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Research Paper

Lockdown timing and efficacy in controlling COVID-19 using mobile phone tracking

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ABSTRACT

Background: Italy's severe COVID-19 outbreak was addressed by a lockdown that gradually increased in space, time and intensity. The effectiveness of the lockdown has not been precisely assessed with respect to the intensity of mobility restriction and the time until the outbreak receded.
Methods: We used processed mobile phone tracking data to measure mobility restriction, and related those data to the number of new SARS-CoV-2 positive cases detected on a daily base in the three most affected Italian regions, Lombardy, Veneto and Emilia-Romagna, from February 1 through April 6, 2020, when two subsequent lockdowns with increasing intensity were implemented by the Italian government.
Findings: During the study period, mobility restriction was inversely related to the daily number of newly diagnosed SARS-CoV-2 positive cases only after the second, more effective lockdown, with a peak in the curve of diagnosed cases of infection occurring 14 to 18 days from lockdown in the three regions and 9 to 25 days in the included provinces. An effective reduction in transmission must have occurred nearly immediately after the tighter lockdown, given the lag time of around 10 days from asymptomatic infection to diagnosis. The period from lockdown to peak was shorter in the areas with the highest prevalence of the infection. This effect was seen within slightly more than one week in the most severely affected areas.
Interpretation: It appears that the less rigid lockdown led to an insufficient decrease in mobility to reverse an outbreak such as COVID-19. With a tighter lockdown, mobility decreased enough to bring down transmission promptly below the level needed to sustain the epidemic.
Funding: No funding sources have been used for this work.

1. Introduction

As SARS-CoV-2 spread rapidly, the inability to control COVID-19 through contact tracing left few options to public-health officials. The major approach has been the adoption of strict rules to decrease individual mobility and increase social distancing, accompanied by use of personal protective measures such as masks and gloves [1]. When these measures were sufficiently tight, they have been described as a 'lockdown'. These lockdowns were implemented in varying degrees and at different times, and while they appeared to be effective in interrupting transmission [2,3], details of their efficacy are yet to be elaborated and are currently under active investigation [2,4–9].

Northern Italy was affected early and severely by SARS-CoV-2. Lockdowns across Italy and elsewhere were implemented in stages amid intense sociopolitical and scientific debate [7,10–13]. Here we report on how effective these restrictions in Italy have been in reducing individual mobility and controlling spread of SARS-CoV-2. In response to suggestions to use mobile phone data to study and curb COVID-19 [12,14,15], we assessed mobility through cellphone tracking data as a proxy for individual mobility and lockdown efficacy, and examined the relation of the mobility data to SARS-CoV-2 positivity, obtained from nationwide open access data [16].

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Research in context

Evidence before this study

The COVID-19 outbreak severely affected Northern Italy, prompting two successive lockdowns, the second more stringent than the first. However, little data are available about effective compliance of the population with these mobility restrictions, and their effect on curbing the outbreak. We used publicly available processed data about cellphone movements and spread of SARS-CoV-2 infection in the three most affected Italian regions, Lombardy, Veneto and Emilia-Romagna, to examine the effect of each lockdown on mobility and the outbreak.

Added value of this study

Based on mobile phone tracking data, we found that the second lockdown produced a considerably greater decrease in individual mobility, which stemmed the outbreak. The peak in new cases occurred 14 to 18 days after the tighter lockdown in the three study regions and 9 to 25 days in the included provinces. Reduced transmission must have occurred much earlier, given the lag time between asymptomatic infection and result of the testing. Greater reduction in cellphone mobility and a higher prevalence of SARS-CoV-2 infection at time of lockdown implementation were associated with a shorter lag in curbing the outbreak.

Implications of all the available evidence

In this highly industrialized and mobile Western population, the milder lockdown had little effect on individual mobility. However, after the near total lockdown there was a substantial reduction in individual mobility that promptly stemmed the outbreak, with a peak of new diagnoses of infections ranging from 9 to 25 days after its implementation. A higher intensity of mobility reduction and a higher prevalence of the infection are associated with larger effectiveness of the intervention.

2. Methods

This study used data available without cost from publicly available sources. We focused on the Lombardy, Veneto and Emilia-Romagna regions of Italy, which were in early March the most highly affected areas of Italy, with 82% of cases [17].

We used cellphone mobility data during the period February 1-March 27 (the latest date available) as a proxy for individual mobility. We then examined, within provinces, the relation of these mobility data to daily positive tests for SARS-CoV-2. We also examined the influence of Italian national rules adopted to counteract the COVID-19 outbreak. The first rule was a nationwide lockdown decreed on February 23, 2020 following the detection of the first case of SARS-CoV-2 infection in Italy on February 20, 2020 [18]. This first 'soft' lockdown included among other measures the closure of all schools and universities in the country, and all non-essential industrial and commercial activities; limiting the activities of public offices; prohibiting any gathering of people in churches, museums, and leisure areas; and decreasing public transportation. In addition, on the same day (February 23, 2020), an integrative rule [19] imposed a tighter, nearly complete lockdown on two hot spots with the highest COVID-19 incidence in Italy (so called 'red zones'): ten municipalities in the Lodi province in Lombardy and one in the Padua province in Veneto. The second rule established a tight lockdown on March 8, 2020 for most of the population of the Veneto and Emilia-Romagna regions and the entire Lombardy region, and extended to the rest of Italy one day later [20]. The rule prohibited any kind of mobility apart from certain health or professional needs.

To track mobile phone movements, we used anonymous data from the subscriber identification module (SIM) cards of 27 million people processed and made available by Teralytics [21-23]. Through call detail records, information on the position of mobile phones within the carrier network can be used in conjunction with transport models to construct people's movements based on a daily trip counter. Mobility for a community was expressed as the number of journeys made per capita during the period February 1, 2020 to March 27, 2020. Journeys included all trips into, out of, and within each province. A trip was considered to end when the cellphone remained in place for at least one hour. Journeys shorter than 2 kms were not captured by the model. All data made available to us were entirely anonymous, pursuant to current data protection rules in Italy. These rules allow personal phone calls to be divulged only to the judicial system [24], whereas anonymous processed data are available to public and private entities for monitoring and research purposes. As no individuals were identified, the study was exempt from ethical review [25].

Our health endpoint was the diagnosis of newly diagnosed infections from SARS-CoV-2 as reported and publicly available in the website of the Italian Ministry of Health / Civil Protection [16] from February 24 up to April 6, 2020. It corresponded to the number of positive tests of infection based on quantitative reverse transcription polymerase chain reaction [26], by date and province as reported to the National Civil Protection Agency by the Health Services of the Italian regions [16]. No municipality-specific data were available from that source or other sources. All such positive SARS-CoV-2 cases were laboratory-confirmed by an officially accredited laboratory and by the National Institute of Health in Rome [26]. It was mandatory for all regions of Italy, and the two independent provinces of Bolzano and Trento, to communicate this information daily [27].

We modeled the province- and region-specific time trends of daily residents' mobility based on time-series of mobile phone movements, using a linear regression taking into account heteroskedasticity and autocorrelation up to 7 days using a Newey−West estimator [28]. In modeling the mean number of movements, we used calendar time in days with a mix constant and linear splines to allow shift in both level and trend at the two major intervention dates, February 23, 2020 and March 8, 2020.

Using the same statistical methodology, we also modeled the time trends in SARS-CoV-2 infection based on the mean number of newly diagnosed cases reported on a daily basis to the Ministry of Health from each province and region. To do that, we used calendar time in days with restricted cubic splines using 5 knots at fixed percentiles (5th, 27·5th, 50th, 72·5th and 95th) of its distribution to estimate the day of peak occurrence. In the second stage, we examined the relation between the proportional reduction in daily movements during lockdown compared with the period before restrictions were imposed, before the first lockdown. Percentiles of time to peak, censored for provinces that did not reach the peak by April 6, 2020, were derived from the Kaplan-Meier method. We used a Laplace regression model [29] to assess the association between proportional reduction in daily movements and SARS-CoV-2 infection prevalence (per 1000 inhabitants) on March 8, 2020 with median time to peak, adjusting for the population of the province. We used Stata 16·1 software to perform all analyses (codes available on request from TF and NO).

Role of funding: no funding sources have been used for this work.

3. Results

Fig. 1 is a map of the three study regions, indicating the comparative cumulative incidence of newly diagnosed SARS-CoV-2 infected cases by province up to April 6, 2020. During the study period, the mean reduction of cellphone movements after the March 8, 2020 lockdown compared with the first week of February was 52% overall, with a range of 44% – 63%, and by region, 58% in Lombardy, 49% in Veneto and 52% in Emilia-Romagna, with movements decreasing over time.

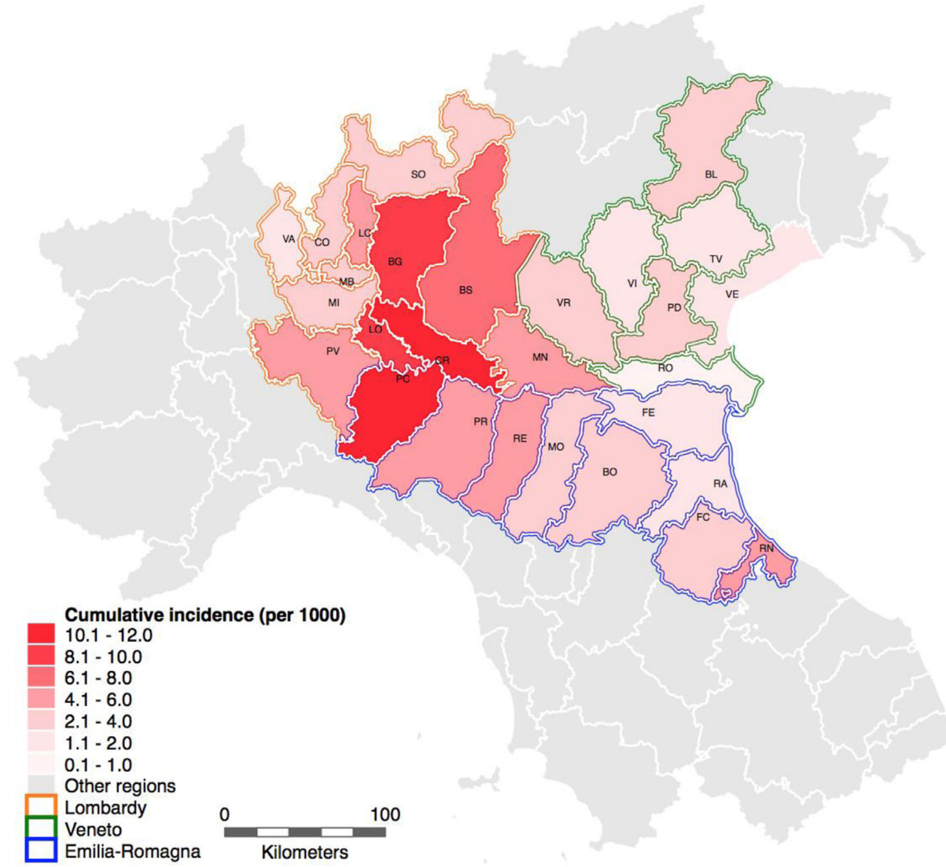

Fig. 1. Northern Italy study area with the cumulative incidence (per 1000) of SARS-CoV-2 infected cases diagnosed through April 6, 2020 in the provinces of the Lombardy, Veneto and Emilia-Romagna regions.

In Fig. 2, we report the day-specific absolute numbers of mobile phone tracking movements and new positive tests of SARS-CoV-2 infection from February 24, 2020 through April 6, 2020 within the Lombardy, Veneto and Emilia-Romagna regions. In Lombardy, the region with the highest spread of the outbreak, the peak of new infected cases came 14 days after the second lockdown, following a 58% reduction in mobile phone tracking daily movements, while in Veneto and Emilia-Romagna the peak came after 18 days, with a movement reduction of 49% and 52%, respectively.

In Figs. 3,4 we report the corresponding analysis for the province of Lodi, where the first and largest 'red area' was located, and in the six provinces closest to this area (Bergamo, Brescia, Cremona, Milan, Pavia and Piacenza). In particular less than 25% of Lodi province was tightly locked down on February 23. The remainder was subject to the national light lockdown on February 23 and the tight one on March 8, resulting in a 'mixed' pattern of lockdown: in this province the peak of SARS-CoV-2 infected cases was reached 13 days after (on March 7, 2020) the beginning of its 'mixed' lockdown. Bordering Lodi, Milan had the highest number of cases (11,538 on April 6), followed by Bergamo (9815 on April 6), which experienced a severe spread of the outbreak immediately before the March 8 lockdown. All but one of these Lodi-bordering provinces (i.e. Bergamo, Brescia, Cremona, Milan, and Piacenza) showed a flattening and then a drop in new cases after a period ranging from 9 to 18 days from the lockdown (shorter for the three provinces with the highest infection prevalence, Cremona, Bergamo and Brescia, and longer for the remaining Piacenza and Milan provinces). Conversely, Pavia showed flattening of the curve 9 days after the lockdown (on March 17, 2020), but instead of a decline, new cases plateaued and then resumed climbing. This province, however, had fewer cases than the other provinces. Data about all the remaining provinces of Lombardy and Emilia-Romagna regions, and of the Veneto region, are reported in Supplemental Figures 1–3. The number of days from the tight lockdown to the peak ranged from 9 to 25 days among these provinces, omitting the four that did not reach a peak within the study period (Pavia, Varese, Rovigo, and Ferrara).

Table 1 shows the estimated number of days from the March 8, 2020 lockdown to the peak occurrence, according to province. It also lists for each of the study areas the number of positive cases of SARS-CoV-2 and their prevalence, the day of peak infection, and days after the March 8 lockdown to the peak (except for Lodi, which had an earlier lockdown). The median days from lockdown to peak (after exclusion of Lodi) was 18 days, with a minimum of 9, a 25th and 75th percentiles of 15 and 21, respectively. The shortest period from tight lockdown to peak was generally typical of the provinces (and the Lombardy region) having the highest prevalence of the infection. As noted, in Lodi the peak number of cases occurred one day before the March 8, 2020 lockdown, as an earlier lockdown was already in place as of February 23, 2020. In the four small provinces generally characterized by the lowest prevalence the number of cases was still increasing at the latest date available, April 6, 2020. The intensity of the mobility reduction in the provinces and a higher virus prevalence on March 8, 2020 were inversely associated with the time from lockdown to the peak of the infection, with this interval being as short as 9–12 days in the provinces located at the center of the outbreak (Fig. 5). In a time to peak analysis, after exclusion of Lodi province and adjusting for population size, a 10% decrease in cell phone mobility was associated with a reduction of 3.3 days in the median time to peak until the peak occurrence (95% confidence interval: −7.1 to 1.1). Further, an increase of 1/1000 in prevalence rate of SARS-CoV-2 infections on March 8, 2020 was associated with a reduction of 5.7 days of the median time to peak (95% confidence interval: −8.3 to −3.1).

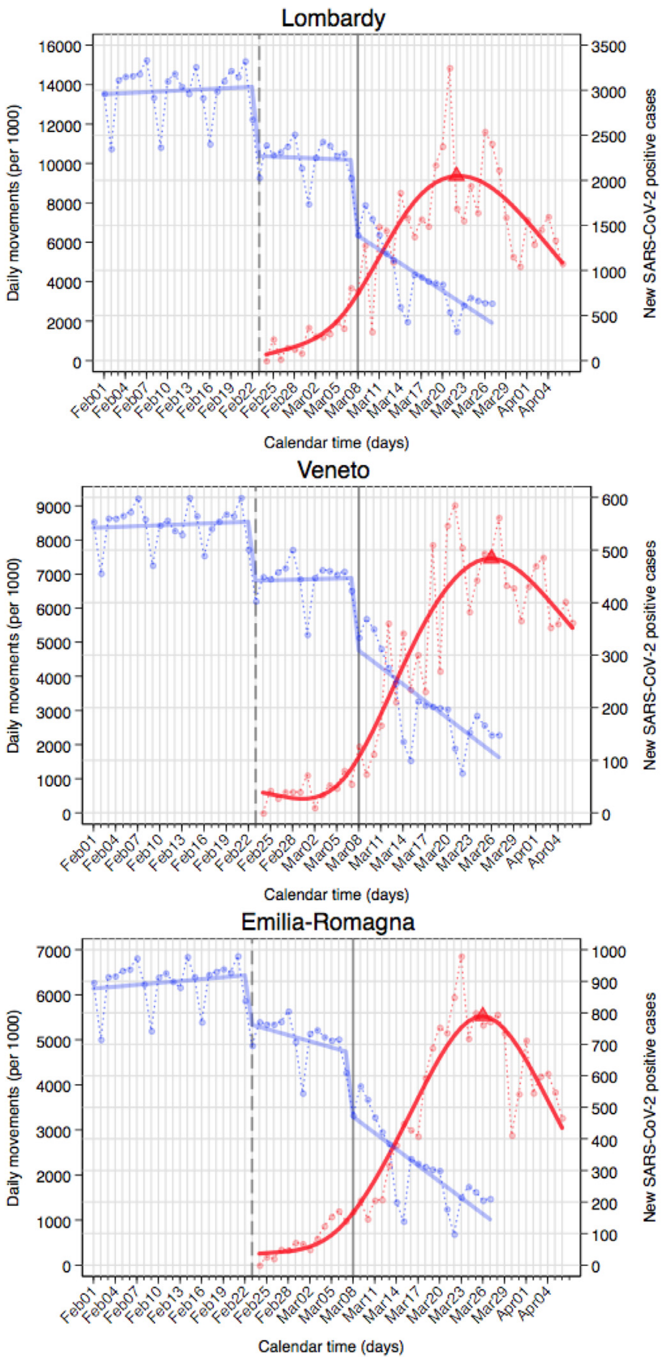

Fig. 2. Day-specific absolute numbers of people movements (blue dots) and SARS-CoV-2 positive cases (red dots) in the Lombardy, Veneto and Emilia-Romagna regions from February 1, 2020-April 6, 2020. Blue line shows the predicted mean number of movements obtained with a mix of constant and linear splines of calendar days with two knots at the major events of interest in determining lockdowns of different intensity (February 23, 2020 – dashed gray line, and March 8, 2020 – solid gray line). Red line shows the predicted mean number of new COVID-19 cases obtained with restricted cubic splines of calendar days with 5 knots to identify the maximum predicted value (i.e. day of peak occurrence – red triangle). The two series were modeled using the Newey–West estimator.

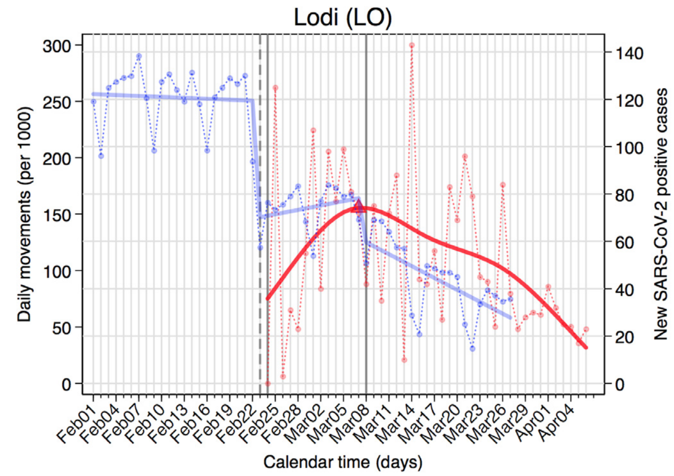

Fig. 3. Day-specific absolute numbers of people movements (blue dots) and SARS-CoV-2 positive cases (red dots) in Lodi province (Lombardy region) during February 1, 2020-April 6, 2020. Blue line shows the predicted mean number of movements obtained with a mix of constant and linear splines of calendar days with two knots at the major events of interest in determining lockdowns of different intensity (February 23, 2020 – dashed gray line for the light lockdown in most of the province, solid gray line for the tight lockdown in the 'red zone', around one quarter of the province; and March 8, 2020 – solid gray line extended to the entire province). Red line shows the predicted mean number of new COVID-19 cases obtained with restricted cubic splines of calendar days with 5 knots to identify the maximum predicted value (i.e. day of peak occurrence – red triangle). We fitted time-series data using Newey–West regression models.

4. Discussion

Italy has extremely high penetration of cellphone ownership, and ranks among the highest countries in the world in mobile phone use [30]. Thus, localization information and mobility based on cellphone positioning should be a reliable proxy for individual mobility. Cellphone location has been also recently used to assess population mobility and associate it with spatial-temporal COVID-19 distribution [22,23], and it has been proposed as a tool to assess compliance with lockdown rules in a population [15].

Our data indicate that the imposed lockdowns were followed by a peak in case occurrence about 14 days later in the most affected region, and in some heavily affected provinces as early as 9–10 days later. This peak followed a continuous reduction over time of personal mobility, presumably due to increasing compliance with the restrictions, as awareness of the health emergency grew and law enforcement intensified. Greater compliance with the mobility restrictions was associated with a swifter and more marked decrease in SARS-CoV-2 positive tests, particularly among medium-to-large provinces with rapid spread of the virus. The limited effect of the 'light' lockdown imposed by the partial nationwide restrictions issued by the national government on February 23, mainly as a consequence of the 'Codogno' hot spot in Lodi linked to patient-1 detection on February 20 [31], is evidenced by the subsequent steep increase in new SARS-CoV-2 positive cases. While limited in scope, the data appear consistent with the hypothesis that within the range of interventions enacted, the intensity of the mobility restrictions was related to the timing and effectiveness of the epidemic control. Our results are also consistent with preliminary data from the US, also based on cellphone movements, that have identified a lag time of 11 days, with a range of 9 to 12 days, since the beginning of social distancing to the onset of COVID-19 case growth reduction [22].

Unlike the majority of provinces, four of them, Pavia, Varese, Rovigo and Ferrara, did not reach a peak in incidence of the infection through the end of the investigated period. This delay might be related to the relatively low incidence and prevalence of the infection in these provinces. In those circumstances, small outbreaks in hospitals, retirement homes and other restricted environments may play a relatively larger role in the spread of the infection, and be less susceptible to the beneficial effects of the lockdown.

The lag observed between lockdown and epidemic peak should be interpreted in relation to what is known about the natural history of the disease and the incubation period. The median/mean incubation period until first symptoms appears to be slightly more than 5 days

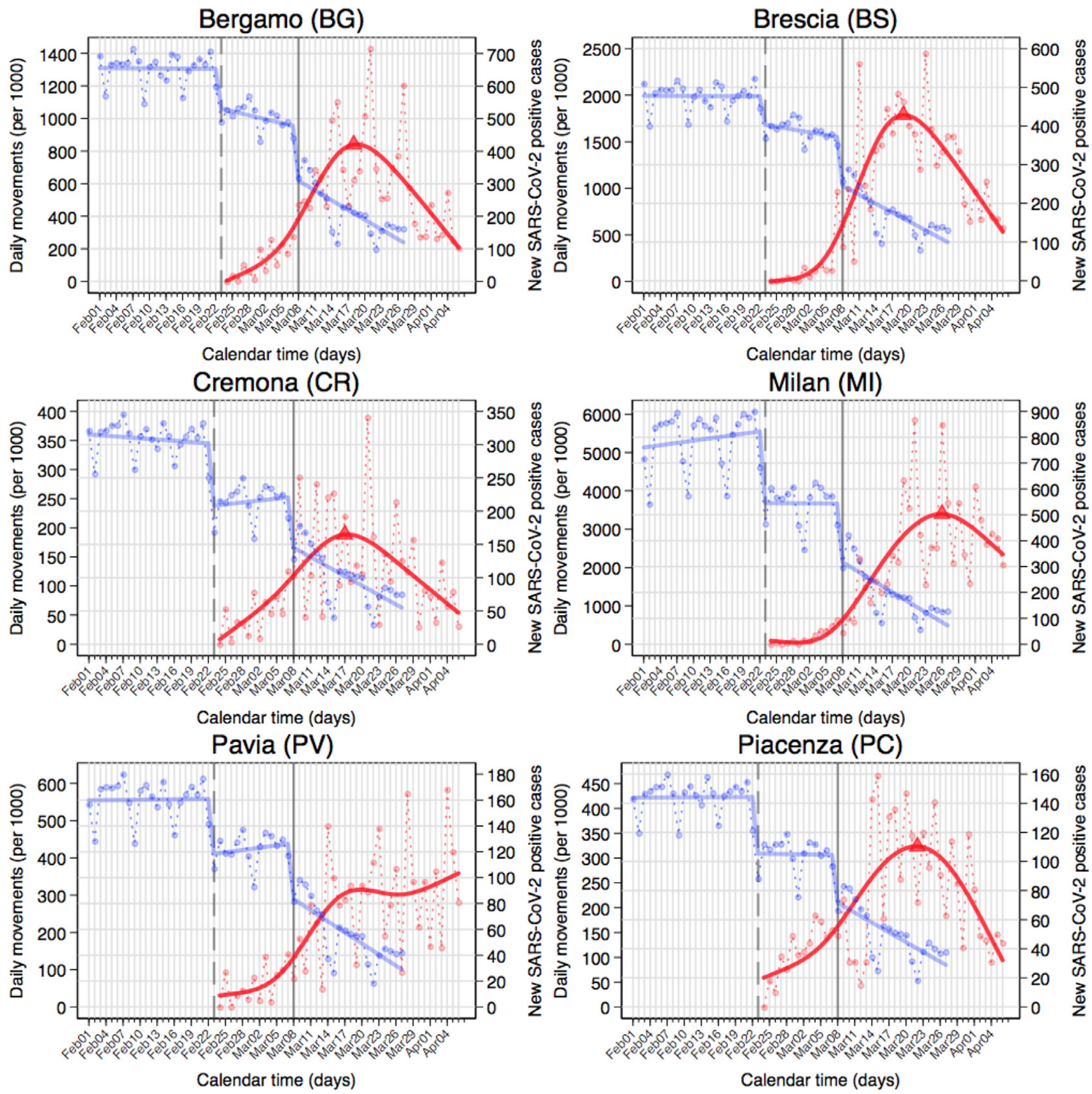

Fig. 4. Day-specific absolute numbers of people movements (blue dots) and SARS-CoV-2 positive cases (red dots) in the provinces bordering Lodi – i.e. Bergamo, Brescia, Cremona, Milan, Pavia (Lombardy region) and Piacenza (Emilia-Romagna region) during February 1, 2020-April 6, 2020. Blue line shows the predicted mean number of movements obtained with a mix of constant and linear splines of calendar days with two knots at the major events of interest in determining lockdowns of different intensity (February 23, 2020 – dashed gray line, and March 8, 2020 – solid gray line). Red line shows the predicted mean number of new COVID-19 cases obtained with restricted cubic splines of calendar days with 5 knots to identify the maximum predicted value (i.e. day of peak occurrence – red triangle). We fitted time-series data using Newey–West regression models.

[32,33]. There was an additional lag, estimated in Italy to be 5–6 days [34], until test results led to a diagnosis. These intervals imply that the effect of the tight lockdown on transmission of virus was considerably shorter than our computed estimates of time to peak, because the peak of the infection curve would have occurred around 10 days earlier than the peak in official diagnoses. Therefore, the tight lockdown presumably reduced transmission within 5 days or less in the most affected regions and nearly immediately in the most affected provinces. Potential environmental sources of exposures and transmission, such as viral spread through air pollutants (particulate matter) [35,36], or drinking water [37], were likely unimportant.

Other important public health measures also help to curb an outbreak such as this. These measures include swift identification and quarantine of new infections, tracking and quarantine of close contacts of infected cases, and use of personal protective equipment such as face masks [38–41]. All these measures were adopted in the study area from the beginning of the outbreak i.e. February 20, pursuant to national and regional regulations and general awareness of the population. While these steps presumably reduced transmission, it is impossible to say to what extent they contributed to the containment of the Italian outbreak.

An important limitation of these results is that patterns of the infection and disease spread may influence testing and consequently the number of positive tests. For example, the detection of case clusters in hospitals or nursing homes may affect the daily pattern of positive test results. These fluctuations should be expected to be more apparent in smaller communities. On the other hand, these admissions for COVID-19 were not independently validated and therefore their completeness is unknown. Changes in testing eligibility over time or space would have influenced our results about the time to peak period, but these changes were minor, as testing followed guidance from the National Institute of Health. Testing was restricted to symptomatic individuals who had suspected contact with an infected person. An exception was Veneto, which expanded testing also to some asymptomatic individuals since the beginning of the outbreak [42].

These findings should be considered specific for the SARS-CoV-2 outbreak in Italy and may not necessarily apply to outbreaks based on other viruses, having different transmission features, or occurring in other places characterized by a different social structure, family structure, culture, and work habits. Finally, we acknowledge that the time to peak endpoint we computed following the implementation of a

Table 1
Number of total SARS-CoV-2 positive cases and tests (available only by region) through April 6, 2020, peak of the curve after the tight lockdown date (March 8, 2020), percent reduction in people daily movements at peak date, and interval between lockdown and peak date (days).

	Population at Jan 1, 2019[a]	Total cases, March 8, 2020	Infection Prevalence March 8, 2020 (per 1000)	Total cases, April 6, 2020	Cumulative Incidence as of April 6, per 1000	COVID-19 tests implemented through April 6, 2020 (n/1000 residents)	Peak date (spline regression analysis)	Movement% reduction after lockdown	Interval between lockdown and outbreak peak (days)
Lombardy	**10,060,574**	**4189**	**0·42**	**51,534**	**5·12**	**154,989 (15·4)**	**March 22**	**58**	**14**
Bergamo (BG)	1,114,590	997	0·89	9815	8·81		March 18	57	10
Brescia (BS)	1,265,954	501	0·40	9477	7·49		March 19	53	11
Como (CO)	599,204	27	0·05	1473	2·46		March 29	55	21
Cremona (CR)	358,955	665	1·85	4260	11·87		March 17	58	9
Lecco (LC)	337,380	53	0·16	1712	5·07		March 23	49	15
Lodi (LO)	230,198	853	3·71	2278	9·90		March 7	55	−1 /13[b]
Mantua (MN)	412,292	56	0·14	2084	5·05		March 25	51	17
Milan (MI)	3,250,315	406	0·12	11,538	3·55		March 26	63	18
Monza/Brianza (MB)	873,935	59	0·07	3157	3·61		March 27	58	19
Pavia (PV)	545,888	243	0·45	2700	4·95		NA	53	NA
Sondrio (SO)	181,095	6	0·03	614	3·39		March 27	49	19
Varese (VA)	890,768	32	0·04	1293	1·45		NA	58	NA
Veneto	**4,905,854**	**670**	**0·14**	**11,588**	**2·36**	**146,288 (29·8)**	**March 26**	**49**	**18**
Belluno (BL)	202,950	23	0·11	558	2·75		March 26	45	18
Padua (PD)	937,908	255	0·27	2863	3·05		March 27	54	19
Rovigo (RO)	234,937	5	0·02	203	0·86		NA	46	NA
Treviso(TV)	887,806	126	0·14	1726	1·94		March 23	47	15
Venice (VE)	853,338	126	0·15	1487	1·74		March 23	55	15
Verona (VR)	926,497	63	0·07	2755	2·97		March 27	47	19
Vicenza (VI)	862,418	50	0·06	1704	1·98		March 30	45	22
Emilia-Romagna	**4,459,477**	**1180**	**0·26**	**17,556**	**3·94**	**72,163 (16·2)**	**March 26**	**52**	**18**
Bologna (BO)	1,014,619	62	0·06	2617	2·58		March 28	54	20
Ferrara (FE)	345,691	6	0·02	510	1·48		NA	49	NA
Forlì-Cesena (FC)	394,627	15	0·04	1015	2·57		April 2	46	25
Modena (MO)	705,393	97	0·14	2691	3·81		March 26	53	18
Parma (PR)	451,631	276	0·61	2317	5·13		March 24	58	16
Piacenza (PC)	287,152	528	1·84	2936	10·22		March 22	55	14
Ravenna (RA)	389,456	13	0·03	510	1·31		March 25	44	17
Reggio Emilia (RE)	531,891	70	0·13	3167	5·95		March 27	54	19
Rimini (RN)	339,017	113	0·33	1575	4·65		March 20	54	12
Italy	**60,359,546**	**7375**	**0·12**	**132,547**	**2·20**	**721,732 (12·0)**			

NA: not available, cases still increasing at April 6;.
[a] Most recent data available from Italian National Institute of Statistic [43] .
[b] Lodi province, the one from which the Italian outbreak started, had already experienced its tight lockdown in a part of its territory (‘red zone’) on February 23, 2020 from which the figure of 13 is computed, while the remainder of the territory implemented the lockdown on March 8, 2020.

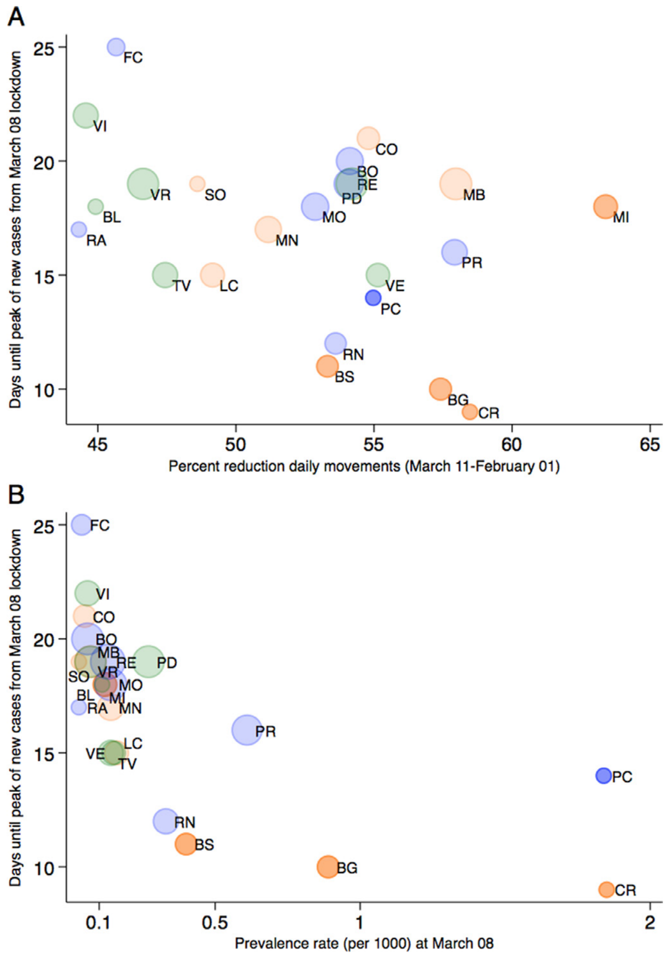

Fig. 5. Days until the peak of the SARS-CoV-2 positive cases and percent reduction of people movements for provinces within the three investigated regions (A); days until the peak of SARS-CoV-2 positive cases and SARS-CoV-2 infection prevalence on March 8, 2020 in the study provinces (B). Area of circles reflects total number of cases on April 6, 2020. Provinces without a peak within the study period (Pavia, Varese, Rovigo and Ferrara) and the province with a mixed lockdown (Lodi) were not included in the figure.

tight lockdown is not the only endpoint suitable to assess lockdown benefits. Another endpoint of interest would be the total number of infections occurring in a specific area. It is conceivable that a community might have a longer time to peak with fewer infections. Unfortunately, we lacked municipality-specific incidence data to assess this possibility in the only two provinces where there was differential timing of the lockdown, in Lodi province (for the Codogno hot spot) and Padua province (for the hot spot within the tiny Vò municipality).

In conclusion, our study provides evidence that the intended effects of the mobility restrictions adopted in Italy to counteract spread of SARS-CoV-2 infection were generally seen within 14 to 18 days after the implementation of tight lockdown measures. In the areas having the highest prevalence of the infection, the effect was seen as early as 9 days, implying little lag between imposing decreased mobility and slowing person-to-person transmission.

Declaration of Competing Interest

The authors have no conflict of interests to disclose.

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None

Author contributions

MV and TF designed the original study, and with KJR analyzed and interpreted the data, and wrote the manuscript. NO designed and carried out data analysis with TF. FF, AG and GM downloaded and processed cellphone movements. All authors read and approved the final manuscript.

Supplementary materials

Supplementary material associated with this article can be found in the online version at doi:10.1016/j.eclinm.2020.100457.

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