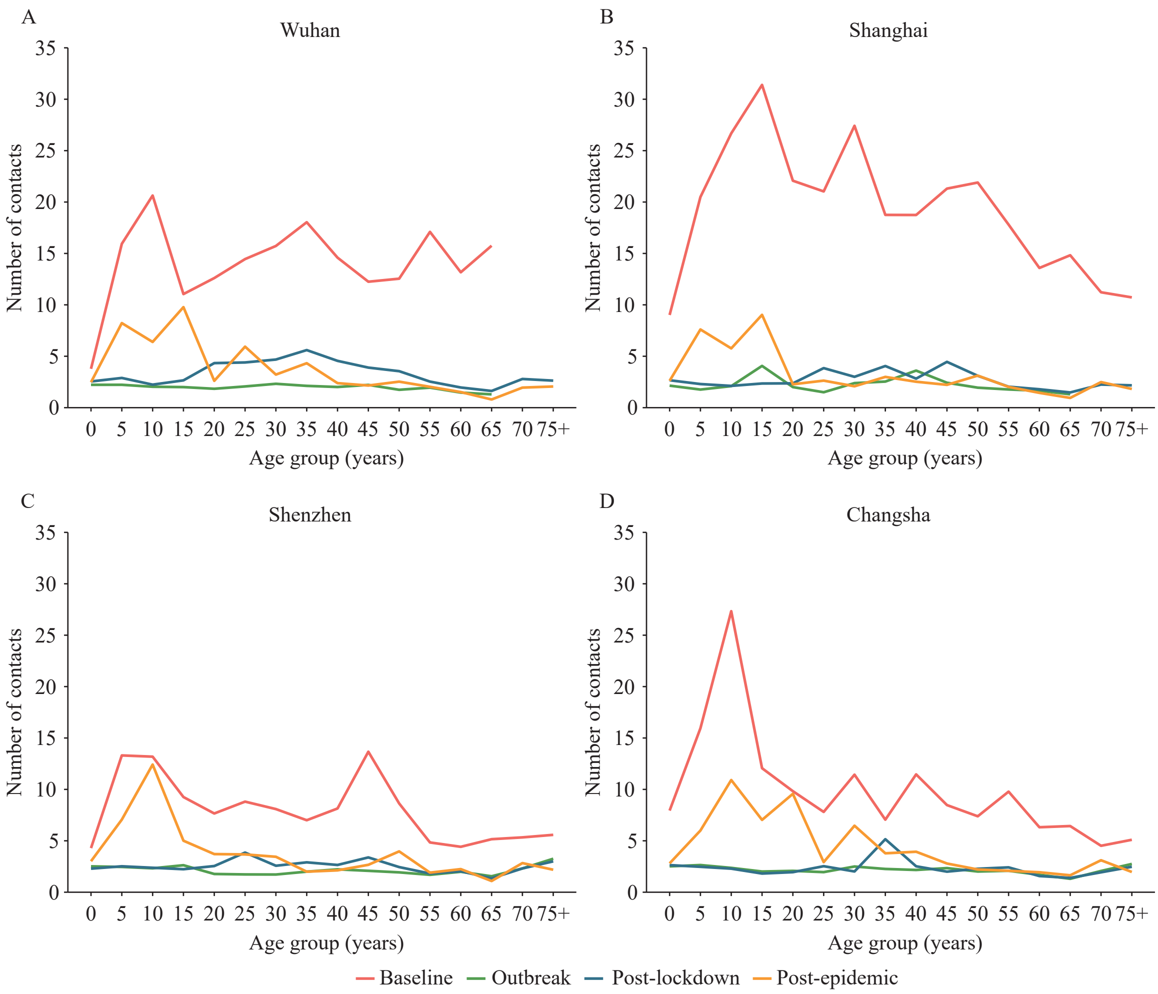
¶ For students and workers, weekday refers to the day going to work/school. For baseline period of Wuhan, Shenzhen, and Changsha, we only investigated the contact patterns of weekdays. For outbreak period, weekdays and weekends are not distinguished due to the lockdown.

SUPPLEMENTARY TABLE S2. Mean of the number of reported contacts by setting during post-epidemic period.

City	Overall, mean (95% *CI*)*	Household, mean (%)*,†	Workplace, mean (%)*,†	School, mean (%)*,†	Community, mean (%)*,†
Wuhan	3.9 (3.0, 5.3)	1.9 (48.7)	0.9 (23.1)	1.0 (25.6)	0.3 (7.7)
Shanghai	2.8 (2.4, 3.1)	1.5 (53.6)	0.6 (21.4)	0.5 (17.9)	0.3 (10.7)
Shenzhen	3.7 (2.8, 4.6)	1.6 (43.2)	0.9 (24.3)	0.9 (24.3)	0.7 (18.9)
Changsha	4.2 (3.3, 5.3)	2.0 (47.6)	0.9 (21.4)	1.3 (31.0)	0.4 (9.5)

* The mean and 95% confidence interval (*CI*) of mean were calculated based on bootstrap-adjusted samples. Specifically, the 95% *CI* are 2.5% quantiles and 97.5% quantiles of 100 means calculated from 100 representative samples.

† Proportion of the overall number of reported contacts were calculated as dividing the mean of each setting by the mean of overall contacts. As some contacts occurred at multiple locations, the sum of proportion may exceed 100%.



SUPPLEMENTARY FIGURE S1. Mean number of reported contacts by participant age during the baseline, outbreak, post-lockdown, and post-epidemic periods in (A) Wuhan, (B) Shanghai, (C) Shenzhen, and (D) Changsha.
Note: The last age group for the baseline and outbreak periods in Wuhan, and the outbreak period in Shanghai, was 65 years and older due to the small sample size of older people.

vaccinated but whose immunity to infection has waned) can acquire the infection through contacts with infectious individuals. Infectious individuals move to the removed compartment after an average infectious period of length equivalent to the generation time (*4*). Individuals in the removed compartment (corresponding to temporarily protected individuals) were not involved in the transmission process. Given that we were interested in simulating a short period of time (a few months), we did not consider waning of protection and thus removed individuals could not be re-infected.

SUPPLEMENTARY FIGURE S2. Contact type, contacts with face masks, and contact environment by age. (A) The proportion of physical contacts, non-physical contacts without 1m distancing, and non-physical contacts with 1m distancing by age for Wuhan. (B–D) The same proportions for Shanghai, Shenzhen, and Changsha, respectively. (E–H) The same proportions as (A–D), but for whether the participants and contacts were wearing face masks. (I–L) The same proportions as (A–D), but for the proportion of contacts that occurred indoors, outdoors, and both.

Each model compartment is divided into sixteen 5-year age groups (0–4, 5–9, …, 60–64, 75 years and above). Susceptible and partially protected individuals are exposed to an age-specific force of infection regulated by the average number of contacts per day that individuals of a given age group have with individuals of all age groups (i.e., the contact matrix). We used the following set of differential equations to simulate this process:

$$\begin{cases} \dot{S}_i = -\beta \sum_{j=1}^{n} M_{ij} \frac{I_j}{N_j} S_i \\ \dot{I}_i = \beta \sum_{j=1}^{n} M_{ij} \frac{I_j}{N_j} S_i - \gamma I_j \\ \dot{R}_i = \gamma I_j \end{cases}$$

where,

i and j represents the age group;

n=16 is the total number of age classes;

Si is the number of susceptible/partially protected individuals in age group i;

Ii is the number of infectious individuals in age group i;

Ri is the number of recovered/temporary protected individuals in age group i;

Ni is the total number of individuals in age class i (i.e., $Ni= Si + Ii + Ri$). The age structure was derived from Shanghai official records and the total population size is 24,197,001 (5).

β is the transmission rate, which is determined to obtain the desired value of the reproduction number using the next generation matrix approach;

γ is the recovery rate. In an SIR model, the recovery rate is equivalent to the inverse of the duration of the generation time, which was estimated to be 5.1 days (*6*).

Mij is the average number of contacts between individuals in age group *i* with individuals in age group *j*.

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