Article

Examining the Change of Human Mobility Adherent to Social Restriction Policies and its Effect on COVID-19 Cases in Australia

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Abstract: Policy induced decline of human mobility has been recognised to be effective in controlling the COVID-19 spread especially in the initial stage of the outbreak, although the relationship among mobility, policy implementation, and virus spread remains contentious. Coupling data of confirmed COVID-19 cases with Google mobility data in Australia, we present a state-level empirical study to: 1) inspect the temporal variation of COVID-19 spread and the change of mobility adherent to social restriction policies; 2) examine the extent that different types of mobility are associated with the COVID-19 spread in eight Australian states/territories; and 3) analyse the time-lag effect of mobility restriction on the COVID-19 spread. We find that social restriction policies implemented in the early stage of the pandemic controlled the COVID-19 spread effectively; the restriction of human mobility has a time-lag effect on growth rates, and the strength of the mobility-spread correlation increases up to seven days after policy implementation but decreases afterwards. The association between mobility and COVID-19 spread varies across space and time, and subjects to the types of mobility. Thus, it is important for governments to consider the degree to which lockdown conditions can be eased by accounting for this dynamic mobility-spread relationship.

Keywords: human mobility; COVID-19 spread; global pandemic; social restriction policy; Australia

1. Introduction

A novel coronavirus disease, called COVID-19 by the World Health Organisation (WHO), was first monitored and reported in December, 2019 by the Chinese health authorities [1]. The outbreak of COVID-19 has spread across China and infected 72,436 Chinese of which 1,868 died by February 17th [2]. On March 11th 2020 when WHO announced COVID-19 outbreak as a global pandemic the confirmed COVID-19 cases have been spreading up to 118,000 cases in 114 countries, including Italy, Spain, Iran, the United States, Germany, France, and South Korea as the top eight infected nations in the early stage of the pandemic [1]. Australia, as an island country in the Global South, had the first confirmed COVID-19 case on January 25th, 2020, a Victorian resident in early 50s returning from Wuhan, China. COVID-19 has been spreading rapidly in Australia to 298 confirmed cases by March 15th, 2020 [3]. Since then, the Australian Government has implemented a series of 'lockdown' policies to limit the transmission of COVID-19 infection by restricting human mobility, keeping social distances, shutting down local communities, and encouraging residents to stay at home with exceptions of limited outdoor activities in local neighbourhoods [3]. As the growth rate of confirmed cases declined since early April and the growth curve further flatted in May, some national restrictions were lifted on May 12th. However, Australia experienced the second wave of pandemic since mid-June due to international travelers coming back to Victoria. A series of local closure policies were re-introduced, mainly in Victoria and New South Wales, while other states remain borders closed.

45   With the two-wave pattern in Australia, a growing debate has emerged regarding the efficacy
46 of the lockdowns, how much these policies affect human mobility, when and how the lockdowns
47 should be eased, and whether it is possible to lift restrictions without unleashing additional waves of
48 infection. An assessment of how the change of human mobility is adherent to social restriction
49 policies, and how mobility levels are associated with the growth rate of COVID-19 cases has been,
50 and continues to be, urgently required and valuable in helping to navigate the policy dilemma and
51 understanding the determinants of controlling infection.

52   In response to this pressing need, by coupling data for COVID-19 confirmed cases with Google
53 mobility data, this study aims to achieve three objectives: 1) examining the temporal variation of
54 COVID-19 spread and the change of mobility levels adherent to social restriction policies; 2)
55 modelling and assessing the extent that different types of mobility are associated with the COVID-19
56 spread in eight Australian states/territories; and 3) evaluating the time-lag effect of mobility
57 restriction on the COVID-19 spread. Our analytical results show that the social restriction policies
58 implemented in the early stage of the 1st wave controlled the COVID-19 spread effectively, and the
59 restriction of human mobility has a time-lag effect on growth rates, which is more effective in
60 controlling COVID-19 spread in within 7 days after the implementation of restrictions; whereas the
61 types of mobility associated with the COVID-19 spread vary across the two waves and across the
62 Australian states/territories. We interpret these results with caution and link them to the findings
63 from other countries for a discussion of policy implications.

2. Materials and Methods

65   We collected the daily confirmed COVID-19 cases from February 15th to August 15th, 2020 from
66 the Department of Health, Australian Government [3]. Mobility data was retrieved from Google
67 COVID-19 Community Mobility Reports in the same period of time [4]. Google provides GPS-derived
68 location information about the amount of time people spent in six types of locations, including
69 workplaces, residential, parks, grocery and pharmacy, retail and recreation, and transit stations. Each
70 type of data stream is encoded as a percentage change in the mobility metric, based on a baseline
71 derived for the period of January 3rd to February 6th, 2020. These mobility data are regularly updated
72 and released to the public for the express purpose of supporting public health bodies in their response
73 to COVID-19. All of these datasets are fully anonymised and aggregated at the level of either Australian
74 states and territories over each day.

75   Since March 15th, 2020, the Australian Government has started to implement a series of travel
76 restrictions, self-isolation, social distancing and lockdown policies at the national level with border
77 closure policies implemented by state governments (Table 1). After the growth curve of COVID-19
78 flatted in May, some national restrictions were lifted on May 12th but re-introduced in mid-June in
79 Victoria State due to the second wave of pandemic. A series of local closure policies were implemented
80 again, mainly in Victoria and New South Wales while other states remain borders closed. Considering
81 this unique two-wave pattern, our inspection of the temporal variation of COVID-19, mobility levels
82 and policy implementation at the first stage focuses on the full timeline from February 15th to August
83 15th, while the examination of the relationship between COVID-19 and mobility levels is divided to 2
84 periods, covering Australia as a whole and all states/territories in the 1st wave (March 15th to June 15th)
85 and focusing on Victoria as the main source of confirmed cases in the 2nd wave (June 15th to August
86 15th).

94   Table 1. Social restriction policies implemented at the national and state level in Australia

Date	Policy Restrictions
March-15:	Outdoor gathering limited to 500 persons
March-18:	Indoor gathering limited to 100 persons
March-19:	*TAS border closure*
March-20:	Strict social distancing of 4 sqm per person
March-22:	*NSW and VIC shut down non-essential services*
March-24:	*QLD, WA, SA and NT border closure*
March-26:	Further lockdown of restaurants, cafes, food courts, auction houses, open house inspections; weddings restricted to 5 people; funerals to 10 people
March-29:	All gatherings 2 persons only
April-2:	Australian supermarkets increase in store social distancing measures
May-12:	National restrictions eased
June-1:	National restrictions further eased
June-21:	*VIC gatherings restricted*
June-30:	*VIC 10 postcode lockdown*
July-7:	*NSW border closure with VIC*
July-8:	*VIC Stage-3 restriction*
August-1:	*QLD border closure with NSW again*
August-2:	*VIC Melbourne Stage-4 restriction*

95 Note: *italic*: Policies are implemented at the state level; Source: [3]; NSW: New South Wales; VIC: Victoria; QLD: Queensland; SA:
96 South Australia; WA: West Australia; TAS: Tasmania; NT: North Territory; ACT: Australian Capital Territory

98 Methodically, we first generated a combined mobility index (CMI) to represent the overall mobility
99 change in a day compared the pre-pandemic period, calculated as the mean of mobility of each type i
100 in a day t:

$$CMI(t) = \frac{\sum_{i=1}^{6} Mobility_i}{6} \tag{1}$$

103 For COVID-19 cases, we examined its change over time alongside the implementation of the key
104 policy interventions. Next, we calculated the growth rate and the doubling time of COVID-19 cases.
105 Growth rate (percentage) at day t is calculated as [5]:

$$GR(t) = \frac{C(t) - C(t-1)}{C(t-1)} \tag{2}$$

107 where C(t) is the cumulative number of confirmed cases at day t.

109 We also calculated the doubling time which is usually used as a dynamic measure to inform the
110 impact of interventions on epidemic transmission especially at the initial stage of the exponential
111 growth. The doubling time (day) of confirmed cases at day t is calculated as [5]:

$$DT(t) = \frac{Ln(2)}{Ln(1 + GR(t))} \tag{3}$$

114 It has been acknowledged that the median incubation period was estimated to be 5.1 days and
115 97.5% of COVID-19 patients develop symptoms within 11.5 days of infection [6]. Therefore, we selected
116 three scenarios accounting for the delays in incubation and testing over three time periods — right after
117 the lockdown date, 7 days and 14 days after the lockdown date — to examine the relationship between
118 mobility change and growth rate/doubling time of COVID-19 cases. We then conducted a correlation
119 analysis between CMI and the growth rates/doubling time of COVID-19 cases, and further investigated
120 the association between each of the six types of mobility measures and growth rates/doubling time in

121 Australia as a whole and in each state/territory via a series of ordinary least square regression models
122 accounting for the time-lag effect:

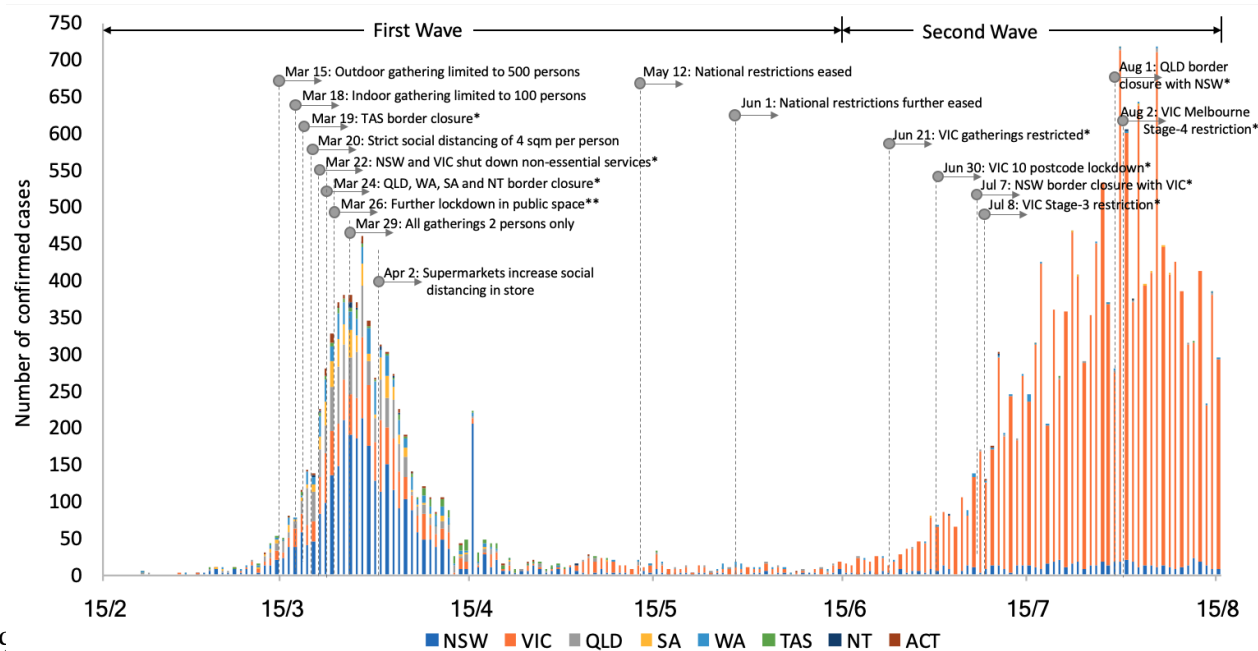$$C_{s,t} = \alpha_S + \beta_i Mob_{i,s,t-n} + \gamma_t + \varepsilon_{s,t} \quad (n = 0, 1, \cdots, t-1) \tag{4}$$

125 where C is the growth rate/doubling time of COVID-19 cases in state s on date t as described
126 above; Mob_i denotes each type i ($i = 1, 2 \dots 6$) of mobility and $Mob_{i,s,t-n}$ is the mobility index in state
127 s on the date (t-n). In this research, n equals 0, 7 and 14. β_i is the standardised coefficient for each type
128 of mobility; ε is the standardised error; α_S denotes the fixed place effect of state s and γ_t denotes the
129 fixed date effect for a transmission period after date t.
130   In our interpretation of the regression model, we emphasise on the magnitude and significance of
131 the coefficients indicating the extent of the association between COVID-19 spread and the different
132 types of mobility, rather than the fixed place effect and fixed date effect denoting the variations of
133 unobserved potential confounders underlying virus spread across space and time.

3. Results

3.1. The change of human mobility and policy intervention

136   We first examine the two-wave pattern of COVID-19 spread in Australia alongside the timeline of
137 policy implementation (Figure 1). It is observed that COVID-19 cases increased exponentially from
138 early March to April 1st, 2020. Since March 15th, Australian Government has started to implement a
139 series of travel restrictions, self-isolation, social distancing and lockdown policies at the national level,
140 including outdoor gathering limited to 500 people on March 15th, indoor gathering limited to 100
141 people on March 18th, further lockdown of restaurants, cafes, food courts, auction houses, open house
142 inspections on March 26th, and all gatherings 2 persons only on March 29th. Simultaneously, Tasmania
143 State Government closed its border on March 19th; New South Wales and Victoria shut down non-
144 essential services on March 22nd; Queensland, West Australia, South Australia, and North Territory
145 State Government also implemented border closure policies on March 24th to prevent virus
146 transmission across states. After almost two weeks since the first social restriction implemented on
147 March 15th, daily confirmed cases reached the peak of 311 on March 31st as the turning point and
148 started to decrease afterwards. With the prompt response of governments at the different levels and the
149 control of human mobility, the daily confirmed cases have dropped from 611 on March 23rd to 7 on
150 May 12th. National restrictions were eased on May 13th and further eased on June 1st. However, daily
151 confirmed cases started to increase again in mid-June mainly caused by international travelers back to
152 Victoria, leading to the second wave of pandemic after three months of control. Victoria Government
153 locked down 10 postcode areas on June 30th, applied Stage-3 Stay at Home restrictions on July 8th and
154 then upgraded to Stage-4 restriction on August 2nd after it reached the peak of 717 daily confirmed
155 cases on July 30th. Overall, the restriction policies implemented in the early stage of the 1st wave
156 controlled the COVID-19 spread effectively. Although the international travel led to the 2nd wave,
157 domestic policies have been reintroduced to quickly intervene local transmission and reduce the daily
158 confirmed cases to 293 on August 15th.

Note: NSW: New South Wales; VIC: Victoria; QLD: Queensland; SA: South Australia; WA: West Australia; TAS: Tasmania; NT: North Territory; ACT: Australian Capital Territory; *: Policies at the state level; **: Further lockdown includes the closure of restaurants, cafes, food courts, auction houses, open house inspections; weddings restricted to 5 people; funerals to 10 people

Figure 1. Confirmed COVID-19 cases in each state/territory and timeline of policy intervention

Following this timeline, we examine the average CMI within 3 days after the implementation of the key policies (Figure 2). The CMI in all states/territories have decreased consistently with the increasing restriction of travel ban, social distancing, and self-isolation from March 15th to April 2nd. After the turning point on April 2nd, the CMI in all states/territories started to increase and the sharpest increase of mobility appeared in North Territory from April 2nd to May 12th. After June 1st, the CMI of each state/territory varied over time. The human mobility in Tasmania remained in a relatively low level (e.g. around -20% on June 30th and afterwards) compared to the CMI in North Territory increasing from 0% on May 15th to 13.3% on August 1st. It may be possible that weather in North Territory on winter days (May to August in Australia) is warmer and more friendly for outdoor activities compared to cold winter days in Tasmania making people less active and mobile. It is noteworthy that the CMI in Victoria started to decrease after June 21st and so did for New South Wales and Australian Capital Territory after July 8th. It means that the re-introduction of restriction policies in Victoria responding to the second wave of pandemic also affects the mobility in the adjacent state/territory.
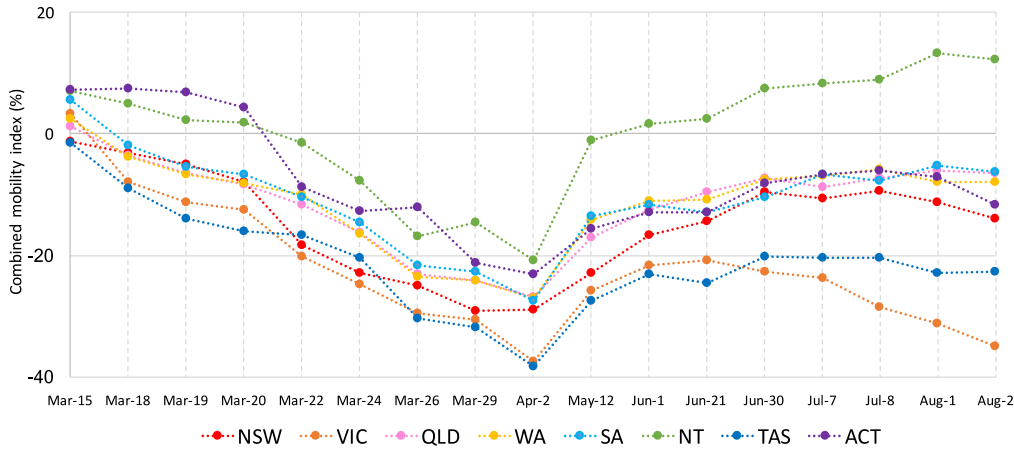
Figure 2. Combined mobility index within 3 days after the implementation of each policy

Note: *italic* policies are at the state level. March-15: Outdoor gathering limited to 500 persons; March-18: Indoor gathering limited to 100 persons; March-19: *TAS border closure;* March-20: Strict social distancing of 4 sqm per person; March-22: *NSW and VIC shut down non-essential services;* March-24: *QLD, WA, SA and NT border closure;* March-26: Further lockdown of restaurants, cafes, food courts, auction houses, open house inspections; weddings restricted to 5 people; funerals to 10 people; March-29: All gatherings 2 persons only; April-2: Australian supermarkets increase in store social distancing measures; May-12: National restrictions eased; June-1: National restrictions further eased; June-21: *VIC gatherings restricted;* June-30: *VIC 10 postcode lockdown;* July-7: *NSW border closure with VIC;* July-8; *VIC Stage-3 restriction;* August-1: *QLD border closure with NSW again;* August-2: *VIC Melbourne Stage-4 restriction.*

We further examine each type of mobility in each state/territory (Figure 3). The pattern of mobility clearly presents a regular variation across weeks, evident as weekly-cycles in most types of mobility with couples of 'outliers' indicating a substantial change of mobility on public holidays. Compared to the baseline (the period of January 3rd to February 6th, 2020 before the global COVID-19 pandemic), there are some common changes of mobility observed in all states/territories: the mobility to residence increased, indicating that more people stayed at home; the mobility to transit stations and retail/recreation decreased, reflecting that people less used public transport and recreational facilities; the mobility to workspace dropped substantially from March 15th to April 15th but started to increase from April 15th to August 15th except Victoria, indicating that people have been getting back to their work/business routines; the mobility to grocery/pharmacy substantially increased right after the implementation of social restriction policy on March 15th, which was coincided with the reported 'panic-buying' that people stockpiled groceries and medicines to cope with the virus. Finally, the mobility to parks varies across states/territories. The overall trend of mobility to parks decreased from March 15th to April 15th in all states but turned to increase slightly after April 15th. Compared to the time before COVID-19 outbreak, most of states have less mobility to parks from March 15th to June 15th, while North Territory has more since May. Australian Capital Territory is observed to have a clear weekly circle with a substantial increase of mobility to parks over weekends. Some spikes are also observed in Victoria, New South Wales, and South Australia on June 14th as the Queen's Birthday, reflecting the increase of park visiting on public holidays. In sum, the implementation of social restriction policies at the early stage of COVID-19 outbreak largely reduced human mobility to public facilities and spaces and such a reduction has been gradually eased with the lifting of restrictive policies although the overall mobility during the COVID-19 outbreak remained lower than that in the period before the outbreak.
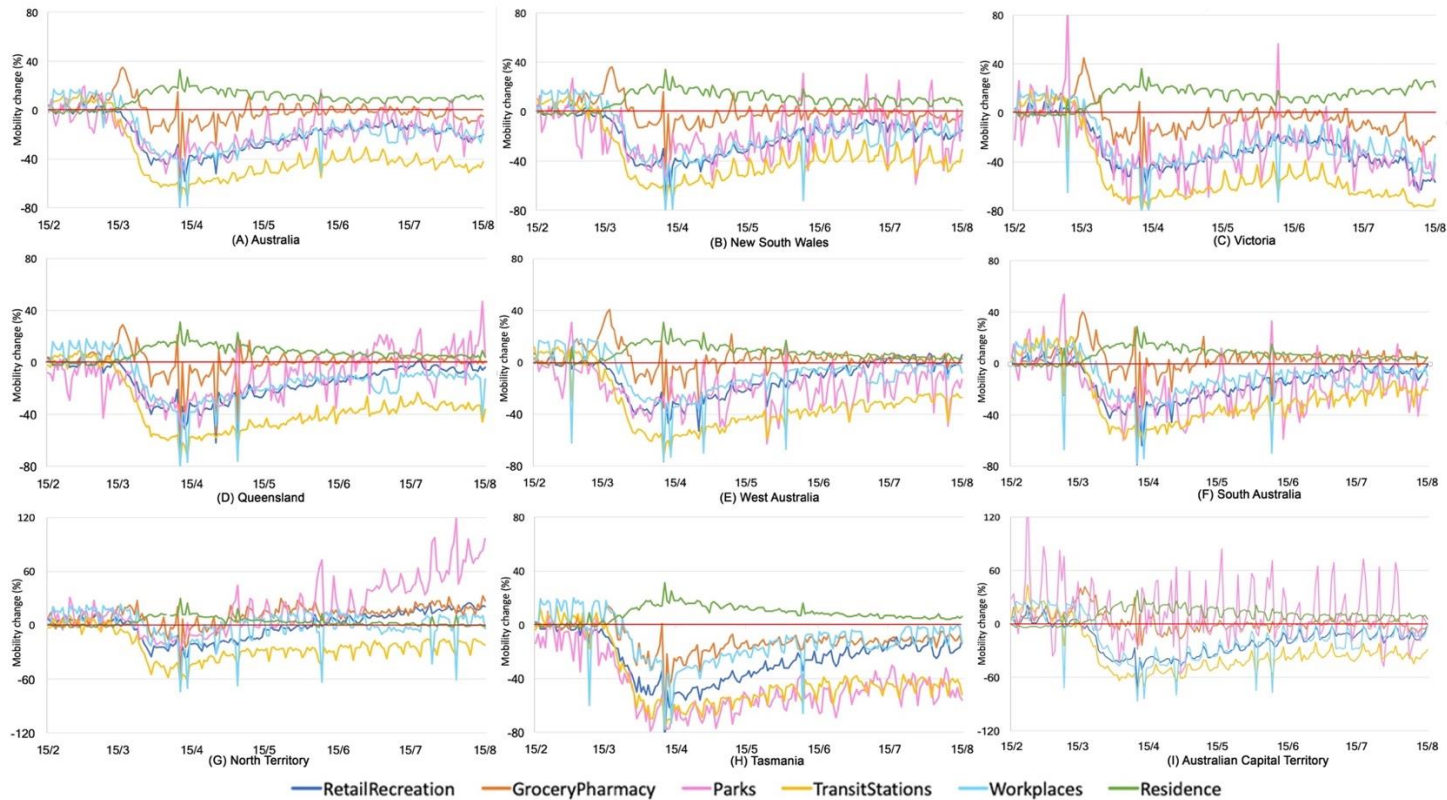
Figure 3. Six types of mobility in each Australian state/territory

3.2. The association between human mobility and COVID-19 spread

Figure 4 shows the pattern of CMI, growth rates and doubling time of COVID-19 cases during the pandemic in Australia and in each state/territory. The growth rate of confirmed cases reached peaks in most states/territories (except North Territory and Australian Capital Territory) before March 15th when the social restriction policies started to implement. Two weeks of the increasing level of social restrictions from March 15th to March 30th (light and dark grey shadowed periods in Figure 4) largely reduced the growth rate and lengthened the doubling time of confirmed cases, accompanied by a substantial decrease of human mobility. The growth rate after April 15th remained at a low level in all states/territories except Victoria, where an increasing curve of growth rate appeared after June 15th but gradually flatted towards August 15th.
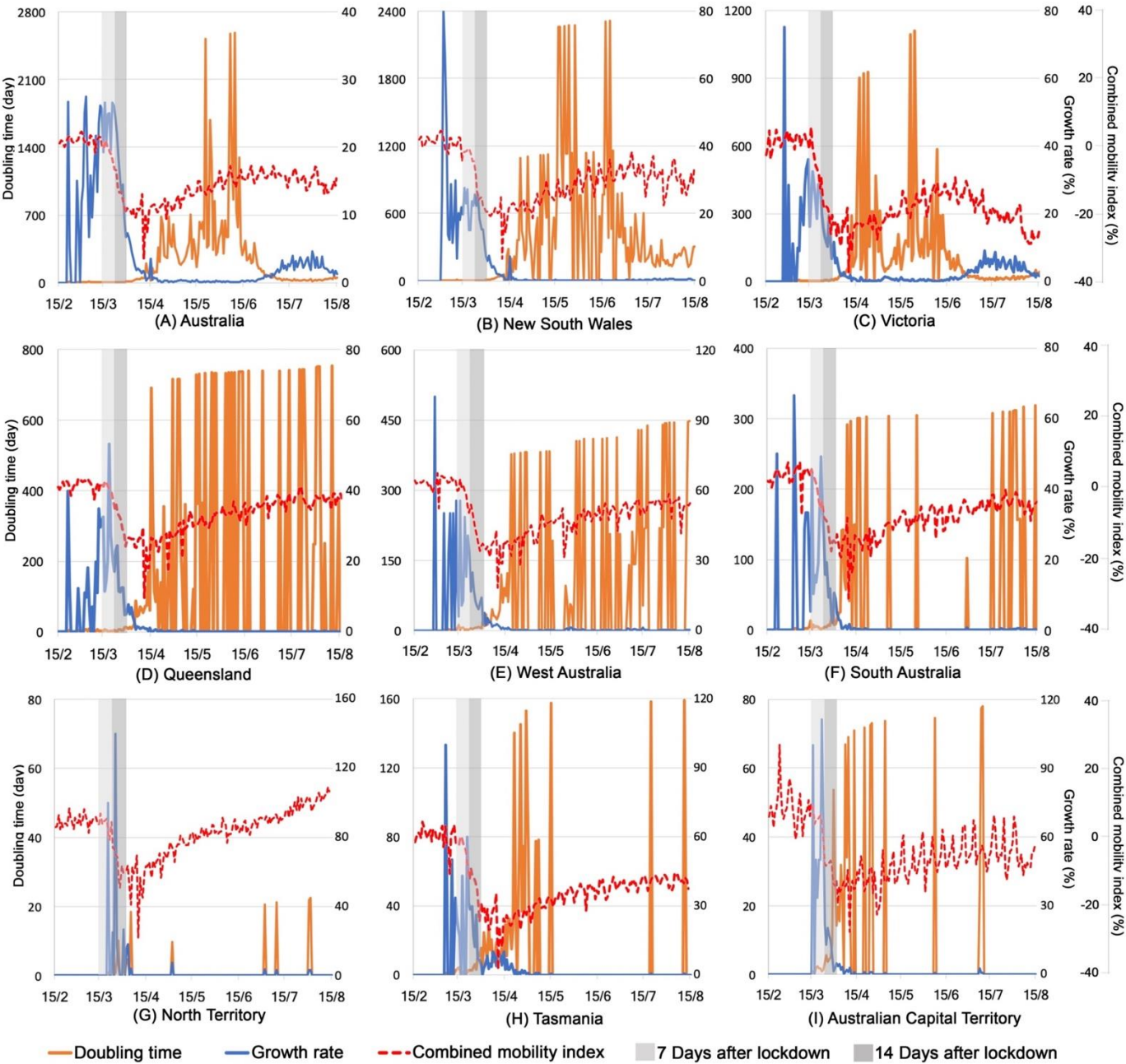
Figure 4. Combined mobility index, growth rates and doubling time in each Australian state/territory

Note: In each graph, Y-axis on the left denotes doubling time (day); Y-axis on the right denotes growth rates (%); A combined mobility index is shown in the Y-axis on the right of each row.

The correlation coefficients between CMI and growth rates in the 1st wave (March 15th to June 15th) are significantly ($p < 0.01$) positive in most states except North Territory (Figure 5A), indicating that a higher level of mobility is associated with a higher level of growth rates. The magnitude of correlation coefficients in most states increases from the period right after lockdown to the period 7 days after lockdown, reflecting that the incubation period from 7 days to 14 days brings in a time-lag effect of human mobility on growth rates. However, the correlation between CMI and growth rates is insignificant in Victoria in the 2nd wave (June 15th to August 15th). Different to growth rates, the correlation between CMI and doubling time across three periods of time is insignificant in most of states in both waves.
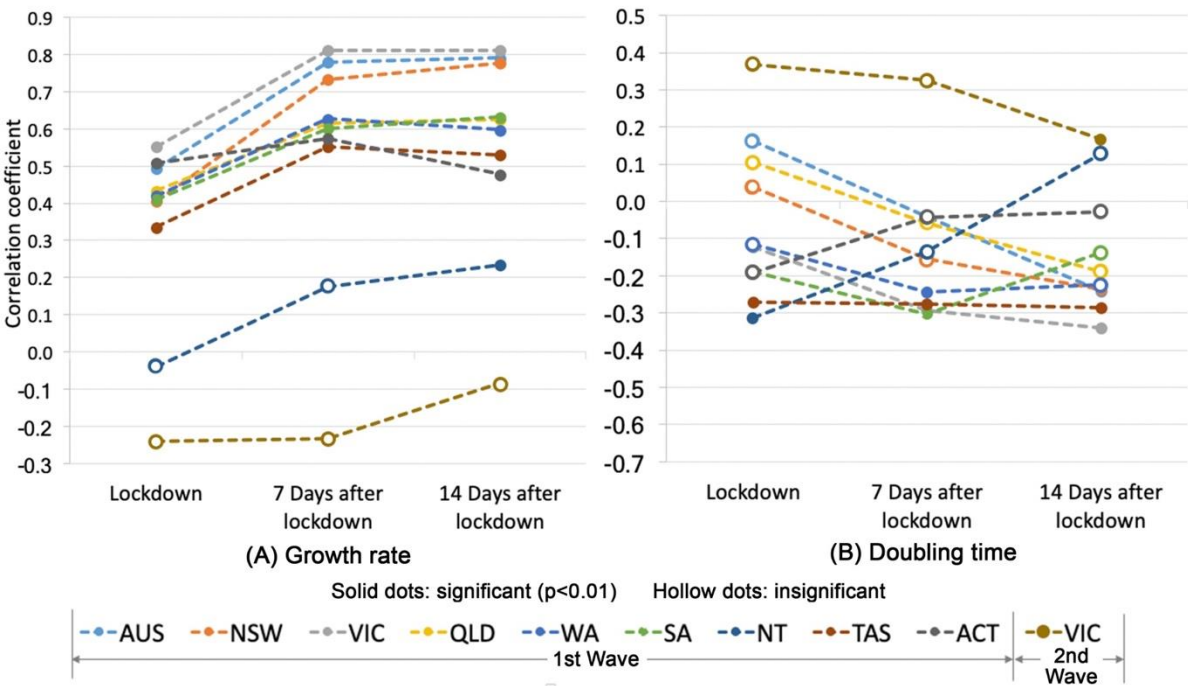
Figure 5. Correlation between CMI and growth rates (A), and between CMI and doubling time (B) in Australia and each state/territory over three periods of time

Note: the values of correlation coefficients are provided in Supplementary Materials

Figure 6 compares the regression coefficients of each type of mobility in each state/territory over three periods of time (right after, 7 days and 14 days after the lockdown date). In the 1st wave, the growth rate of confirmed cases has a negative association (significant at $p<0.01$) with the mobility to retail/recreation only in the period right after lockdown (Figure 6A) and with the mobility to workspaces in most states only in the period in the period 7 days and 14 days after lockdown (Figure 6B-C); while the mobility to transit stations is positively (significant at $p<0.01$) associated with growth rates in all states across three periods of time and its magnitude increases over time (Figure 6A-C), indicating a higher level of public transit usage is linked to a higher level of growth rates. Such a linkage becomes stronger after 7-day incubation period and slightly weaker after 14-day incubation period, reflecting the time-lag effect of mobility on COVID-19 spread and the delay of policy intervention.

Different to the 1st wave, the mobility to transit stations in Victoria in the 2nd wave is significantly and negatively associated with growth rates across three periods of time (Figure 6A-C) and positively associated with doubling time (Figure 6D-E); while the mobility to workspaces is positively associated with growth rates only in the period right after lockdown (Figure 6A) but negatively associated with doubling time (Figure 6D). It indicates that growth rates are largely tied to the increasing level of people getting back to workspaces after 3-month working at home in the 2nd wave of pandemic.
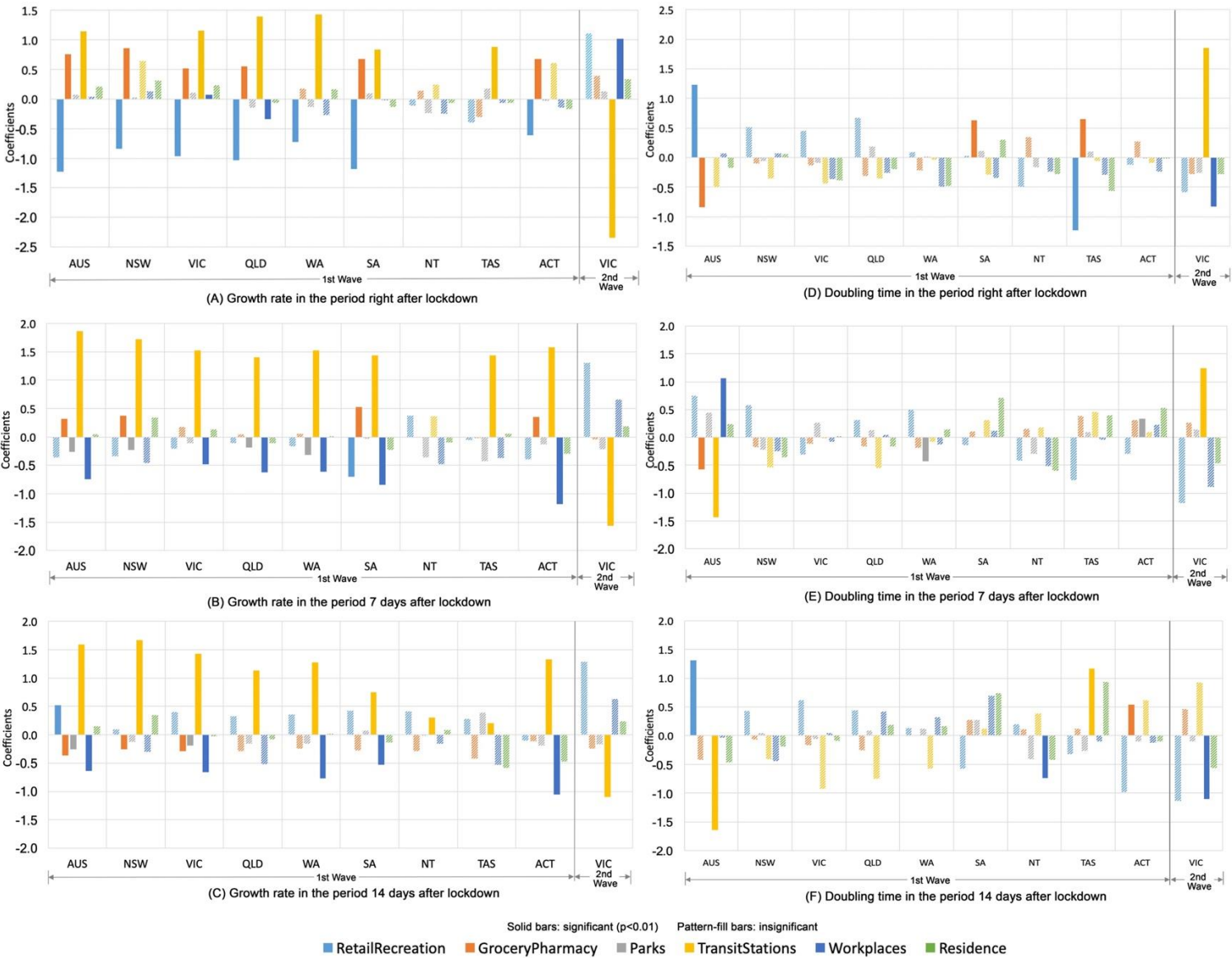
Figure 6. Regression coefficients of six types of mobility in Australia and each state/territory over three periods of time

Note: Regression coefficients are provided in Supplementary Materials

4. Discussion

Drawing on the COVID-19 data and Google mobility data, our study contributes an empirical study of the relationship among human mobility, social restriction policies, and COVID-19 spread in Australia. Due to the transmission dynamics and confounders underlying the epidemiological studies, we interpret our findings with caution and link them to the empirical experiences in other countries for more holistic understanding of how human mobility intertwines with COVID-19 spread and for better policy implications.

First, a visual inspection of the COVID-19 cases and mobility level alongside the timeline of policy interventions in Australia suggests that social restriction policies controlled the COVID-19 spread effectively in the early stage of the 1st wave of pandemic, during which the substantial decrease of human mobility as the consequence of the increasing level of social restriction was followed by a steep drop in growth rates and a sharp increase in doubling time of COVID-19 spread. This dramatic decline of growth rates could potentially reflect the fundamental association between the dynamics of the intense lockdown orders and virus transmission in the initial stage of pandemic, also observed by [11]. The reduction of mobility has been gradually eased with the lifting of restriction policies in mid-May. However, the overall mobility still remained at a low level afterwards and has not been fully restored

285   to the pre-pandemic level after the national restrictions lifted. Moreover, there are also imperfect
286   correspondences between social restriction and mobility levels to some degree, with mobility declining
287   prior to formal restriction and in certain circumstances increasing prior to formal restriction easing, and
288   such observations have also been found in other countries including China, U.S., Sweden, and South
289   Korea [5,7,8]. People may have intended to reduce access to public facilities and spaces with the
290   precautions of virus spread before the implementation of social restriction.
291   Second, the control of mobility has a time-lag effect on COVID-19 spread, as the span of the
292   mobility-spread relation lasts from 7 to 14 days possibly tied to the incubation period. We observe an
293   increase in the strength of the mobility-spread correlation over the period from the time when
294   restriction policies were implemented to 7 days after the policy implementation, but a decline in
295   correlation from 7 days to 14 days after the policy implementation. There are more mixed patterns of
296   mobility-spread correlation after the initial stage of intensive lockdowns. The possible explanation is
297   that social restriction policies may influence virus spread not merely because of their direct effect on
298   mobility levels, but also through their impact on other forms of individual behaviours including
299   individual social distancing, hygiene, and mask wearing [9]. The government-level supervision and the
300   efficacy of policy implementation, together with environmental conditions (such as changes in weather
301   conditions) also affect growth rates in a manner which weakens the association between mobility and
302   virus spread [10,11]. For example, the increase of mobility in North Territory after April 1st was
303   followed by a well-controlled flat curve of growth rates compared to an obvious increase of growth
304   rates in Tasmania in the same circumstance, possibly due to the temperature on winter days in North
305   Territory is much higher than that in Tasmania which helps to control the virus spread.
306   Third, there exists a dynamic association between mobility in different types and COVID-19
307   spread, and the magnitude of such an association varies across space and time. In the 1st wave, growth
308   rates are positively associated with the mobility to public transit and grocery/pharmacy in most states
309   but negatively associated with the mobility to retail/recreation and workspaces. As the growth of
310   COVID-19 cases, people prefer to stay at home and avoid the places of retail/recreation. In the
311   meantime, they are required to work from home instead of workspaces. Such a finding has been also
312   observed by Kissler et al. [12] in their study of New York City where the reduction in commuting
313   movements is negatively correlated with COVID-19 prevalence. Furthermore, the mobility to public
314   transit appears to be the only factor positively linked to the rise of growth rates over three periods of
315   time in most states and such a linkage becomes stronger after 7-day incubation period. However,
316   different to the 1st wave, the mobility to public transit become negatively associated with the COVID-
317   19 spread in the 2nd wave of pandemic in Victoria, where the rise in growth rates may be more subject
318   to the increasing number of people moving back to workspaces after 3-month working at home. This
319   inconsistent relationship between mobility and COVID-19 spread reflects that virus spread is not only
320   relevant to variation in mobility levels but also subject to variation in other forms of preventative
321   behaviours and perceptions, whether voluntary or government enforced [13]. Without consideration of
322   the complex of other potential confounders which may have tangible and intangible impacts on the
323   COVID-19 spread, it would be arbitrary to conclude that any observed drop in growth rates is attributed
324   to changes in mobility levels.
325   While the interpretation of our analytical results provides by no means definitive conclusions, it
326   serves as an initial attempt that draws on publicly available measures of human mobility and COVID-
327   19 data to study an epidemiological question with enormous social import. There are certain limitations,
328   imposing challenges in understanding the mobility-spread relationship. First, Google mobility data
329   provides a relative measure of mobility change compared to the period from January 3rd to February
330   6th, 2010 as the baseline. The selection of the baseline may introduce some biases across different
331   geographic contexts where human mobility may start to decline as an early reaction to COVID-19, and
332   thus it may not representative to the pre-pandemic level. Second, examining more precise time intervals
333   after the date of policy implementation (e.g., extending from 7-day to 1-day interval) would provide a
334   more detailed assessment to the time-lag effect of mobility on virus spread. Third, further attention can
335   give to the exploration of fixed place and date effect in the regression model to capture temporal
336   variation in potential confounders that may occur within geographic contexts over time. Since Google

337 only provides state/regional level mobility reports, some other big data sources (such as Geotagged
338 Tweets) can also help estimate human mobility changes in smaller scale geographic area [14-16]. Fourth,
339 it is necessary to have a comparative study on the mobility-spread relation between Australia and those
340 highly populated countries which have successfully contained the COVID-19 spread (e.g., South
341 Korean and Japan) for policy implications. The Oxford COVID-19 Government Response Tracker
342 (OxCGRT) systematically collects information on several different common policy responses that
343 governments have taken to respond to the pandemic and proposes a stringency index for each country
344 [17]. The quantitative policy index provides a new way to explore the associations among policies,
345 human mobility, and the COVID-19 spread in future work.

346   Nevertheless, a great deal of caution must be exercised in understanding our findings, which may
347 not be sufficient to indicate any causal direction between mobility control and virus spread. Although
348 there is no straightforward way to infer policy prescriptions from our analytical results, we find
349 suggestive evidence, which may help to mitigate virus spread especially in the initial stage of pandemic.
350 First, the implementation of robust contact tracing systems and self-isolation within the 14-day
351 incubation period would be crucial to attenuate the strength of the mobility-spread relation. Second,
352 the dynamics between the initial lockdown and the later phase of the outbreak driven by individual
353 behavioural changes reflect the importance of government-level supervision and policy
354 implementation should be lasting for a longer-term to keep its efficacy. Third, as the span of the
355 relationship between mobility and virus spread is suggested to be up to 14 days in our study, it is
356 important for governments to consider the degree to which lockdown conditions can be eased by
357 accounting for this span window.

5. Conclusions

359   Drawing on data of confirmed COVID-19 cases and Google mobility data in Australia, we present
360 a state-level empirical study to examine how the change of human mobility is adherent to social
361 restriction policies and how such changes affect the COVID-19 spread. Our findings show that social
362 restriction policies implemented in the early stage of the pandemic controlled the COVID-19 spread
363 effectively, which largely reduced mobility levels. The overall mobility still remained in a low level
364 afterwards and has not been fully restored to the pre-pandemic level after the national restrictions lifted
365 at the later stage. The restriction of human mobility has a time-lag effect on growth rates in the initial
366 stage, as the strength of the mobility-spread correlation increases up to 7 days after policy
367 implementation but decreases afterwards. However, there are more mixed patterns of mobility-spread
368 correlation after the initial stage of intensive lockdowns. The association between mobility and COVID-
369 19 spread varies across space and time, and subjects to the types of mobility. Thus, it is crucial for
370 governments and policy makers to consider the degree to which lockdown conditions can be eased by
371 accounting for this dynamic mobility-spread relationship.

388   **Supplementary Materials:** The following are available online at www.mdpi.com/xxx/s1.

389   Table S1. Correlation coefficients

	1st Wave									2nd Wave
	AUS	NSW	VIC	QLD	WA	SA	NT	TAS	ACT	VIC
Between growth rate and mobility change										
Lockdown	**0.494**	**0.406**	**0.551**	**0.435**	**0.420**	**0.411**	-0.039	**0.337**	**0.508**	-0.241
7 Days after lockdown	**0.780**	**0.733**	**0.812**	**0.615**	**0.627**	**0.601**	0.176	**0.553**	**0.573**	-0.233
14 Days after lockdown	**0.792**	**0.777**	**0.812**	**0.625**	**0.598**	**0.633**	**0.233**	**0.531**	**0.478**	-0.085
Between doubling time and mobility change										
Lockdown	0.162	0.038	-0.121	0.105	-0.115	-0.190	**-0.314**	**-0.272**	-0.191	**0.369**
7 Days after lockdown	-0.041	-0.155	**-0.293**	-0.057	**-0.244**	**-0.303**	-0.135	**-0.276**	-0.042	**0.326**
14 Days after lockdown	**-0.242**	**-0.235**	**-0.339**	-0.189	**-0.225**	-0.138	0.128	**-0.286**	-0.028	0.167

390   Note: values in bold indicate $p<0.01$.

391

392   Table S2. R square of each regression model

	1st Wave									2nd Wave
	AUS	NSW	VIC	QLD	WA	SA	NT	TAS	ACT	VIC
Growth rate as the dependent variable										
Lockdown	0.578	0.481	0.560	0.656	0.581	0.476	0.040	0.309	0.493	0.525
7 Days after lockdown	0.867	0.769	0.907	0.881	0.807	0.814	0.339	0.68	0.792	0.262
14 Days after lockdown	0.923	0.880	0.881	0.704	0.610	0.649	0.162	0.489	0.496	0.136
Doubling time as the dependent variable										
Lockdown	0.302	0.042	0.088	0.145	0.082	0.250	0.084	0.207	0.097	0.412
7 Days after lockdown	0.237	0.067	0.398	0.272	0.391	0.429	0.278	0.441	0.373	0.253
14 Days after lockdown	0.214	0.094	0.159	0.101	0.086	0.138	0.116	0.223	0.116	0.182

393

394   Table S3-1. Coefficients of each type of mobility with growth rate as the dependent variable

		1st Wave									2nd Wave
		AUS	NSW	VIC	QLD	WA	SA	NT	TAS	ACT	VIC
Lockdown	RetailRecreation	**-1.227**	**-0.841**	**-0.966**	**-1.037**	**-0.725**	**-1.186**	-0.108	-0.401	**-0.609**	1.115
	GroceryPharmacy	**0.761**	**0.864**	**0.513**	**0.558**	0.172	**0.675**	0.140	-0.298	**0.679**	0.391
	Parks	0.075	0.029	0.107	-0.139	-0.129	0.096	-0.232	0.171	-0.026	0.134
	TransitStations	**1.141**	0.642	**1.159**	**1.402**	**1.434**	**0.840**	0.240	**0.879**	0.614	**-2.352**
	Workplaces	**0.036**	0.130	**0.074**	**-0.334**	-0.269	-0.017	-0.249	-0.060	-0.140	**1.019**
	Residence	0.213	0.315	0.237	-0.068	0.160	-0.133	-0.060	-0.060	-0.164	0.335
7 Days after lockdown	RetailRecreation	-0.360	-0.339	-0.200	-0.101	-0.159	**-0.700**	0.372	-0.051	-0.394	1.304
	GroceryPharmacy	**0.325**	**0.375**	0.177	0.050	0.058	**0.529**	-0.002	-0.022	**0.354**	-0.042
	Parks	**-0.259**	**-0.231**	-0.108	**-0.186**	**-0.320**	-0.031	-0.361	-0.425	-0.129	-0.214
	TransitStations	**1.862**	**1.724**	**1.522**	**1.402**	**1.526**	**1.434**	0.366	**1.439**	**1.585**	**-1.563**
	Workplaces	**-0.737**	-0.455	**-0.482**	**-0.623**	**-0.609**	**-0.843**	-0.480	-0.369	**-1.181**	0.656
	Residence	0.047	0.346	0.129	-0.112	0.008	-0.226	-0.094	0.063	-0.296	0.193
1	RetailRecreation	**0.524**	0.093	0.407	0.330	0.355	0.419	0.417	0.280	-0.104	1.285

GroceryPharmacy	**-0.369**	**-0.252**	**-0.286**	-0.286	-0.244	-0.276	-0.286	-0.417	-0.116	-0.245
Parks	**-0.252**	-0.124	**-0.191**	-0.154	-0.152	0.072	-0.006	0.390	-0.187	-0.166
TransitStations	**1.595**	**1.672**	**1.431**	**1.132**	**1.271**	**0.748**	0.308	0.201	**1.330**	-1.095
Workplaces	**-0.633**	-0.300	**-0.660**	-0.519	**-0.769**	**-0.534**	-0.162	-0.526	**-1.055**	0.627
Residence	0.145	0.348	-0.022	-0.081	0.023	-0.139	0.079	-0.580	-0.478	0.232

Note: values in bold indicate $p<0.01$.

Table S3-2. Coefficients of each type of mobility with doubling time as the dependent variable

		1st Wave									2nd Wave
		AUS	NSW	VIC	QLD	WA	SA	NT	TAS	ACT	VIC
Lockdown	RetailRecreation	**1.227**	0.510	0.447	0.671	0.092	0.028	-0.491	**-1.226**	-0.123	-0.588
	GroceryPharmacy	**-0.842**	-0.100	-0.131	-0.315	-0.212	**0.629**	0.344	**0.650**	0.273	-0.275
	Parks	0.005	-0.056	-0.085	0.189	0.013	0.113	-0.164	0.098	-0.016	-0.253
	TransitStations	-0.502	-0.348	-0.435	-0.351	-0.032	-0.294	0.005	-0.061	-0.087	**1.853**
	Workplaces	0.066	0.065	-0.365	-0.263	-0.494	-0.340	-0.242	-0.285	-0.240	**-0.829**
	Residence	-0.177	0.056	-0.388	-0.192	-0.483	0.299	-0.277	-0.569	-0.007	-0.276
7 Days after lockdown	RetailRecreation	0.745	0.572	-0.309	0.309	0.492	-0.134	-0.417	-0.766	-0.293	-1.177
	GroceryPharmacy	**-0.574**	-0.176	-0.114	-0.161	-0.182	0.104	0.148	0.378	0.309	0.26
	Parks	0.441	-0.223	0.258	0.125	**-0.427**	0.005	-0.293	0.090	**0.331**	0.141
	TransitStations	**-1.432**	-0.541	-0.007	-0.547	-0.078	0.304	0.173	0.458	0.089	**1.244**
	Workplaces	**1.056**	-0.245	-0.075	0.049	-0.123	0.111	-0.519	-0.037	0.230	-0.886
	Residence	0.243	-0.354	0.016	-0.162	0.143	0.709	-0.604	0.400	0.524	-0.46
14 Days after	RetailRecreation	**1.314**	0.435	0.622	0.444	0.127	-0.570	0.195	-0.315	-0.980	-1.137
	GroceryPharmacy	-0.423	-0.070	-0.167	-0.253	0.013	0.272	0.113	0.123	**0.540**	0.459
	Parks	0.003	0.046	-0.051	0.090	0.116	0.276	-0.410	-0.262	-0.097	-0.094
	TransitStations	**-1.647**	-0.409	-0.929	-0.753	-0.571	0.116	0.382	**1.165**	0.619	0.925
	Workplaces	-0.037	-0.440	0.048	0.419	0.321	0.689	**-0.735**	-0.102	-0.124	**-1.097**
	Residence	-0.465	-0.186	-0.088	0.190	0.167	0.738	-0.421	0.932	-0.098	-0.559

Note: values in bold indicate $p<0.01$.

References

1.   World Health Organization. Coronavirus disease 2019 (COVID-19) Situation Report – 67. Available online:

412   https://apps.who.int/iris/bitstream/handle/10665/331613/nCoVsitrep27Mar2020-eng.pdf
413   (accessed on September 6th, 2020)

414 2. NHCPRC (National Health Commission of the People's Republic of China). COVID-19 Report.
415   Available online: http://www.nhc.gov.cn/xcs/yqtb/list_gzbd.shtml (accessed on September 6th,
416   2020)

417 3. Department of Health, Australian Government. Coronavirus (COVID-19) current situation and
418   case numbers. Available online: https://www.health.gov.au/news/health-alerts/novel-
419   coronavirus-2019-ncov-health-alert/coronavirus-covid-19-current-situation-and-case-numbers
420   (accessed on September 6th, 2020)

421 4. Google LLC. Google COVID-19 Community Mobility Reports. Available online:
422   https://www.google.com/covid19/mobility/ (accessed on September 6th, 2020)

423 5. Tran, T. H., Sasikumar, S., Hennessy, A., O'Loughlin, A., & Morgan, L. Interpreting the effect
424   of social restrictions on cases of COVID-19 using mobility data. *The Medical Journal of Australia*
425   2020, *1*.

426 6. Lauer SA, Grantz KH, Bi Q et al. The incubation period of Coronavirus Disease 2019 (COVID-
427   19) From Publicly Reported Confirmed Case: Estimation and Application. *Annals of Internal*
428   *Medicine* 2020, *172*, 577-582.

429 7. Chinazzi, M., Davis, J. T., Ajelli, M., Gioannini, C., Litvinova, M., Merler, S., ... & Viboud, C.
430   The effect of travel restrictions on the spread of the 2019 novel coronavirus (COVID-19)
431   outbreak. *Science* 2020, *368*(6489), 395-400.

432 8. Gupta, Sumedha, Thuy D. Nguyen, Felipe Lozano Rojas, Shyam Raman, Byungkyu Lee, Ana
433   Bento, Kosali I. Simon, and Coady Wing. Tracking Public and Private Response to the COVID-
434   19 Epidemic: Evidence from State and Local Government Actions. National Bureau of
435   Economic Research Working Paper No. 27027, 2020.

436 9. Bergman, N. K., & Fishman, R. Mobility Levels and Covid-19 Transmission Rates. *medRxiv*
437   2020 (preprint).

438 10. Tosepu, R., Gunawan, J., Effendy, D. S., Lestari, H., Bahar, H., & Asfian, P. Correlation between
439   weather and Covid-19 pandemic in Jakarta, Indonesia. *Science of The Total Environment*, 2020,
440   *725*, 138436.

441 11. Chang, S. L., Harding, N., Zachreson, C., Cliff, O. M., & Prokopenko, M. Modelling
442   transmission and control of the COVID-19 pandemic in Australia. *arXiv,* 2020 (preprint:
443   arXiv:2003.10218).

444 12. Kissler, Stephen M., Nishant Kishore, Malavika Prabhu, Dena Goffman, Yaakov Beilin, et al.
445   Reductions in commuting mobility predict geographic differences in SARS-CoV-2 prevalence
446   in New York City. Harvard University Library, Boston, USA. Available online:
447   http://nrs.harvard.edu/urn-3:HUL.InstRepos:42665370 (accessed on 6 September, 2020)

448 13. Wang, J., Tang, K., Feng, K., & Lv, W. High temperature and high humidity reduce the
449   transmission of COVID-19. *SSRN 3551767*, 2020.

450 14. Huang, X., Li, Z., Jiang, Y., Li, X., & Porter, D. Twitter, human mobility, and COVID-19. *arXiv*
451   2020, 2007.01100. (preprint)

452 15. Yang, C., Sha, D., Liu, Q., Li, Y., Lan, H., Guan, W. W., ... & Wang, Z. Taking the pulse of
453   COVID-19: A spatiotemporal perspective. *International Journal of Digital Earth* 2020, 1-26.

16. Hu, T., Guan, W., Zhu, X., et al. Building an Open Resources Repository for COVID-19 Research, *Data and Information Management* 2020, 4(3), 130-147.

17. Hale, Thomas, Noam Angrist, Emily Cameron-Blake, Laura Hallas, Beatriz Kira, Saptarshi Majumdar, Anna Petherick, Toby Phillips, Helen Tatlow, Samuel Webster. Oxford COVID-19 Government Response Tracker, Blavatnik School of Government, 2020.