SI Appendix

The effect of public health measures on the 1918 influenza pandemic in US cities.

1. Data on interventions adopted by different US cities

We review the sources used for our dating of interventions in different US cities below. The sources used are primarily secondary, ranging from contemporary newspapers to a disparate collection of web pages. A more comprehensive and systematic review of primary material for 45 US cities is currently being conducted by Dr Howard Markel and colleagues at the University of Michigan, in collaboration with the Centers of Disease Control, Atlanta. The results of their study will be invaluable to extensions of the work presented here.

The dates highlighted in color in the text below represent those dates used for the start and end of intervention periods in the model (see Table 1). Highlighting in red, blue and green represents intervention 1, 2 and 3 respectively.

Table S1: Starting and stopping times of interventions in the 16 cities as used in the model

	Start int. 1	Stop int. 1	Start int. 2	Stop int. 2	Start int. 3	Stop int. 3
Atlanta	7-Oct-18	5-Nov-18				
Baltimore	7-Oct-18	3-Nov-18				
Chicago	1-Oct-18	30-Oct-18				
Fall River	27-Sep-18	28-Oct-18				
Indianapolis	10-Oct-18	2-Nov-18				
Kansas City	9-Oct-18	9-Nov-18	3-Dec-18	2-Jan-19		
Milwaukee	10-Oct-18	2-Nov-18	10-Dec-18	2-Jan-19		
Minneapolis	13-Oct-18	2-Dec-18				
New York	5-Oct-18	3-Nov-18	12-Oct-18	3-Nov-18		
Newark	10-Oct-18	21-Oct-18				
Philadelphia	4-Oct-18	27-Oct-18				
Pittsburgh	3-Oct-18	9-Nov-18	24-Oct-18	18-Nov-18		
San Francisco	18-Oct-18	25-Nov-18	5-Jan-19	2-Feb-19		
Spokane	9-Oct-18	25-Nov-18	3-Dec-18	2-Jan-19		
St. Louis	7-Oct-18	14-Nov-18	8-Nov-18	13-Nov-18	28-Nov-18	2-Jan-19
Washington	2-Oct-18	4-Nov-18				

Atlanta

October 7 “Acting upon a recommendation from the U.S. Public Health Service, the Atlanta City Council Declared all public gathering places closed for two months as a precautionary measure against the epidemic of Spanish influenza sweeping the nation. This ban included schools, libraries, churches, and theaters. Street cars were directed to keep all windows open -- except in rain. In a precautionary move, the University of Georgia announced it was indefinitely suspending classes.”(1)

October 8 “The president of the Atlanta Chamber of Commerce, urged landlords not to evict those infected with Spanish influenza, saying they had no authority to do so and added that any such evictions be reported to his office.” “All Fulton County school children reported to class, got their books and some final instructions, then were sent home for the duration of the public gathering ban announced the previous day.” (1)

October 11 “The University of Georgia announced classes would resume October 21. Classes had been suspended October 7 as a precaution against the Spanish flu epidemic.” (1)

October 12 “A Liberty Loan parade was held.” (1)

October 13 “Atlanta city health officer Dr. J.P. Kennedy announced the public gathering ban would last at least one more week. It had originally been instituted for two months.” (1)

October 18 “The State Board of Health met and recognized the seriousness of the Spanish influenza epidemic. Along with federal health authorities present a resolution was passed allowing an executive committee of the State Board to take whatever actions necessary to control the disease wherever it might appear in Georgia.” (1)

November 5 “Fulton County public schools were re-opened after having been closed to help prevent the spread of Spanish influenza.” (1)

Baltimore

October 1 “Red Cross volunteers in Baltimore make 18,000 face masks to protect those coming into contact with flu victims.” (2)

October 2 “City health commissioner John D. Blake bans public dances.” (2)

October 5 “Health commissioner Blake abruptly cancels the women's [Liberty Loan parade” (2)

October 7 “Blake closes public schools. The Johns Hopkins University and Loyola College are closed, as are area private schools.” (2)

October 9 “Morgan College is closed.” (2)

October 12 “Churches and synagogues are closed. So are bowling alleys, pool and billiard halls and Laurel Race track.” (2)

October 17 “City orders firemen and others to wash the streets to keep down dust and dirt believed to carry germs.” (2)

October 28 “Ban against going to churches and synagogues is lifted. Ban is partially lifted to allow attendance at theaters and moving picture parlors except for matinee performances.” (2)

November 1 “Blake lifts all remaining bans in Baltimore.” (2)

November 3 Schools reopen. (2)

Chicago

Source: [5-11]

General Schools and churches remained open throughout **-** albeit with public health measures, e.g., windows kept open.

September 16 “Warning that the epidemic would spread to Chicago within two weeks.” (3)

September 17 Influenza-like disease becomes a reportable disease. (3)

September 20 “Police Department requested to start another anti-spitting crusade.” (3)

September 21 “Warning issued that persons having symptoms of influenza should go to bed and not to expose others.” (3)

September 24 “Begin of campaign to have all dwellings well heated and citizens [were] asked to telephone to the Health Department if landlord did not furnish sufficient heat. Placards warning against danger of sneezing, coughing and spitting [were] placed in all street and elevated cars.” (3)

September 25 “Warning in regard to pneumonia following influenza.” (3)

September 26 “The following rigid measures adopted to prevent the spread of the disease in the schools: (a) Open window ventilation of all schoolrooms. (b) Pupils warmly dressed. (c) Daily thorough inspection of all pupils. (d) Pupils coughing or sneezing to be sent home at once. (e) Daily check on absentees in all schools.” (3)

September 27 “Pictures [appeared] in daily papers demonstrating the use of masks. Landlords refusing to supply heat sued.” (3)

September 28 "Health Commissioner appointed on a committee appointed by the Medical Section of the State Council of Defense to mobilize all forces to fight the outbreak in the city and state." (3) "A conference of prominent representatives of the various agencies actively interested in the children's welfare was called by the commissioner of health, and the question of closing schools was thoroughly debated. It was noted that the sanitation in the schools was uniformly good and that the hygienic conditions of environment are better in schools than those which obtain among the children when classes were discontinued. When in school the children are under the observation of doctors, nurses and teachers, while on the outside there is no limit to their possible contact, under conditions in which this supervision is lacking. The consensus of opinion was in favor of keeping the schools open." (4)

September 30 "All street and elevated cars required to be renovated and disinfected at least once in twenty-four hours." (3)

October 1 "Quarantine ordered for all influenza cases, also isolation of cases in hospitals. (Pneumonia has been subject to quarantine for a number of years.)" (3)

October 2 "Further attention called to the value of masks by ordering same to be employed in hospitals. Masks placed on street sweepers. Visiting stopped in hospitals." (3)

October 3 "Interviews given and printed in all newspapers warning against panic, also urging that all precautionary measures be continued. United States Public Health Service Circular on 'Spanish Influenza' carried in papers as a half page 'ad,' with a subjoined warning against undue fear. Police requested to arrest 'open' coughers and sneezers on streets-and in public places." (3)

October 4 "Home nursing provided for by the Visiting Nurses' Association. Check made on hospitals to facilitate prompt hospitalization of all cases." (3)

October 5 "Churches warned against coughing and sneezing; also required to improve ventilation." (3)

October 10 "Smoking on all cars stopped." (3)

October 11 "Thirty-five field nurses of Municipal Tuberculosis Sanitarium Staff detailed for home nursery service to cooperate with the Visiting Nurses' Association." (3)

October 12 "Public dance halls closed. Health Commissioner meets with the presidents of forty civic organizations who agree to cooperate. One hundred and fifty health officers of the city put on full-time service at a salary of $200.00 per month, United States Public Health Service paying the difference. All sworn in as United States employees. Eighteen field nurses from Health Department Quarantine Service loaned to Visiting Nurses' Association. Public funerals prohibited. Attendance at all funerals limited to ten, and burial required from the place of death." (3)

October 14 "Conference to facilitate hauling by ambulances" (3)

October 15 "Theaters, skating rinks, moving picture shows, night schools and lodge halls closed." (3) "All public schools which are lacking in adequate medical and nursing supervision were included in the order." (5)

October 16 "Sixteen Municipal Tuberculosis Sanitarium dispensary physicians detailed to field duty for care and treatment of families afflicted with the disease." (3)

October 17 "Arrangements completed for federalizing health officers of the city; the same also to give treatment to the needy and first-aid treatment to those unable to procure a physician. The manner of obtaining this assistance announced in the public press. Street and elevated cars required to keep doors open, also windows as weather permits. Employees in down-town district ordered to and from work at various hours so as to stagger load on cars. The Influenza Commission recommends general immunization by the use of the Dr. E. C. Rosenow vaccine and appointed a commission, consisting of the professors of bacteriology and pathology in the local universities to manufacture and distribute such vaccine. Manufacture of prophylactic vaccine under supervision of the aforesaid commission begun in the city laboratory." (3)

October 18 "All public gatherings not essential to the war, such as banquets, conventions, lectures, social affairs, athletic contests of a public nature stopped. Music, cabarets and other entertainments stopped in restaurants and cafes. Crowding prohibited in poolrooms, saloons, etc. Assistance of the school board enlisted to help health officers in carrying out measures which have been employed since the outbreak of the epidemic to guard the health of school children. These measures have been carried out in lieu of closing the schools." (3)

October 19 “Hospitals canvassed with a view of getting more space for influenza cases. Report received from a representative of the department sent East to study vaccines used there.” (3)

October 20 “Conference with superintendents of all hospitals to arrange for additional space for influenza cases. They ordered that no surgery, except emergency surgery, should be done until further notice.” (3)

October 21 “Further efforts made to cope with shortage of nurses. Request made that physicians send all women over forty, willing to serve as housekeepers in afflicted homes, to the Health Department for registration and reference to the Visiting Nurses' Association.” (3)

October 22 “Rosenow vaccine received from Rochester ready for distribution. An issue of preference to draft boards, hospitals and nurses, industrial plants and general public was in order.” (3)

October 23 “[A] conference with laboratory men of all hospitals and laboratories was held. Urged that they make preparations at once to collect and administer immune human serum.” (3)

October 24 “Check up on street cars to see if all available cars are used so that crowding be reduced to minimum.” (3)

October 25 “During cold spell the public warned to wear heavy clothing, also warned as to the dangers of cold and wet feet.” (3)

October 29 “Ban lifted on music and usual entertainment in restaurants.” (3)

October 30 “Theaters allowed to reopen on north side of the city, the next day in the middle and business section, and later on the south side portions of the city. Thorough renovation of all theaters required as a condition for a permit to reopen. Two-minute health talks given at each performance, and watch kept on coughing, sneezing and spitting. Ban also lifted on other public meetings in theaters and assembly halls on the same date as for theaters, but all theaters and meetings allowed to reopen required to close at 10 p. m.” (3)

October 31 “Most Halloween celebrations are cancelled due to quarantines.” (6)

November 4 “Ban lifted on social functions, entertainments and athletic contests. Public dance halls, skating rinks and lodge halls allowed to reopen after thorough renovation and inspection, and approval by the Department.” (3)

Comments: There is some ambiguity in the days the interventions started and stopped. On Oct 1st case isolation and some other measures were brought in. Only at Oct 15. Theaters, skating rinks, moving picture shows, night schools and lodge halls were closed. On October 30 the first measures were lifted, while on November 4 all bans were lifted.

Fall River

September 27 All schools were closed. (7)

October 28 Schools reopened. (7)

Indianapolis

October 9 “The Indiana State Department of Health issued an order complying with the advice of the U.S. Public Service by closing schools, churches, theatres, and public gatherings”(8), including Halloween parties (9). “Citizens were required to wear masks in stores and streetcars, offices and factories, public buildings and theatres.” (9)

October 10

October 30 “The ban on public gatherings in Indiana is gradually being lifted. Indianapolis will get out from under the ban tomorrow morning. The Gary public schools opened this morning.” (10)

November 2 “The order remained in effect until midnight, November 2, 1918. It was rescinded because this prevention method showed little, if any, effect in controlling the spread of disease.” (8)

Kansas City

October 9. "The situation was grave. Dr. C. W. McLaughlin and the Board of Education conferred about school closing and warned children to stay home. Cases to the number of 100 and over were reported every day. No church services were held, some businesses were closed, and a statewide ban went into effect. Funerals were private." (11)

October 14 "It was decided to close schools another week. The anti-spitting law was rigidly enforced." (11)

October 17 "The Kansas City Star proclaimed, 'A DRASTIC BAN IS ON.' It was. Ordered closed immediately and indefinitely were all schools, churches and theaters. Public gatherings of 20 or more people were all prohibited, including dances, parties, weddings, or funerals. Crowding in stores was banned. Streetcars were forbidden to carry more than 20 standing passengers. Elevators were sterilized once a day. Telephone booths were sterilized twice." (9)

"Dr. Crumbine arrived from Topeka on October 19. He reported eight deaths, 62 ambulance4 calls, and 219 new cases. After 376 cases in ten days, the "flu" was said to be on the wane, and the ban would be off on November 6." (11)

November 9 Schools reopened. (11)

November 11 "The country went wild when the armistice ending World War I was signed. Everything closed except the schools and the whole town went celebrating." (11)

"Then on November 27 a new outbreak occurred. Forty members of the senior class of the Medical College on the Missouri side went to the schools, one to each, to try to detect signs of the disease in the children. When schools opened on Monday December 2, they had the greatest number of absentees in history. The seven deaths and 120 new cases over the weekend brought another ban, in spite of the protests of principals." (11)

December 3 "The commissioners ordered children to stay away from shows." (11)

After Christmas "The schools opened." (11)

January 2

Milwaukee

September 28 "During the week of September 28,(….) the city health department requested physicians to report any new influenza cases immediately." (12)

October 10 State Board of Health ordered all public institutions in Wisconsin to close. [17, (12)] "This included all schools, theaters, saloons, churches, and places of public amusement statewide - virtually every public venue other than factories, offices, and workplaces" (13)"including hotels, restaurants and stores in which food and clothing were sold were closed for periods varying from three weeks to eight weeks or more. " (14) "Within a day, virtually every local government in Wisconsin had cooperated and put the order into effect." (12)

November 2 Schools reopen [Markel]

December 10 Schools close again. (12)

"In no other state was such a comprehensive order issued." (12) "For almost three months, isolation rather than socialization became the norm." (12)

January 2

Minneapolis

September 29 "University President Burton announced that the fall opening of the University of Minnesota would be postponed for one week, 'as a measure of precaution.'"(15)

October 6 "…the postponement of the fall opening of the University of Minnesota was extended a week." (15)

October 11 "H. M. Guilford, M.D., head of the Minneapolis Department of Health closed churches, schools, theaters, dance halls, and all other meeting places for the duration of the epidemic." (15, 16)

October 12 “The city’s health commissioner ordered all churches, schools, dance halls, theaters and all other meeting places closed, beginning Sunday, Oct.”(17) “for the duration of the epidemic.” (15)

October 13

October 21 “The Minnesota State Safety Commission banned public meetings throughout the state. This did not include schools, churches, or theatres, which were placed under local control.” [24]

October 23 “The annual meeting of the Minneapolis chapter of the Red Cross, to have been held on October 23, has been postponed indefinitely because of the epidemic.”(17)

End of October “The influenza had waned just enough for the University to open its doors to students.” (15)

November 2 “The State Board of Health banned all public funerals throughout the state.” (18)

December 2 “The public ban is lifted in New Ulm. After 7 weeks, schools reopened, including New Ulm Public Schools, and the parochial schools. Dr. Martin Luther College remained closed until December 11. Picture shows, church services, and meetings were allowed once again, but influenza cases would continue to be throughout the winter.” (18)
December 7 “Schools reopened in the New Ulm area.” (18) “The influenza ban was lifted in Redwood Falls for the second time.” (18)
January 4, 1919 “As of the new year, no new cases of influenza were reported in New Ulm. The Minnesota mandated public ban on church funerals had been lifted, except in the case of death from influenza, pneumonia, and other communicable diseases.” (18)

New York

October 4 “Health Commissioner Copeland, by proclamation ordered a change in the hours for opening stores, theatres and other places of business” (19) (Schools and churches were not closed).

October 5

October 12 Most theatres in NYC closed (20), some sporting events by Oct 13. (21-23) ”Health Commissioner Copeland told a conference of theatrical managers that he would not close the theatres, but that smoking in them had to be suspended for the present. He also informed the board of education that schools would not be ordered shut.” (24 1918, 1918)

October 19 “Copeland (NYC Public Health Official) refuses to close schools or ban public assemblages.”(23)

November 3 “Health Commissioner Copeland announced that the Health Department now feels justified in allowing industry to abandon on Tuesday evening the schedule of opening and closing business that was enforced when the situation was serious.” (25)

November 3

Newark

October 10 “In compliance with a state ban against all public gatherings Decreed by the New Jersey Board of Health, Newark ordered all schools, churches, theaters, moving picture houses, dance halls, saloons and sporting arenas closed.”(26) “Restaurants were exempt from the state ban on public gatherings.” (26)

October 19 “City authorities agreed to permit meditation and prayer in churches.”(26)

October 21 “Mayor Charles Gillen lifted the state closing order.” (26)

October 26 “The Board of Health’s closing order was revoked in almost 200 communities throughout the state.” (26)

Philadelphia

September 28 “Two hundred thousand gathered for a 4th Liberty Loan Drive.” (27)

October 4 Schools, churches are closed. Possibly theaters and other places of public amusement were closed a few days earlier. (27) (28)

October 11 “Local businessmen voluntarily close their shops.”(27)

October 26 “The order closing public places was lifted.” (29)

October 27 Churches reopened in Philadelphia. (23, 28, 30)

October 28 Schools reopened (28)

October 30 Theaters, vaudeville houses, and bars reopened. (28)

Pittsburgh

October 3 Bars/theatres close. Schools churches left to ‘discretion of local boards’. City schools stay open. (31)

October 22 “City schools not closed by Grip Epidemic.” (31)

October 24 Schools close. (31)

November 2 “Mayor E.V. Babock last night lifted the influenza ban on Pittsburgh, as far as the city authorities are concerned.” (31) “While the proclamation does not specifically lift the ban, which was ordered by Dr. Royer and enforced by the city through its health department, it serves notice to the public that this enforcement will no longer be effective. Churches, however, and schools, which were closed by Director Davis on the advice of the state authorities, were not included in the original closing order, and the ban on them, therefore is removed. While no official notification will be sent to pastors, Maj. Davis last night issued a statement saying that they may resume services tomorrow if they desire In Regard to saloons and theatrical enterprises, the opening is dependent upon the judgment of the proprietors. These places were closed by the state authorities. If they open in violation of this order, they may come in conflict with the state health commissioner. The city, however, will refuse to act as prosecuting agent and will even aid in their defense should the state authorities take action.” “Several hours before Mayor Babcock issued his proclamation Acting State Health Commissioner Royer had held a telephonic communication with the Mayor in which Dr. Royer had set Saturday, November 9, as the data on which the closing order would be rescinded.” (31)

November 8 “Schools In City Will Reopen November 18” (31)

November 9 “All theaters in city open today. Royer gives ban-lifting regulations” (31)

November 12 “Board Decides Schools Open Next Monday” (31)

November 18 Schools reopen

Comments: There is some ambiguity whether the first intervention stopped at November 2 or November 9. We used the latter date.

San Francisco

October 18 “Board of Health issued a closing order (..) All of San Francisco’s amusement and public gathering places and schools were shut down.” (28) “Hassler recommended that all store clerks wear masks while on the job and ordered all barbered to do so” (28)

October 20 Mask wearing by all 'urged', compulsory for those serving public. (32) Church services were forbidden. (28)

November 1 Mask wearing compulsory for all. (28, 32) “Even before the mask ordinance actually became law, the great majority of San Franciscans – the Board of Health said 99 percent’- donned the masks. ” (28)

November 2 “50 without masks are arrested.” (32)

November 16 Public gathering ban lifted. (32)

November 21 Mask order lifted. (32) (28)

November 25 Schools reopen. (28)

January 5 Mask wearing reintroduced in schools. (32)

January 9 Public asked to wear gauze masks. (33)

January 11 Mask wearing reintroduced - compulsory from 17 Jan. (28)

February 2 Mask wearing lifted. (28)

Spokane

October 1 “The City Health Department declared that some cases might be in Spokane but saw no need for alarm. The Department recommended covering the mouth and nose while sneezing and using antiseptic sprays and gargles to prevent infection.” (34)

October 8” Dr. Anderson declared that Spokane was in the throes of the influenza epidemic, and ordered that as of midnight, all schools, theatres, places of amusement, dance halls, churches, and Sunday Schools would be closed and that conventions and other public meetings were prohibited. Schools were closed the next day and students who showed up were sent home. (…) Department stores were forbidden to have special sales as these would draw crowds. Rules regarding ventilation, sanitation, and spitting were strictly enforced. Jury trials were stopped and the Spokane Stock Exchange was closed.” (34)

October 9

October 11 “Bowling alleys were closed. As a result, toy and game departments of stores were flourishing as people looked for entertainment at home.” (34)

November 3 “The State Board of Health ordered that flu masks be worn throughout the state in all public conveyances, corridors, lobbies, and other public buildings. Stores were ordered to keep their doors wide open.” (34)

November 4 “The Superior Court closed for three weeks in response to the epidemic.” (34)

November 10 “The State Board of Health withdrew the mask regulation and stated that the quarantine might be lifted the following Sunday (November 17), after which theaters, schools, and churches could open.” (34)

November 25 “Spokane Public schools opened.” (34)

December 3 “Spokane closes schools, children under 12 forbidden to attend church.” (33)

December 5 “The Health Department re-instituted a modified flu ban. Theaters were required to close and air out between 5 and 7 p.m. and to use only alternate rows of seats. Churches were allowed to have services only if they used alternate row seating and did not allow singing. Street cars could carry only as many passengers as could be seated. All homes with flu patients posted warning placards.” (34)

December 19 “The City Health Department ruled that Christmas church services could be held but would not allow any congregational singing.” (34)

December 24 “Dr. Anderson said that restrictions would be lifted after the first of the year and that theaters having modern systems of ventilation would be the first to be allowed to open.” (34)

December 31 “The papers announced that schools would reopen on January 2 and that churches and theaters could also reopen. Dance halls had to stay closed.” (34)

January 2 Reopening of schools, churches and theaters.

St. Louis

October 7 - Health Commissioner orders closure of “all picture houses, theaters, and public places of amusement and such other places as may be necessary” (35) - such as schools and other venues where people gathered, including Sunday schools and churches. (35)

Other measures - "Individuals diagnosed with influenza were subject to the placement of a quarantine placard on their homes, usually for a period of 14 days." (35)

November 8 "... all business places be closed and discontinued, and remain closed and discontinued for a period of 4 days, beginning Saturday morning November 9." (35)

November 13 "The Advisory Committee recommended lifting the ban on businesses and schools" (35) Business reopens the same day. (35)

November 14 "Schools reopen Thursday morning." (35)

November 28 "The ban on public gatherings was reinstated, and schools were closed again. This time, elementary schools were to remain closed until after the holidays." (35)

December 22 "Lifting of the influenza ban from all except some children's venues was announced." (35)

January 2 Elementary schools reopened.

Comments: 4) There is ambiguity in the date the third intervention was stopped. The ban was lifted on December 22, but elementary schools remained closed till January 2. We used this last day in our analysis.

Washington

October 2 Schools close, and "with the closing of the school closure all athletic activities would cease." (36 1918, 1918)

October 3 "hours of opening in government departments are 'staggered'" (37 1918, 1918) "With the closing of the theaters under consideration, with the schools already closed and all public meetings under ban, with the hours of opening for stores and government departments greatly altered to relieve the usual congestion of morning traffic, Washington resident today will grasp the real significance of the determined measures that the authorities are taking to combat the further spread of influenza."(38 1918, 1918)

October 4 "As a further means of combating Spanish influenza in the District, all theaters, motion picture houses and public dance halls were closed last night at midnight and ordered to remain closed until further order from the District commissioners." (39 1918, 1918)

October 6 "All branches of George Washington University have been ordered closed indefinitely because of the epidemic of Spanish influenza. The order becomes effective at once and all classes will be suspended until the epidemic in the city is under control." (40 918, 918)

October 9 The public schools in all branches are closed. (41 1918, 1918)

October 30 "The action of the commissioners of the District in raising the ban against the churches, theaters, schools and other places where the public was accustomed to foregather before the outbreak of the influenza epidemic will be glad tidings to thousands of persons in this District. As a means of preventing a spread of infection and checking the disease after it reached its acute stage the action of the commissioners in closing all public places was commendable, and the people acquiesced." (42 1918, 1918)

November 3 Churches and night schools are reopening. (43 918, 918, 44 1918, 1918, 45 1918, 1918).

November 4 The schools reopened. (41 1918, 1918, 45 1918, 1918, 46 1918, 1918, 47 1918, 1918)

2. Mortality data

2.1 Sources

We use excess pneumonia and influenza data for the 47 largest cities of the US reported by Collins (48). Excess mortality was estimated by Collins using the following procedure: "Excess over the estimated median rate for corresponding weeks for the period 1910-1916. The monthly median rates (annual basis) for each city were plotted and a smooth line passing through each of the 12 monthly medians was drawn to represent the seasonal curve of mortality from influenza and pneumonia. From this graph the approximate medians for each week were read." (48).

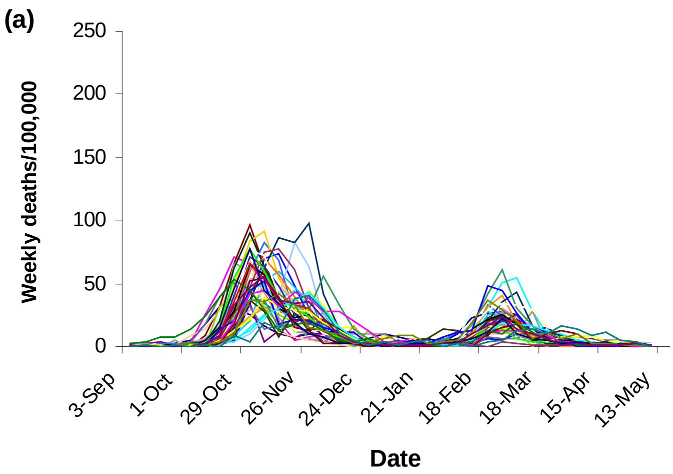
Since the calculation of excess mortality is approximate at best, and excess mortality is in any case not a perfect proxy for infection incidence, we also examine the results obtained by fitting transmission models to total pneumonia and influenza mortality data(49, 50) for the 16 cities for which we could obtain intervention dates. This analysis is described in section 7 below.

2.2 Comparison of the 1918 pandemic in the UK and the US

Figure S1 plots weekly mortality per 100,000 in the 47 most populous boroughs of England and Wales (51) and for the 47 largest cities of the US (48). It should be noted that boroughs (even the largest ones) are typically smaller population units than US cities (average population size of 223 thousand, versus 509 thousand for the US cities). We might therefore expect the population in the UK boroughs to be slightly more well mixed than for the US cities, though the difference is probably not significant..

It is clear that the pandemic was significantly more homogenous in the UK, with no evidence of the clear double-peaked autumn epidemics seen in many US cities. There are some general differences also – the UK saw a clearly epidemic in February-March 1919, while there was much less consistency in the timing of secondary and tertiary peaks in the US following the October-November primary epidemic. That the epidemic in England and Wales was more homogenous is no surprise – no control measures were attempted, England and Wales has a much smaller area, and even in 1918 there was much more population movement between different urban areas than between US cities.

A noticeable difference between the 1918 pandemic pattern seen in England and Wales (and indeed, much of Europe) was the occurrence of a late epidemic 'wave' in March 1919. This was not seen in the US except in one or two cities. The reason for such a late spring pandemic wave are unclear – it is not able to be explained by social distancing or public health measures (there were none in most of Europe). Comparison with 1957 (where the main pandemic wave occurred in October 1957, with a second much smaller epidemic early in 1958) might suggest a common mechanism. Antigenic variation is one possibility – with the Spring 1918 and 1958 minor epidemic waves representing the first seasonal influenza epidemics caused by antigenic drift of the new subtypes. However, while interesting, it is not the purpose of this paper to explain the origins of multiple pandemic waves – rather we focus on why the autumn wave of the 1918 epidemic exhibited very different characteristics in different US cities.



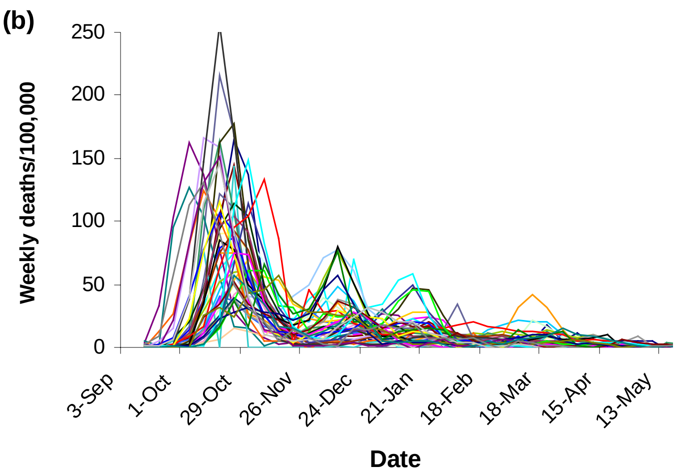


Fig S1: (a) Weekly influenza related mortality per 100,000 for the 47 most populous boroughs of England and Wales, for the period 1st September 1918-10th May 1919 (51) (b) Excess mortality from influenza and pneumonia for the 47 largest cities of the US (48).

Note that the absolute scale of deaths shown in Figure S1 cannot be compared between the UK and US, as different measures of mortality are being reported in the source data. However, the variability in the level of mortality seen in different US cities was greater than seen across the UK (Figure S2) – the coefficient of variation in per capita mortality was 0.18 for the largest 47 UK boroughs versus 0.26 for the 47 US cities, while the interquartile ranges are 320-420 and 400-640 respectively.

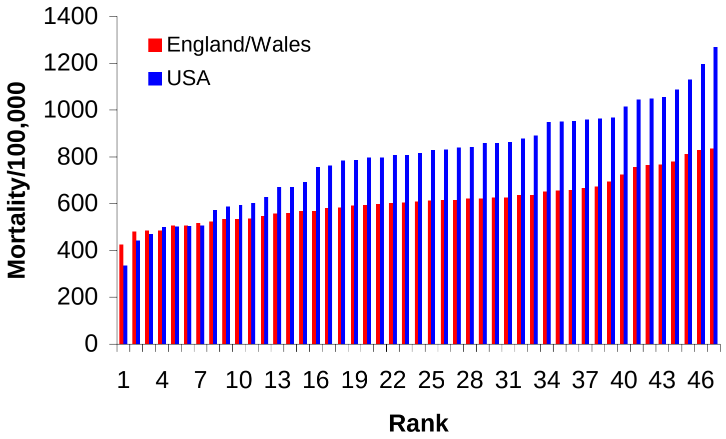


Figure S2: Rank-ordered mortality/100000 from September 14th 1918 to 10th May 1919 for the 47 US cities in (48) and the 47 largest boroughs in England and Wales (51). Each bar represents a city/borough. Influenza-related mortality is shown for England and Wales, and excess pneumonia and influenza related mortality for the US.

3. Predictors of 1918 pandemic mortality in US cities

We examined the correlation of total and peak (weekly) excess mortality per 100,000 in 1918 in 45 US cities (Jersey City and Memphis were excluded because of large numbers of weeks of missing mortality data) with a number of covariates:

- Population size of city – not significant [corr.=-0.017, p (for slope of regression=0) =0.91 for total mortality, corr.=0.075, p=0.63 for peak mortality].
- Land area of city – not significant [corr.=0.062, p=0.69 for total mortality, corr.=0.034, p=0.83 for peak mortality].
- Average population density – not significant [corr.=-0.054, p=0.73 for total mortality, corr.=0.11, p=0.45 for peak mortality].
- All cause mortality per 100,000 in 1917 – significant [corr.=0.44, p=0.003 for total mortality, corr.=0.57, p<0.0001 for peak mortality], see Figure S3a.
- Proportion of total excess mortality occurring in peak week – significant correlation for total mortality [corr. =0.40, p=0.006], see Figure S3b.
- Number of epidemic peaks in autumn 1918 (always either 1 or 2) – significant [corr. =0.40, p=0.006 for total mortality, corr. =0.76, $p<10^{-8}$ for peak mortality], see Figure S3c.
- Date of first week in which excess deaths exceeded 20/100,000 – significant [corr. =-0.49, p<0.001 for total mortality, corr. =-0.55, p<0.0001 for peak mortality], see Figure S3d. There is also a weaker but still significant correlation with the timing of the first peak of the autumn wave.

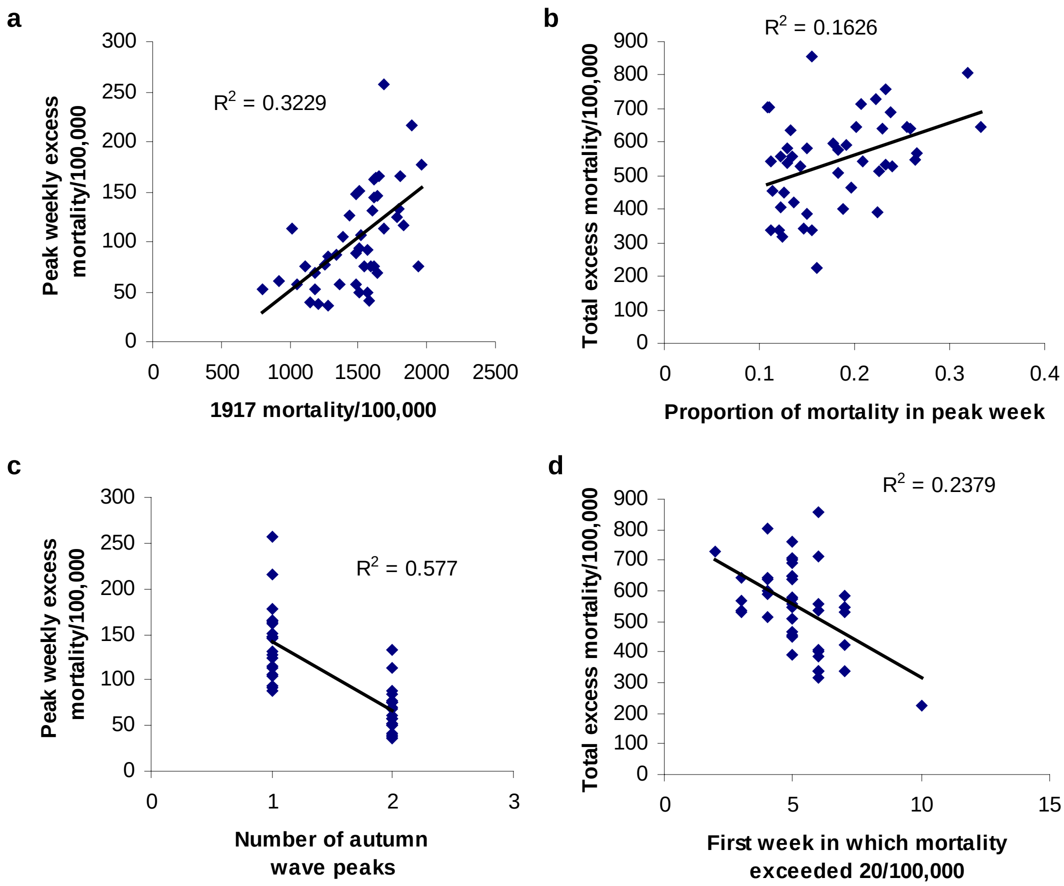


Figure S3: Correlation of (a) peak mortality with 1917 mortality us; (b) total mortality with the proportion of total mortality occurring in the peak week; (c) peak mortality with the number of autumn waves; (d) total mortality with the week (counting from the week of Sept 7th-13th) weekly mortality first exceeds 20/100,000. Correlations shown for the 45 US cities for which mortality data was relatively complete. See text for more details. (a) and (d) are identical to Figure 1 (a) and (b) of the main text.

We draw three simple conclusions from these results. First, cities with higher than average mortality (perhaps due to socio-economic conditions, or the age structure of the population) also suffered more in the 1918 pandemic. Second, cities affected later in the 1918 pandemic experienced lower mortality. Third, lower mortality was associated with having a double-peaked autumn epidemic. If 1917 mortality and the date of the first week where deaths exceeded 20/100,000 were both included in a multivariate regression as the only predictor variables, but lost significance if the number of autumn peaks was also included.

For the 23 cities for which we had data on the timing of the start of public health interventions, we also examined the correlation of total and peak mortality (per 100,000) with the following covariates:

- Date of start of interventions – not significant [corr.=-0.052, p=0.82 for total mortality, corr.=-0.23, p=0.28 for peak mortality].
- Number of weeks prior to the first peak interventions were introduced – not significant [corr.=-0.31, p=0.15 for total mortality, corr.=-0.39, p=0.063 for peak mortality].
- Mortality per 100,000 up to the date interventions were introduced (calculated by interpolation between weekly totals) – significant for total mortality [corr.=0.60, p=0.003] but not for peak mortality [corr.=0.40, p=0.06], see Figure S4a.
- Mortality per 100,000 up to 12 days after interventions were introduced (calculated by interpolation between weekly totals) – highly significant [corr.=0.83, $p<10^{-6}$ for total mortality, corr.=0.84, $p<10^{-6}$ for peak mortality], see Figure S4b. From the distribution (Figure S5)

reported by Mills (52), 12 days was the mean delay from infection to death due to 1918 pandemic influenza.

- Proportion of all mortality occurring up to 12 days after interventions were introduced (calculated by interpolation between weekly totals) – significant [corr.=0.66, p<0.001 for total mortality, corr.=0.78, p<0.0001 for peak mortality], see Figure S4c.
- Mortality per 100,000 up to 10 days after interventions were introduced (calculated by interpolation between weekly totals) – significant [corr.=0.81, $p<10^{-5}$ for total mortality, corr.=0.77, p<0.0001 for peak mortality]. From the distribution reported by Mills (52), 10 days was the median delay from infection to death due to 1918 pandemic influenza. Results are very similar for mortality up to 7 days post interventions.
- Proportion of all mortality occurring up to 10 days after interventions were introduced (calculated by interpolation between weekly totals) –significant [corr.=0.65, p<0.001 for total mortality, corr.=0.69, p<0.001 for peak mortality], see Figure S4d. Results are very similar for mortality up to 7 days post interventions.

The last four covariates above are proxy measures for the total infections occurring in the community by the time interventions have been introduced. Deaths lagged infections by days or weeks (see Figure S5). To estimate infections up to the start of interventions rigorously would require formal back-calculation to be used; here we just note that the 7-14 lagged mortality is much more strongly correlated with total and peak mortality than the un-lagged mortality.

Of course, it might be argued that absolute mortality per 100,000 up to 12 days after interventions were introduced is always likely to be correlated with total or peak mortality if there were intrinsic differences between cities which affected per-case mortality throughout the epidemic. We therefore also examined the correlation between total/peak mortality and the proportion of all mortality occurring up to 12 days after interventions were started. The correlation is weaker, but still substantial and significant.

This, coupled with the lack of correlation with the absolute timing of interventions is strongly suggestive that interventions affected both the peak mortality (and hence the shape of the epidemic curves) and the overall mortality experienced by different US cities. There is confounding with the timing of the epidemics (i.e. cities affected later had generally lower mortality), but the strength of correlation between either peak or total mortality and the timing of the start of the epidemic (as defined by the week in which mortality exceeded 20/100,000) is weaker than that between peak or total mortality and the proportion of mortality occurring up 12 days after interventions start. In a linear regression of either total or peak mortality against both covariates, only the proportion of mortality occurring up to 12 days after interventions remains significant (p=0.02 vs p=0.56 for total mortality, p=0.002 vs p=0.53 for peak mortality).

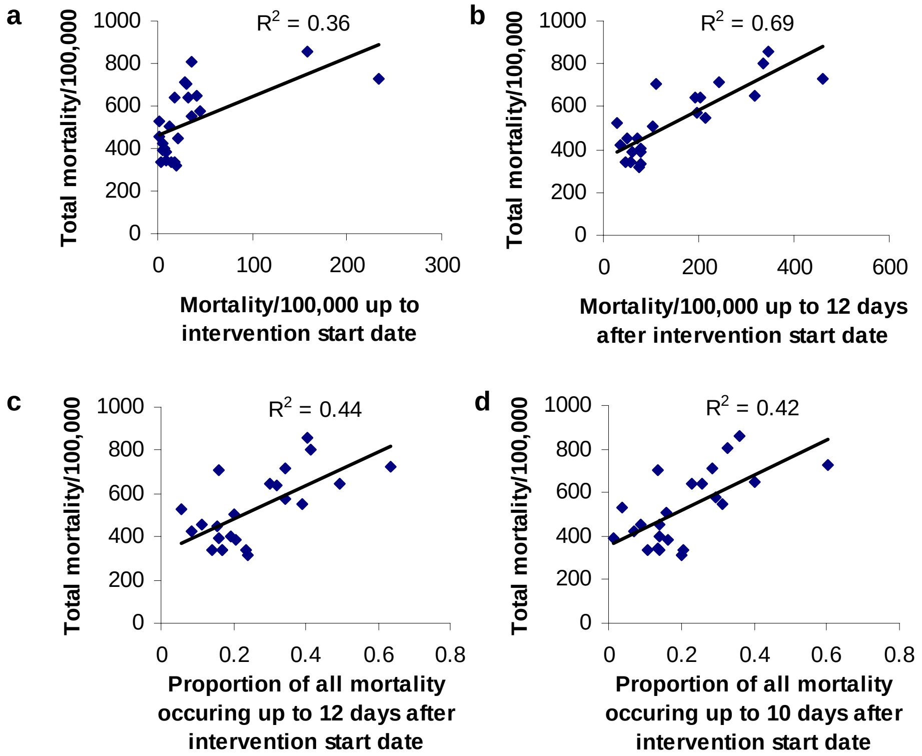


Figure S4: Correlation of (a) Total mortality with mortality up to start date of interventions; (b) Total mortality with mortality up to 12 days after start date of interventions; (c) Total mortality with proportion of total mortality occurring up to 12 days after start date of interventions; (d) Total mortality with mortality up to 10 days after start date of interventions. Correlations shown for the 23 US cities for which we could obtain intervention start dates. See text for more details. (b) is identical to Figure 1(c) in the main text.

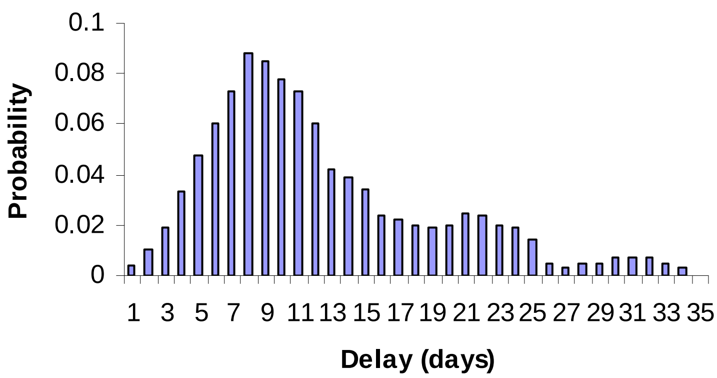


Figure S5: Distribution of delay in days from infection to death from 1918 pandemic influenza, as reported in Mills et al. (52).

4. Theoretical impact of imperfect and transient interventions

Control of an epidemic requires transmission rates to be reduced so that the reproduction number, *R*, of the epidemic is brought below unity. Control needs to be kept in place for as long as there are sufficient susceptible individuals left in the population to support self-sustaining transmission. In the absence of vaccine, this means controls need to be maintained for as long as the disease poses a threat.

However, even if this level of control is not feasible, imperfect and transient intervention measures can have some impact on the size of the epidemic for the reasons outlined in the main text. The optimal result would be to ensure that just enough people in the population would have acquired immunity in the population to prevent further self-sustaining transmission. Assuming random mixing, this requires a proportion $1\text{-}1/R_0$ of the population to have been infected (i.e. 50% for $R_0=2$). The difference between this minimal infection attack rate ($I_{total}=1\text{-}1/R_0$), also called the epidemic final size, and the proportion who would have been infected had no controls been implemented (which is given by the solution of the transcendental equation $-R_0\, I_{total} = log[1- I_{total}]$) can be substantial (see Figure 2 in main text), e.g. for R_0=2.0 (appropriate for influenza), the difference is between a 50% with controls and 80% without.

If we include reactive contact reduction in response to high infection rates into the model (i.e. by modifying the force of infection thus $\lambda(t)=\beta(t)\, I(t)(\kappa/[\kappa+I(t)])$, the unmitigated attack rate is reduced substantially (Figure S6a) – in essence such behaviour modification is equivalent in effect to an organised temporary control policy. Note that in the main paper we model behaviour change occurring in response to mortality rather than infection rates; the impact on final size is similar however. Even a moderate reactive response which only gives a 20% reduction in the number of contacts at the height of an epidemic would lead to a 9% reduction in the overall infection attack rate (for R_0=2.0) and would reduce peak incidence by 27% (Figure S6b).

Looking in more detail at the effect of intervention measures in absence of reactive contact reduction, consider an intervention which reduces R_0 to R_{eff} which starts at the beginning of the epidemic and lasts till the epidemic is finished. After this first wave, we assume the pathogen is reintroduced and that no interventions are taken during this second episode. One can conclude immediately that if $R_{eff}<1$, the first wave of the epidemic is completely prevented, but by the end of the second wave the overall attack rate would be the same as if no interventions had been taken at all. Thus paradoxically, if interventions can only be imposed for a finite period of time, they can be *too* effective (see Figure 2b in the main text). Instead of stopping transmission by reducing R_0 to $R_{eff}<1$, it is better to reduce transmission only partially, so that $R_{eff}>1$ but the overall proportion infected in the epidemic is reduced to the minimum of $I_{total} =1\text{-}1/R_0$. Figure S7a looks at such interventions, and shows the intermediate level of control policy effectiveness which minimizes the infection attack rate overall. Figure S7b shows (for R_0=2.0) the effect of the timing and the efficacy of interventions on the infection attack rate.

Lastly, in considering imperfect interventions, it is important to note that even if interventions are too effective initially (leading to $R_{eff}<1$ and a sharp decline in transmission) but sufficient susceptible people remain after controls are lifted to allow case numbers to again increase, then it is still possible to achieve the optimal outcome of a final size of $I_{total} =1\text{-}1/R_0$ by reintroducing less effective controls for the second wave of the epidemic.

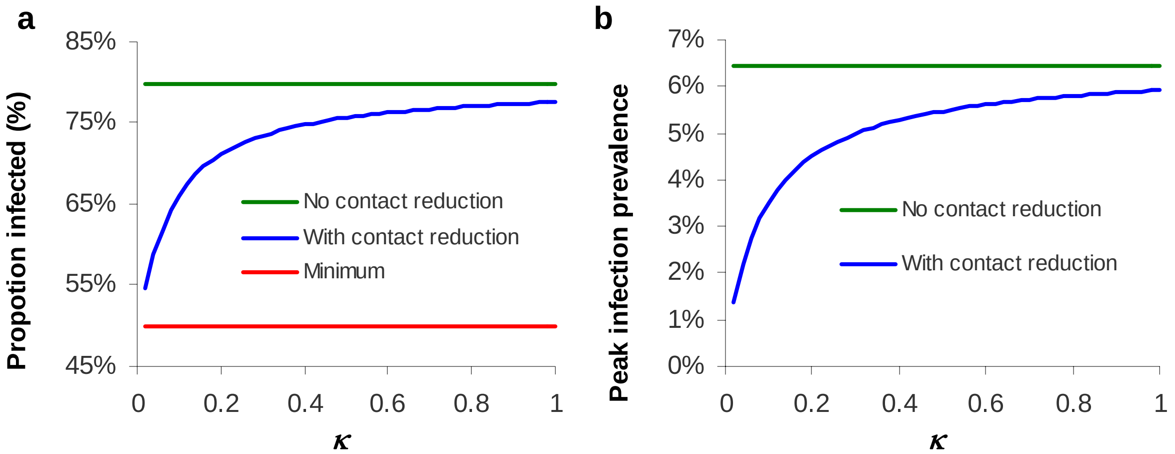


Figure S6: Final size (a) and peak number of infectious individuals (b) for an SIR-model with R_0=2.0 in case where the population reactively reduces its contact rates in response to high infection prevalence, (*i.e.* where the force of infection, $\lambda(t)$, is given by $\lambda(t)=\beta(t)\ I(t)\ \kappa/[\kappa+I(t)]$ where β is the transmission coefficient, κ is a threshold parameter governing the intensity of reactive social distancing, and $I(t)$ the fraction infectious individuals in the population at time t). When people reduce contact rates at very low infection prevalence, the peak in the number of infectious individuals is low and the final infection attack rate is close to the minimum required to stop transmission (the level which gives 'herd-immunity').

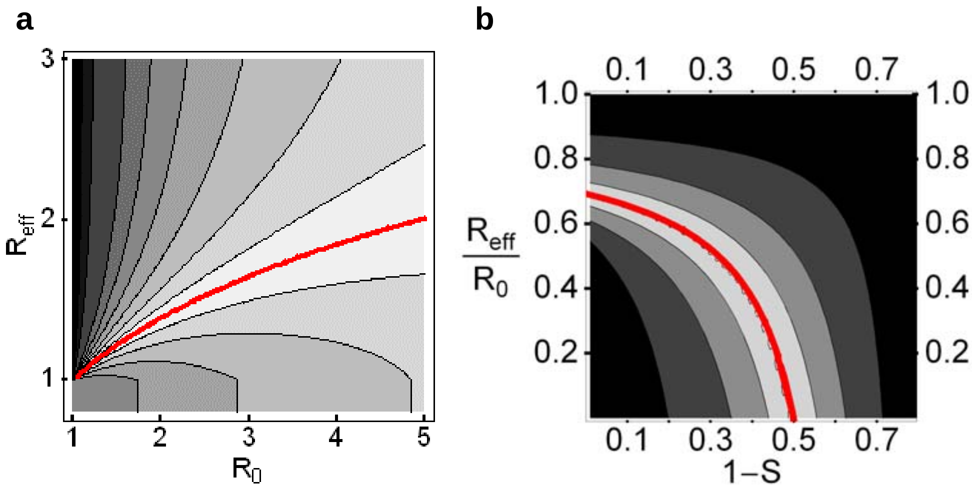


Figure S7: Contour plot of the reciprocal of the total infection attack rate (=final size) of an epidemic in which control measures are imposed during the first wave which reduce the reproduction number to R_{eff}. Following the first wave, infection is reintroduced into the population, potentially causing a second wave. The red line corresponds to the R_{eff}-values which minimize the infection attack rate (i.e. which cause just enough people to be infected in the first wave to prevent further transmission and therefore a second wave). Results shown for the cases that (a) intervention measures are present from the start till the end of the first wave, and (b) intervention measures start when a fraction (1-S) of the population has been infected (for a fixed R_0 of 2.0).

5. Model Parameter Estimates

Figure S8 shows the quality of fit of the best-fitting model variant presented in Table 1 of the main text – namely that with all parameters fitted on a city-specific basis. While the fit is better than that shown in Figure 3 of the main text (for model variant 4 which fits 2 fewer parameters as city-specific), the differences are not as visually apparent as the 850 difference in log-likelihood values would suggest. This perhaps indicates that our use of a poisson likelihood for the weekly excess mortality is unduly conservative in evaluating model goodness of fit (i.e. the data have extra-Poisson variation). This may also at least partly explain the rather tight credibility intervals obtained for many parameters. However it is difficult to build any more realistic likelihood model in the absence of any detailed information on the biases which might affect the mortality data.

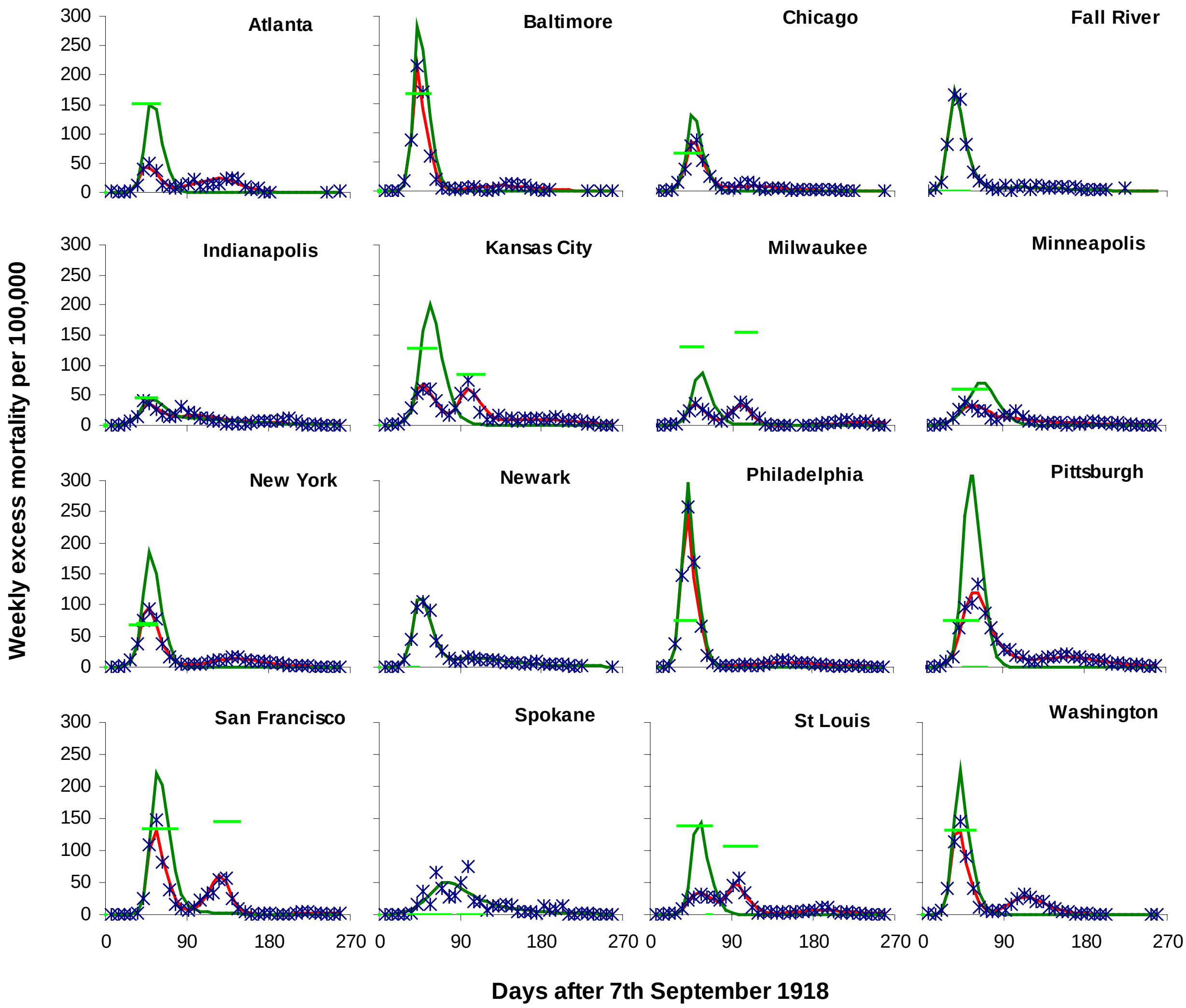


Figure S8: As Figure 3 in main text, but showing results for the best-fitting model variant 1 (all parameters local). Blue points indicate weekly excess mortality (per 100,000) resulting from the 1918 pandemic in 16 US cities, and red curves the model fit. Estimated weekly mortality had controls not been implemented is also plotted (dark green curves). The effectiveness and period of implementation of control measures are shown as light green horizontal lines, the horizontal position and length of which indicate the start date and duration of interventions, and the vertical position of which indicates estimated effectiveness, with the top of the vertical axis being 100% effectiveness, and the bottom, 0%.

Figure S9 presents the model fit for variant 2 of the model – which assumes no reactive social distancing. The fit is obviously worse than those presented in Figure 3 of the main text or Figure S7 above. However, qualitative features of the epidemics in each city are still reproduced.

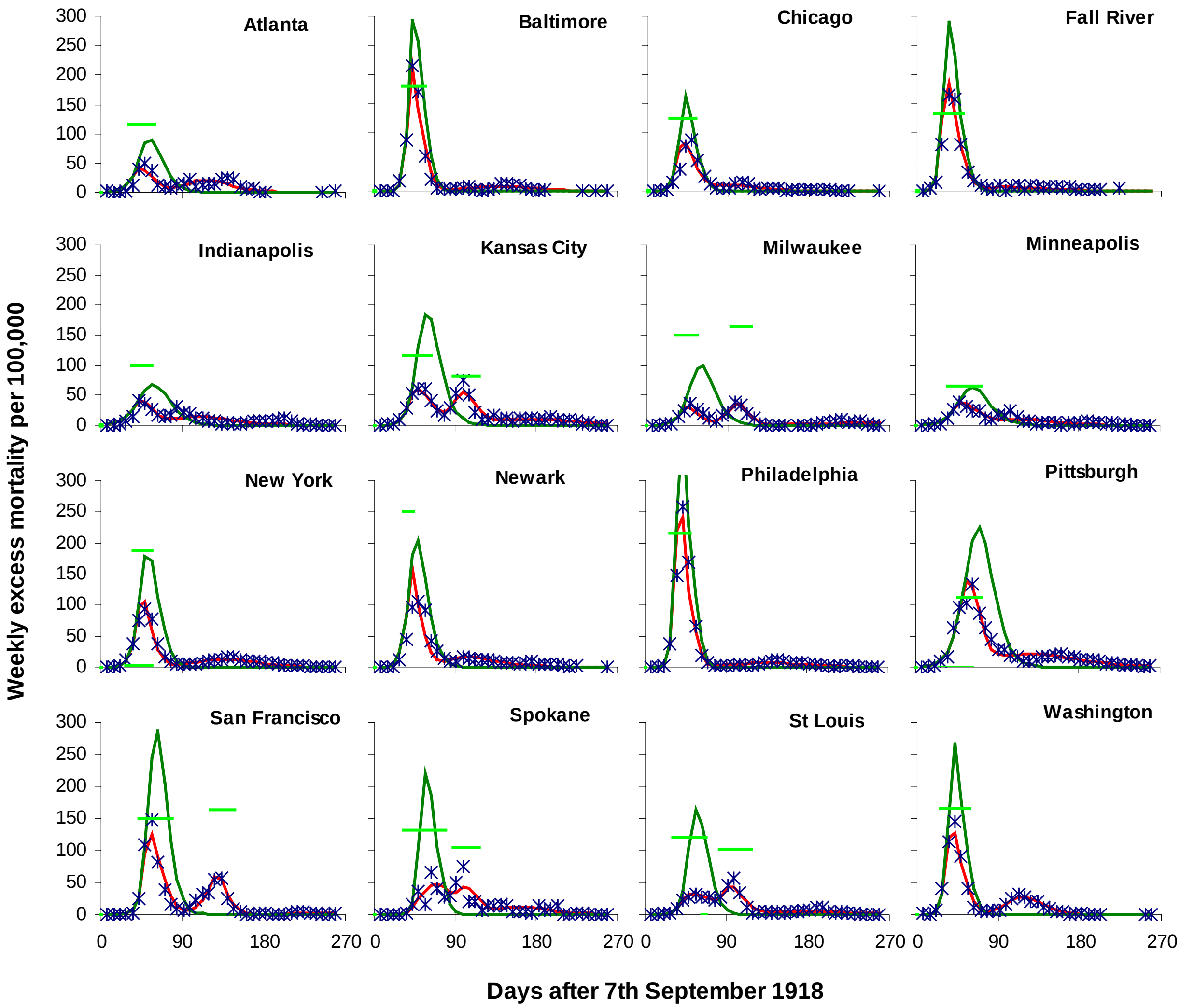


Figure S9: As Figure S8, but showing results for the model variant 2.

Table S2 presents the detailed city-specific parameters estimates for the model variants presented in Table 1 of the main text. We do not present the estimates of the start date of the epidemic in each city, as these are fairly meaningless – we make the simplifying assumption that the epidemic is seeded by a single case in each city, when in reality multiple infections will have been imported. Hence the estimated dates of seeding are probably rather earlier than was really the case.

Table S2: Estimates of all parameters for model variants listed in Table 1 of main text. Refer to Table 1 of main text for a description of the parameters and details of which parameters are fitted as city-specific or common to all cities. Posterior mean values and 95% credibility intervals are quoted. Control policy effectiveness is fitted separately for every distinct period of interventions in a city-see Table S1 for details.

variant	city	μ_s	R_0	κ	T	p_c
1	Atlanta	0.72% (0.65%, 0.79%)	1.96 (1.81, 2.12)	10 (7.1, 13.5)	51.4 (43.8, 58.1)	1st: 47% (43%, 51%)
	Baltimore	0.98% (0.94%, 1.01%)	2.75 (2.62, 2.88)	69 (27, 175)	0.6 (0.2, 1.3)	1st: 49% (39%, 58%)
	Chicago	0.66% (0.64%, 0.68%)	2.27 (2.22, 2.32)	14 (12, 15)	5.2 (3.8, 6.9)	1st: 21% (17%, 25%)
	Fall River	1.13% (1.03%, 1.24%)	2.25 (2.07, 2.45)	15 (13, 18)	2.4 (0.9, 4.4)	1st: 0% (0%, 0%)
	Indianapolis	0.87% (0.77%, 0.97%)	1.7 (1.57, 1.84)	47 (35, 62)	0.1 (0.1, 0.1)	1st: 13% (6%, 19%)
	Kansas City	1.57% (1.46%, 1.68%)	1.68 (1.61, 1.77)	538 (305, 918)	0.1 (0.1, 0.1)	1st: 38% (34%, 41%) 2nd: 25% (22%, 28%)
	Milwaukee	0.74% (0.68%, 0.81%)	1.87 (1.76, 1.98)	11 (9, 14)	10.7 (6.8, 15.8)	1st: 44% (41%, 47%) 2nd: 48% (44%, 53%)
	Minneapolis	0.99% (0.89%, 1.1%)	1.39 (1.34, 1.44)	29 (23, 38)	58.1 (53.4, 59.9)	1st: 19% (17%, 22%)
	New York	0.94% (0.92%, 0.96%)	1.96 (1.93, 1.99)	22 (20, 25)	26.9 (24.8, 29)	1st: 24% (21%, 27%) 2nd: 20% (15%, 26%)
	Newark	1.08% (1.02%, 1.14%)	2.06 (1.96, 2.15)	24 (13, 36)	0.5 (0.2, 1.4)	1st: 0% (0%, 0%)
	Philadelphia	1.25% (1.22%, 1.27%)	2.6 (2.54, 2.66)	19 (16, 25)	5.8 (4.6, 7.8)	1st: 28% (19%, 39%)
	Pittsburgh	1.83% (1.73%, 1.94%)	1.89 (1.8, 1.98)	30 (28, 32)	33.5 (30, 36.8)	1st: 26% (22%, 29%) 2nd: 0% (0%, 0%)
	San Francisco	1.39% (1.31%, 1.47%)	2.16 (2.07, 2.24)	190 (160, 229)	0.1 (0.1, 0.1)	1st: 42% (40%, 45%) 2nd: 46% (42%, 51%)
	Spokane	1.75% (1.55%, 1.98%)	1.35 (1.3, 1.41)	184 (144, 234)	0.1 (0.1, 0.1)	1st: 0% (0%, 0%) 2nd: 0% (0%, 0%)
	St Louis	0.72% (0.68%, 0.76%)	2.18 (2.05, 2.32)	228 (164, 322)	0.1 (0.1, 0.1)	1st: 44% (42%, 46%) 2nd: 0% (0%, 0%) 3rd: 33% (31%, 35%)
	Washington	0.98% (0.94%, 1.03%)	2.42 (2.33, 2.53)	144 (33, 246)	0.2 (0.1, 1.1)	1st: 46% (42%, 50%)
2	Atlanta	0.78% (0.7%, 0.86%)	1.54 (1.47, 1.62)	N/A	N/A	1st: 39% [35%, 43%]
	Baltimore	0.97% (0.93%, 1.01%)	2.72 (2.6, 2.86)	N/A	N/A	1st: 61% [59%, 64%]
	Chicago	0.66% (0.64%, 0.68%)	2.13 (2.07, 2.19)	N/A	N/A	1st: 42% [40%, 43%]
	Fall River	1.04% (0.96%, 1.14%)	2.39 (2.2, 2.61)	N/A	N/A	1st: 46% [42%, 49%]
	Indianapolis	1.01% (0.95%, 1.08%)	1.37 (1.36, 1.38)	N/A	N/A	1st: 33% [32%, 35%]
	Kansas City	1.61% (1.51%, 1.73%)	1.64 (1.58, 1.7)	N/A	N/A	1st: 39% [36%, 42%] 2nd: 27% [25%, 29%]
	Milwaukee	1.05% (0.95%, 1.16%)	1.49 (1.44, 1.54)	N/A	N/A	1st: 48% [44%, 52%] 2nd: 55% [51%, 58%]
	Minneapolis	0.89% (0.83%, 0.96%)	1.37 (1.35, 1.41)	N/A	N/A	1st: 21% [19%, 23%]
	New York	0.98% (0.96%, 1%)	1.78 (1.77, 1.8)	N/A	N/A	1st: 0% [0%, 0%] 2nd: 62% [61%, 62%]
	Newark	1.08% (1.03%, 1.14%)	1.87 (1.8, 1.94)	N/A	N/A	1st: 82% [79%, 86%]
	Philadelphia	1.17% (1.14%, 1.19%)	2.81 (2.77, 2.88)	N/A	N/A	1st: 72% [71%, 73%]
	Pittsburgh	2.6% (2.5%, 2.69%)	1.4 (1.38, 1.42)	N/A	N/A	1st: 0% [0%, 0%] 2nd: 36% [35%, 38%]
	San Francisco	1.59% (1.5%, 1.69%)	1.91 (1.85, 1.97)	N/A	N/A	1st: 49% [48%, 51%] 2nd: 54% [50%, 58%]
	Spokane	1.15% (0.82%, 1.51%)	1.74 (1.43, 2.26)	N/A	N/A	1st: 28% [16%, 43%] 2nd: 23% [15%, 34%]
	St Louis	0.81% (0.75%, 0.87%)	1.9 (1.8, 2.02)	N/A	N/A	1st: 42% [39%, 46%] 2nd: 4% [0%, 18%]

						3rd: 36% [33%, 38%]
	Washington	0.96% (0.92%, 1.01%)	2.36 (2.26, 2.47)	N/A	N/A	1st: 55% [52%, 57%]
3	Atlanta	0.77% (0.7%, 0.85%)	1.89 (1.78, 2.01)	38 (31, 44)	0.1 (0.1, 0.1)	N/A
	Baltimore	0.94% (0.91%, 0.98%)	3.15 (3.03, 3.27)	55 (50, 60)	0.1 (0.1, 0.1)	N/A
	Chicago	0.71% (0.69%, 0.72%)	2.15 (2.11, 2.19)	9 (8, 10)	0.9 (0.8, 1)	N/A
	Fall River	1.05% (0.97%, 1.13%)	2.49 (2.34, 2.66)	83 (71, 97)	0.1 (0.1, 0.1)	N/A
	Indianapolis	0.87% (0.76%, 1.02%)	1.77 (1.56, 1.98)	34 (24, 52)	0.1 (0.1, 0.1)	N/A
	Kansas City	1.48% (1.39%, 1.58%)	2.1 (1.98, 2.21)	41 (36, 48)	0.1 (0.1, 0.1)	N/A
	Milwaukee	0.69% (0.64%, 0.73%)	2.2 (2.08, 2.33)	3 (2, 6)	0.7 (0.2, 1.1)	N/A
	Minneapolis	0.75% (0.67%, 0.85%)	1.69 (1.56, 1.84)	44 (33, 57)	0.1 (0.1, 0.1)	N/A
	New York	1.07% (1.05%, 1.09%)	1.87 (1.85, 1.88)	9 (9, 10)	7.8 (7.5, 8.2)	N/A
	Newark	1.06% (1.01%, 1.11%)	2.11 (2.03, 2.19)	75 (68, 83)	0.1 (0.1, 0.1)	N/A
	Philadelphia	1.25% (1.22%, 1.28%)	2.65 (2.59, 2.71)	12 (11, 12)	3.4 (3.1, 3.8)	N/A
	Pittsburgh	2.54% (2.44%, 2.66%)	1.51 (1.49, 1.54)	31 (29, 33)	8.6 (7.3, 9.8)	N/A
	San Francisco	1.15% (1.11%, 1.19%)	2.57 (2.5, 2.65)	50 (47, 54)	0.1 (0.1, 0.1)	N/A
	Spokane	1.76% (1.56%, 1.98%)	1.35 (1.3, 1.41)	184 (144, 232)	0.1 (0.1, 0.1)	N/A
	St Louis	1.43% (1.38%, 1.49%)	1.33 (1.33, 1.34)	153 (143, 163)	0.1 (0.1, 0.1)	N/A
	Washington	1.02% (0.98%, 1.07%)	2.6 (2.51, 2.7)	55 (51, 60)	0.1 (0.1, 0.1)	N/A
4	Atlanta	0.74% (0.68%, 0.8%)	1.96 (1.95, 1.97)	10 (8, 13)	10.7 (10.5, 10.9)	1st: 32% [30%, 35%]
	Baltimore	1.3% (1.25%, 1.34%)	1.96 (1.95, 1.97)	169 (161, 178)	10.7 (10.5, 10.9)	1st: 52% [51%, 53%]
	Chicago	0.75% (0.73%, 0.76%)	1.96 (1.95, 1.97)	26 (24, 27)	10.7 (10.5, 10.9)	1st: 30% [29%, 30%]
	Fall River	1.31% (1.25%, 1.38%)	1.96 (1.95, 1.97)	51 (37, 59)	10.7 (10.5, 10.9)	1st: 33% [30%, 35%]
	Indianapolis	0.72% (0.68%, 0.78%)	1.96 (1.95, 1.97)	7 (7, 7)	10.7 (10.5, 10.9)	1st: 38% [37%, 39%]
	Kansas City	1.31% (1.24%, 1.36%)	1.96 (1.95, 1.97)	267 (87, 511)	10.7 (10.5, 10.9)	1st: 53% [51%, 55%] 2nd: 36% [33%, 38%]
	Milwaukee	0.7% (0.66%, 0.73%)	1.96 (1.95, 1.97)	11 (10, 12)	10.7 (10.5, 10.9)	1st: 48% [46%, 50%] 2nd: 43% [38%, 49%]
	Minneapolis	0.56% (0.53%, 0.6%)	1.96 (1.95, 1.97)	57 (54, 62)	10.7 (10.5, 10.9)	1st: 37% [36%, 38%]
	New York	0.97% (0.96%, 0.98%)	1.96 (1.95, 1.97)	16 (15, 16)	10.7 (10.5, 10.9)	1st: 26% [26%, 27%] 2nd: 3% [2%, 5%]
	Newark	1.1% (1.06%, 1.13%)	1.96 (1.95, 1.97)	25 (22, 26)	10.7 (10.5, 10.9)	1st: 51% [48%, 53%]
	Philadelphia	1.54% (1.52%, 1.56%)	1.96 (1.95, 1.97)	46 (43, 50)	10.7 (10.5, 10.9)	1st: 38% [37%, 39%]
	Pittsburgh	1.74% (1.69%, 1.79%)	1.96 (1.95, 1.97)	31 (30, 33)	10.7 (10.5, 10.9)	1st: 22% [22%, 22%] 2nd: 0% [0%, 0%]
	San Francisco	1.53% (1.47%, 1.59%)	1.96 (1.95, 1.97)	827 (601, 954)	10.7 (10.5, 10.9)	1st: 54% [53%, 55%] 2nd: 55% [51%, 58%]
	Spokane	0.96% (0.87%, 1.05%)	1.96 (1.95, 1.97)	516 (152, 937)	10.7 (10.5, 10.9)	1st: 37% [36%, 38%] 2nd: 30% [26%, 34%]
	St Louis	0.8% (0.78%, 0.81%)	1.96 (1.95, 1.97)	218 (193, 284)	10.7 (10.5, 10.9)	1st: 44% [43%, 44%] 2nd: 0% [0%, 1%] 3rd: 37% [36%, 38%]
	Washington	1.11% (1.05%, 1.17%)	1.96 (1.95, 1.97)	702 (326, 949)	10.7 (10.5, 10.9)	1st: 47% [46%, 49%]
5	Atlanta	0.76% (0.76%, 0.77%)	1.79 (1.78, 1.81)	N/A	N/A	1st: 47% [47%, 47%]
	Baltimore	1.26% (1.25%, 1.27%)	1.79 (1.78, 1.81)	N/A	N/A	1st: 46% [46%, 46%]
	Chicago	0.77% (0.76%, 0.78%)	1.79 (1.78, 1.81)	N/A	N/A	1st: 37% [37%, 37%]
	Fall River	1.12% (1.11%, 1.13%)	1.79 (1.78, 1.81)	N/A	N/A	1st: 42% [41%, 42%]
	Indianapolis	0.87% (0.87%, 0.88%)	1.79 (1.78, 1.81)	N/A	N/A	1st: 51% [51%, 52%]
	Kansas City	1.51% (1.51%, 1.51%)	1.79 (1.78, 1.81)	N/A	N/A	1st: 48% [48%, 48%] 2nd: 29% [29%, 29%]

	Milwaukee	0.96% (0.95%, 0.96%)	1.79 (1.78, 1.81)	N/A	N/A	1st: 65% [65%, 66%] 2nd: 56% [56%, 57%]
	Minneapolis	0.73% (0.72%, 0.74%)	1.79 (1.78, 1.81)	N/A	N/A	1st: 35% [34%, 35%]
	New York	0.98% (0.98%, 0.99%)	1.79 (1.78, 1.81)	N/A	N/A	1st: 0% [0%, 0%] 2nd: 62% [62%, 62%]
	Newark	1.17% (1.16%, 1.17%)	1.79 (1.78, 1.81)	N/A	N/A	1st: 86% [85%, 87%]
	Philadelphia	1.62% (1.6%, 1.64%)	1.79 (1.78, 1.81)	N/A	N/A	1st: 52% [52%, 53%]
	Pittsburgh	1.84% (1.82%, 1.86%)	1.79 (1.78, 1.81)	N/A	N/A	1st: 0% [0%, 0%] 2nd: 52% [51%, 53%]
	San Francisco	1.77% (1.76%, 1.77%)	1.79 (1.78, 1.81)	N/A	N/A	1st: 48% [48%, 48%] 2nd: 53% [52%, 53%]
	Spokane	0.95% (0.95%, 0.96%)	1.79 (1.78, 1.81)	N/A	N/A	1st: 31% [31%, 31%] 2nd: 0% [0%, 0%]
	St Louis	0.89% (0.88%, 0.89%)	1.79 (1.78, 1.81)	N/A	N/A	1st: 38% [38%, 39%] 2nd: 4% [4%, 4%] 3rd: 32% [32%, 33%]
	Washington	1.18% (1.18%, 1.19%)	1.79 (1.78, 1.81)	N/A	N/A	1st: 42% [42%, 42%]
6	Atlanta	0.86% (0.81%, 0.89%)	1.61 (1.6, 1.63)	21.9 (21.4, 22.4)	7.2 (7, 7.4)	1st: 29% [27%, 31%]1.61 (1.6, 1.63)
	Baltimore	1.03% (0.99%, 1.06%)	2.46 (2.43, 2.54)	21.9 (21.4, 22.4)	7.2 (7, 7.4)	1st: 41% [40%, 43%]
	Chicago	0.68% (0.67%, 0.7%)	2.24 (2.2, 2.29)	21.9 (21.4, 22.4)	7.2 (7, 7.4)	1st: 28% [27%, 28%]
	Fall River	1.45% (1.39%, 1.51%)	1.83 (1.8, 1.87)	21.9 (21.4, 22.4)	7.2 (7, 7.4)	1st: 0% [0%, 0%]
	Indianapolis	1.06% (1.01%, 1.1%)	1.5 (1.49, 1.52)	21.9 (21.4, 22.4)	7.2 (7, 7.4)	1st: 19% [18%, 20%]
	Kansas City	1.35% (1.28%, 1.4%)	1.87 (1.82, 1.91)	21.9 (21.4, 22.4)	7.2 (7, 7.4)	1st: 34% [32%, 36%] 2nd: 17% [16%, 17%]
	Milwaukee	0.88% (0.82%, 0.92%)	1.67 (1.66, 1.69)	21.9 (21.4, 22.4)	7.2 (7, 7.4)	1st: 44% [42%, 46%] 2nd: 49% [46%, 51%]
	Minneapolis	0.81% (0.78%, 0.85%)	1.5 (1.49, 1.52)	21.9 (21.4, 22.4)	7.2 (7, 7.4)	1st: 15% [14%, 16%]
	New York	0.99% (0.98%, 1%)	1.87 (1.86, 1.89)	21.9 (21.4, 22.4)	7.2 (7, 7.4)	1st: 0% [0%, 0%] 2nd: 37% [36%, 38%]
	Newark	1.21% (1.19%, 1.25%)	1.81 (1.79, 1.85)	21.9 (21.4, 22.4)	7.2 (7, 7.4)	1st: 22% [21%, 24%]
	Philadelphia	1.25% (1.23%, 1.28%)	2.56 (2.51, 2.6)	21.9 (21.4, 22.4)	7.2 (7, 7.4)	1st: 34% [32%, 35%]
	Pittsburgh	2.1% (2.03%, 2.15%)	1.63 (1.61, 1.65)	21.9 (21.4, 22.4)	7.2 (7, 7.4)	1st: 0% [0%, 0%] 2nd: 0% [0%, 0%]
	San Francisco	1.68% (1.63%, 1.73%)	1.97 (1.95, 2.03)	21.9 (21.4, 22.4)	7.2 (7, 7.4)	1st: 36% [35%, 37%] 2nd: 68% [66%, 70%]
	Spokane	1.35% (1.29%, 1.44%)	1.51 (1.49, 1.55)	21.9 (21.4, 22.4)	7.2 (7, 7.4)	1st: 10% [9%, 10%] 2nd: 5% [4%, 5%]
	St Louis	0.66% (0.64%, 0.68%)	2.35 (2.31, 2.39)	21.9 (21.4, 22.4)	7.2 (7, 7.4)	1st: 46% [45%, 47%] 2nd: 0% [0%, 0%] 3rd: 33% [32%, 35%]
	Washington	1.7% (1.65%, 1.78%)	1.69 (1.68, 1.72)	21.9 (21.4, 22.4)	7.2 (7, 7.4)	1st: 0% [0%, 0%]
7	Atlanta	0.63% (0.6%, 0.65%)	1.96 (1.96, 1.98)	21.1 (20.8, 21.4)	7.4 (7.2, 7.8)	1st: 41% [39%, 43%]1.96 (1.96, 1.98)
	Baltimore	1.26% (1.23%, 1.3%)	1.96 (1.96, 1.98)	21.1 (20.8, 21.4)	7.4 (7.2, 7.8)	1st: 14% [13%, 14%]
	Chicago	0.76% (0.74%, 0.77%)	1.96 (1.96, 1.98)	21.1 (20.8, 21.4)	7.4 (7.2, 7.8)	1st: 20% [20%, 21%]
	Fall River	1.54% (1.5%, 1.56%)	1.96 (1.96, 1.98)	21.1 (20.8, 21.4)	7.4 (7.2, 7.8)	1st: 0% [0%, 0%]
	Indianapolis	0.79% (0.75%, 0.83%)	1.96 (1.96, 1.98)	21.1 (20.8, 21.4)	7.4 (7.2, 7.8)	1st: 30% [29%, 31%]
	Kansas City	1.27% (1.23%, 1.31%)	1.96 (1.96, 1.98)	21.1 (20.8, 21.4)	7.4 (7.2, 7.8)	1st: 38% [36%, 40%] 2nd: 20% [20%, 21%]
	Milwaukee	0.74% (0.71%, 0.76%)	1.96 (1.96, 1.98)	21.1 (20.8, 21.4)	7.4 (7.2, 7.8)	1st: 60% [59%, 61%] 2nd: 55% [53%, 58%]
	Minneapolis	0.57% (0.55%, 0.6%)	1.96 (1.96, 1.98)	21.1 (20.8, 21.4)	7.4 (7.2, 7.8)	1st: 29% [28%, 30%]
	New York	0.95% (0.94%, 0.96%)	1.96 (1.96, 1.98)	21.1 (20.8, 21.4)	7.4 (7.2, 7.8)	1st: 0% [0%, 0%] 2nd: 40% [39%, 41%]
	Newark	1.1% (1.06%, 1.13%)	1.96 (1.96, 1.98)	21.1 (20.8, 21.4)	7.4 (7.2, 7.8)	1st: 32% [30%, 35%]
	Philadelphia	1.61% (1.58%, 1.64%)	1.96 (1.96, 1.98)	21.1 (20.8, 21.4)	7.4 (7.2, 7.8)	1st: 0% [0%, 0%]

	Pittsburgh	1.68% (1.64%, 1.71%)	1.96 (1.96, 1.98)	21.1 (20.8, 21.4)	7.4 (7.2, 7.8)	1st: 11% [11%, 11%] 2nd: 0% [0%, 0%]
	San Francisco	1.66% (1.6%, 1.71%)	1.96 (1.96, 1.98)	21.1 (20.8, 21.4)	7.4 (7.2, 7.8)	1st: 35% [34%, 36%] 2nd: 67% [65%, 68%]
	Spokane	0.91% (0.87%, 0.95%)	1.96 (1.96, 1.98)	21.1 (20.8, 21.4)	7.4 (7.2, 7.8)	1st: 27% [26%, 29%] 2nd: 13% [12%, 13%]
	St Louis	0.72% (0.69%, 0.74%)	1.96 (1.96, 1.98)	21.1 (20.8, 21.4)	7.4 (7.2, 7.8)	1st: 35% [35%, 36%] 2nd: 0% [0%, 0%] 3rd: 23% [22%, 24%]
	Washington	1.19% (1.16%, 1.23%)	1.96 (1.96, 1.98)	21.1 (20.8, 21.4)	7.4 (7.2, 7.8)	1st: 30% [29%, 31%]
8	Atlanta	1.21% (1.2%, 1.22%)	1.94 (1.93, 1.95)	5.6 (4.9, 6.5)	9.9 (9.5, 10.2)	1st: 15% [10%, 20%]
	Baltimore	1.21% (1.2%, 1.22%)	1.94 (1.93, 1.95)	529 (161, 939)	9.9 (9.5, 10.2)	1st: 53% [50%, 55%]
	Chicago	1.21% (1.2%, 1.22%)	1.94 (1.93, 1.95)	7 (7, 8)	9.9 (9.5, 10.2)	1st: 0% [0%, 0%]
	Fall River	1.21% (1.2%, 1.22%)	1.94 (1.93, 1.95)	14 (13, 15)	9.9 (9.5, 10.2)	1st: 0% [0%, 0%]
	Indianapolis	1.21% (1.2%, 1.22%)	1.94 (1.93, 1.95)	6 (5, 8)	9.9 (9.5, 10.2)	1st: 31% [28%, 34%]
	Kansas City	1.21% (1.2%, 1.22%)	1.94 (1.93, 1.95)	36 (30, 40)	9.9 (9.5, 10.2)	1st: 45% [42%, 47%] 2nd: 29% [26%, 32%]
	Milwaukee	1.21% (1.2%, 1.22%)	1.94 (1.93, 1.95)	5 (5, 6)	9.9 (9.5, 10.2)	1st: 35% [32%, 38%] 2nd: 27% [21%, 33%]
	Minneapolis	1.21% (1.2%, 1.22%)	1.94 (1.93, 1.95)	2 (2, 2)	9.9 (9.5, 10.2)	1st: 0% [0%, 0%]
	New York	1.21% (1.2%, 1.22%)	1.94 (1.93, 1.95)	9 (9, 9)	9.9 (9.5, 10.2)	1st: 0% [0%, 0%] 2nd: 0% [0%, 0%]
	Newark	1.21% (1.2%, 1.22%)	1.94 (1.93, 1.95)	17 (15, 19)	9.9 (9.5, 10.2)	1st: 23% [20%, 27%]
	Philadelphia	1.21% (1.2%, 1.22%)	1.94 (1.93, 1.95)	15 (15, 15)	9.9 (9.5, 10.2)	1st: 0% [0%, 0%]
	Pittsburgh	1.21% (1.2%, 1.22%)	1.94 (1.93, 1.95)	19 (18, 20)	9.9 (9.5, 10.2)	1st: 13% [12%, 13%] 2nd: 0% [0%, 0%]
	San Francisco	1.21% (1.2%, 1.22%)	1.94 (1.93, 1.95)	133 (60, 236)	9.9 (9.5, 10.2)	1st: 49% [46%, 51%] 2nd: 41% [38%, 45%]
	Spokane	1.21% (1.2%, 1.22%)	1.94 (1.93, 1.95)	366 (85, 920)	9.9 (9.5, 10.2)	1st: 36% [33%, 38%] 2nd: 29% [25%, 34%]
	St Louis	1.21% (1.2%, 1.22%)	1.94 (1.93, 1.95)	74 (70, 77)	9.9 (9.5, 10.2)	1st: 39% [38%, 40%] 2nd: 0% [0%, 0%] 3rd: 34% [33%, 36%]
	Washington	1.21% (1.2%, 1.22%)	1.94 (1.93, 1.95)	8 (8, 8)	9.9 (9.5, 10.2)	1st: 0% [0%, 0%]

6. Models with age structure

We argue in the main text that including reactive reductions in contact rates in response to recent mortality substantially improves model fit, for 2 reasons: (a) because such time-delayed negative frequency dependent processes increase the tendency for oscillations in disease incidence, and (b) the mortality data from 1918 shows slowing of exponential epidemic growth at a much earlier stage than would be expected from exhaustion of the susceptible population.

A counter explanation to (b) is that the population is structured, with heterogeneity in contact rates between compartments. The simplest model with such structure is a two compartment SEIR model (53), with a symmetric 2x2 mixing matrix (with three elements νR_{11}, $\nu R_{12}= \nu R_{12}$, νR_{22}, where $1/\nu$ is the infectious period, 1.8 days) describing transmission between compartments. We extended the model outlined in the text to incorporate such structure. This introduces three new parameters (we now have three transmission parameters rather than just R_0, plus a parameter describing the proportion of the population in the first compartment), but conversely we lose the two parameters governing the reactive contact reduction mechanism. Hence overall, this model variant has one more parameter than our default model. It should be emphasized that we still assume public health interventions had an effect: we are only trying to substitute heterogeneous mixing for the reactive contact rate reduction of the original model.

Fitting this model with all parameters being city-specific gives an equally good fit as the default non-structured model (albeit at the cost of one additional parameter per city, namely 15 more parameters in total), as shown in Table S3. However, allowing *all* the mixing matrix parameters to be city-specific is highly unrealistic, as reflected in the extreme values of some of the parameter estimates (Table S3). In reality we would expect the causes of heterogeneity (e.g. age-structure) to be similar in all cities.

If we impose the conditions that 20% of the population needs to be in the first compartment (school age children made up approximately 20% of the population in 1918), and that R_{11} is the largest of the transmission parameters, then the model fit worsens, despite the fact that two of the mixing parameters are still being fitted as city-specific. The log likelihood obtained is approximately equal to that found for the default model variant 4 (see Table 1 and Figure 3 of main text), which fits two fewer parameters per city overall. Indeed, in terms of the numbers of parameters fitted, this variant (B in Table S3) is most properly compared with model variant 1 in Table 1 of the main text. Moreover, some individual cities (especially those with pronounced double peaks) are now fitted very poorly. Most importantly, the resulting parameter estimates are rather extreme – in nearly all cases, 80%+ of transmission occurs within the first compartment, with transmission being non self-sustaining in the other compartment.

Such extreme heterogeneity in transmission is more reminiscent of a large fraction of the population having pre-existing immunity than contact-rate based heterogeneity in transmission. However, there is also considerable variation between cities in transmission parameters – R_0 (the dominant eigenvalue of the next generation matrix defined from the mixing matrix) varies between 1.4 and 3.6 for model variant B, with similar levels of variation in individual compartment transmission parameters. There are also distinct differences in transmission estimates between the cities with a single-peaked epidemic and those with two peaks – the model reproduces the latter by fitting a slower epidemic in the larger, lower transmission compartment – rather than by attributing differences to control measures. Indeed, when we attempted to fit a model variant with a common R_0 value for all cities (while allowing mixing matrix parameters to vary on a city-specific basis subject to the constraint on R_0), it was impossible to achieve satisfactory convergence of the MCMC algorithm (log likelihood below -15,000).

We conclude that while heterogeneity in transmission (due to immunity or contact rate heterogeneity) cannot be completely ruled out as an explanation of the early slowing of the rate of growth of the epidemic curves seen in 1918, the resulting models fit much less well for an equivalent number of parameters (or, equivalently, need more parameters to be fitted as city-specific). If we make the reasonable assumption that at least some of the transmission parameters in heterogeneous mixing models should be universal to all cities, then such models largely fail to reproduce the trends seen in 1918.

Table S3: As table 1 of main text, except showing results for 2 model variants with age structure.

	mean posterior log likelihood	μ, per-capita death rate	Transmission parameters	Proportion of population in first (smaller) compartment	p_c, effectiveness of control measures	Reduction in mortality due to controls	Reduction in mortality for optimal controls
A	-2308	per-city – 1.3% [0.8%-2.8%]	per-city – R_{11}=2.6 [1.6–4.2] R_{12}= R_{21}=0.1 [0.0–0.5] R_{22}=2.1 [0.0–7.2]	per-city 0.27 [0.03-0.48]	per-city – 32% [0%-69%]	29% [0%–72%]	71% [0%–100%]
B	-3247	per-city – 1.2% [0.7%-2.6%]	per-city – R_{11}=9.9 [7.2–14.5] R_{12}= R_{21}=0.2 [0.0–2.0] R_{22}=0.6 [0.0–1.7]	fixed at 20% for all cities	per-city – 30% [0%-72%]	37% [0%–74%]	76% [0%–100%]

7. Alternative mortality data sets

Throughout the above analysis we have used the mortality dataset derived by Collins (48) giving estimates of excess pneumonia and influenza related mortality due to the pandemic of that year. However estimating excess mortality is always difficult (see Section 2.1), and in any case it is not immediately apparent that excess mortality above previous years' pneumonia and influenza-related deaths is the best proxy for infection incidence. We therefore also undertook some analyses of the total pneumonia and influenza related weekly mortality reported for the period 7 September 1918-1 March 1919. In total we found 25 weeks of data for the largest 47 cities of the US (a shorter period than for the excess mortality, which was available up till mid May 1919) (49, 50).

The conclusions of the correlative analyses reported in the main text and in Section 3 above remained unchanged using total pneumonia and influenza mortality data. We also fitted model variant 4 to the data. The quality of fit was good (log-likelihood of -2848, though note that only 25 weeks of data for each city were fitted, compared with 37 for the excess mortality dataset), as shown in Figure S10 (compare with Figure 3 in the main text). Table S4 summarizes the parameter estimates for this model, which again were very comparable to those obtained using the excess mortality dataset.

We conclude that the conclusions of our study are robust to the precise choice of mortality dataset used.

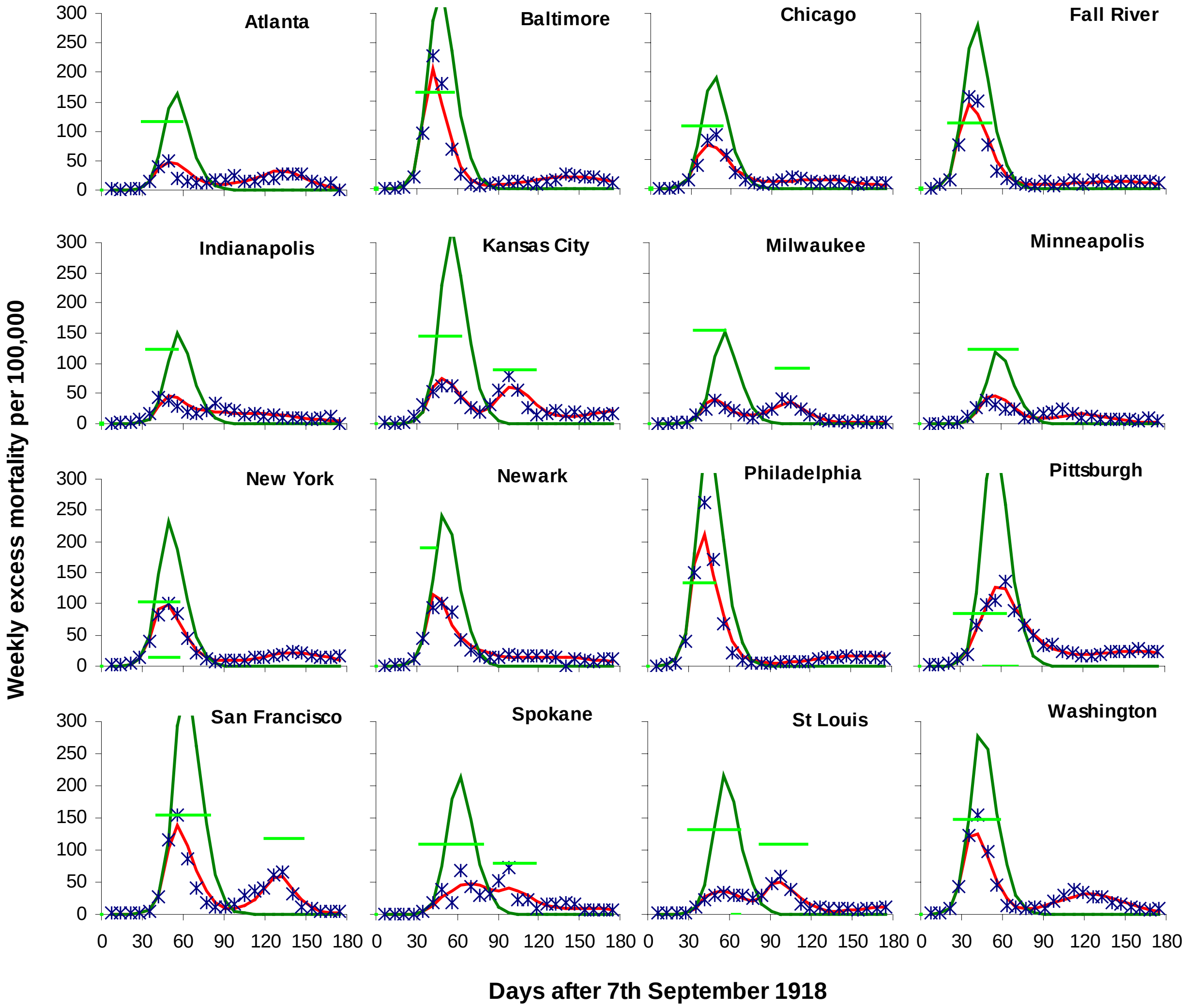


Figure S10: As Figure 3 in main text, but showing fit of model variant 4 to total weekly pneumonia and influenza related deaths for the period 7 September 1918-1 March 1919.

Table S4: As Table 1 in main text, showing fit of model variant 4 to total weekly pneumonia and influenza related deaths for the period 7 September 1918-1 March 1919.

mean posterior log likelihood	μ, per-capita death rate	R_0	κ, threshold for contact reduction (per 100,000)	*T*, memory period for contact reduction	p_c, effectivenes s of control measures	Reduction in mortality due to controls	Reduction in mortality for optimal controls
-2848	per-city – 1.3% [0.6%-2.1%]	common– 1.92 (1.91, 1.93)	per-city – 170 [9.7-843]	common – 20.4 (20.1, 20.6)	per-city – 37% [0%-65%]	42% [21%–66%]	87% [36%–100%]

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