CORONAVIRUS

Assessing the impact of coordinated COVID-19 exit strategies across Europe

N. W. Ruktanonchai[1,2]*†, J. R. Floyd[1]*†, S. Lai[1]*†, C. W. Ruktanonchai[1]†, A. Sadilek[3], P. Rente-Lourenco[4], X. Ben[3], A. Carioli[1], J. Gwinn[5], J. E. Steele[1], O. Prosper[6], A. Schneider[3], A. Oplinger[3], P. Eastham[3], A. J. Tatem[1]

As rates of new coronavirus disease 2019 (COVID-19) cases decline across Europe owing to nonpharmaceutical interventions such as social distancing policies and lockdown measures, countries require guidance on how to ease restrictions while minimizing the risk of resurgent outbreaks. We use mobility and case data to quantify how coordinated exit strategies could delay continental resurgence and limit community transmission of COVID-19. We find that a resurgent continental epidemic could occur as many as 5 weeks earlier when well-connected countries with stringent existing interventions end their interventions prematurely. Further, we find that appropriate coordination can greatly improve the likelihood of eliminating community transmission throughout Europe. In particular, synchronizing intermittent lockdowns across Europe means that half as many lockdown periods would be required to end continent-wide community transmission.

The ongoing coronavirus disease 2019 (COVID-19) pandemic rapidly spread across Europe in February and March 2020, making it the largest cluster of cases worldwide for much of March and April 2020 (*1*). In response, most of Europe implemented strict lockdown measures to control disease spread, which have been shown to be effective at reducing transmission (*2*–*4*). As rates of new cases decline, countries are now implementing various exit strategies to relax restrictions (*5*). Long-term success of any potential exit strategy hinges on what happens regionally, as international importation could overwhelm efforts to prevent resurgence through testing and contact tracing (*6*, *7*). To account for potential international importation the European Commission recommended that governments provide advance warning of plans to relax nonpharmaceutical interventions (NPIs) (*8*) and has specifically focused on coordinated easing of travel restrictions (*9*). To better evaluate the importance and nature of an internationally coordinated exit strategy, governments require an evidence base for understanding importation and the consequences of easing interventions in an uncoordinated way.

Data from mobile phones can help address this need by informing connectivity patterns, contact rates, and the effect of various NPIs on mobility. In other settings, mobile phone data have been instrumental for understanding where infection occurs for various diseases (*10*) such as malaria (*11*, *12*), predicting disease spread (*13*), and quantifying population mobility during and after catastrophic events (*14*). More recently, for the COVID-19 pandemic, these data have been valuable in assessing NPI effectiveness (*3*, *4*) and remain a leading way to understand whether populations are adhering to social distancing policies (*15*–*18*). These data also link well with theoretical models that provide a basis for understanding how heterogeneous mobility and exposure will affect disease invasion (*19*) in spatially structured populations (*20*).

Here, we provide an evidence base for coordinated exit strategies across Europe using mobile phone data and a metapopulation model of COVID-19 transmission (*21*). Specifically, we quantify the progression of a second continent-wide epidemic if countries act in a coordinated or uncoordinated manner. We also quantify how coordination could influence regionally interrupted transmission of COVID-19, testing the importance of synchronized NPIs if countries phase them to limit economic impact. We accomplished this by (i) estimating pre-COVID-19 mobility using a newly compiled anonymized and aggregated call data record dataset from Vodafone and an anonymized and aggregated continental NUTS3 (Nomenclature of Territorial Units for Statistics) mobility dataset from Google (table S1), (ii) measuring mobility reductions due to NPIs using a separate COVID-19 Google dataset, and (iii) propagating these reductions in an epidemiological model (see fig. S1 for data flow). All analyses were undertaken at the NUTS3 administrative unit level, which are administrative boundaries regulated by the European Union (EU) for use within EU member states (*22*), with spatial extents defined by population thresholds ranging from 150,000 to 800,000 residents.

[1]WorldPop, School of Geography and Environmental Science, University of Southampton, Southampton, UK. [2]Population Health Sciences, Virginia Tech, Blacksburg, VA, USA. [3]Google, Mountain View, CA, USA. [4]Vodafone Group, London, UK. [5]College of Public Health, University of Kentucky, Lexington, KY, USA. [6]Department of Mathematics, University of Tennessee, Knoxville, TN, USA.
***Corresponding author. Email: nrukt00@gmail.com (N.W.R.); jrf1g15@soton.ac.uk (J.R.F.); shengjie.lai@soton.ac.uk (S.L.)**
†These authors contributed equally to this work.

Baseline mobility and COVID-19–related reductions

First, we predicted the baseline probability of moving between NUTS3 regions across Europe using the Vodafone data in Spain and Italy and the continental Google NUTS3 dataset (Fig. 1). We then analyzed the Google COVID-19 dataset to quantify reductions in mobility and contact rates from January 2020 through the end of March 2020 in response to the COVID-19 pandemic (Fig. 2). In our simulations, we used observed reductions in mobility in each NUTS3 area to proportionally reduce outgoing flows, incoming flows, and local contact rates for that area.

Using these baseline mobility patterns and reductions in mobility, we simulated the spread of COVID-19 over 6 months, starting on 4 April 2020 while making various assumptions about where and when NPIs would be relaxed or reinstated. Across all simulations, we started transmission on 20 March 2020 because this predates large reductions in mobility (Fig. 2B), allowing the disease to spread initially in a data-driven way that can help account for spatial biases in reporting and testing. We parameterized the initial numbers of people infected using a repository maintained by the Johns Hopkins University Center for Systems Science and Engineering (CSSE) (*23*). Because the case data from this repository were at the country level, we distributed cases across NUTS3 area proportionally on the basis of population size (fig. S10).

To simulate different exit strategies and the overall impact of the different NPIs enacted, we reduced mobility the week after 28 March (29 March to 4 April) on the basis of the observed change between 15 to 21 March and 22 to 28 March to account for changes caused by further uptake of existing NPIs (Fig. 2). On average, we predicted an overall mean reduction in mobility of 65% compared with 28 January to 18 February through this process, agreeing with recent studies on contact rate reductions in the United Kingdom (*24*), which observed a 73% reduction in daily contacts. When simulating active lockdowns on dates after 4 April, we used the predicted mobility reduction for each NUTS3 area from 29 March to 4 April. When we simulated countries lifting their NPIs entirely, we used the relative mobility patterns observed from 1 to 7 March.

Modeling the effect of lifting interventions early

First, we compared secondary epidemic timing when all countries coordinated their exit strategies with simulations where one country ended its interventions early. We iteratively tested the impact of each country in Europe easing lockdowns starting 15 April, while all other countries extended their NPIs for 4, 8, or 12 weeks, depending on the simulation run. For the country that lifted its NPIs early, we assumed that people in each NUTS3 area

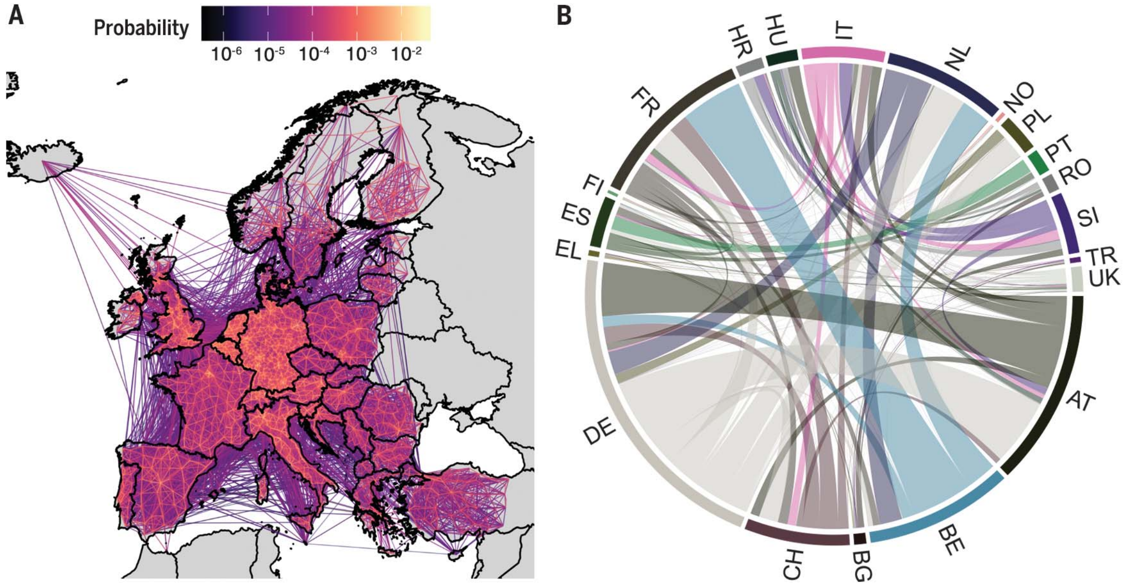

Fig. 1. Predicted baseline mobility patterns for 28 January to 18 February 2020. (**A**) Probability of moving from one NUTS3 administrative unit to another after 8 hours. (**B**) Individual probability of moving between the top 20 European countries with the greatest outward mobility. For example, an individual in Germany (DE) is roughly twice as likely to travel internationally than an individual in Austria (AT). Colors shown in (B) correspond to the source country, and country codes are from Eurostat (*34*). EL, Greece; ES, Spain; FI, Finland; FR, France; HR, Croatia; HU, Hungary; IT, Italy; NL, Netherlands; NO, Norway; PL, Poland; PT, Portugal; RO, Romania; SI, Slovenia; TR, Turkey; UK, United Kingdom; BE, Belgium; BG, Bulgaria; CH, Switzerland.

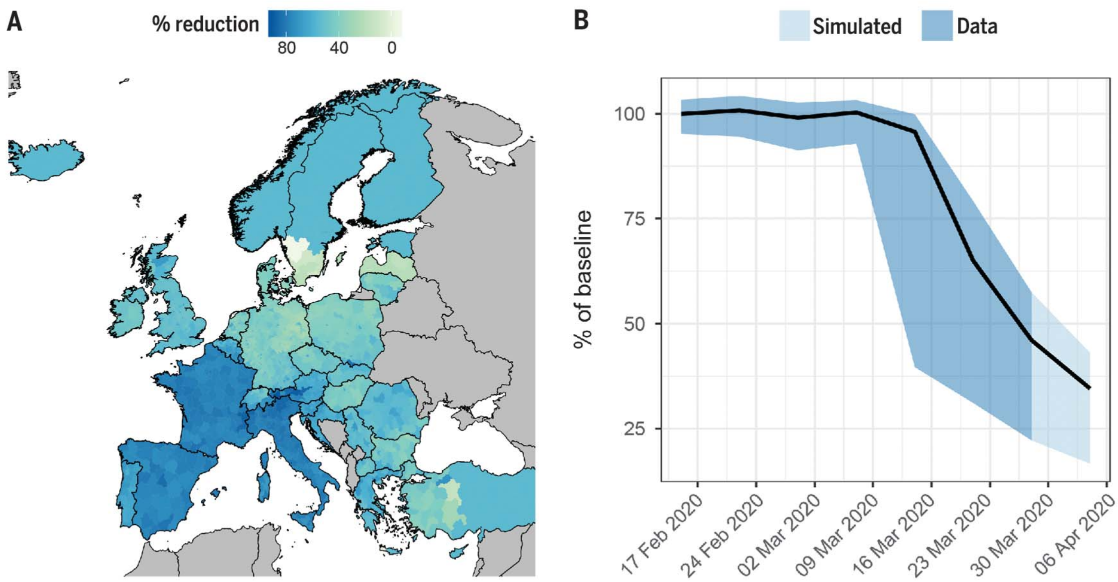

Fig. 2. Reduction in mobility observed in NUTS3 areas from 11 February to 6 April 2020. (**A**) Reduction in mobility observed in each NUTS3 administrative unit across Europe for the week of 21 to 28 March 2020 compared with average movement observed from January to February 2020. Movement data were not available for countries in gray. (**B**) Weekly average change in mobility across all NUTS3 areas. Dark blue shows reductions observed in the Google COVID-19 dataset, and light blue shows extrapolation of reductions by 1 week. Black line shows mean change compared with baseline. When implementing NPIs in various NUTS3 areas, we used the movement reduction estimates for the end of this period, 6 April 2020.

would voluntarily reduce their average contact rate by 20% compared to the January and February baseline, or slightly less than the reduction in mobility observed on 23 March, because countries that have lifted NPIs have observed sustained limited mobility reductions beyond the relaxing of various restrictions (*16*).

If a country lifted its NPIs early, we found that a second epidemic could occur much earlier (Fig. 3B). Figure 3A illustrates the earlier timing (in days) to reach 25% of people across Europe having had COVID-19 (infected + recovered + exposed; see fig. S13 for plot showing this explicitly). This measure captures when uncontrolled widespread transmission occurred, while accounting for multiple peaks and varying peak heights in Fig. 3B. The time to 25% infection was particularly sensitive to well-connected countries that implemented strong NPIs, such as France and Italy (Fig. 3A). France lifting its NPIs early led to the earliest second epidemic, 35 days earlier than if all countries lifted their NPIs simultaneously (interquartile range: 32.3 to 36.8 days). Despite having experienced relatively low reductions in mobility through 28 March, Germany remains important to continental resurgence, because of its high connectivity with neighboring countries (Fig. 1B). When exploring the epidemic curves over time for different countries lifting their NPIs early, we found that different types of mobility initiated continental epidemics. Whereas

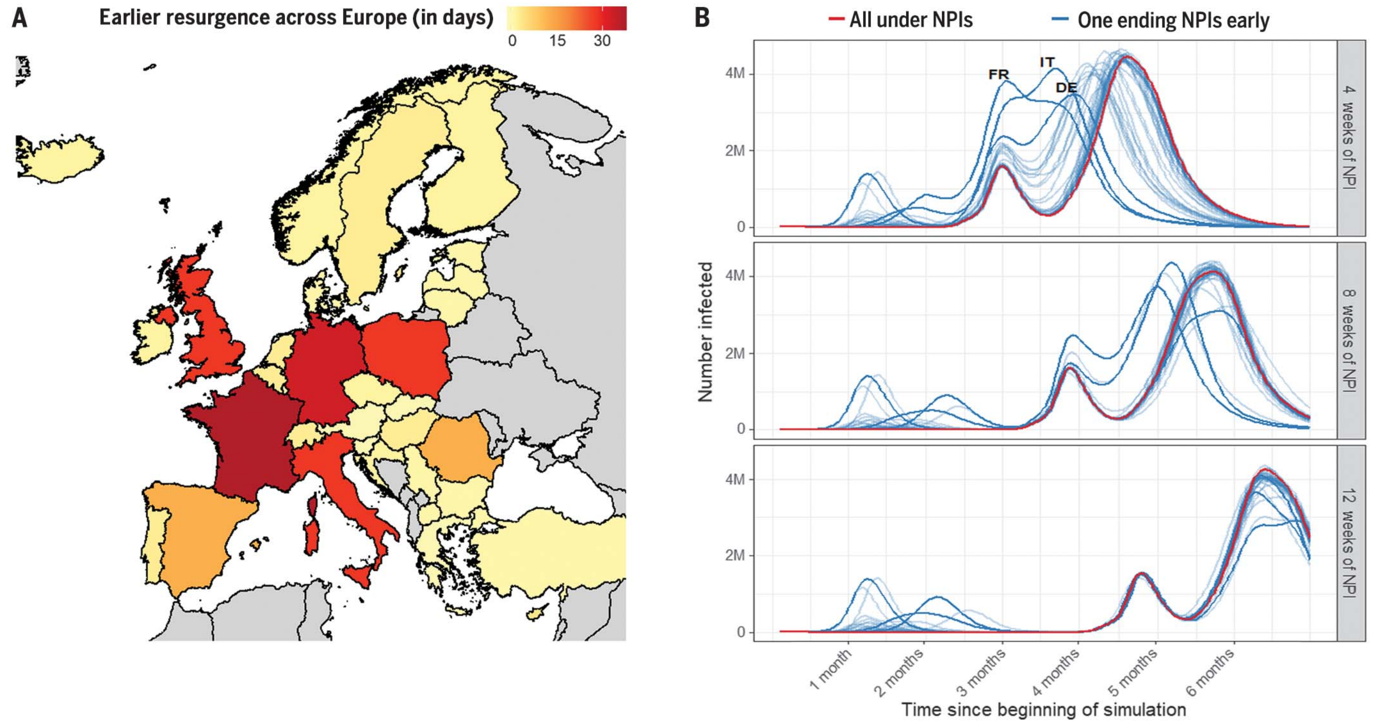

Fig. 3. Epidemic spread if all countries but one maintain existing NPIs. (**A** and **B**) When lifting NPIs early, countries reverted to baseline mobility on 15 April. (B) Epidemic curves, with NPIs implemented for 4, 8, or 12 weeks. Curves indicate the number of active cases (M, million) at any given time rather than numbers of new cases per day. Red lines indicate epidemic curves where all countries maintain NPIs for the specified number of weeks. Blue lines indicate epidemic curves if one country ends intervention policies early (each line represents one randomly chosen country that ends its policies early); France, Germany, and Italy are highlighted. (A) For the 4-week NPI scenario, the number of days earlier that an uncontrolled second epidemic occurs continent-wide if each country ends NPIs early, measured as the time to 25% of the population of Europe having had COVID-19. Movement data were not available for countries in gray.

France lifting its NPIs early led to resurgence in major population centers across the continent, Germany lifting its NPIs early led to resurgence in neighboring countries first (fig. S15). Further, certain areas keeping the reproductive number (R) slightly above 1 under NPIs also led to an initial peak in some simulations and maintained the threat of resurgence even after 12 weeks of continent-wide NPIs (Fig. 3B) (for more detail, see the supplementary materials section "Exploring spatiotemporal dynamics of spread"). Along these lines, our simulations included consistent reproductive numbers above 1 in central Turkey, which drastically affected continental spread. In simulations where smaller or less-connected countries lifted their NPIs early, we found that resurgence was largely driven by importation from central Turkey and exhibited epidemic curves very similar to the scenario in which all countries maintained NPIs (Fig. 3B, red line).

Modeling the effect of synchronized intermittent NPIs

We also tested how cycling NPIs—alternating between being under interventions for several weeks and under no interventions for the same number of weeks for several cycles—in a synchronized or unsynchronized manner affected the continent-wide epidemic. Synchronized NPIs meant all countries implemented lockdowns at the same time, while unsynchronized NPIs meant half of all countries (randomly chosen for each simulation run) were under lockdown at any time. Cycling NPIs reflect the intermittent lockdowns that could occur if countries reinstate interventions after surpassing threshold numbers of new cases (*25*, *26*). Therefore, this test helps predict what may happen if countries do not coordinate the easing and reinstating of NPIs on the basis of regional rates of new cases. We ran various simulations where lockdown and nonlockdown periods were 3 or 4 weeks long over the course of two, three, or four cycles.

Across 1200 simulations, we found that synchronized NPIs were always more likely to end community transmission over 6 months and generally lowered transmission more than unsynchronized NPIs did (Fig. 4). In the most notable example, synchronizing four cycles of 3-week-long lockdowns led to local elimination of COVID-19 cases in 90% of simulations, whereas unsynchronized cycles only led to elimination 5% of the time (Fig. 4, bottom left). Two synchronized cycles of 4-week NPIs were also sufficient to end community transmission, whereas four unsynchronized cycles of 4-week NPIs were necessary to end community transmission (Fig. 4, right). The only simulations in which unsynchronized NPIs resulted in fewer cases than synchronized NPIs at the end of simulation was with two cycles of 3-week-long NPIs (Fig. 4, top left), which occurred because enough people were infected under unsynchronized NPIs that herd immunity reduced transmission. Because these simulations do not include any importation from other regions of the globe, simulations reflecting zero local cases after a certain number of intermittent lockdowns are very unlikely to be realized. Instead, this result reflects the likelihood of reducing local cases to a low enough level that strong test-and-trace systems can catch importations before large outbreaks occur.

Intergovernmental organizations such as the World Health Organization have stressed the importance of international solidarity in terms of sharing resources and expertise in combating COVID-19 (*1*). Our results reiterate this, as one country ending NPIs before others could mean disease resurgence across Europe as many as 5 weeks earlier, reducing the time

available to expand test-and-treat and to develop new therapeutics or vaccines (Fig. 3). Heterogeneities in mobility reduction (Fig. 2), baseline mobility patterns (Fig. 1), and population sizes mean that certain countries—for example, France, Germany, Italy, and Poland—play a particularly important role in continental resurgence (Fig. 3).

These key countries varied in how local cases led to continental resurgence, implying the need for different key interventions for each. For example, while spread out of Germany led to epidemics in neighboring countries initially, spread out of France led to epidemics in population centers across the continent (fig. S12). Further, we found that small pockets of community transmission under NPIs could assure a second continent-wide epidemic wave. In our study, a small pocket of sustained community transmission occurred even under NPIs, because of central Turkey experiencing limited mobility reductions (Fig. 2) and exhibiting a high starting reproductive number (fig. S2) that kept local R slightly above 1 when under NPIs. Although the actual mobility reduction in central Turkey is uncertain and has likely changed since late March 2020, this highlights the importance of countries ensuring that R stays below 1 during lockdown periods and the importance of effective screening of international travelers from areas with sustained transmission well into the future.

We also found that the nature of coordination was key to reducing resurgence risk. When cycling NPIs, synchronized interventions across all countries meant that cases could be driven down more quickly (Fig. 4). Fewer cases at the end of the synchronized lockdowns led to much higher likelihoods of reaching zero cases locally, owing to a higher chance of stochastic recovery processes leading to interrupted transmission. In real terms, the synchronized scenario approximates what could happen if countries set case thresholds for lifting NPIs regionally, whereas the unsynchronized scenario simulates what could happen if countries only consider case numbers within their own boundaries.

Our study has several limitations that influence the direct applicability of the case number predictions across Europe. For example, we used observed mobility reductions as a proxy for reductions in contact rate, which may not reflect reality, although the contact rate reduction estimates from this process accord with those observed in other studies (*24*). Further, COVID-19 is known to exhibit age-dependent severity, and contact rates are strongly age-dependent (*27*, *28*), which could introduce heterogeneities that we did not incorporate into our simulations. However, because we ran our simulations over different values of R and varying the serial interval, we believe that our results should be robust to these limitations. In these sensitivity analyses,

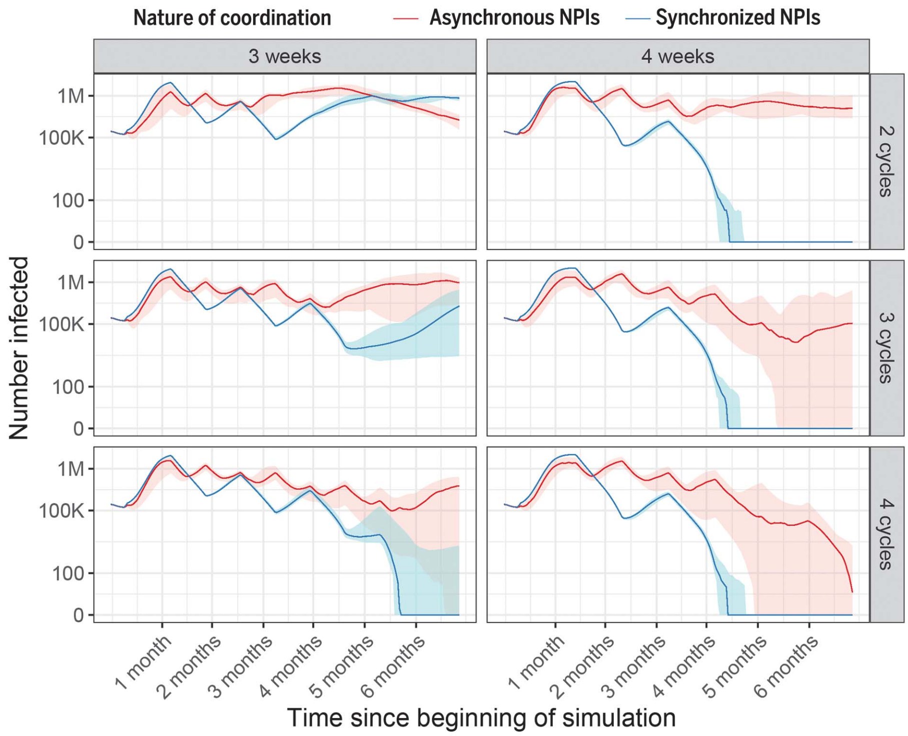

Fig. 4. Cases over time, when NPIs are synchronized or unsynchronized across all European countries. Rows vary the number of on-off cycles that occur, and columns indicate the number of on-off cycles implemented. For example, 4 weeks with two cycles (top right) indicates that we simulated two cycles of 4 weeks on lockdown, 4 weeks off lockdown for each country. Red: Cases when European countries do not synchronize NPI timing. Blue: Cases when European countries are all synchronized in NPI timing. Shaded areas indicate intervals within which 95% of the 200 simulations fell. K, thousand.

we found that the existence of key countries and the importance of coordinated NPIs were robust to these changes (see supplementary materials), although varying the serial interval could extend or shrink the second epidemic timings and epidemic peaks observed in Fig. 3. Additionally, we reduced mobility for each NUTS3 area uniformly, but long-distance movement reduced much more than short-distance movement owing to country-level travel restrictions and other NPIs (fig. S8). This likely provides a continental protective effect against early resurgence compared with our results, particularly if quarantining measures are put in place for long-distance travelers.

Our mobility estimates may also be biased owing to the populations included in the Google and Vodafone data. Google's consumer location history feature is only available for smartphone users, is turned off by default, and is viewed through the lens of differential privacy algorithms designed to protect user privacy and obscure fine detail. Vodafone's anonymized and aggregated data were based on network data from customers who had full control over their privacy settings, potentially introducing biases as well. This work takes a step toward using multiple datasets to capture population-level patterns that go beyond any one service or system. Further, because both the Google and Vodafone data are aggregate datasets, we could not account for individual-level correlation in mobility patterns in our model (i.e., individuals who travel elsewhere but return home shortly thereafter). This likely means our model will overestimate spread and resurgence in general, as infectious people will end up less likely to return home.

Coordination will be key to an effective, equitable response to COVID-19. This means not just sharing resources but also ensuring that exit strategies account for neighboring countries and regions. Although coordinating exit strategies across an entire continent may prove politically difficult, the presence of key countries and community structure offer possible coordination groups that do not require engagement from all countries. We have explored some of these coordination groups in a community detection analysis in the supplementary materials (fig. S16). Further, coordinated exit strategies that account for real-time case data will likely improve outcomes compared with our predictions, as we simulated intermittent NPIs that were lifted regardless of actual transmission context. A multifaceted, reactive approach to lifting NPIs will be necessary to minimize resurgence risk. This means

that, beyond international cooperation, robust test-and-treat (*29*) and household quarantine (*30*) measures should be in place. Future work will further inform the role that mobility, NPIs, and international coordination can play in slowing COVID-19 resurgence, building on existing work (*31*) examining invasion, reinvasion, and disease extinction (*32*) in spatially structured populations. Critically, even if community transmission is reduced to very low levels within Europe (for example, through the intermittent NPIs shown in Fig. 4), importation from other regions of the globe mean coordination will be necessary to prevent continent-wide epidemics well into the future.

The implications of our study extend beyond Europe and COVID-19, broadly demonstrating the importance of communities coordinating the easing of various NPIs for any potential pandemic. In the United States, NPIs have been generally implemented at the state level, and because states will be strongly interconnected, our results emphasize national coordination of pandemic preparedness efforts moving forward. Elsewhere, relatively porous national borders between many lower and middle income countries mean that without coordination, these countries may have to deal with considerable international importation after controlling local transmission (*33*). COVID-19 transmission and the transmission of any infectious disease will ignore national and provincial borders; preventing resurgence and spread will mean ensuring that pockets of transmission do not persist in areas with limited interventions at the expense of later epidemics in others.

REFERENCES AND NOTES

1. C. Sohrabi *et al*., *Int. J. Surg.* **76**, 71–76 (2020).
2. K. Prem *et al*., *Lancet Public Health* **5**, e261–e270 (2020).
3. S. Lai *et al*., *Nature* (2020).
4. M. U. G. Kraemer *et al*., *Science* **368**, 493–497 (2020).
5. T. Colbourn, *Lancet Public Health* **5**, e236–e237 (2020).
6. S. Lai *et al*., medRxiv 2020.02.04.20020479 [Preprint]. 9 March 2020. https://doi.org/10.1101/2020.02.04.20020479.
7. M. Chinazzi *et al*., *Science* **368**, 395–400 (2020).
8. M. McKee, *BMJ* **369**, m1556 (2020).
9. U. von der Leyen, C. Michel, "Joint European Roadmap towards lifting COVID-19 containment measures" (Communication, European Commission, Brussels, Belgium, 2020); https://ec.europa.eu/info/sites/info/files/communication_-_a_european_roadmap_to_lifting_coronavirus_containment_measures_0.pdf.
10. A. Wesolowski, C. O. Buckee, K. Engø-Monsen, C. J. E. Metcalf, *J. Infect. Dis.* **214** (suppl. 4), S414–S420 (2016).
11. N. W. Ruktanonchai *et al*., *PLOS Comput. Biol.* **12**, e1004846 (2016).
12. D. K. Pindolia *et al*., *Malar. J.* **11**, 205 (2012).
13. A. J. Tatem, D. L. Smith, *Proc. Natl. Acad. Sci. U.S.A.* **107**, 12222–12227 (2010).
14. R. Wilson *et al*., *PLOS Curr.* **8**, 10.1371/currents.dis.d073fbece328e4c39087bc086d694b5c (2016).
15. L. Queiroz *et al*., "Large-scale assessment of human mobility during COVID-19 outbreak," Open Science Framework Preprints (2020); https://doi.org/10.31219/osf.io/nqxrd.
16. Google LLC, "COVID-19 Community Mobility Reports"; www.google.com/covid19/mobility.
17. N. M. Kavanagh, R. R. Goel, A. S. Venkataramani, medRxiv 2020.04.06.20055632 [Preprint]. 11 April 2020. https://doi.org/10.1101/2020.04.06.20055632.
18. A. L. Wright, K. Sonin, J. Driscoll, J. Wilson, "Poverty and Economic Dislocation Reduce Compliance with COVID-19 Shelter-in-Place Protocols" (University of Chicago, Becker Friedman Institute for Economics Working Paper No. 2020-40, 2020); http://dx.doi.org/10.2139/ssrn.3573637.
19. P. C. Cross, J. O. Lloyd-Smith, P. L. F. Johnson, W. M. Getz, *Ecol. Lett.* **8**, 587–595 (2005).
20. V. Colizza, A. Vespignani, *J. Theor. Biol.* **251**, 450–467 (2008).
21. N. Ruktanonchai, wpgp/BEARmod: EU model code, Zenodo (2020); https://doi.org/10.5281/zenodo.3932111.
22. R. Smith, in *Core EU Legislation* (Macmillan Education UK, 2015), pp. 183–186.
23. Johns Hopkins University Center for Systems Science and Engineering, 2019 Novel Coronavirus COVID-19 (2019-nCoV) Data Repository by Johns Hopkins CSSE (2020); https://github.com/CSSEGISandData/COVID-19.
24. C. I. Jarvis *et al*., "Impact of physical distance measures on transmission in the UK," Centre for Mathematical Modelling of Infectious Diseases Repository (2020); https://cmmid.github.io/topics/covid19/comix-impact-of-physical-distance-measures-on-transmission-in-the-UK.html.
25. L. Tarrataca, C. M. Dias, D. B. Haddad, E. F. Arruda, arXiv:2004.06916 [q-bio.PE] (15 April 2020).
26. M. Gollwitzer, C. Platzer, C. Zwarg, A. S.Göritz, PsyArXiv (14 April 2020); https://doi.org/10.31234/osf.io/3a85z.
27. G. Onder, G. Rezza, S. Brusaferro, *JAMA* **323**, 1775–1776 (2020).
28. F. Zhou *et al*., *Lancet* **395**, 1054–1062 (2020).
29. Royal Society DELVE Initiative, "Test, Trace, Isolate" (27 May 2020); https://rs-delve.github.io/reports/2020/05/27/test-trace-isolate.html.
30. A. Aleta *et al*., *Nat. Hum. Behav.* 10.1038/s41562-020-0931-9 (2020).
31. C. Poletto, M. Tizzoni, V. Colizza, *J. Theor. Biol.* **338**, 41–58 (2013).
32. G.-Q. Sun, Q.-X. Liu, Z. Jin, A. Chakraborty, B.-L. Li, *J. Theor. Biol.* **264**, 95–103 (2010).
33. K. Wangdi, M. L. Gatton, G. C. Kelly, A. C. A. Clements, in *Advances in Parasitology, Volume 89*, D. Rollinson, J. R. Stothard, Eds. (Academic Press, 2015), pp. 79–107.
34. European Commission, Eurostat, Statistics Explained, Glossary: Country codes; https://ec.europa.eu/eurostat/statistics-explained/index.php/Glossary:Country_codes.
35. N. Ruktanonchai, Synthetic data based on IPUMS microcensus data for mobility between NUTS3 areas of Europe, Version 1, Zenodo (2020); https://doi.org/10.5281/zenodo.3931987.

ACKNOWLEDGMENTS

We acknowledge E. Fawkes, J. Park, S. Woods, and the Data Gudes Group for insightful discussions on heterogeneously applied interventions. **Funding:** This study was supported by grants from the Vodafone Institute, the Bill & Melinda Gates Foundation (OPP1134076), and the European Union Horizon 2020 (MOOD 874850). A.J.T. is supported by funding from the Bill & Melinda Gates Foundation (INV-002697, OPP1106427, OPP1032350, OPP1134076, and OPP1094793), the Clinton Health Access Initiative, the U.K. Department for International Development (DFID), and the Wellcome Trust (106866/Z/15/Z and 204613/Z/16/Z). N.W.R. is supported by funding from the Bill & Melinda Gates Foundation (OPP1170969 and OPP1209812). O.P. is supported by the National Science Foundation (1816075). **Author contributions:** N.W.R., J.R.F., S.L., P.R.-L., and A.J.T. designed the research. N.W.R., J.R.F., S.L., C.W.R., P.R.-L., O.P., and A.C. built the model and ran simulations. N.W.R., J.R.F., S.L., C.W.R., A.Sa., P.R.-L., and A.C. carried out analyses. A.Sa., P.R.-L., X.B., A.C., J.E.S., A.Sc., A.O., and P.E. provided technical support. A.Sa., P.R.-L., X.B., A.Sc., A.O., and P.E. helped with data curation. A.Sa. and X.B. created the Google COVID-19 aggregated dataset. N.W.R., J.R.F., S.L., C.W.R., A.C., A.Sa., P.R.-L., J.G., O.P., and A.J.T. wrote and edited the manuscript. **Competing interests:** The authors declare no competing interests. **Data and materials availability:** Code for the model simulations is available at the following GitHub repository: https://github.com/wpgp/BEARmod. The specific version of the model used in this study, with simulation code, *R* estimates shown in fig. S2, and initial numbers infected shown in fig. S10 can be found in Zenodo (*21*). The population movement data obtained from Google and Vodafone for this study are not publicly available owing to stringent licensing agreements. The Google COVID-19 Aggregated Mobility Research Dataset used for this study is available with permission from Google LLC (contact: A.Sa., sadilekadam@google.com). The Vodafone datasets can also be accessed with the permission of Vodafone through correspondence with the corresponding authors. A synthetic NUTS3-level dataset of mobility across Europe is also available in Zenodo (*35*).

SUPPLEMENTARY MATERIALS

science.sciencemag.org/content/369/6510/1465/suppl/DC1
Materials and Methods
Supplementary Text
Figs. S1 to S16
Tables S1 and S2
References (*36*–*46*)
MDAR Reproducibility Checklist

View/request a protocol for this paper from *Bio-protocol*.

1 May 2020; accepted 13 July 2020
Published online 17 July 2020
10.1126/science.abc5096

Science

Assessing the impact of coordinated COVID-19 exit strategies across Europe

N. W. RuktanonchaiJ. R. FloydS. LaiC. W. RuktanonchaiA. SadilekP. Rente-LourencoX. BenA. CarioliJ. GwinnJ. E. SteeleO. ProsperA. SchneiderA. OplingerP. EasthamA. J. Tatem

Science, 369 (6510), • DOI: 10.1126/science.abc5096

Better relaxing lockdown together
Even during a pandemic, all countries—even islands—are dependent in one way or another on their neighbors. Without coordinated relaxation of nonpharmaceutical interventions (NPIs) among the most closely connected countries, it is difficult to envisage maintaining control of infectious viruses such as severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2). Ruktanonchai *et al.* used mobility data from smartphones to estimate movements between administrative units across Europe before and after the implementation of NPIs for coronavirus disease 2019 (COVID-19). Modeling disease dynamics under alternative scenarios of countries releasing NPIs, in particular stay-at-home orders, showed that if countries do not coordinate their NPIs when they relax lockdown, resurgence of disease occurs sooner. Coordination of on-off NPIs would significantly increase their effectiveness at reducing transmission across Europe.

Science, this issue p. 1465

Science (ISSN 1095-9203) is published by the American Association for the Advancement of Science. 1200 New York Avenue NW, Washington, DC 20005. The title *Science* is a registered trademark of AAAS.