

**COVID-19: examining
the effectiveness of
non-pharmaceutical
interventions**

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COVID-19: examining the effectiveness of non-pharmaceutical interventions

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Executive summary

Introduction

The purpose of this report from the Royal Society is to assess what has been learnt about the effectiveness of the application of non-pharmaceutical interventions (NPIs) during the COVID-19 pandemic of 2020 – 2023 by assembling and examining evidence from researchers around the world. These NPIs were a set of measures (described in Box 1) aimed at reducing the person-to-person transmission of severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2), the virus that caused the pandemic.

Six groups of researchers were commissioned to assemble evidence reviews for this report, examining the effectiveness of a range of NPIs that were applied with the aim of reducing the transmission of SARS-CoV-2. Researchers were tasked with documenting what has been learnt, identifying gaps in knowledge and considering how these might be filled in the future. This report summarises these evidence reviews and interprets them alongside national case studies. It pays particular attention to the context and the constraints on the types of research that could be and were performed during the pandemic.

The report is non-judgemental on the timing and manner in which NPIs were applied in different regions and countries around the world. It focuses on understanding the impact of NPIs on SARS-CoV-2 transmission and makes no assessment of the economic or other societal impacts of the different NPIs. Assessing these other impacts are important tasks for the many different COVID-19 inquiries that are underway around the world.

From the start of the pandemic, rapidly growing scientific information was deployed continuously to help to control its spread. The genome of the causative virus, SARS-CoV-2, was sequenced from some of the very earliest samples available from infected humans in China. This sequence information enabled the development of precise molecular diagnostic

tests that could be used for diagnosis and mass testing of populations, the development of vaccines and continuous monitoring of the evolution of the virus. The development of tests led to the widespread implementation of ‘test, trace and isolate’ interventions early in the pandemic. COVID-19 was the first pandemic in which it was feasible to conduct prophylactic and therapeutic drug trials and to create novel vaccines during the course of the pandemic, saving lives and modifying the outcomes.

However, despite extraordinary scientific capabilities, for most of the first year of the pandemic the only measures available to slow the transmission of the novel virus were NPIs. For those that were infected and seriously ill, there were no specific treatments or preventative measures in the form of drugs or vaccines. The supportive measures of modern medicine, such as oxygen supplementation, pulmonary ventilation and other forms of advanced life support, saved many lives, but did nothing to slow transmission.

What are NPIs?

The principles behind NPIs are firmly grounded in prior knowledge about the epidemiology and biology of infectious diseases. In essence, the transmission of an infection from one human to another can be prevented if the transmission pathway can be blocked effectively. For an airborne virus such as SARS-CoV-2, effective measures reduce exposure to virus that has been exhaled by infected people (by breathing, talking, coughing or sneezing). Measures that can assist, in theory, include the wearing of face masks, enhanced ventilation and social distancing. Where infectious virus survives on surfaces (furniture, clothes or hands), cleaning regimes including enhanced handwashing can help. Personal protection equipment (PPE), common in healthcare environments (including gloves, visors, gowns and masks) potentially offers protection against exposure.

Early clinical studies of COVID-19 strongly suggested that the primary routes for acquiring infection were likely to be by direct inhalation or exposure of the mucosal surfaces of the nose and mouth to virus suspended in airborne droplets or, as was realised some months into the pandemic, in aerosols. Early evidence of fomites (contaminated surfaces), extensively contaminated with SARS-CoV-2 viral nucleic acid shed from infected people, pointed to the possibility that hand-to-face contact might also transmit the infection.

This view was informed by prior knowledge of the transmission mechanisms of other respiratory viruses, such as influenza, respiratory syncytial virus (RSV) and the coronavirus (now named SARS-CoV-1) that caused the SARS outbreak in several countries around the world in 2003.

Use of NPIs for infectious disease control

Considering the incomplete knowledge about this new viral infection and prior knowledge, many governments around the world implemented measures similar to those used just over a century earlier during the 1918 influenza pandemic. Some countries in Asia implemented measures based on their more recent experience of outbreaks of SARS and Middle East Respiratory Syndrome (MERS).

NPIs included the wearing of masks and enhanced personal hygiene measures, including enhanced surface cleaning and handwashing. Social distancing was introduced and enforced to variable extents. Social distancing measures included closures of schools and workplaces, as well as entertainment, leisure and sporting venues.

These closures were often augmented by stay-at-home orders for all but essential workers. Border controls and closures were put in place in many countries with the aim of reducing the movement of cases across national borders. The precise measures, and the ways they were implemented, varied between countries according to their social and political-economic contexts and prior experiences.

In most of the world, NPIs remained the dominant mechanism for control of the pandemic until well into its second year. The UK was the first country to approve the use of vaccines against SARS-CoV-2, approving three vaccines during December 2020 and January 2021. By July 2021, approximately half of the UK's population had received two doses of vaccine. However, it took until January 2022 for half of the global population to have had two doses – and a year later in January 2023 the global figure had risen to approximately 63%¹.

The challenge for governments around the world facing a pandemic is how to minimise the harms to their populations. The harms of a pandemic are the morbidity and mortality from the viral infection, coupled with the social disruption and harms that follow from the direct and indirect consequences of that morbidity and mortality. The latter can be exceptionally severe if the extent of illness and social response to the illness disrupts the healthcare systems, infrastructure, goods and services on which the health, wellbeing, resilience and security of the population depend.

BOX 1

What are non-pharmaceutical interventions (NPIs)?

NPIs include any measure that is implemented during an infectious disease outbreak to attempt to reduce transmission that is not a vaccine or drug. NPIs can be behavioural, social, physical, or regulatory in nature. Their uptake and use can be encouraged through a variety of approaches, escalating from advice and guidance through to regulation. NPIs are therefore the first line of defence in the effort to contain outbreaks and to limit the impacts on affected populations before biological interventions become available. They have also been used alongside vaccines and drugs, especially where these interventions fail to prevent transmission. The precise ways in which NPIs were implemented during the COVID-19 pandemic varied between different countries and contexts.

The programme of work described in this report covered six broad categories of NPIs and the evidence available concerning their effectiveness at reducing transmission of SARS-CoV-2. The six categories are as follows:

Masks and face coverings

Masks act as barriers to virus particles in air being inhaled and/or exhaled through the nose or mouth. Virus-carrying droplets (larger, heavier particles) or aerosols (smaller, lighter particles)² captured on the inside or outside of the mask can no longer spread via the air. The materials and features of masks affect the size of the particles that are filtered out, and their resulting effectiveness. How well the mask fits the face of the wearer is also key. N95 masks (also known as respirators), when worn correctly, are highly effective barriers.

Social distancing and 'lockdowns'

Respiratory diseases are transmitted by infectious material carried by exhalations (eg breathing, talking, coughing or sneezing) from one individual to another. Increasing physical distance between individuals can reduce the amount of infectious material being carried to others in droplets and aerosols, although aerosols typically transmit over longer distances than droplets. A commonly recommended minimum distance of separation between individuals during the COVID-19 pandemic was two metres. Interventions on populations and communities included closures of schools, workplaces, places of worship and entertainment venues, as well as 'stay-at-home' orders ('lockdowns') that prevented most people from coming into contact with anyone outside their own homes.

Test, trace and isolate

SARS-CoV-2 is transmitted when infected individuals are in close proximity to others. A strategy employed to break the chain of transmission is to identify infectious people ('test'), determine with whom they have come into physical contact ('trace') and encourage or enforce both infected individuals and their contacts to stay at home and avoid physical contact with others until the risk of being infectious has subsided ('isolate').

Travel restrictions and controls across international borders

During a pandemic, where an infectious disease is spreading across international borders, restricting the ability of people to move between countries can be used to try to prevent the global movement of the pathogen. Border controls applied during the pandemic varied in stringency and took the form of complete or partial bans targeted at international travellers from particular regions perceived as being at higher risk. Often border controls were accompanied by requirements for international travellers to test and/or quarantine at the border of departure and/or arrival to enable some travel.

Environmental controls

Particles carrying infectious material vary in size from droplets that settle on surfaces close to the point of exhalation through to very fine aerosols which can linger in the air and travel further. Certain elements of building design and management can be implemented with the intention of restricting the spread of respiratory pathogens. These include enhancing ventilation systems to replace air carrying infectious aerosols with outside air, and filtering or treating air inside buildings to reduce infectious virus. Screens made of a variety of materials and reduced occupancy limits for rooms or buildings can also be used. Environmental controls also include cleaning of surfaces to remove droplets carrying infectious material and enhanced handwashing.

Communications

Effective communication about any of the physical, social or behavioural interventions is essential if people are to understand and be convinced of the reason for their use, as well as being willing to adopt and maintain the practices, and to do so correctly, so as to maximise effectiveness.

Two approaches to assessing the evidence on NPI effectiveness

There are two main approaches to generating and analysing evidence about the effectiveness of any intervention intended to alter health outcomes.

The first and most rigorous approach is to conduct carefully designed controlled trials, in which two or more closely matched groups of people are randomised to receive interventions that differ in strictly defined and limited ways. The advantage of this approach is that any changes in health outcome or any side effects of the intervention can be attributed with high confidence to the specific intervention(s).

One potential disadvantage is that typical controlled trials of new interventions include groups of people amounting at most to a few thousand people in each comparison arm, with participants chosen to enter trials chosen on the basis of very strict criteria. Extrapolating the results of such carefully supervised and monitored studies to much larger and more heterogeneous populations ‘in the real world’ is not straightforward. The intervention may turn out to be less effective in demographically more diverse populations; new and harmful interactions may be discovered when the intervention is provided to people with other conditions or taking other treatments; or rare but important adverse effects may only be discovered when the new intervention reaches a much larger population for the first time.

It is possible to conduct randomised controlled trials in populations, through study designs such as cluster-randomised studies, in which populations rather than individuals are randomised to different interventions.

The second approach is to conduct observational studies, ideally with large numbers of individual participants, to evaluate a new intervention by comparing the outcomes with similar observational data, which might be:

- **Historical** – for example, examining the outcomes in the same population before and after the intervention;
- **Geographical** – for example, comparing the outcomes in a population receiving the intervention with those in a population not receiving the intervention in a different region of a country or another country;
- **Modelled** – for example, comparing the outcomes in a population receiving an intervention with modelled data projecting the health outcome in the same population in the absence of the intervention, based on prior observed data about the progression of the condition in that population.

The observational approach has the advantage that an intervention can be evaluated ‘in the real world’ among very large numbers of people. The disadvantage is that there is a risk that the evidence is less reliable, because it may be confounded by other variables between the different groups under observation (eg demographic and social differences between the comparison populations, and/or incomplete and non-standardised observational datasets).

In the case of pharmaceutical and biotechnological interventions during the COVID-19 pandemic, controlled clinical trials of drugs and vaccines were conducted in many countries to examine their clinical effectiveness and to identify the side effects of new therapies and vaccines. The data from these trials formed the basis for licensing decisions by regulators. For example, the RECOVERY Trial enrolled more than 47,000 patients into a rigorously designed trial to test the efficacy of anti-inflammatory and anti-viral treatments to see if these could be repurposed for the treatment of the life-threatening consequences of COVID-19³. Similarly, newly created vaccines developed in Europe and the USA against SARS-CoV-2 were tested rigorously and found to be highly effective in reducing severe morbidity and mortality.

In comparison, controlled trials played a relatively small role in the evaluation of NPIs during the pandemic. There were three main reasons for this:

1. The first was that, in the face of significant knowledge gaps and immediate threats to health and life, the need for urgent actions took precedence over designing and implementing complex trials of NPIs in the absence of pre-prepared protocols. At the beginning of 2020, SARS-CoV-2 infection was spreading rapidly across the world. There was early evidence that respiratory spread was very likely to be the dominant route of transmission. NPIs were the only available steps that might slow or stop the spread of infection. These measures were known to be most likely to be effective when applied when infection numbers were still low. So, it was not a dominant consideration for policymakers to undertake prior formal evaluation of NPIs before their large-scale implementation.
2. The second reason was that that NPIs were typically implemented at a national scale, and applied in combinations on the grounds that NPIs would be expected to be complementary in their actions, eg masks + handwashing + social distancing + good ventilation. These measures were augmented by local or large-scale 'lockdowns' as numbers of cases rose. As soon as accurate diagnostic tests became available at scale, it became feasible to undertake large-scale testing, tracing and isolation of infected individuals and their contacts. These policy approaches to limiting the transmission of SARS-CoV-2 made trials to investigate the efficacy of individual NPIs almost impossible to implement.
3. The third reason was that excellent and rigorous protocols for controlled studies of drugs, vaccines and other biomedical interventions were available 'off the shelf'. By contrast, similar trials for complex interventions with strong social and behavioural elements are harder to design and implement and historically have been carried out much less frequently. An adequate design for studying the efficacy of NPIs would have needed to include measures of their desired impact in reducing SARS-CoV-2 transmission alongside measures of their potential undesirable impacts on a large variety of personal and societal variables. These ranged from the mental and physical health consequences of social isolation to the consequences of loss of education, jobs and businesses, and broader economic impacts.

This approach to the implementation of NPIs, which largely precluded formal large-scale comparison studies of the effects of different individual NPIs, or of any deliberate comparisons between the effect of packages of NPIs and that of using no NPIs, meant that there were no easy means of evaluating their uptake and effectiveness. There were very few studies of adequate scale to achieve reliable results that compared different types of NPI or that were able to compare, for example, the presence or absence of mask-wearing, or that could measure the effects of different levels of social distancing.

There were however a very large number of observational studies that were performed around the world during the pandemic and it is possible to learn a great deal from well-conducted observational studies performed at large scale. Such observational studies were used to explore the effectiveness of stringent social distancing measures, including stay-at-home orders, and closures of work, school, leisure, entertainment, and sporting facilities. In the case of mask usage, there were comparisons in healthcare settings between masks that provided lesser or greater barrier function. International comparisons were also helpful because some countries took markedly different approaches to the use of NPIs, although demographic and other societal differences mean that these should be interpreted with caution.

Evidence reviews and national case studies of the effectiveness of NPIs

For the purpose of this report, two approaches were taken to considering the evidence accrued during the pandemic on the effectiveness of NPIs. The first approach was to conduct six evidence reviews^{4, 5, 6, 7, 8, 9} examining each of the NPIs individually to examine what has been learnt about their effectiveness. Despite all of the caveats about the difficulties of interpreting data from observational studies, clear signals of effectiveness against transmission of SARS-CoV-2 could be discerned from the evidence reviews for several specific measures.

The second approach was to examine observational data on SARS-CoV-2 infections from three of the small number of regions or countries around the world where cases associated with domestic transmission were first identified in early 2020 and were subsequently contained at very low numbers for approximately the first 18 months of the pandemic. These were Hong Kong, New Zealand and South Korea. In each of these, stringent packages of NPIs were implemented and enforced throughout the pandemic until the second half of 2021. By that time there were large waves of the highly transmissible Delta and Omicron variants of SARS-CoV-2, which caused little harm to the vast majority of those that were fully vaccinated, and their national strategies switched to 'living with the virus'.

The evidence reviews were undertaken with the aim of establishing the quality and strength of the deductive evidence about the effectiveness of individual NPIs. They were conducted according to a rigorous well-established methodology, which was originally developed to bring together evidence from well-designed clinical trials. When this methodology was applied to observational studies of NPIs it highlighted the inevitable limitations of these studies. Firstly, because interventions were almost invariably implemented in combinations, it was extremely hard to distinguish and measure the effects of any single intervention independently of the others. Secondly, many studies used routinely collected data sets, which were not designed with post hoc evaluation in mind. Thirdly, comparison groups were not always included and when available, they were rarely well matched. These and other limitations are classified in such evidence reviews as causing potential biases in the outcomes of individual studies. The word 'bias', when used in this way, does not have the same meaning as it does when used in common parlance. Specifically, it does not imply that the researchers were biased or partial in seeking a particular outcome for their research, but instead that there were inherent characteristics in the study design that could reduce the reliability of the conclusions of the research. Such biases could result in either overestimation or underestimation of a measured effect.

The evidence reviews focused on the effectiveness of NPIs in relation to the transmission of SARS-CoV-2 infection (Box 2). They did not attempt to explore indirect, social or economic impacts. Nor did they attempt to explore the effects of social context and implementation style on effectiveness; these matters would have required complementary studies using different methods, including qualitative analysis.

BOX 2

What has been learnt about NPI effectiveness?

Masks and face coverings

The weight of evidence from all studies suggests that wearing masks, particularly higher quality masks (respirators), supported by mask mandates, generally reduced the transmission of SARS-CoV-2 infection. Studies consistently, though not universally, reported that mask wearing and mask mandates were an effective approach to reduce infection. There is also evidence, mainly from studies in healthcare settings, that higher-quality 'respirator' masks (such as N95 masks) were more effective than surgical-type masks. The evidence suggested that masks with greater barrier function were more effective than those with lower barrier function; and mask wearing in the context of a mandate to wear masks was more effective than mask wearing in the context of voluntary behaviour.

Social distancing and 'lockdowns'

Most effective of all the NPIs were the social distancing measures. Stay-at-home orders, physical distancing, and restrictions on gathering size were repeatedly found to be associated with significant reduction in SARS-CoV-2 transmission, with more stringent measures having greater effects. Early in the pandemic certain sub-populations, such as the elderly, were found to be particularly vulnerable to severe disease and death resulting from SARS-CoV-2 infection. Social distancing measures aimed specifically at

protecting the elderly, such as restrictions on visitors and 'cohorting' staff with residents in care homes (separating residents into groups, each cared for by a specific group of staff), were frequently associated with reduced transmission and reduced outbreaks within care homes. Regarding school closures and other school-based measures, the evidence suggests that they were associated with reduced COVID-19 incidence within schools and the community. However, the effectiveness of these measures was varied (compared to community-wide measures such as stay-at-home orders), time-dependent, and often contingent on the adherence to the measures implemented and the targeted age group of school children.

Test, trace and isolate

Test, trace and isolate approaches were used as a key intervention in many countries, especially those pursuing zero-COVID policies. Studies from several countries that implemented high levels of contact tracing with isolation of infected individuals and their contacts found reductions in COVID-19 deaths. Strong evidence was also found for the effectiveness of contact tracing apps. For example, a trial of the UK's app (alongside communications and manual tracing interventions) on the Isle of Wight was associated with a substantial reduction in transmission¹⁰.

Travel restrictions and controls across international borders

Observational evidence from national case studies, including New Zealand, showed that comprehensive border control policies could reduce but not eliminate the number of infected travellers or their contacts at the borders entering the country. However, despite most countries introducing travel restrictions during the COVID-19 pandemic, few studies have been published so far examining the effectiveness of these measures when implemented alone. Based on the available evidence, symptomatic or exposure-based screening, including temperature screening before travel, was found to have had no meaningful effect on reducing importation or transmission. Targeted travel restrictions including banning entry early in the pandemic from specific countries probably had a moderate effect on transmission but quickly became less effective once the number of cases rose, whereas quarantine at entry borders was found to have the highest levels of effectiveness.

Environmental controls

The review found evidence that enhanced ventilation, air treatment to remove infectious virus and reduced room occupancy did reduce transmission within particular settings. However, these measures were typically applied in combination with other NPIs, so accurately and individually quantifying

their effectiveness was not possible. Many were observational studies conducted retrospectively rather than planned prospectively. As a consequence the studies were unable to control fully for possible confounding factors. It is also the case that the effectiveness was only judged within the setting in which the control was applied, and not at the wider population level. There was insufficient evidence to judge the effectiveness of enhanced surface cleaning or the use of barriers. These are important gaps where laboratory studies could help provide insight.

Impact of communication in the UK on uptake of NPIs

Communications in this review were considered specifically in the UK context because political, social and cultural differences make it extremely hard to extrapolate findings about the effectiveness of communications from one country to another. The limited evidence confirmed that communication was sufficiently effective to ensure high adherence to NPIs, although also identifying the characteristics that led to non or less rigorous adherence. Trust and confidence in those communicating was important as was the clarity and consistency of the messaging and the opportunity for personal control. The limited evidence suggests that social media communications are less likely to be associated with higher adherence than those via the traditional media.

Three country experiences with NPIs to control viral transmission

There are important lessons to be learnt from how different nations implemented NPIs to control the transmission and spread of SARS-CoV-2. The implementation of NPIs differed between and within different countries by time, region, and stringency. There were prominent differences in the timing and intensity of test and tracing, social distancing and 'lockdown' measures. Asian countries that had more recently experienced SARS and other emerging infectious diseases, including MERS and avian influenza, such as China, Hong Kong, Taiwan, Singapore, South Korea and Vietnam, used that experience to take a strategic approach aimed at reducing transmission and thereby slowing the spread of infection as quickly as possible. These countries implemented early stringent NPIs, followed by Australia and New Zealand¹¹.

Three case studies from Hong Kong, New Zealand, and South Korea (summarised in Box 3) are used to illustrate these lessons. Over the course of the pandemic these were among a small number of locations worldwide that maintained low rates of transmission over a prolonged period.

These national and regional case studies show that it was possible, in certain contexts, to control transmission of SARS-CoV-2 for over a year by implementing early, stringent border controls accompanied by other strict NPIs to prevent and control domestic transmission. They also demonstrate that the effectiveness of NPIs varied inversely in relation to the transmissibility of the infection. As the pandemic progressed, the evolution of increasingly transmissible variants, particularly Omicron, became harder and harder to control using even the most stringent application of NPIs. However, by this point in the pandemic, effective vaccines were becoming widely available and countries pursuing 'zero-COVID' strategies switched to policies of high vaccine coverage and 'living with COVID'.

This adjustment was seen in all three of the country case studies, despite early success in containing the pandemic.

However, the results reported in the three national and regional case studies cannot simply be replicated in other countries and regions. The national and regional contexts for NPIs varied significantly around the world, according to geographical, political, demographic, socio-economic and regulatory factors. The nature of the national implementation of NPIs and their resulting effectiveness can only be understood in the context of a series of other extremely important interacting factors.

Cross-country comparisons of the effectiveness of NPIs are affected by multiple factors, most notably differences in demographic factors, healthcare systems, levels of economic prosperity, degrees of trust between citizens and public authorities, and testing and reporting of cases of COVID-19. Different countries or regions were differentially affected by COVID-19 with particular impacts on those with older populations¹²; higher levels of obesity¹³; greater incidence of chronic non-communicable diseases such as diabetes and cardiovascular disease; larger concentrations of lower income and larger households; and higher population densities¹⁴.

Countries also differed in their categorisation of COVID-19 deaths. For instance, Belgium included all deaths where COVID-19 was suspected to contribute, resulting in higher reported death rates early in the pandemic¹⁵, while others included only deaths in hospitals¹⁶. There were also stark differences in the availability of testing and thereby the numbers of reported cases.

BOX 3

Summary of case studies of countries that maintained low levels of transmission over a prolonged period of time.

Hong Kong Special Administrative Region

Hong Kong suffered some of the more severe effects of the SARS outbreak in 2003, experiencing almost a quarter of the 8,098 cases worldwide, with 302 deaths. This precipitated significant public investment in health infrastructure and diagnostic testing capacity. Strict policies were put in place during the COVID-19 pandemic that required those who tested positive to isolate for 21 days and those with whom they had been in contact to isolate for 14 days. Quarantine at borders for international travellers was similarly strict. It was estimated that only 27% of all cases that occurred in Hong Kong were confirmed by laboratory test, meaning that Hong Kong's containment of the pandemic cannot be attributed to these policies alone. Further measures included minimum distancing, curfews on restaurant opening times, bans on large events, requirements to work from home and school closures. Mask wearing was also mandated in all public settings with high compliance from the population. Vaccines were used to immunise approximately 60% of the population by the end of 2021. Uptake was lower in older adults. When the more transmissible Omicron variant arrived and rapidly spread, more than 10,000 deaths occurred largely in vulnerable elderly unvaccinated people.

New Zealand

New Zealand is a geographically isolated island group with a small population and hence is atypical. However, it is a useful example of how a country developed and implemented a national strategy for use of NPIs to enable the prolonged control and near elimination of SARS-CoV-2 infection. This strategy was built around stringent border controls, including tightly restricted entry criteria, with pre-departure and post-arrival testing of travellers; 14-day quarantine (initially by self-isolation, subsequently by supervised hotel-managed isolation and quarantine); strict test, trace and isolate measures; and local or national 'lockdowns' when domestic transmission was detected or at high risk of occurrence.

This approach controlled the initial outbreak of COVID-19 in New Zealand, where the first recorded case

was on 28 February 2020. By 8 June 2020, all domestic NPIs had been lifted and a total of 1504 cases and 22 deaths had been recorded. New Zealand remained mostly transmission-free until late 2021, despite regular positive tests among quarantined international arrivals.

The more transmissible Delta variant of SARS-CoV-2 was first detected in August 2021. By this stage the population of New Zealand was highly vaccinated and facing an increasing number of daily cases and the prospect of an extended 'lockdown', the government declared the end of the elimination strategy on 4 October 2021.

Whilst local NPIs were eased at this time, strict border controls remained in place. In mid-December, the highly transmissible Omicron variant was first detected in entering travellers. Community transmission was not identified until 23 January 2022, and this was followed by a large wave of Omicron infections across New Zealand.

South Korea

South Korea had experienced an outbreak of MERS in 2015 in which there were 186 cases and 38 deaths. This experience had prompted significant policy reform for pandemic preparedness. Testing infrastructure was well established and ready to be rolled out nationwide in drive-through testing facilities. Testing provided effective estimates of caseload in the country and was coupled with innovative use of technology to great effect. Global Positioning System (GPS) data from mobile phones were used to monitor movements of citizens who were alerted if they had been near a confirmed COVID-19 case and instructed to isolate. Arrivals from other countries were quarantined for 14 days at the border and those from Hubei in China were banned outright.

Citizen compliance with policies designed to mitigate transmission was also demonstrably higher than it had been during the MERS outbreak, suggesting that the population was more conscious of the risks around an emerging respiratory disease. The early adoption of these packages of NPIs contained the pandemic effectively and meant that an early 'lockdown' was avoided.

Conclusion

There is clear evidence from studies conducted during the pandemic that the stringent implementation of packages of NPIs was effective in some countries in reducing the transmission of COVID-19. There is also evidence for the effectiveness of individual NPIs, although, especially as the pandemic progressed and the virus became more transmissible, NPIs became less effective in controlling the transmission of SARS-CoV-2.

A common denominator of the evidence from the studies of individual NPIs and from the national case studies is that NPIs were, in general, more effective when the case numbers and the associated transmission intensity of SARS-CoV-2 were lower. This is because the size of the exposure, and therefore the risk of infection, of uninfected, non-immune people to viral infection is proportional to the number of cases in the community. Similarly, the stringency of the application of individual NPIs and groups of NPIs was important, so there was evidence that respirator masks were more effective than surgical masks and that two weeks of quarantine were more effective than shorter periods.

Lessons for the future

There are important lessons for the future. For policymakers and their professional advisers, there is a need to learn from national and international experience of the implementation of NPIs during the COVID-19 pandemic, and to understand in detail the differing national contexts and ways in which NPIs were implemented. National context was an important influence on the outcome of the COVID-19 pandemic.

For researchers and their funders, there is a lesson that observational studies can be facilitated if national and international collaborations can be established in advance of a future pandemic, with standardised protocols for data collection. While Randomised Controlled Trials (RCTs) should not be discounted, it is highly likely that most information in a future pandemic will continue to be observational. It should be possible to exploit more effectively, for the purposes of evaluation, the consequences of differences in the implementation of NPIs within and between countries and this would be much easier to achieve if protocols could be prepared in advance. So for the future, it is important to design protocols for observational research that can disaggregate the effects of NPIs by social groups and other demographic factors within countries.

Future assessments should also consider the costs as well as the benefits of NPIs, in terms of their impacts on livelihoods, economies, education, social cohesion, physical and mental wellbeing, and potentially other aspects. Drug regulators are able to make recommendations on the use of drugs based upon evidence of their effects and side effects. Similarly, policymakers will be able to make the best policy decisions on NPIs, which are in the main complex social interventions, if they have access to better evidence regarding their broader health and societal impacts. They could consider these alongside their effects on reducing the transmission of the infectious agent. The provision of such evidence will require pre-planned protocols, and in some cases prior research, to collect a wide variety of relevant health and social data systematically and, alongside this, an embedded system of expert research advice to assist policymakers in making extremely difficult policy decisions in the face of a severe pandemic.

The evidence assembled for the development of this report shows that, in the context of COVID-19 that was caused by a virus dominantly transmitted by a respiratory route, controlling the transmission of the virus required a clear plan for the stringent application of combinations of NPIs.

One of the most important lessons from this pandemic is that it proved possible to influence the outcome of the COVID-19 pandemic by means of the rapid development, evaluation and implementation at scale of specific treatments and vaccines. The effective application of NPIs ‘buys time’ to allow the development, evaluation and manufacturing of such therapies and vaccines at scale. So there is every reason to think that the application of combinations of NPIs will be important in future pandemics, particularly at early stages with novel pathogens when there are knowledge gaps and when therapeutics and vaccines are not yet available.

Introduction

The Royal Society's Programme on COVID-19 NPIs

The purpose of this report is to consider what current scientific evidence tells us about the effectiveness of non-pharmaceutical interventions (NPIs, Box 4) in preventing the transmission of severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2). It is intended for a wide audience including interested members of the public, public health workers, policymakers and those involved in inquiries in the UK and other countries seeking to learn from the COVID-19 pandemic.

At the beginning of the pandemic, effective vaccines and medications were not available and so NPIs were the only means that policymakers could use to try to reduce rates of transmission, with some countries aiming to eliminate domestic transmission altogether, and others aiming to reduce the number of severe cases and protect their healthcare systems from being overwhelmed. While vaccines were developed at an unprecedented pace, countries were solely reliant on NPIs until near the end of 2020. NPIs remained a key tool as nations began vaccine rollouts through 2021 and into 2022. Given that NPIs are likely to remain the first line of defence to resist any future novel pathogens, it is critical to understand their effectiveness, particularly as this has to be balanced against their social and economic costs.

The Royal Society commissioned six evidence reviews that are published alongside this report to establish what has been learnt about NPI effectiveness in the context of the COVID-19 pandemic. Each of these reviews was based on published research in English conducted during the pandemic. This report contains brief summaries of their conclusions. It also considers some of the key national geographical, demographic and socio-economic issues that affected how packages of NPIs were implemented in different countries. Some of these are illustrated in three case studies focused on Hong Kong, New Zealand, and South Korea, each of which managed to contain SARS-CoV-2 transmission at very low levels for a prolonged period.

With the worldwide rollout of COVID-19 vaccines and therapeutics, NPIs are no longer the dominant strategy for controlling SARS-CoV-2 transmission. Now is therefore an opportune time to learn lessons from the COVID-19 pandemic.

COVID-19 emergence and transmission as a pandemic

SARS-CoV-2, the viral cause of the disease coronavirus disease 2019 (COVID-19), led to the most significant pandemic in over a hundred years. The COVID-19 pandemic began with reports of pneumonia-like symptoms of unknown cause, affecting individuals in the city of Wuhan, capital of Hubei Province in China. The disease was subsequently confirmed to have arisen from infection with a novel coronavirus, now named SARS-CoV-2. Following these first cases in December 2019, SARS-CoV-2 spread rapidly in the city of Wuhan and within weeks¹⁷, began to be reported outside of China.

In response to the virus's rapid transmission, the World Health Organization (WHO) declared a 'Public Health Emergency of International Concern' on 30 January 2020. By February 2020, COVID-19 cases were recorded across Europe, Asia and the United States, with numbers of hospitalisations and deaths rapidly increasing^{18, 19}. Responding to the exponential increase in cases, the WHO declared a pandemic on 11 March 2020²⁰.

SARS-CoV-2 was a virus novel to humans and no effective vaccinations or medicines were available to protect people from the severe effects of COVID-19 disease. Instead, governments were reliant on NPIs. The purpose of implementing NPIs was to prevent the virus spreading between people by cutting off routes of transmission from person to person. In some countries a strategy was implemented for the application of NPIs that aimed to eliminate domestic transmission of SARS-CoV-2, a 'zero COVID strategy'. These countries applied NPIs to minimise importation of cases by infected travellers, accompanied by stringent application of local, regional or national NPIs to eliminate domestic transmission. In other countries, NPIs were implemented with the aim of slowing, but not eliminating, the transmission of infection, thereby reducing the number of severe cases and preventing healthcare systems from becoming overwhelmed. By the end of March 2020, NPIs had been introduced around the world. The measures introduced remained in place in different combinations and to different extents across the world throughout 2020 and into 2021, representing the largest global disruption to day-to-day life since the Second World War.

BOX 4

What are non-pharmaceutical interventions (NPIs)?

NPIs include any measure that is implemented during an infectious disease outbreak to attempt to reduce transmission that is not a vaccine or drug. NPIs can be behavioural, social, physical, or regulatory in nature. Their uptake and use can be encouraged through a variety of approaches, escalating from advice and guidance through to regulation. NPIs are therefore the first line of defence in the effort to contain outbreaks and to limit the impacts on affected populations before biological interventions become available. They have also been used alongside vaccines and drugs, especially where these interventions fail to prevent transmission. The precise ways in which NPIs were implemented during the COVID-19 pandemic varied between different countries and contexts.

The programme of work described in this report covered six broad categories of NPIs and the evidence available concerning their effectiveness at reducing transmission of SARS-CoV-2. The six categories are as follows:

Masks and face coverings

Masks act as barriers to virus particles in air being inhaled and/or exhaled through the nose or mouth. Virus-carrying droplets (larger, heavier particles) or aerosols (smaller, lighter particles)²¹ captured on the inside or outside of the mask can no longer spread via the air. The materials and features of masks affect the size of the particles that are filtered out, and their resulting effectiveness. How well the mask fits the face of the wearer is also key. N95 masks (also known as respirators), when worn correctly, are highly effective barriers.

Social distancing and 'lockdowns'

Respiratory diseases are transmitted by infectious material carried by exhalations (eg breathing, talking, coughing or sneezing) from one individual to another. Increasing physical distance between individuals can reduce the amount of infectious material being carried to others in droplets and aerosols, although aerosols typically transmit over longer distances than droplets. A commonly recommended minimum distance of separation between individuals during the COVID-19 pandemic was 2 metres. Interventions on populations and communities included closures of schools, workplaces, places of worship and entertainment venues, as well as 'stay-at-home' orders ('lockdowns') that prevented most people from coming into contact with anyone outside their own homes.

Test, trace and isolate

SARS-CoV-2 is transmitted when infected individuals are in close proximity to others. A strategy employed to break the chain of transmission is to identify infectious people ('test'), determine with whom they have come into physical contact ('trace') and encourage or enforce both infected individuals and their contacts to stay at home and avoid physical contact with others until the risk of being infectious has subsided ('isolate').

Travel restrictions and controls across international borders

During a pandemic, where an infectious disease is spreading across international borders, restricting the ability of people to move between countries can be used to try to prevent the global movement of the pathogen. Border controls applied during the pandemic varied in stringency and took the form of complete or partial bans targeted at international travellers from particular regions perceived as being at higher risk. Often border controls were accompanied by requirements for international travellers to test and/or quarantine at the border of departure and/or arrival to enable some travel.

Environmental controls

Particles carrying infectious material vary in size from droplets that settle on surfaces close to the point of exhalation through to very fine aerosols which can linger in the air and travel further. Certain elements of building design and management can be implemented with the intention of restricting the spread of respiratory pathogens. These include enhancing ventilation systems to replace air carrying infectious aerosols with outside air, and filtering or treating air inside buildings to reduce infectious virus. Screens made of a variety of materials and reduced occupancy limits for rooms or buildings can also be used. Environmental controls also include cleaning of surfaces to remove droplets carrying infectious material and enhanced handwashing.

Communications

Effective communication about any of the physical, social or behavioural interventions is essential if people are to understand and be convinced of the reason for their use, as well as being willing to adopt and maintain the practices, and to do so correctly, so as to maximise effectiveness.

NPI implementation at different stages of the pandemic

NPIs were implemented in different ways, typically depending on the amount of virus transmission at a given time. Other contextual factors, such as assessments by policymakers in different countries of what would be acceptable to their populations at different times throughout the pandemic, also affected policy decisions. Metrics used as proxies for the severity of the pandemic included symptomatic COVID-19 cases, Intensive Care Unit (ICU) admissions and deaths. The estimated reproduction (R) number (the average number of secondary infections produced by a single infected person) was also used as a measure of whether the incidence was increasing ($R > 1$) or decreasing ($R < 1$).

Between January and March 2020, confirmed cases increased exponentially around the world. Early public health advice focused on NPIs such as handwashing and surface cleaning to reduce the potential risk of infection via contaminated surfaces and, in many countries, on mask wearing. Those displaying symptoms of a fever and new persistent dry cough were encouraged or instructed to self-isolate. Many countries started to operate enhanced screening measures at international borders for travellers from Wuhan or the Hubei province of China. Some countries banned travel from China altogether. As the disease spread and became established in other countries, such as Iran and Italy, border controls began to encompass travellers from those countries too. Some large public gatherings started to be cancelled, but early on this was usually on a voluntary basis. Those which went ahead were scrutinised subsequently as potential key moments of rapid spread (also described as ‘super spreader’ events).

By March 2020, as mortality rose across the world, it had become clear that there were many more cases across the world than were confirmed using diagnostic testing. At that time, tests were only available in limited numbers in many countries, because these were newly developed and the global scale-up of manufacturing and distribution had not yet happened. At the same time, most countries did not have the infrastructure in place for large-scale diagnostic testing, though there were important exceptions, including some countries that had recently experienced significant outbreaks of other emerging infections such as avian influenza, SARS and MERS. The limit on testing capacity meant that tests were often reserved for the most severely ill patients. With no accurate measure of cases in the population and rapidly growing need for ICU care, there was significant concern that healthcare systems could be overwhelmed.

In many countries with high incidence rates of COVID-19, all but essential workplaces were closed, education was moved ‘online’ and all public gatherings were stopped. Stay-at-home orders (commonly referred to as ‘lockdowns’) were put in place alongside other NPIs, with exceptions only for key workers. Reductions in ICU occupancy, death rates and the R number were observed subsequently in countries associated with stringent implementation of NPIs and rigorous and, in some countries, enforced compliance.

The most stringent ‘lockdown’ measures were associated with widespread disruption to social relationships, education, work and recreation. These had adverse effects on mental and economic health and wellbeing at personal and population levels. As metrics indicated reduced transmission of the virus, many governments opted for a policy of phased reintroduction of normal activity. A different approach to NPI implementation was required to enable greater social mixing, while keeping transmission rates as low as possible.

Diagnostic testing capacity was increased as new tests became available and, in many countries, tests were made available to the whole population via test, trace and isolate (TTI) schemes. This meant that a more accurate estimate of the incidence of COVID-19 cases and SARS-CoV-2 infections (including asymptomatic infections) could be made and those infected, and their recent physical contacts, were instructed to isolate until such a time that they were no longer deemed a significant infection risk. Diagnostic testing capacity in the general population was expanded by the development and widespread distribution of lateral flow devices, which could be conducted at home.

Businesses and public services deemed non-essential during ‘lockdowns’, were gradually reopened. Face coverings were often made mandatory in public spaces including transport, shops and entertainment venues. Some countries stipulated the use of N95/ FFP2 respirator masks with a higher barrier specification than typical surgical masks.

Public venues were often required by authorities to institute enhanced cleaning and ventilation regimes to try to limit transmission via the environment. Occupancy limits for smaller spaces and one-way movement systems were also deployed, as well as screens at customer service points to form a barrier between customers and staff. Hand sanitising stations and handwashing guidance posters became widespread.

As countries relaxed the implementation of NPIs, and as more transmissible variants of SARS-CoV-2 evolved (Alpha, Delta, Gamma and Omicron), further waves of SARS-CoV-2 infection occurred. These led policymakers in many countries to reintroduce more stringent packages of NPIs, including further ‘lockdowns’.

Towards the end of 2021, many populations around the world were becoming less vulnerable to the consequences of COVID-19. This was due to increasing population immunity as a consequence of either natural infection and/or vaccination largely preventing the worst clinical outcomes of the infection. This immunity was less effective at preventing the asymptomatic transmission of SARS-CoV-2 or the milder manifestations of COVID-19. This was seen in the waves of COVID-19 infection after mid-2021 where, despite high rates of transmission and resulting large case numbers, the number of deaths was considerably lower. The very high transmissibility of the Omicron variant, compared with the early variants of SARS-CoV-2, reduced the efficacy of even the most stringent NPIs. At this point most countries stepped down the implementation of NPIs and moved to a policy of ‘living with the virus’ and lifted most or all restrictions.

Challenges of NPI policy implementation

The decision to apply NPIs in countries around the world was one reserved to government policymakers. They faced the extremely difficult task of rapidly responding to a new, poorly understood virus that was causing many severe illnesses and deaths. This required them to balance the potential benefits to the population of applying NPIs, particularly saving lives and protecting health care systems, with the other health, social and economic consequences of those same NPIs. These other consequences, in the absence of prior evidence and experience, could only be estimated or were unknown.

Understanding a new virus

Improving understanding of the biology of SARS-CoV-2 was critical to optimising the implementation of NPIs. There was very little specific evidence on the duration of infectiousness and the precise route of transmission of SARS-CoV-2 at the start of the pandemic.

Authorities were initially reliant on what was known about other respiratory viral pathogens such as the closely related coronavirus, renamed SARS-CoV-1, which caused severe acute respiratory syndrome (SARS). There was a major outbreak of SARS in several countries around the world in 2003. It became clear that SARS-CoV-2 transmission differed markedly compared to SARS-CoV-1. For SARS-CoV-1, infectiousness peaked at a similar time to the peak of symptoms. In the case of SARS-CoV-2, individuals could transmit the virus even if they did not present with any symptoms, accounting for up to 40% of cases^{22, 23, 24, 25} which made it much harder to limit the spread of infection. Asymptomatic or pre-symptomatic cases could only be identified using diagnostic tests, which were not widely available at the start of the pandemic.

This meant that initial policies of requiring those with symptoms to self-isolate would not capture an important fraction of active infections.

This partly prompted early policies of nationwide movement restrictions as a means of trying to contain all individuals who were infectious. Establishing the relationship between viral load (the level of virus in a person's blood), viral kinetics (ie how viral load changes over the course of infection) and infectiousness was important to inform advice on the duration of self-isolation required upon testing positive.

It was also thought initially that SARS-CoV-2 was spreading primarily via droplets rather than aerosols²⁶. Droplets are larger-sized airborne particles expelled in the breath that travel only a short distance in the air before depositing on surfaces. In contrast, smaller particles in aerosols can remain suspended over several metres from the source and for several hours after expulsion. In the early months of 2020, greater emphasis was placed on implementation of NPIs such as cleaning surfaces and hand hygiene. As the pandemic progressed, more evidence emerged on the role of aerosols in transmission of SARS-CoV-2 and by October 2020, many authorities modified advice to reflect this^{27, 28}.

NPIs require compliance at a population level to be fully effective

Many NPIs are social and behavioural measures. As such, their effectiveness depends on compliance by the population. If, for example, social mixing continues to occur during a 'lockdown', then there are still routes for the virus to be transmitted between individuals.

Effective communication and enforcement are key to compliance. Alongside public communication, many countries introduced legally enforced requirements to comply with particular NPIs. Consequently, the effectiveness of communication, coupled with the degree of enforcement of any rules, regulations or legislation, in the context of differing national and local cultures, social norms and levels of trust, were important determinants of the uptake and effectiveness of NPIs.

NPIs impose costs and burdens on society

As social measures, NPIs, by design, alter human behaviour and interactions. Alongside reducing the ability of individuals to transmit the virus between one another, changes in behaviour and human interaction have other consequences. For example, social distancing can lead to loneliness, unhappiness and disturbance to mental health, due to disruption of family life, social relationships and lack of physical contact. School and workplace closures cause disruption to education and work, with potentially adverse educational and economic consequences. Movement restrictions cause disruptions to people's livelihoods and social networks, with consequences for access to food and income. In many countries, such effects were experienced differently according to geography, ethnicity, socioeconomic status and gender, often amplifying existing social and health disparities.

Understanding all these other health, social and economic impacts of NPIs is of course extremely important and is a key question for inquiries being conducted around the world. However, this report focuses specifically on the impacts of NPIs on SARS-CoV-2 transmission while acknowledging the need for similar analyses of all the other consequences of the implementation of NPIs.

Challenges of testing the effectiveness of NPIs during the pandemic

Assessing the impact of NPIs on transmission of SARS-CoV-2 in real time presented a considerable challenge. NPI policies were implemented at pace without evidence of how effective they would be in preventing COVID-19. The predominant consideration when these policies were implemented was the priority to save lives.

The outcomes of RCTs are considered the gold standard for evidence of the effectiveness of a clinical intervention. RCTs rely on precisely controlling a clinical study so that the only thing that differs between two groups being compared is the treatment. This applies whether the comparison is a drug vs no drug/another drug or, in the case of NPIs, an NPI vs no NPI/another NPI. However, NPIs were usually implemented in combinations throughout the COVID pandemic, which meant that there were very few studies that were capable of establishing the effectiveness of a single NPI (for example, when mask and social distancing policies were implemented simultaneously). Similarly, new variants of the virus with enhanced abilities to be transmitted and to evade immune responses became dominant throughout the pandemic making it harder to compare effectiveness of NPI measures over time.

Despite the challenges of conducting robust scientific studies on the effectiveness of NPIs during a pandemic, a wealth of observational data were collected and analysed. Analysis of these data provide important insights into the effectiveness of different NPIs in reducing transmission of SARS-CoV-2 and preventing serious COVID-19 outcomes, especially when complemented by carefully constructed case studies from specific countries to demonstrate how NPIs were operationalised during the pandemic.

Evidence reviews considering the effectiveness of NPIs on transmission of the SARS-CoV-2 virus

Scope

The Royal Society commissioned six evidence reviews covering scientific publications in the English language for the following categories of NPIs:

- Masks and face coverings
- Social distancing and ‘lockdowns’
- Test, trace and isolate
- Travel restrictions and controls across international borders
- Environmental controls
- Communication of NPIs in the UK

The six NPI categories were chosen to ensure evidence was considered for the majority of NPIs that were implemented during the pandemic. Handwashing and other hand hygiene measures (such as use of gloves and hand sanitiser) and coughing etiquette measures (eg recommendations for people to cough into their elbows) were not considered directly in this programme. Several other systematic reviews of evidence collected during the COVID-19 pandemic, including one conducted by a team that developed the evidence review on the effectiveness of masks for this report, found very few studies considering effectiveness of these measures for reducing transmission of SARS-CoV-2^{29, 30, 31}.

The six evidence reviews were peer reviewed and are published in full in a themed edition of *Philosophical Transactions A*³², alongside this report.

Reflecting the heterogeneity of available data and the difficulties of measuring transmission directly, assessment of NPI impact on viral transmission was evaluated from a variety of measures including the effective reproduction number (R_t), numbers of reported cases, hospitalisation rates and mortality rates.

Evidence variability and evaluation of quality

Challenges in the evaluation of NPIs were the large variation in the types of evidence and analyses and finding the best ways to evaluate the quality of evidence, bias and cause-effect relationships. Evaluation criteria such as GRADE (Box 5) were applied where appropriate. This assumes a hierarchy of preferred study designs and includes tools for detecting bias. RCTs are viewed as the ‘gold standard’ and application of GRADE criteria to other types of study design, including observational studies, means that these can only achieve a lower score³³ and are classified as ‘lower methodological quality or biased.’

Using tools that evaluate behavioural interventions as if they are pharmaceutical interventions does not adequately embrace the complexity and variation in high-quality NPI observational studies. This strict stance can wrongly lead to claims that, given a lack of RCTs, there is no evidence and hence no action should be taken.

Alongside the evidence reviews, a second approach was taken to analyse the effectiveness of NPIs. Observational data on the use of NPIs collected systematically throughout the pandemic were investigated for correlations with COVID-19 case numbers and transmission at national or regional level.

Three case studies were chosen from the small number of regions or countries around the world in which cases associated with domestic transmission were first identified in early 2020 and subsequently contained at very low numbers for approximately the first 18 months of the pandemic. These were Hong Kong, New Zealand and South Korea.

BOX 5

What is GRADE and how was it applied here?

GRADE (Grading of Recommendations, Assessment, Development, and Evaluations)³⁴ is an established framework for developing and presenting summaries of evidence, and for systematically judging the certainty of evidence, before making recommendations in medicine and public health.

The GRADE system classifies the certainty of evidence into four subjective categories: Very low, Low, Moderate and High. ‘Very low’ means that the true effect could be markedly different from the estimated or measured effect. ‘High’ means that the authors are confident, on the basis of the evidence, that an estimate or measurement is close to the true effect.

The certainty of evidence from RCTs is usually ‘High’ because the intervention and outcomes are controlled in a formal experiment. Cause can confidently be linked to effect.

When the evidence consists of observations made without a formal study design, the certainty is usually ‘Low’. Between the two extremes are other study designs, including cohort studies and case-control studies, plus mathematical modelling studies, which typically give evidence of Low or Moderate certainty.

In general, the certainty of evidence is lower if there is reason to suspect bias, if it is imprecise or inconsistent, or if the size of the measured effect is small.

GRADE was not formally used across all of the commissioned evidence reviews. However the majority of studies carried out during the pandemic were observational; a minority had formal designs such as case-control or RCTs. Therefore much of the evidence from these NPI studies was considered to have a low certainty rating. Nevertheless, the evidence from these studies is informative and, combined with other information, helps to assess the effectiveness of each NPI.

Masks and face coverings

Recommendations and/or mandatory policies to use masks such as medical masks (also known as surgical masks), respirators (ie close fitting masks that filter out small particles), and other facial coverings, including cloth masks, were commonplace during the COVID-19 pandemic. Initially implemented in healthcare settings, mask recommendations and mandates for members of the public became more common globally as the pandemic progressed through 2020 and 2021.

Previous systematic reviews have examined evidence of the effectiveness of mask wearing in reducing the transmission of respiratory viruses or SARS CoV-2, or both^{35, 36, 37}. In general, evidence drawn solely from RCTs has not yielded firm conclusions about the effectiveness of masks in reducing transmission, whereas a large volume of observational studies suggests, with low to moderate confidence, that masks are effective in reducing transmission.

Against this background, a new, rapid synthesis was carried out of evidence from RCTs and observational studies, including information published up to 27 January 2023, on the effectiveness of masks in reducing the transmission of SARS CoV-2, both in community and in healthcare settings.

Review approach

The primary question was: What is the best available evidence about the effectiveness of masks in reducing transmission of SARS-CoV-2 in community-based and healthcare settings? Two subsidiary questions were also asked:

What is the best available evidence about the types of masks (respirators, surgical masks, or other face coverings such as cloth masks) that were the most effective at reducing transmission of SARS-CoV-2 in community-based and healthcare settings?

What is the best available evidence about the effectiveness of mandatory masking policies in reducing transmission of SARS-CoV-2 in community-based and healthcare settings?

The investigation included 35 studies in community settings (three RCTs and 32 observational studies) and 40 in healthcare settings (one RCT and 39 observational). 95% of studies included were conducted before the highly transmissible Omicron variants emerged.

Most observational studies relied on self-reported mask wearing among participants (n=42/46; 91%). The majority of studies evaluated whether individual mask wearers were protected from SARS-CoV-2 infection, but studies that measured effects in whole populations (eg cluster RCTs, communities living under differing mask mandates) did not distinguish between whether transmission was reduced from infected mask wearers or to uninfected mask wearers, or both.

Standard risk of bias tools were used for RCTs (ROB-2) and observational studies (ROBINS-I). Results are not presented as a meta-analysis owing to the great heterogeneity in study design and the variety of outcome measures across the included studies. For the same reason of study design heterogeneity, formal GRADE assessment to assess the certainty of evidence was not universally applied. Rather, each study was evaluated separately in terms of its design, risk of bias, precision and direction of reported effects.

Effectiveness of masks in reducing SARS-CoV-2 transmission

The majority of studies found that masks (n=39/45; 87%) and mask mandates (n=16/18; 89%) reduced infection compared to those that found no effect (n=8/66; 12%). Figure 1 shows, for a subset of 26 studies, the evidence that mask wearing led to a reduction in SARS-CoV-2 transmission in community (14 comparisons) and healthcare settings (12 comparisons). A further seven observational studies found that respirators were more protective than surgical masks, while five found no statistically significant difference between the two mask types. Two studies found increases in transmission though these were not statistically significant.

Although most of the numerous studies included in this review found that masks reduce transmission, almost all were at critical risk of bias in at least one of the domains embodied in ROB tools. In addition, the size of measured effects was variable and typically of low precision.

Conclusion

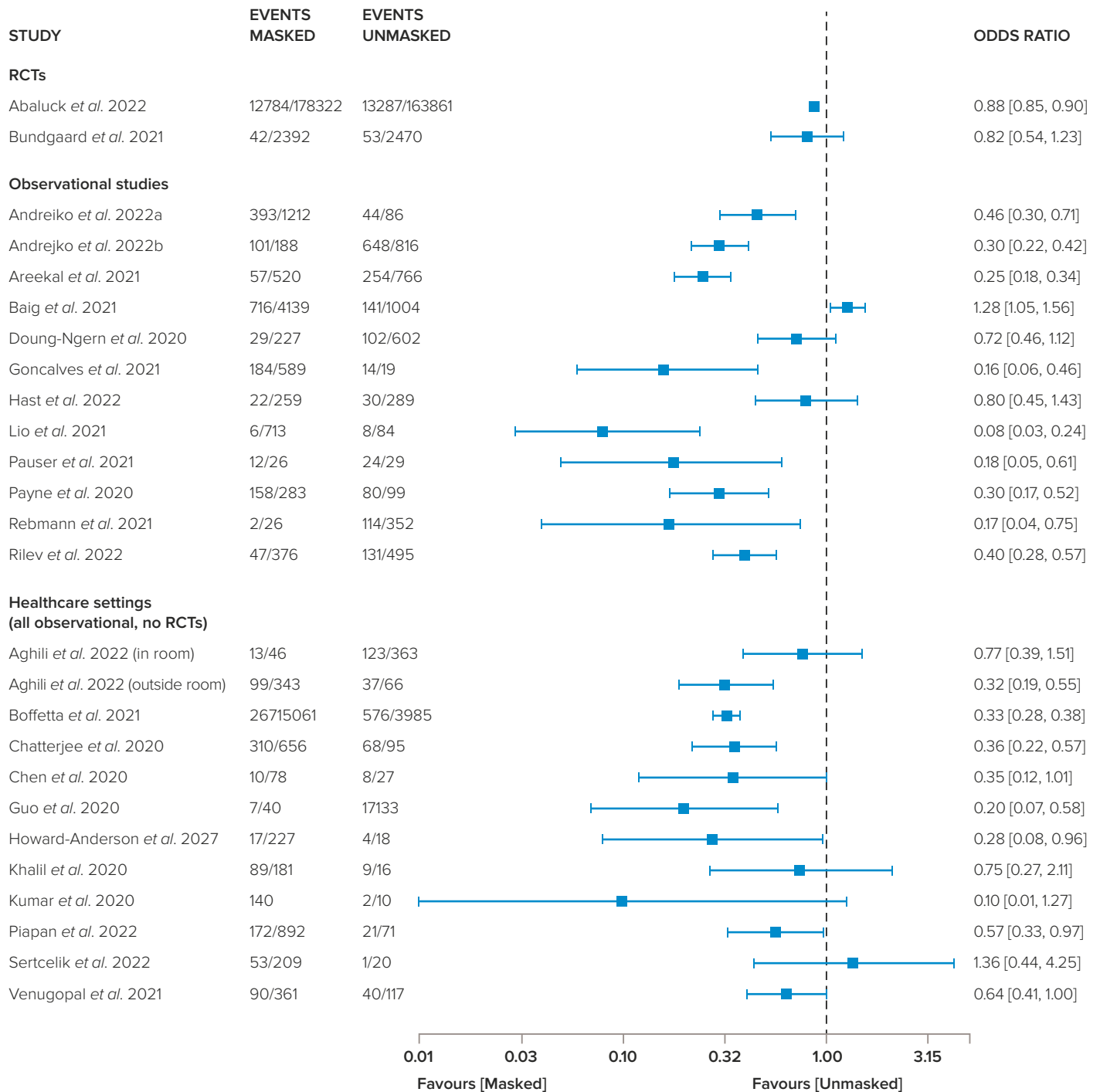
Most of the studies included in this rapid systematic review were observational rather than experimental. Study designs commonly suffered from a critical risk of bias. The effects measured in each study were variable in magnitude and generally of low precision. Nevertheless, the weight of evidence from all studies suggests that wearing masks, wearing higher quality masks (respirators), and mask mandates generally reduced the transmission of SARS-CoV-2 infection.

Masks and face coverings

FIGURE 1

Forest plot summarising outcome of studies comparing masked and unmasked.

Forest plot summarising the outcomes of studies that compared SARS CoV-2 infection in people or groups of people classified as wearing or not wearing masks, addressing the primary question of the review. The plot includes the subset of studies for which published data permitted the calculation of odds ratios and 95% confidence intervals. A value of less than one means the study found that masks reduced infection.



Social distancing and ‘lockdowns’

Social distancing measures, including recommendations for people to stay separated from other individuals, alongside legal mandates to stay at home (‘lockdowns’), represent an evolving category of intervention that changed as the pandemic progressed and often differed markedly between countries.

Review approach

To investigate the effectiveness of social distancing and ‘lockdowns’, the review divided this broadly-framed NPI into nine specific social distancing measures all designed to limit person-to-person contacts within the community.

- School closures (104 studies)
- School measures – other than closures (18 studies)
- Workplace closures (37 studies)
- Workplace measures – other than closures (12 studies)
- Catering, fitness and personal care service measures (9 studies)
- Care home measures (16 studies)
- Restrictions on mass gatherings (28 studies)
- Physical distancing (34 studies)
- Stay-at-home orders (151 studies)

The evidence assessed included observational studies, simulation studies, quasi-experimental studies, and RCTs. Multinational studies were more frequently focused on more homogeneous measures (such as stay-at-home orders and restrictions on gatherings) while sub-national and national studies were common for more heterogeneous measures (such as care home measures and workplace measures).

Variations in study types, geographic scope and outcome metrics made the drawing of generalised conclusions challenging. However, the more fundamental challenge was that the epidemiological conditions when the NPIs began, their duration and the level of adherence to the interventions varied considerably between different settings and times. Furthermore, few social distancing measures were implemented individually. There were frequently a set of complementary measures in place (often with multiple social distancing measures, as well as provisions such as mask wearing, test-and-trace programmes, and vaccination)³⁸. Thus, this review focussed on evidence from rigorously conducted studies which estimated the effects of interventions and considered their scientific and causal structure while acknowledging and discussing the potential associated confounders. Most published evidence considered and analysed observational data, reflecting the reality of conducting policy-relevant epidemiological research during an unfolding pandemic in which interventions were rarely randomised to facilitate their evaluation.

Social distancing and ‘lockdowns’

Social distancing measures reduced epidemic growth of SARS-CoV-2

In general, the studied social distancing measures were associated with considerable reductions in community-level transmission of SARS-CoV-2 and the growth of the epidemic. Measures of greater stringency were typically associated with greater reductions in transmission during the COVID-19 pandemic, demonstrating what epidemiologists call a biological gradient³⁹. Stay-at-home orders, physical distancing measures, and restrictions on gathering sizes were repeatedly found to be associated with substantial community-wide reductions in SARS-CoV-2 transmission and were frequently assessed using the time-varying reproduction number, Rt.

Effectiveness of social distancing in care homes and schools

In countries with care homes for the elderly, care home residents were among those most vulnerable to COVID-19 among all sub-populations. Within care home settings, strict cohorting of staff alongside residents and restrictions on visitors were frequently found to be associated with reduced SARS-CoV-2 transmission among residents and reduced outbreaks within care homes^{40, 41, 42, 43}. Most children, on the other hand, were at much lower risk of severe outcomes of COVID-19. Nonetheless, to reduce overall transmission, school closures were implemented in many countries, and when schools remained open for children of key workers or were reopened, social distancing measures were frequently implemented to limit transmission risks.

The evidence generally indicated that school closures and other school-based measures were associated with reduced COVID-19 incidence within schools and the community^{44, 45, 46, 47, 48, 49}. However, the effectiveness of these measures was more varied (compared to community-wide measures such as stay-at-home orders), time-dependent, and often contingent on the degree of adherence to the measures implemented (for example, mask wearing) and the targeted age group of school children^{50, 51, 52}.

Effectiveness of workplace social distancing

There was less consistent evidence for workplace measures⁵³, with evidence of impact more frequently found for more stringent measures such as workplace closures^{54, 55, 56, 57}. Similarly, the impact associated with restrictions on sizes of gatherings^{58, 59}, frequently depended on the stringency of the measures implemented. For example, in workplaces, mandatory mask wearing⁶⁰ for all but those with exemptions was found to be more effective than temperature screening⁶¹.

Inferring causality

The ability to draw causal conclusions from individual studies is, in most cases, limited by the nature of the data analysed. However, the systematic review produced here focussed on nine specific social distancing measures, used multiple assessors, encompassed a wide range of independent studies, across varying geographies and time periods. The body of evidence consistently pointed to substantial community-level benefits of social distancing measures for reducing SARS-CoV-2 transmission, preventing large-scale outbreaks, and controlling rapid epidemic growth. Stringent social distancing measures, whether applied to particular settings or to the entire population, were identified to be the most effective means of reducing transmission.

When epidemiologists look to demonstrate that a particular exposure causes a disease, the consistency of the specific disease consistently associated with the exposure is seen as strengthening the case for a causal link⁶². In this setting, however, reduced transmission of other directly transmitted diseases (such as influenza and RSV) being associated with the social distancing measures implemented to limit SARS-CoV-2 transmission, strengthens the case for the measures limiting person-to-person contact and thereby limiting pathogen transmission. In short, there is considerable coherence in the evidence base and plausibility that fewer close contacts between people will yield fewer opportunities for transmission.

Additionally, observational data collected on human mobility, such as mobile-phone-based movement data^{63, 64}, have also indicated in many settings that (i) social distancing policies did substantially, and often dramatically, change population mobility and (ii) substantially reduced mobility was usually associated with substantial reductions in SARS-CoV-2 transmission. This additional evidence, which might usefully itself be the subject of a subsequent targeted systematic review, contributes further coherence and plausibility to the evidence base reviewed in detail here.

Limitations

Nonetheless, there are limitations for inferences based on the amassed evidence base in this area. The key limitation is the dearth of experimental studies. The risks associated with this limitation are mitigated in part by the large number of independent studies considered from a wide range of settings and by consideration of the coherence and plausibility of the causal pathways associated with social distancing measures. Another limitation is the scope of this study. Here, the focus is on inferences based on quantitative studies, which explored the impact of social distancing measures on SARS-CoV-2 transmission and COVID-19-related mortality, without any direct focus on the socioeconomic, developmental, or mental-health-related impacts. While the coherence of evidence from a range of study settings and types makes inferences more robust, these inherent heterogeneities present challenges. The heterogeneities, including the dominant SARS-CoV-2 variant, the immune history of the population under study and the pre-COVID-19 mixing patterns, considerably complicate the comparison across the evidence from different studies. This is a natural limitation of a large systematic review.

Conclusion

Taken together, the breadth, strength and consistency of evidence relating to nine types of social distancing measures indicate that many stringent social distancing measures and combinations of such interventions substantially reduced SARS-CoV-2 transmission. The evidence does not indicate what would be the 'right' measure (or measures) for a future pathogen, but it does indicate that stringent social distancing measures can be effective at limiting transmission.

Test, trace and isolate

TTI and associated diagnostics were applied in combination or individually, firstly to identify infected individuals and then to encourage them to isolate, with the aim of reducing the interaction between infectious and susceptible individuals and hence reducing the degree of community transmission. Different combinations of TTI elements (together with other NPIs) were used in different countries, over different time periods, and against different phases of the pandemic.

Review approach

To understand whether TTI measures were effective, this review focussed on articles that quantified their real-world impact on transmission (measured in a variety of ways) and attempted to take account of confounding factors. Many theoretical (model and simulation based) studies were identified that examined the theoretical impact of TTI but were excluded from this review as they did not measure real-world effectiveness.

In total 25 papers, published between 1 January 2020 and December 2022, were assessed in detail out of over 26,000 that were identified through online database searches. For each of these papers the key results were extracted, and risk of bias assessments were conducted.

The papers were separated to consider different forms of TTI intervention, including:

- The population impact of testing strategies (12 papers)
- TTI as part of a package of measures with other NPIs (two papers)
- Contact tracing (seven papers) and isolation (four papers)

Of these papers, 11 used COVID-19 data from multiple countries together with rather coarse characterisations of the levels of control⁶⁵ used to generate estimates of the impact of TTI and other mitigation measures. The remaining 14 papers used more detailed information from within single countries or regions to estimate the impact.

Effectiveness of testing strategies

Twelve papers examined testing strategies, of which nine were statistical analyses of global trends. The analyses of early data found weak or non-significant impacts of TTI^{66, 67}, presumably because effects were overwhelmed by the impact of more intense measures such as national ‘lockdowns’. Analyses of later data^{68, 69, 70, 71, 72, 73, 74} generally showed that TTI elements were significantly correlated with a reduction in transmission, although reduced transmission was measured in different ways in the studies.

Three other studies examined testing strategies. The mass-testing of all individuals in Slovakia in October and November 2020 was shown to generate a 56% reduction of infection⁷⁵. The introduction in Liverpool of self-testing with lateral flow devices from November 2020 – January 2021 led to a 43% and 25% reduction in hospital admissions over early and late time periods⁷⁶. These findings echo the study of regular work-place testing in the Canton Grisons area of Switzerland during February and March 2021 which led to a 50% reduction in incidence over three weeks⁷⁷.

Effectiveness of contract tracing

Seven papers focused exclusively on contact tracing. A broad-scale analysis of data from five countries (October 2020 – January 2021) found no significant correlation between contact tracing and cases. However, a more focused study on 313 Chinese cities (January – July 2020) found that strict implementation of contact tracing rules led to a significant decrease in the number of cases.

Three papers used detailed data from the UK. Following the introduction of the contact tracing app on the Isle of Wight during May and June 2020, a substantial drop in R from 1.3 to 0.5 was observed. During October – December 2020, regions with higher app usage recorded lower numbers of cases, even when various methods to control for potential confounders were applied. Data handling issues that occurred in September 2020 led to a delay in contact tracing and this can be correlated to an increase in infections and deaths. These UK findings are supported by similar studies from Colombia^{78,79} where high levels of tracing (followed by isolation) led to a reduction in COVID-19 deaths.

Effectiveness of isolation

Once an individual contact has been identified by testing or tracing, the question arises of how that person is isolated. The four studies that considered this problem suggest that there is a benefit from the rapid isolation of contacts before laboratory results are available, ideally away from the home environment to avoid household transmission. An RCT conducted in England (April – July 2021) found that the effect of daily testing of contacts was at least equivalent to that of isolation of these contacts in terms of subsequent transmission.

TTI as part of packages of interventions

The two papers that considered TTI alongside a broader package of measures again took a population-level statistical approach and reported a spectrum of outcomes. In keeping with other early analysis, a broad-scale study

of 50 countries (January – July 2020) failed to find statistically significant results⁸⁰, while a more detailed analysis of South Korean data (January – November 2020) suggested TTI combined with public information campaigns was statistically correlated with a reduction in cases⁸¹.

Data quality challenges

Except for one RCT⁸², all of the articles identified were observational studies that analysed the impact of changes in national or regional control measures. This left many of the studies vulnerable to serious uncertainty, especially the use of simple classifications of TTI levels in many cross-country comparisons. Given that the priority during the pandemic was to protect lives, the lack of RCTs is unsurprising, but it does mean that there are major knowledge gaps, especially in how the impact of TTI is affected by the pandemic dynamics and the variant characteristics.

Conclusion

These 25 studies illustrate that TTI is a powerful tool for reducing transmission, although its effects may be eclipsed by other control measures such as extreme social distancing measures. When well-resourced compared to the number of infections (such that there is the capacity to rapidly test and obtain test results, rapidly trace contacts and for individuals to comply with isolation), TTI has the potential to interrupt chains of transmission and prevent establishment of infection. This was seen in Australia and New Zealand where travel restrictions helped to reduce the number of infections that were imported, allowing TTI to suppress any incursions. When COVID-19 cases are higher, TTI still has an important role to play in suppressing transmission, with electronic contact-tracing apps having substantial impacts, but without the burden on contact tracing teams. Rapid testing via lateral flow devices can also help to identify more cases in the community and suppress chains of transmission. Rapid testing can also help to reduce the burden of isolation by enabling earlier release of case contacts and could be explored further in future pandemics.

Travel restrictions and controls across international borders

‘International border controls’ is a broad overarching term covering NPIs as diverse as: border closure, centralised or localised (including at-home); quarantine of inbound travellers; restrictions in specific types of travellers, or those from specific geographic regions; temperature screening and testing; and/or vaccination requirements to cross a border. Almost all countries implemented some form of border control during the pandemic, although almost never in isolation, but rather as part of a suite of NPIs.

International border controls during the COVID-19 pandemic were intended to reduce the entry of infected travellers. It was hoped that reducing the number of infected people entering the country in conjunction with local control measures, especially testing for virus, tracing of contacts of infected people and isolation of people with infection and their contacts, could slow the transmission of infection. In a small number of countries, rigorous border closures, coupled with stay-at-home orders and TTI measures, were introduced with the aim of achieving a national ‘COVID-19 free’ status. These countries included Australia, New Zealand, several Pacific islands and Antarctica. These countries are geographically isolated, with small and relatively dispersed populations, and they are not global transport hubs. It should be noted that stringent international border control measures were also implemented with some success in countries such as China, Hong Kong, Japan, Malaysia, Singapore, South Korea and Vietnam which are more densely populated and less isolated.

Border controls had a much less significant effect once COVID-19 became established in a country. In essence, if travellers are coming to the country from a region with a similar prevalence of infection, then the impact of border controls will be negligible. In principle, border controls could help to slow the introduction of new variants, which in the case of SARS-CoV-2 evolved to more transmissible variants and to variants that might be selected to overcome pre-existing natural or vaccine-induced variants.

Border controls can be seen as part of a strategy primarily designed to prevent importation of either a new infectious disease or a new variant of a pre-existing disease, and as such can be seen as subtly different from other NPIs which are designed to prevent ongoing transmission.

Review approach

Despite their widespread usage, there is very limited evidence surrounding the use of border control measures. Therefore, a narrative evidence synthesis approach was used, building on the small number of systematic reviews^{83, 84, 85, 86, 87} already published elsewhere and supplementing it with papers published since the final systematic review.

The review focussed on the following research questions:

1. What were the effects of border control measures, if any, in reducing the transmission of SARS-CoV-2?
2. In which locations, if any, were these measures effective?
3. At what time were such measures effective?

The main findings of each previously published review were considered with regard to the research questions above and the strengths and weaknesses of each review highlighted. Additional evidence from studies that were too recent to have been included in these published reviews which would have otherwise been included in existing reviews was also considered.

In total, 135 unique studies were identified across the reviews, plus three identified since these reviews were published. A total of 88 of these studies were included in only one of the review, while 47 studies had featured in two or more of the reviews. Forty-seven of the studies were observational while 88 were modelled (65%). As the pandemic progressed, further data were published which informed the more recent systematic reviews included in this synthesis. The tables in the full review in *Philosophical Transactions A* provide a detailed breakdown of the types of studies investigated in the systematic reviews.

Evidence of effectiveness of travel screening

Symptomatic or exposure-based screening measures, such as temperature screening or questionnaires about potential exposure, were among the first measures widely adopted by many countries in early 2020. However, these were found not to be effective enough to have had a meaningful effect on reducing importations and transmission. The evidence from the reviews did find that diagnostic-based screening measures applied to all travellers, usually in the form of Polymerase Chain Reaction (PCR)-based testing before departure or upon arrival, increased the effectiveness of screening. More recent studies suggest that screening based on vaccination or recent infection status was potentially more effective than diagnostic testing alone to prevent importation and onward transmission⁸⁸.

Evidence of effectiveness of travel restrictions

Travel restrictions are partial forms of border closure aimed only at specific jurisdictions, for example, a flight route between two locations or specific types of travellers (eg those originating or transiting in specific countries or non-citizens). This is often due to countries restricting travellers from high prevalence areas. Targeted travel restrictions levied against Chinese travellers in early 2020 were likely to have had an immediate effect on reducing transmission, but they quickly became less effective as other jurisdictions, taken together, became the major source of infection. A similar narrative emerged around targeted travel restrictions levied on travellers from Iran, South Korea, and Italy, although there was less evidence on the effectiveness of these measures. Most studies also concluded that early implementation generally led to higher levels of effectiveness. There was limited evidence of the effectiveness of travel restrictions outside of the early phase of the pandemic.

Evidence of effectiveness of quarantine

Quarantine is the physical separation of travellers not known to be infected from the rest of the public, usually for a predetermined period of time (which varied considerably between countries). The evidence around quarantine consistently demonstrated the highest levels of effectiveness of all of the single interventions evaluated. However, most evidence is associated with long quarantine periods (eg 14 days). Studies have also consistently concluded that compliance with quarantines, which tended to be lower when quarantines were self-monitored, was an important determinant of their effectiveness. Also, the literature consistently found that, when coupled with regular diagnostic testing, quarantines were more effective and could be shortened without substantial increased risk of transmission.

Travel restrictions and controls across international borders

Evidence of effectiveness of border control regimes

Border closure is defined as the complete restriction of both inbound and outbound travellers via a specific port (ie air, land, or sea) or all ports. Closely related, though not strictly border closures, are comprehensive border control regimes, such as those that enabled some places to maintain zero-COVID status into 2021 (eg Singapore and New Zealand) or 2022 (eg Hong Kong and mainland China). These were largely excluded from existing systematic reviews due to the inclusion criteria that were based on the evaluation of specific border control measures whereas these are very close to full border closure. It is very difficult to independently evaluate the contribution of these comprehensive border measures given that many were implemented at the same time or at times when there was limited domestic transmission due to the use of previous NPIs. Also, as strong domestic NPIs were necessary to maintain such low transmission levels, not all the ‘success’ of these regions can be attributed to the international border control measures. The likelihood is that they were effective to varying extents (in some cases very effective) as part of the overall packages of NPIs, but this is not reflected in the available study information at an individual border NPI level. Nonetheless, overlooking these cases may potentially overlook important lessons about the effectiveness of border control measures.

Data quality

As noted earlier, compared to many other NPIs, there is very little evidence around the effectiveness of border control measures. Many of the available studies are modelling studies, rather than observational studies, and almost all studies would be deemed to provide low evidence quality, given the limited observational or modelling nature of the studies. Additionally, other NPIs were implemented in many of the cases studied, which act as confounding factors and makes disaggregation of the effectiveness of the travel measures extremely difficult.

Conclusions

Overall, the term ‘border control measures’ covers multiple different NPIs, some of which show evidence of being more effective, such as quarantine, whereas others have little to no evidence of effectiveness. It should also be noted that ‘effective’ will mean different things for different underlying strategies and is not as simple as determining an overall reduction in transmission. There are areas such as full border closures where there is little evaluation evidence of the individual border measures, but it should not be assumed that the absence of evidence, means the absence of effectiveness. In almost all these situations border controls were part of a suite of NPIs stretching well past the border which in some cases proved effective or even very effective. There is also some evidence that the timing of the implementation of the border control measures is of importance. Overall, the evidence synthesis finds that the overall effectiveness of border control measures in reducing transmission during the COVID-19 pandemic remains unclear at an individual measure level. Should a pandemic of such magnitude result again, there is considerable need to capture further evidence of effectiveness of individual border measures.

Environmental controls

Environmental controls were applied in the UK and internationally to varying degrees and in various combinations, very often alongside other NPIs. These measures were aimed at preventing or reducing virus transmission by lowering or eliminating exposure to infectious virus. For this review, environmental controls were defined as physical changes to enclosed spaces.

Review approach

The following measures were investigated: ventilation; air cleaning devices; room occupancy; surface disinfection; use of barrier devices (screens); CO₂ monitoring; and one-way systems.

A literature search identified approximately 14,000 articles, of which 19 peer reviewed studies were selected that reported on the effectiveness at reducing transmission. These studies were sub divided as follows:

- Ventilation (12 studies),
- Air cleaning devices (4 studies),
- Disinfection of surfaces (5 studies),
- Room occupancy (6 studies),
- Barrier devices (1 study)

Almost all of the studies reported on combinations of measures. No studies were identified that directly addressed CO₂ monitoring or one-way systems, although CO₂ monitoring was used as a proxy measure of ventilation with respect to room occupancy.

Although not explicitly tested in the papers, the effectiveness of the measures would seem likely to arise from their ability to reduce transmission via a combination of reducing aerosols or droplets that might be inhaled and the amount of infectious SARS-CoV-2 present on surfaces.

Effectiveness of air treatment / ventilation

The introduction of outside air or removal of viable virus by air treatment (eg filtration or biological inactivation) will dilute the concentration of virus particles and should in theory (and as predicted by modelling) reduce transmission within a given enclosed scenario⁸⁹. In laboratory-based studies, air treatment measures were shown to be effective in reducing the amount of viable virus in a set volume of air as well as preventing long range airborne transmission in a controlled animal model study^{90, 91}. The review found evidence, albeit of low quality due to confounding factors, that improved ventilation reduced the transmission of virus between humans in real world scenarios. Two studies were judged to represent the strongest evidence for the effectiveness of ventilation in reducing the transmission of SARS-CoV-2.

Effectiveness of room occupancy limits

A common feature of pandemic mitigation measures was the imposition of room occupancies below levels found under normal circumstances. In theory, fewer people in each space with the same air flow lessens the possibility for transmission of SARS-CoV-2 as the probability of an infectious person(s) being present and encountering a susceptible person reduces, and reduced occupancy can improve the rate of ventilation per person. The review found evidence that reduced occupancy reduced the transmission of SARS-CoV-2 under real-world conditions⁹², but the studies which were identified also reported combinations with other measures or involved confounding factors, leading to low confidence.

Environmental controls

Effectiveness of surface disinfection routines

Enhanced cleaning of surfaces was implemented early in the pandemic. Viruses which transmit via an individual's direct contact with infectious virus on a surface would be expected to be sensitive to enhanced cleaning regimes. It is unclear how significant transmission via surface contact was to the transmission of SARS-CoV-2. The review identified studies which demonstrated that enhanced cleaning reduced viral material on surfaces. The review examined several studies analysing transmission but did not find sufficient evidence to conclude whether enhanced cleaning practice was an effective measure in reducing transmission.

Effectiveness of screens

The use of screens in public spaces, including shops and restaurants, was a feature in many countries. Barrier devices (such as aerosol boxes) were also used in hospitals during procedures that generated aerosols. While any physical barrier may well be effective in mitigating short range, direct person-to-person transmission, there is a lack of evidence as to whether barrier devices were useful in reducing transmission of airborne SARS-CoV-2. This review found some studies that suggested the introduction of screens can impede the effectiveness of room ventilation by creating stagnant zones. Such zones could lead to the build-up of infectious aerosols. The only study identified in the review that provided direct evidence for an effect on transmission was low-quality and reported no reduction in transmission⁹³. Laboratory style measurements could be useful to understand the impact of barriers upon concentrations of infectious virus particles.

Data quality challenges

Evidence indicated that ventilation, air-filtration and limiting room-occupancy may have a role in reducing transmission in specified settings but the studies typically led to low confidence in their conclusions. The low quality of the evidence highlights the challenges involved in studying transmission and the effectiveness of environmental NPIs at the height of a rapidly evolving global pandemic. Environmental NPIs were rarely the sole measures that were in effect during the studies that were surveyed and since the studies were almost always retrospective, excluding or controlling for confounding factors was essentially impossible. Thus, evidence graded by scales that work well for controlled laboratory experiments resulted in all but two studies having at least one factor that led to an expression of low confidence in the findings. Examples of such factors included differences in the strains of the virus studied, differences in community infection rates, whether infected people were present, high variability in viral emission rates, inclusion of transmission in spaces other than those where NPIs are adopted, the differing immune status of individuals, and inconsistency in recording data. When compared with laboratory-based studies where each factor can be controlled and thus individual measures isolated, conclusions drawn from these real-world studies as to the effectiveness of these NPIs are unavoidably less certain.

Conclusions

There is evidence, albeit of low quality, that increased ventilation, air filtration and lower room occupancy lowered transmission of the SARS-CoV-2 virus within the setting (usually an enclosed space) where the measure was applied. The effect at the population level of these environmental measures was not evaluated. The cost and practicality of implementing environmental controls will vary depending on the situation and should be considered alongside competing health measures and opportunity costs. The magnitude of the effect of an environmental control NPI will vary, dependent on the amount of virus added to the environment by infected individual(s), and this appears to be highly heterogeneous and dependent on multiple factors.

This review found no evidence which would allow simple quantification of the level of transmission reduction provided by each environmental control measure. The review also did not find evidence of effectiveness of a measure at the population level.

A conclusion from the review is that it is important to identify knowledge gaps regarding the effectiveness of environmental controls used as NPIs to inform research priorities and policy decisions. Several approaches must be taken to study transmission, including the establishment of an agreed global quality checklist for data collection from field studies (akin to that used in clinical trials) which would enable a higher degree of confidence to be attached to conclusions from the research. For some environmental measures, while high quality laboratory experiments may be useful in increasing confidence in the findings regarding effectiveness in reducing virus transmission, the obvious caveat is that the laboratory and real world differ.

Impact of communication in the UK on uptake of NPIs

During the COVID-19 pandemic, rapid, effective communication was needed to convey accurate and timely information around NPIs, such as facemask wearing, self-isolation and physical distancing. UK evidence suggests that overall, the adherence to NPIs was generally high, particularly in the early stages of the pandemic, even for the more challenging 'higher cost' NPIs such as 'lockdowns'. Multiple social, economic, and cultural factors influence adherence, but communication is critical.

Health communication is widely understood as a two-way exchange of information designed to inform, educate, influence or persuade, and which is shared by trusted people. This rapid review screened and synthesised published, peer reviewed literature looking at the impact of communication on the uptake of, and action in relation to, NPIs in the UK. Given the well-known problem of the intention-behaviour gap in health communication the focus was on actual behaviour. The focus on UK empirical data and evidence recognised the issue of different and confounding social and cultural settings in international studies.

Therefore, the review's sub-questions were:

1. What is the best evidence as to the types of communication strategies used to encourage adherence to NPIs in community-based settings in the UK?
2. Which strategies are the most effective in encouraging adherence?
3. What is the evidence about the psychosocial determinants of adherence to NPIs?

From an initial literature search identifying 11,500 published papers, only 13 met the review's inclusion criteria. Overall, the limited evidence confirms that communication to the public, particularly by officials and the mainstream media, was good enough to ensure that adherence to NPIs was high, although also identifying the characteristics that led to non or less rigorous adherence. It also confirmed in the COVID-19 context the longstanding understanding from the literatures on psychology and risk that trust and confidence in those who are communicating is important alongside the clarity and consistency of the messaging. The limited evidence suggests that social media communications are less likely to be associated with higher adherence to NPIs than those delivered via traditional media.

The review identifies key features of effective communication as well as important information gaps and lessons for future studies both in terms of timing and content.

Evidence

The 13 studies identified that specifically addressed the impact of communication on adherence to NPIs in the UK were heterogeneous in terms of methods, content and focus (five observational studies; seven qualitative studies and one mixed-method study). Generally, communication was one of several possible factors predicting or impacting on COVID-19 NPI adoption or adherence. Other factors included personal resources, social support, personal and family vulnerability, and positive community perceptions of the effectiveness of the measures. Most studies looked at multiple communication channels. Four studies looked at specific channels: BBC broadcast news; official communications sent out by universities and local government; television; and newspapers. The majority of the studies were conducted in the earlier stages of the pandemic (ie during 2020).

Most studies looked at public adherence to multiple NPIs rather than focusing on specific NPIs. One study looked at contact tracing app use, two studied staying at home (quarantine) and two examined the uptake of community-based COVID-19 testing programmes.

Trust was the most common factor impacting communication effectiveness (10 of the 13 studies) with authoritative messaging from official government and expert health sources or communicating legal requirements predicting higher NPI adherence^{94, 95, 96, 97, 98, 99, 100, 101, 102, 103}. One prevalent theme (six studies) was that low trust in government led to lower adherence or to higher belief in conspiracy theories. Perceived competence, benevolence and integrity were important trust characteristics for government communicators.

The importance of knowledgeable and trusted local groups and leaders as communicators was identified in relation specifically to ethnic minority communities. One study that looked at adherence to NPIs during school closures noted the importance of guidance being delivered by a source that the parent and child trust. Being told to do something by high authority figures such as the Prime Minister was also important.

Clarity and consistency of communication was important (nine of the 13 studies). 'Mixed messages' generated confusion and in some cases non-adherence. Too many (often conflicting) messages resulted in 'alert fatigue' or information overload. After the original 'lockdown', the government guidance (including in the devolved administrations) changed multiple times, generating the potential for non-adherence as people became desensitised to alerts and making it harder to distinguish between important announcements about new rules or less important or superfluous information.

Transparency around technical information and better communication of scientific uncertainty were identified as important to adherence, as was communication emphasising the potential risks and societal benefits as well as simple consistent guidance on how to reduce transmission. Where lack of trust was combined with problems of clarity and consistency this was identified as leading to individuals making their own evaluation about what was reasonable or safe to do. Three studies identified that potentially ambiguous messages, rules and terms (eg 'stay alert') were open to personal interpretation and could be a barrier to adherence.

Impact of communication in the UK on uptake of NPIs

Controlling language was important in five studies. One identified that autonomy-supportive messages encouraged people to spend more time at home, whereas messages containing language perceived as ‘controlling’ (eg ‘you must’, ‘you should’) were associated with people spending less time at home¹⁰⁴. There was limited evidence on the relationship between communication, conspiracy beliefs and NPI adherence.

Conclusions

Determining to what extent communication is effective in increasing the adoption of, or adherence to, NPIs is challenging. Particularly because communication is itself such a multi-faceted construct and because it is difficult to isolate the impact of any one form or strategy of communication in an emergency where rapidly changing information from numerous sources is being transmitted about complex, evolving science and evidence.

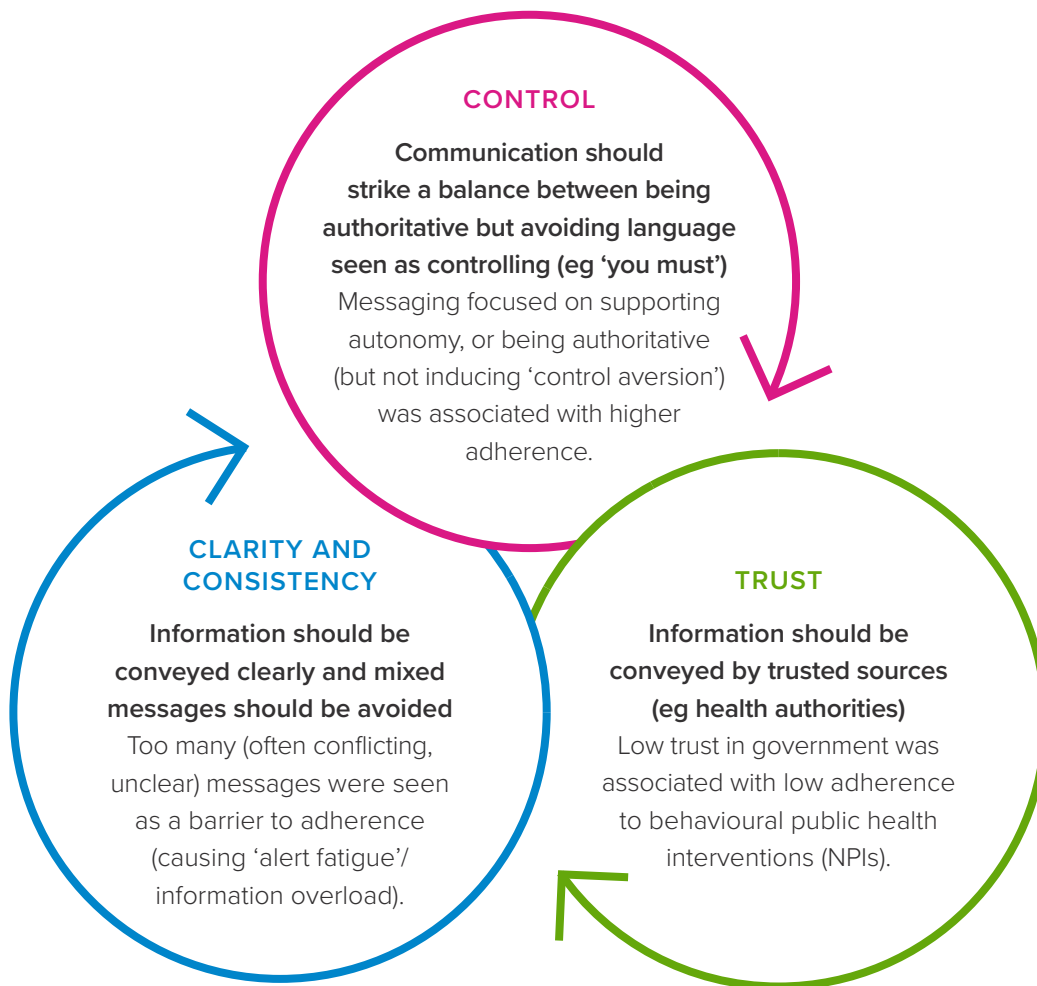
However, this review has identified the key features of effective communication in the context of NPI adoption or adherence (Figure 2):

- a. Information should be conveyed clearly with consistent messages^{105, 106, 107, 108, 109, 110, 111, 112, 113}.
- b. Information should be conveyed by trusted sources such as health authorities^{114, 115, 116, 117, 118, 119, 120, 121, 122, 123}.
- c. Communication should strike a balance between being authoritative while avoiding language perceived as controlling, for example ‘you must’^{124, 125, 126, 127, 128}.

Evidence limitations notwithstanding, this review suggests that communication has had significant or important impacts on NPI adoption or adherence, with the direction or magnitude of these impacts varying by type of message, type of messenger, the audience, and the communication channel.

FIGURE 2

Summary of the key elements of an effective NPI communication campaign.



Cross-national comparisons of NPI effectiveness

Both the introduction of NPIs and the impact of COVID-19 differed across countries, states, regions and population groups, and over time. Some countries, such as the USA and Brazil, experienced markedly higher COVID-19 mortality and excess mortality than others such as New Zealand, Australia, South Korea and Germany¹²⁹.

National responses and introduction of NPIs differed by time, region, and intensity. In particular, there were prominent differences in the timing and intensity of test and trace, social distancing, and ‘lockdown’ measures. Asian countries that had more recently experienced SARS (eg China, Hong Kong, Taiwan, Vietnam, Singapore, South Korea) implemented early stringent NPIs, followed shortly afterwards by Australia and New Zealand¹³⁰. Many Asian countries brought in rapid ‘lockdowns’, while some, such as South Korea rapidly mobilised testing and contact tracing to avoid an early ‘lockdown’. Early action in South Korea, while numbers were relatively low, allowed more effective testing, contact tracing and containment of spread¹³¹. Early responses aimed at containment contrasted with many European and North American countries that were slower to act, thereby making containment more difficult^{132, 133}.

Cross-country comparisons of the effectiveness of NPIs are affected by multiple factors, most notably differences in demographic factors, healthcare systems, levels of wealth and patterns of testing and reporting, as well as differing political, economic, social and trust contexts. Different countries or regions were differentially impacted by COVID-19, with particular impacts on those with older populations¹³⁴; higher levels of obesity; greater concentrations of lower income and larger households; and higher population densities¹³⁵. Countries also differed in their categorisation of COVID-19 deaths. For instance, Belgium included all deaths where COVID-19 was suspected to contribute, resulting in higher reported death rates early in the pandemic¹³⁶, while others included only deaths in hospitals¹³⁷. There were also stark differences in the availability of testing and thereby reported cases.

Many studies exploited the variation in the timing and stringency of NPI implementation over time to examine the effectiveness of NPIs, finding both within and between-country variation^{138, 139, 140, 141, 142}. Some demonstrated that the timing and stringency of government policies and NPIs played a crucial role in the rate of early infection spread¹⁴³ and the case fatality rate¹⁴⁴. Others used cross-national differences in the timing of ‘lockdown’ measures to assess differences in mortality rates¹⁴⁵. One study¹⁴⁶ found that NPIs were more effective in some countries as a result of the effectiveness of their governments, health expenditures and key socioeconomic variables.

Countries that had high population density, a larger extent of informal employment, and higher average household size, exhibited less effect from NPIs¹⁴⁷, given that informally employed workers continued to work to prevent income loss and high-density populations and large households inevitably had higher mixing. Wealthier countries experienced a higher effectiveness of NPIs, attributed to more measures to deploy and ensure compliance, such as furloughing to financially compensate workers to stay at home. Others have shown that levels of societal and household inequality were key predictors, given that socioeconomic status influenced the risk of infection¹⁴⁸ and ability to follow NPIs¹⁴⁹. Finally, others highlighted that political polarisation and lower risk perceptions among certain groups hampered adherence to NPIs¹⁵⁰.

Case studies which illustrate how packages of NPIs were operationalised in a variety of nations and regions across the world are presented in Boxes 6-8. In each case social context played an important role in determining the extent to which these packages mitigated transmission of SARS-CoV-2.

In summary, national, regional and temporal differences in the effectiveness of NPIs can be attributed to multiple factors. Firstly, differences can be attributed to the manner in which different combinations of NPIs were implemented at different times in the pandemic and as the virus evolved to become increasingly transmissible. Secondly, the application, uptake and outcomes of NPIs were influenced by the demographic composition of the population, for example in terms of age, household size and density, resilience of healthcare systems, health expenditures, political and economic systems, societal compliance, and recent prior experiences of novel respiratory epidemics.

BOX 6

NPI measures in Hong Kong, a case study.

By Professor Ben Cowling

Hong Kong is a Special Administrative Region of China, with a population of 7.3 million. Hong Kong was heavily affected by the SARS epidemic in 2003, with 1,755 confirmed cases (out of 8,098 cases worldwide) and 302 deaths. As a consequence of that epidemic, Hong Kong invested heavily in public health capacity to respond to emerging infections, including an increase in public health infrastructure, laboratory testing, and isolation rooms and infection control resources in hospitals.

Hong Kong was one of the earliest locations outside mainland China to report COVID-19 cases, with the first case being identified on 23 January 2020 in a traveler arriving from Wuhan. The initial response was pragmatic: based on the SARS epidemic there was a recognition of the importance of strict isolation as well as contact tracing and quarantine of contacts. However, the boundary between mainland China and Hong Kong was not closed until after a strike of healthcare workers¹⁵¹ demanding the boundary closure occurred in early February. Following a surge in infections in the community in March 2020, resulting from travellers arriving from Europe and North America (rather than from mainland China), a quarantine policy (either at home or in a hotel) for arriving persons was also implemented. From July 2020 onwards, all arriving persons were required to quarantine in hotels, and in November 2020, quarantine was only permitted in designated hotels, with consequent substantial limitations on the number of people who could arrive each day.

Quarantine durations varied between seven days and 21 days throughout the pandemic, and the on-arrival quarantine policy was ultimately lifted on 26 September 2022.

A cornerstone of the approach to COVID-19 containment in Hong Kong was the strict isolation of all confirmed cases, initially mostly in negative pressure isolation rooms in hospitals, and later in hospitals, as well as in purpose-built isolation facilities. The duration of mandatory isolation varied throughout the pandemic, with discharge generally occurring after viral shedding reached low levels, although in late 2021 the mandatory isolation period was extended to a minimum of 21 days for all confirmed cases, even those testing 're-positive' after recovery from an earlier infection. Contact tracing was performed manually by public health officers and at times also by other civil servants, identifying close contacts who would be issued with quarantine orders and generally held for 14 days in designated quarantine facilities (ie forwards contact tracing), and also identifying where clusters of infections had occurred (ie backwards contact tracing)¹⁵².

While isolation and quarantine are likely to have reduced transmission, it is well recognised that many infections were never laboratory confirmed¹⁵³. For example in the wave in summer 2020 it was estimated that only 27% of infections were confirmed. As a consequence, the containment of COVID-19 in Hong Kong cannot be attributed to strict isolation and quarantine alone. PCR testing capacity was steadily increased through the pandemic, initially focused on symptomatic cases seeking medical attention, but soon expanded to all hospital admissions.

It was then broadened through ‘compulsory testing notices’ issued to asymptomatic individuals in the community considered to be at higher risk of infection because of their occupation, contact history or residence location. The highest testing throughput in 2020 and 2021 corresponded to around 1% – 2% of Hong Kong’s population being tested by PCR each day. Rapid antigen tests were not used on a large scale until 2022.

During each of three surges in community incidence in 2020 (shown in Figure 3 below), a number of physical distancing measures were implemented. Individual behaviours also changed in response to perceived risk¹⁵⁴. Schools were closed for prolonged periods in 2020 and early 2021. Civil servants were instructed to work from home with many private businesses following the same recommendations. Large gatherings were prohibited, and restaurant opening hours were restricted (for example being required to close at 6pm). There was a clear correlation between the implementation of packages of physical distancing measures and a consequent change in the effective reproductive number, but as measures were generally implemented together it is not possible to estimate which of the measures had greatest impact on transmission. Face masks were mandated in public (indoors and outdoors) from July 2020 through to February 2023, with very high compliance, but universal masking was unable to prevent community epidemics in 2020/21 (Figure 3) nor a very large Omicron BA.2 epidemic in 2022.

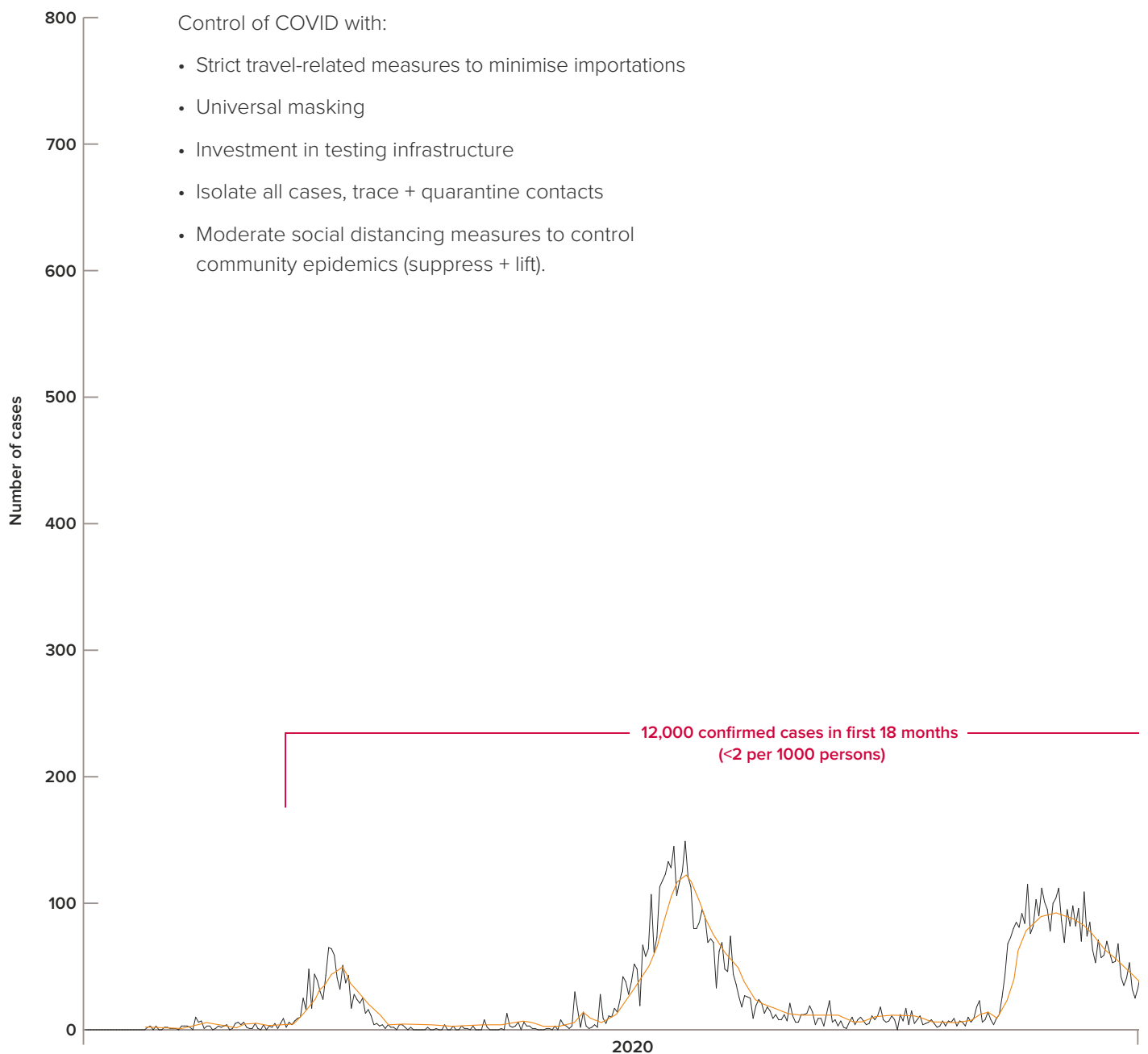
Containment of COVID-19 for two years allowed vaccination rollout with an inactivated vaccine (CoronaVac, Sinovac) and an mRNA vaccine (BNT162b2, BioNTech/Fosun Pharma/Pfizer), starting in early 2021. By the end of 2021 more than 60% of the population had received two doses of vaccination, but uptake remained low in older adults, with only 25% uptake of two doses in individuals over the age of 80 years^{155, 156}. One of the factors linked to low vaccine uptake in older adults was low risk perception, because of the successful containment of COVID-19 transmission for two years¹⁵⁷, and the lack of an explicit exit or transition strategy (in contrast to New Zealand and Singapore, for example). Specifically, whereas those other locations discussed how to transition to ‘living with the virus’ more safely, primarily by achieving very high vaccination uptake in older adults, the Hong Kong government continued to focus on containment, with NPIs as a long-term solution to control of COVID-19 and protection of public health¹⁵⁸.

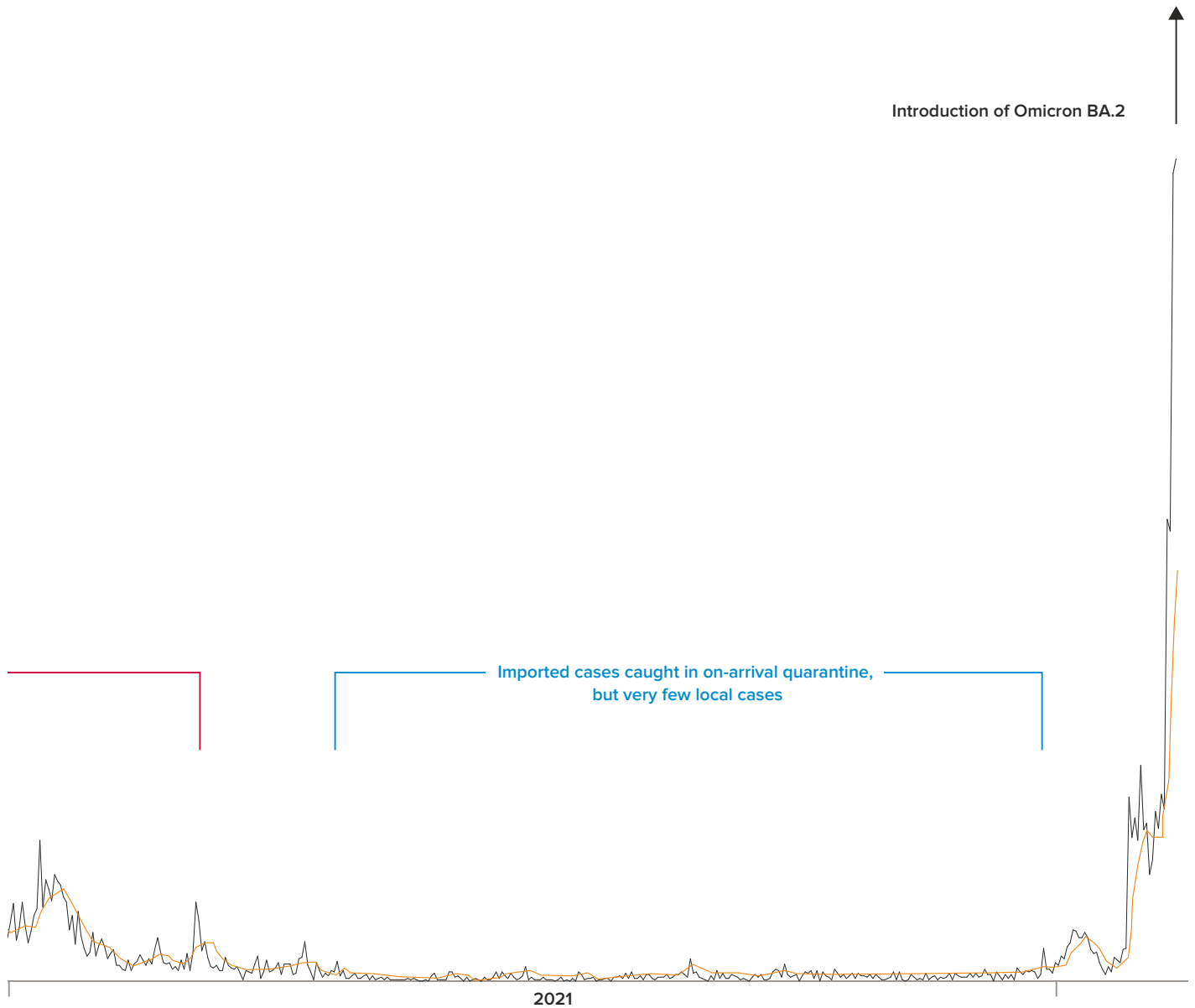
As a consequence, when Omicron BA.2 transmission could not be contained in early 2022, the majority of the population were infected within a short space of time, and more than 10,000 COVID-19 deaths occurred (1.4 per 1000 population)^{159, 160}, with mortality rates rising by threefold at the epidemic peak when hospital resources were under extreme pressure¹⁶¹. The per capita mortality rate in 2022 was among the highest reported COVID-19 mortality rates globally. Thus NPIs played an essential role in controlling COVID-19 transmission and protecting public health in Hong Kong in 2020 and 2021, but these measures were unable to contain Omicron with its substantially higher intrinsic transmissibility.

FIGURE 3

COVID-19 cases in Hong Kong for the first two years of the pandemic.

Hong Kong successfully contained COVID-19 for two years through strict travel restrictions and on-arrival quarantines, along with a mask mandate, strict isolation of confirmed cases, strict quarantine of close contacts of those infected and moderate social distancing measures.





BOX 7

NPI measures in New Zealand, a case study.

By Nicholas Steyn, Dr Kris Parag and Professor Christl Donnelly

New Zealand recorded its first case of COVID-19 on 28 February 2020. Two weeks later, on 14 March, it was announced that anyone entering the country must self-isolate for 14 days¹⁶². Border controls were tightened over the following weeks and, by 9 April, only New Zealand citizens and residents were permitted to enter the country¹⁶³, and they were required to complete a 14-day stay in hotel-managed isolation and quarantine¹⁶⁴. A four-level tiered alert system was simultaneously introduced for the deployment of domestic NPIs¹⁶⁵. After approximately one month in strict 'lockdown', and a period with looser domestic NPIs, New Zealand formally declared the elimination of COVID-19 on 8 June 2020^{166, 167}. This achievement has been credited in-part to an effective communication strategy that ensured the public understood and followed the required measures¹⁶⁸. Except for contact tracing record-keeping requirements (to help in the event of an undetected re-incursion), all domestic NPIs had been lifted by this point. A total of 1,504 cases and 22 deaths had been recorded¹⁶⁹.

New Zealand remained mostly transmission-free until late 2021 (Figure 4). This was despite regular positive tests (typically single digits each day) in quarantined international arrivals¹⁷⁰. Measures designed to prevent the transmission of SARS-CoV-2 from international arrivals to the community consisted of:

- border closures to all but residents and citizens,
- mandatory managed isolation and quarantine in approved hotels,
- pre-departure and post-arrival testing of travellers, and
- testing of border workers^{171, 172}.

Despite difficulties in evaluating the relative contribution of each of these controls, the evidence is consistent that this package of border controls was highly effective at preventing the re-introduction of COVID-19 to New Zealand.

These border controls did not prevent all re-introductions, however. Clusters of SARS-CoV-2 infections with no concrete connection to the border were detected on 12 August 2020 and then again on 14 February 2021¹⁷³. Localised stay-at-home orders and other restrictions were able to control these clusters and allow domestic NPIs to once again be lifted by 21 September 2020 and 12 March 2021 respectively¹⁷⁴. A handful of infections were also detected in border workers¹⁷⁵. Contact tracing and quarantine meant that all such outbreaks were eliminated without the implementation of stay-at-home orders or other strict NPIs.

Finally, in August 2021, a cluster of infections with the Delta variant of SARS-CoV-2 was detected in the community, again with no clear link to the border¹⁷⁶. The first national ‘lockdown’ since April 2020 successfully decreased daily domestic case numbers to between 10 and 20, but elimination remained out of reach. Facing an increasing number of daily confirmed infections and the prospect of an extended ‘lockdown’ in the context of a highly vaccinated population, the government declared the end of the elimination strategy on 4 October 2021¹⁷⁷. Local NPIs in Auckland and surrounding regions were eased

over the following months, although strict international border controls remained in place¹⁷⁸.

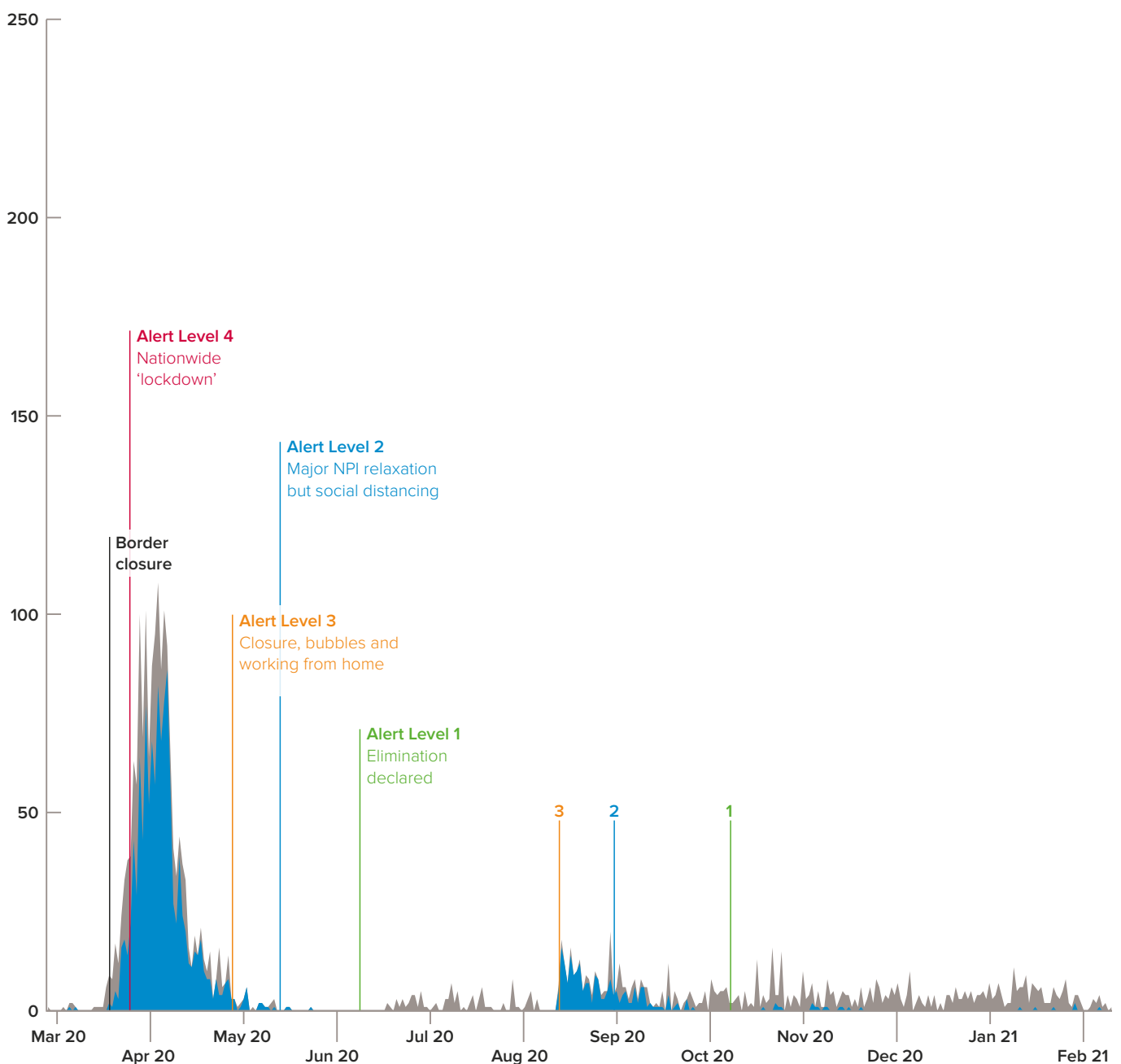
The Omicron variant of COVID-19 was first detected at New Zealand’s border on 16 December 2021¹⁷⁹. By mid-January 2022, it had caused a ten-fold increase in the daily number of positive cases identified at the border¹⁸⁰. Despite the increased cases at the border and the decrease in duration of managed isolation and quarantine from 14 days to 7-to-10 days, the first case of community transmission of Omicron was not detected until 23 January 2022¹⁸¹, suggesting that the border controls had remained at least somewhat effective at delaying the importation of the new, more infectious, strain of SARS-CoV-2 into the community.

The New Zealand experience suggests that a comprehensive package of border controls can be highly effective at preventing the importation of COVID-19. Whether additional controls (short of a total border closure) could have guaranteed no community outbreaks remains an open question.

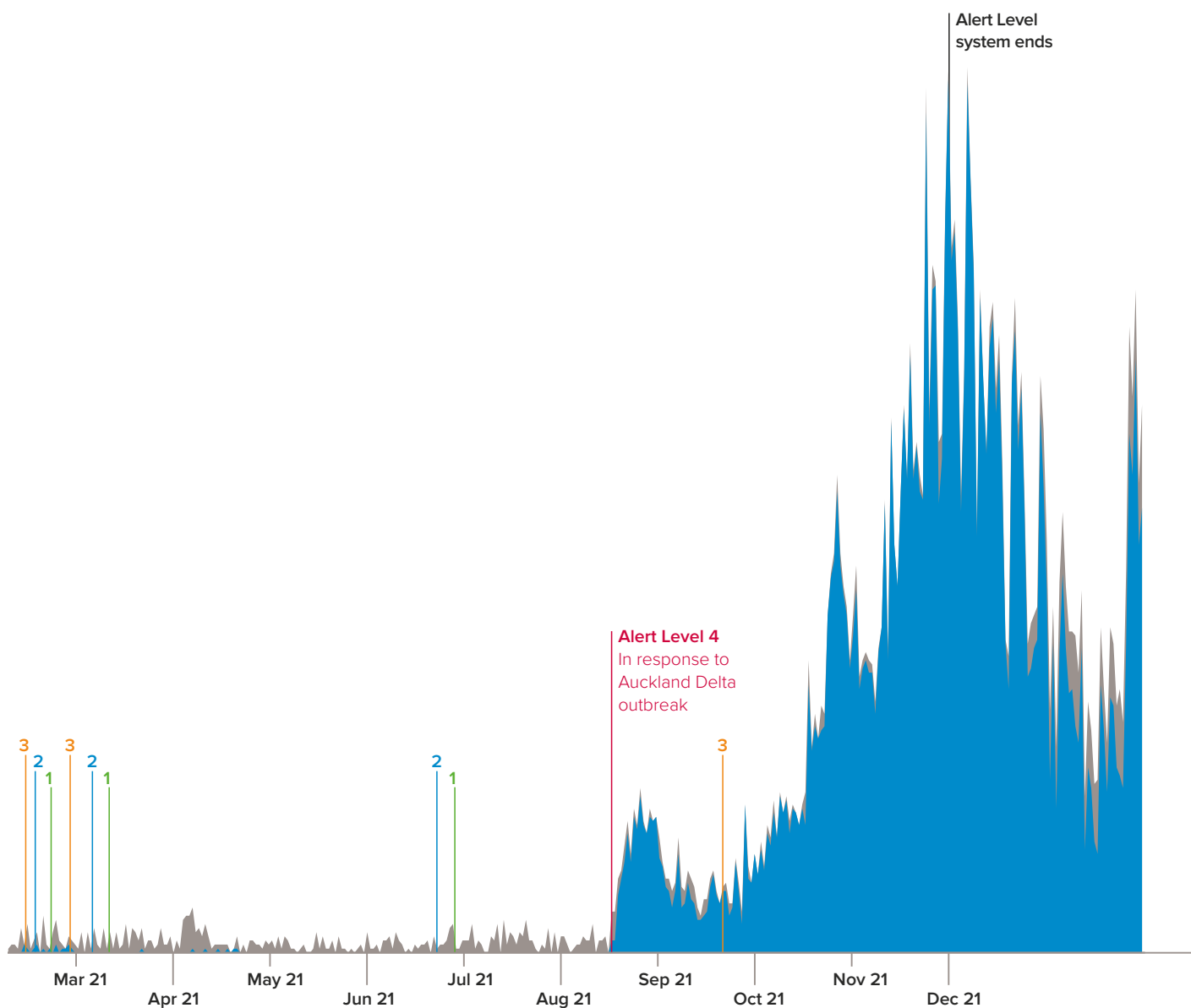
FIGURE 4

Local transmission dynamics of COVID-19 in New Zealand.

Local (blue) and imported (grey, stacked) cases by date reported, sourced from New Zealand government data. Vertical lines pinpoint key policy change-times and alert levels (1, green, 2, blue, 3, orange, 4 red) in response to these case loads. Between June 2020 and August 2021, most cases were contained at the border with very few local outbreaks. The Delta variant started to transmit locally in August 2021 and was not eliminated as in previous local outbreaks. NPIs were reduced to alert level 3 and local cases increased substantially. Beyond the time period of the plot, the Omicron variant arrived and with no NPIs in place, cases increased dramatically to many thousands of cases per day.



Reproduced and expanded version of Figure 1 from Parag *et al*¹⁸².



BOX 8

NPI measures in South Korea, a case study.

By Dr Sukhyun Ryu and Dayeong Lee

South Korea, which is located in the east of mainland Asia and has a population of 51.4 million, achieved universal health care coverage in 1989¹⁸³. In 2015, South Korea experienced an outbreak of MERS. The weakness of the national public health response was exposed in the early stage of the outbreak and improvements were immediately made, including a comprehensive epidemic response framework, in collaboration with ministries, local governments, laboratories, medical centres and the public¹⁸⁴. During the MERS outbreak, Korean public health authorities developed active contact tracing using electronic health registries, the global positioning system (GPS), credit card transaction records and closed-circuit television (CCTV). Furthermore, the public learned the importance of NPIs, including personal hygiene, face masks and social distancing¹⁸⁵.

After experiencing the MERS outbreak, severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) infection was first identified in South Korea on 20 January 2020¹⁸⁶. Many coronavirus disease (COVID-19) cases and deaths resulted from the subsequent super-spreading events in the Daegu-Gyeongsangbuk Province of South Korea over the following weeks. However, on 23 February 2020, as the number of confirmed COVID-19 cases increased, public health authorities in South Korea raised the infectious disease alert to the highest level.

Combined NPIs were implemented over time: including enhanced screening with active case finding; quarantining of individuals with suspected and confirmed COVID-19 cases; mandatory use of face masks; and social distancing measures (Table 1). To identify the super-spreaders, public health authorities provided public advice through mobile text messages on spreader events with locations of confirmed cases. Community-based screening stations were set up and a high-volume testing capacity was available in public and private laboratories from late February 2020, the test kit having gained emergency-use approval from the public health authorities on 4 February 2020 – two weeks after the first case was found¹⁸⁷.

On 1 April 2020, all overseas travellers were included in the self-quarantine programme in South Korea to prevent the spread of SARS-CoV-2¹⁸⁸. The aforementioned interventions in South Korea reduced the transmissibility of SARS-CoV-2 in early 2020 without implementing a nationwide ‘lockdown’ (the first epidemic period was between 20 January and 19 April 2020). Furthermore, NPIs significantly reduced the risk of large clusters of cases during the second epidemic period (20 April to 16 October 2020)¹⁸⁹.

The strict social distancing measures were relaxed on 20 April 2020, because the daily number of confirmed cases was under 50 and the cases of unknown origin of infection were less than 5% among the total investigated cases in the previous two weeks. However, sustained increases in the number of confirmed cases were observed as the strict social distancing measures were further relaxed and public facilities began to open again on 6 May 2020¹⁹⁰.

TABLE 1

Key combined NPIs implemented in early 2020 (Figure 5, inset) to prevent the SARS-CoV-2 transmission in South Korea.

Travel-related measures	Case-based measures	Community-based measures
Foreign travellers from Hubei province, China, barred on 3 February 2020	Nationwide drive-through screening centres launched on 23 February 2020	School openings for new semesters postponed on 23 February 2020
Entry of foreign travellers from Japan barred on 9 March 2020	Private hospitals designated as public relief hospitals nationwide on 27 February 2020	Face masks evenly distributed to the public through public channels to prevent stockpiling on 9 March 2020
A 14-day mandatory self-quarantine implemented for individuals arriving in South Korea on 1 April 2020, and their compliance monitored	Nationwide screening of the elderly and employees in nursing homes implemented on 9 March 2020	Nationwide recommendations issued to cancel social events, avoid social gatherings and refrain from going out on 22 March 2020

In June 2020, Korean public health authorities introduced a system with five different levels of distancing, where the level applied in each region depended on the characteristics and intensity of newly confirmed cases. This was intended to improve public compliance with social distancing rules¹⁹¹. This adjustment in social distancing was considered effective in controlling the SARS-CoV-2 transmission from 2020 to 2021¹⁹².

On 27 April 2021, the SARS-CoV-2 Delta variant was first identified in an international traveller arriving at a South Korean port of entry and on 18 May 2021, the Delta variant was first identified in a South Korean local community¹⁹³. Despite the South Korean authorities' strict implementation of NPIs, the entry of the Delta variant is likely to have increased the difficulty of controlling SARS-CoV-2 transmission, given increased domestic travel volumes and the increased transmissibility of the variant (the effective reproduction number being >1 during most of its main transmission period in Korea)¹⁹⁴.

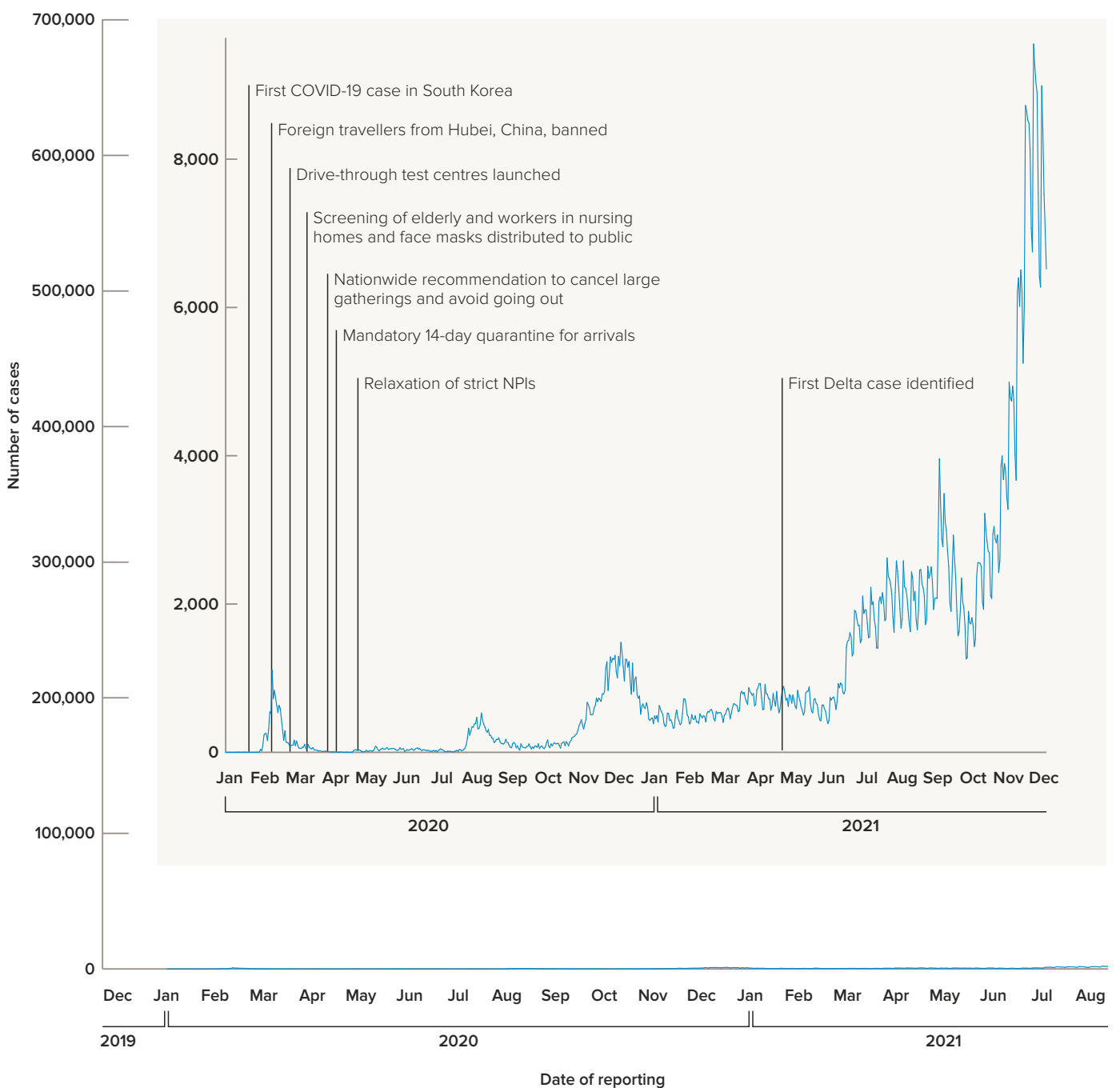
Moreover, on 2 December 2021, the Omicron variant was first identified in community transmissions¹⁹⁵. Nonetheless, in January 2022, during the early transmission of the Omicron variant, South Korea began to relax its strict social distancing measures, which increased the daily number of confirmed cases by approximately 600,000 (Figure 5). This was the largest increase in the number of new daily cases worldwide since the beginning of the pandemic¹⁹⁶. After the relaxation of social distancing measures, the extension of community-wide COVID-19 screening systems and implementation of mandatory school-based screening measures were associated with reduced transmissibility of the Omicron variant¹⁹⁷.

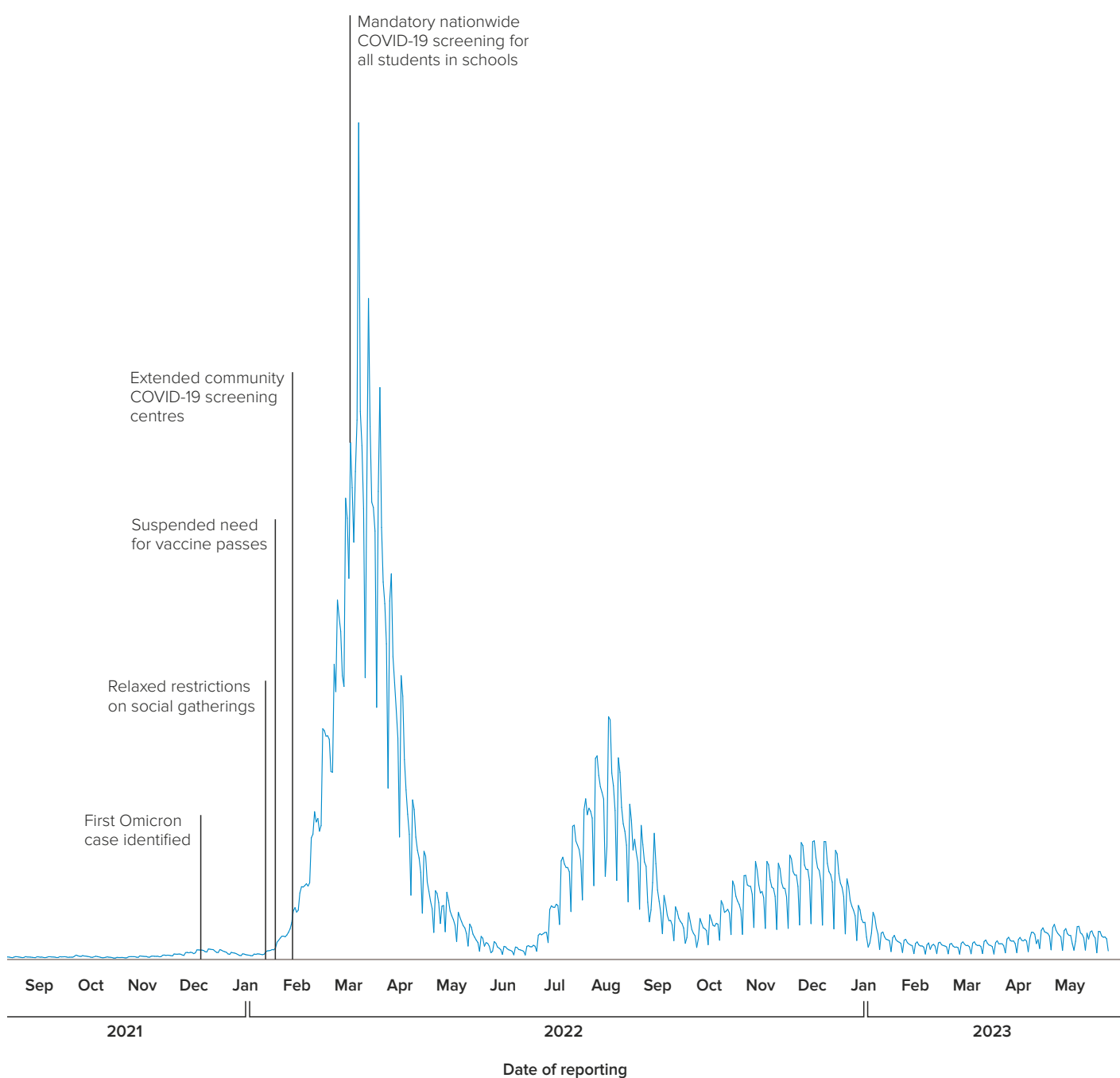
The South Korean experience of the COVID-19 pandemic suggests that strict and comprehensive NPIs could successfully control the transmission of SARS-CoV-2.

FIGURE 5

COVID-19 cases in South Korea across the pandemic.

Inset, first two years of the pandemic, with relatively lower caseloads. NPIs were implemented early following initial news of SARS-CoV-2 spreading in China. Cases were maintained at low levels without need for a mandatory 'lockdown'. When the more transmissible Delta and Omicron variants emerged (main graph, 2022 onwards), cases increased substantially. This also coincided with a relaxation of outstanding NPI measures in January 2022.





Discussion

This report set out to answer an important, but not straightforward, question: Were NPIs effective in reducing SARS-CoV-2 transmission and, if so, which NPIs and to what extent? This question is particularly important given the adverse consequences that NPIs had on many people around the world. Strict ‘lockdown’ measures, including prolonged periods of confinement to home, accompanied by closures of schools, workplaces, hospitality and entertainment venues had major negative personal, educational and economic effects. The pandemic, coupled with the measures that were implemented to try to mitigate the direct health impacts of SARS-CoV-2 infection, disrupted the normal social interactions that are key attributes of being human. It had a range of social and economic impacts, often felt differently between countries and population groups.

In a highly populated, globalised world, where pandemics are likely to be more frequent and to spread more rapidly than in previous eras of human history, understanding what measures were effective against SARS-CoV-2 is important to support and refine the application of NPIs when future pandemics occur.

Despite all the caveats about the difficulties of imperfectly designed observational studies described earlier, a rigorous review of the evidence collected during the pandemic from around the world, has taught us a great deal. There were clear signals from the evidence reviews that many of the NPIs were effective, especially when implemented in combinations. In addition we have the important lessons learnt from how different countries implemented and enforced different combinations of NPIs to control the transmission and spread of SARS-CoV-2. A great deal has been learnt about the effectiveness or otherwise of NPIs – and there is also much more clarity about what is not yet known.

Masks and enhanced hygiene measures

Published studies generally found that masks reduced the transmission of SARS-CoV-2, recognising the risk of bias, and allowing for uncertain and variable efficacy. Importantly, there was a ‘gradient of effectiveness’, with evidence, mainly from studies in healthcare settings, that higher quality N95/FFP2 masks were more effective than surgical-type masks. Additionally, most of the studies that were considered favoured the effectiveness of mask mandate policies to increase compliance and prevalence of mask wearing, and thereby reduce transmission. Taken together, the findings from the different study types identified here, strengthen the conclusion that the wearing of masks was an effective NPI during the COVID-19 pandemic.

In comparison, while there were little data on the effectiveness of hand hygiene in reducing transmission of SARS-CoV-2^{198, 199, 200}, there was other evidence of the benefit of increased handwashing on the transmission of other respiratory viruses. There were also reports of reductions of other gastrointestinal infections during the pandemic, which could potentially be attributed to wider adherence to strict hand hygiene²⁰¹.

Social distancing and ‘lockdowns’

Most effective of all the NPIs were the social distancing measures, with a gradient showing that the most stringent of these had the strongest effects. Stay-at-home orders, physical distancing measures, and restrictions on gathering sizes were repeatedly found to be associated with significant community-wide reductions in SARS-CoV-2 transmission, as was frequently assessed using the time-varying reproduction number, R_t .

Certain sub-populations of people were found early in the pandemic to be especially vulnerable to severe illness and death from SARS-CoV-2 infections. In particular, care home residents were among those most vulnerable to COVID-19. Within care home settings, strict cohorting of staff alongside residents and restrictions on visitors were frequently found to be associated with reduced SARS-CoV-2 transmission among residents and reduced outbreaks within care homes.

In contrast, most children were at much lower risk of severe outcomes of COVID-19. Nonetheless, in many countries, because of the potential for children to transmit SARS-CoV-2 to vulnerable older people (as was known to be the case for influenza infection), school closures were implemented. When schools remained open for children of key workers or were reopened, social distancing measures were frequently implemented in schools to limit transmission risks. The evidence generally indicated that school closures and other school-based measures were associated with reduced COVID-19 incidence within schools and the community. However, the effectiveness of these measures was more varied (compared to community-wide measures such as stay-at-home orders), time-dependent, and often contingent on the adherence to the measure or measures implemented (for example, mask wearing) and the targeted age group of school children.

Test, trace and isolate

A major difference between the SARS outbreak of 2003 (due to the coronavirus now named SARS-CoV-1) and the COVID-19 pandemic is that in 2003, transmission of SARS-CoV-1 largely occurred from infected people who were at their most symptomatic²⁰². This meant that it was much easier to bring the 2003 SARS outbreak under control by isolating infected patients, coupled with rigorous contact tracing.

In contrast, it was discovered that approximately 40% of SARS-CoV-2 transmission occurred from infected people who were asymptomatic²⁰³. TTI measures were observed to be a powerful tool for reducing transmission, with mass testing of individuals reported in several countries associated with reductions in transmission. Evidence from studies in the UK (eg Isle of Wight trial) supports the investigation of digital tracing apps for future pandemics, particularly those with similar challenges to identifying contacts and doing so very quickly. This finding was supported by evidence from other countries, where high levels of testing and contact tracing led to reductions in COVID-19 deaths^{204, 205, 206}. As with the implementation of other NPIs, the effectiveness of the approach of testing, tracing contacts and isolating those infected and their contacts was most effective when case numbers were low.

Travel restrictions and controls across international borders

While most countries implemented some form of border control, there are a limited number of studies examining the effectiveness of their implementation. Based on these, symptomatic screening widely adopted in the early phases of the pandemic was found to have had no meaningful effect on reducing transmission. In contrast, there was consistent evidence that, when quarantines were enforced and coupled with regular diagnostic testing, these were effective and could be shortened without significantly increasing the risk of transmission. Self-monitoring of quarantines was consistently found to reduce their effectiveness. These findings are useful evidence when designing quarantine regimes for future outbreaks.

Current systematic reviews largely excluded evaluation of comprehensive border control regimes that enabled some countries to maintain zero-COVID status for periods including New Zealand and mainland China. The ‘success’ of these measures however, must be caveated with the fact that robust NPIs such as social distancing and testing regimes were also implemented in these countries to reduce transmission of the limited number of cases that were, despite almost complete closures of the borders, still reported to occur.

Environmental controls

The review found real world evidence that enhanced ventilation by introduction of outside air, removing virus particles from the air by treatment or filtration and reduced room occupancy all had beneficial effects in lower transmission of SARS-CoV-2 within the settings where they were applied. The real-world observation studies were reactive and suffered from potential confounding factors. However, the findings of effectiveness chimed with both theoretical models and laboratory-based studies which supported their conclusions. It was noted that the effectiveness was only evaluated within the location that they were applied and there was no evidence for their effectiveness in reducing SARS-CoV-2 transmission at a community level. In common with other NPIs, environmental measures were applied as part of a package in combination with others. The review did not find conclusive evidence for the effectiveness of barriers or enhanced cleaning regimes in preventing transmission.

Impact of communication in the UK on uptake of NPIs

The COVID-19 pandemic was the first to take place in the era of ubiquitous internet-based communication and social media. One of the core challenges experienced by countries across the world was that of misinformation, information overload and conspiracy theories.

The study of communication in the UK highlights the importance of trust in the authority (eg government or health authority) delivering messages, as well as in the information itself. Trust varies between social and cultural groups and over time. The clarity and consistency of information and messaging was important. Mixed messages generated confusion and, in some cases, non-adherence. There was some evidence that the ability to take personal control was important to individuals, favouring autonomy-supporting messages. There is limited evidence on the role of social media in a UK context, although what there is suggests that social media is likely to be associated with lower adherence to NPIs than traditional media.

Future evidence reviews should take an international perspective to understand the impact of different social, cultural, and political contexts around NPI measures. In general, mixed-method research should be adopted, complementing available quantitative studies with those drawing on qualitative and participatory study designs to ensure robust evidence not only on how people receive information but how they interpret it and why.

Drawing the threads together

The rigorous methodology underpinning the evidence reviews undertaken for this report explicitly identifies the limitations of the observational studies of NPI effectiveness in comparison with the ‘gold standard’ of RCTs. This means that the findings from these reviews could be open to an interpretation that ‘we have learnt very little about the effectiveness of NPIs and that what we do know is unreliable.’ This interpretation would be incorrect, though it is the case that one of the lessons from this pandemic is that we need to plan ahead for the next pandemic in order to be able to gather observational data that is of a higher and more consistent quality to enable more robust conclusions.

The evidence reviews were undertaken with the aim of establishing the quality and strength of the deductive evidence (whereby a hypothesis is tested by means of rigorously designed experiments) about the effectiveness or otherwise of individual NPIs. However, there is a second approach to gaining knowledge from observational research. This is an inductive approach, which is to draw together large-scale observational data correlating the timing and progression of SARS-CoV-2 transmission and case numbers with detailed measures of the implementation of different packages of NPIs.

There are important lessons to be learnt from how different nations implemented NPIs in order to control the transmission and spread of SARS-CoV-2. The implementation of NPIs differed between and within different countries by time, region, and stringency. There were prominent differences in the timing and intensity of test and tracing, social distancing and ‘lockdown’ measures. Asian countries that had more recently experienced SARS and other emerging infectious diseases, including MERS and avian influenza (eg China,

Hong Kong, Taiwan, Singapore, South Korea) used that experience to take a strategic approach aimed at reducing transmission and thereby slowing the spread of infection as quickly as possible. These countries implemented early stringent NPIs, followed by Australia and New Zealand.

This stringent and multi-faceted approach is illustrated in this report by three case studies in two countries and one region over the course of the pandemic. These were selected as illustrations of national strategies that proved effective in maintaining extremely low or absent domestic transmission of SARS-CoV-2 for a prolonged period of time. These case studies are of Hong Kong, New Zealand and South Korea.

In each of these countries or regions, tight border controls accompanied by strict quarantine of incoming passengers were applied early in the pandemic. In New Zealand and Hong Kong there were prolonged ‘lockdowns’ to control domestic transmission, which were relaxed when case numbers had fallen to extremely low levels. TTI was used to identify and to attempt to control recurring cases of domestic transmission of disease. This was reinforced by the reimposition of regional or national ‘lockdowns’ whenever multiple or unexplained episodes of domestic transmission occurred.

In South Korea, following the experience of a MERS outbreak in 2015, the country was pre-prepared to develop and scale the production of accurate diagnostic tests rapidly. This allowed the early implementation of large-scale TTI. This programme was supported by sophisticated technology to enhance contact tracing and enforce isolation of contacts. South Korea, unlike New Zealand and Hong Kong, did not implement a national ‘lockdown’.

As the pandemic progressed, new variants of SARS-CoV-2 evolved which had an increased transmission ‘advantage’ over previous circulating variants. By the time the SARS-CoV-2 Omicron variant emerged at the end of 2021, effective vaccines had been developed that largely prevented severe illness and deaths from COVID-19, though only partially prevented viral transmission and mild disease. These vaccines had been delivered to a high proportion of the population in many of the most affluent countries around the world.

At this point, countries that had attempted more or less successfully to maintain a zero COVID-19 status found that the Omicron variant could not be contained and changed their strategy to one of ‘living with the virus’. In the case of New Zealand and South Korea, this change in strategy was followed by a very large wave of Omicron infection, with a limited number of deaths. In the case of Hong Kong, where a large number of older and more vulnerable people had not received full vaccination, the large wave of Omicron infections was accompanied by a substantial number of deaths, mainly among the most elderly and vulnerable.

All three of these case studies illustrate that the application of differing packages of NPIs were associated with near elimination of SARS-CoV-2 transmission for prolonged periods. But it was also clear that this was due to the implementation of several NPIs. Tight border controls, coupled with strict quarantine measures, could reduce but not eliminate the importation of SARS-CoV-2 by entering travellers. The majority of imported infections were discovered and prevented from establishing domestic transmission by TTI. Nevertheless, intermittent episodes of domestic transmission occurred sporadically, presumably imported from travellers and their border contacts. These were controlled and

eliminated by a combination of TTI, coupled with localised, regional or national ‘lockdowns’ in New Zealand and Hong Kong or by mass testing, contact tracing and isolation in South Korea.

What can be learnt from these case studies? The most important lesson is that the strict early application of combinations of NPIs (including rapid scale-up of TTI technologies) was associated in these specific countries with domestic control of the initial wave of the pandemic at the beginning of 2020 and that subsequent small outbreaks of domestic transmission until the end of 2021 could be similarly controlled.

As is the case with all scientific observations, association, by itself, does not prove causation. However, in this case, the argument for a causal link between strict and early NPIs and domestic pandemic control is also supported by what is known about infection transmission generally and by the sharp contrast between countries that applied stringent NPIs early in the pandemic, while the transmission intensity of the virus was still low, and those that waited until late spring and early summer when many were experiencing a major wave of infection with a high transmission intensity.

Second, it should not be concluded that it is possible to extrapolate from these case studies to assert that, if other countries had applied a similar strategy for the implementation of NPIs, they would necessarily have achieved the same results. For example, natural geographic features mean that border controls can be imposed much more easily in some countries than others. Such studies can, however, be used to ‘ground-truth’ key assumptions in epidemiological models of transmission dynamics which can be used, with appropriate caveats, to explore possible outcomes in other situations.

Some remote Pacific Island nations and Antarctica managed to remain free of SARS-CoV-2 for a prolonged period by virtue of their isolation and relative ease in imposing border controls. The risk of infection is proportional to exposure to infection, so countries and regions with a low population density can achieve a lower exposure much more easily than in towns, cities and countries with a high population density. Political and cultural factors influence the willingness of politicians to impose, and of citizens to adopt and maintain, strict guidance and/or enforcement of ‘lockdown’ orders or other social distancing measures.

Another important incidental finding²⁰⁷ associated with the implementation of NPIs during the pandemic was that there was an almost complete lack of circulation of other seasonal viruses during the pandemic while NPI measures were in place. Many countries around the world reported much less influenza and RSV during the winters of 2020/21 and 2021/22 than in previous years. The US Centers for Disease Control and Prevention (CDC) for example reported around 100-fold fewer influenza cases in 2020/21 than in the previous year²⁰⁸.

In summary, evidence about the effectiveness of NPIs applied to reduce the transmission of SARS-CoV-2 shows unequivocally that, when implemented in packages that combine a number of NPIs with complementary effects, these can provide powerful, effective and prolonged reductions in viral transmission. The evidence also shows, as indicated by epidemiological models of transmission dynamics, that NPIs are most effective when applied when transmission intensity is low, indicating that it is important to implement these measures early during the emergence of a pandemic and at the earliest signs of resurgence of infection. Thirdly, while there is supportive evidence for the effectiveness of most of the NPIs applied during the pandemic

in reducing the transmission of infection, there are some notable absences of evidence, for handwashing and for environmental measures, in particular.

However, ‘absence of evidence’ is not the same as ‘evidence of absence’ – and this report was focused on establishing the extent of ‘real world’ evidence of effectiveness. In the case of handwashing, the importance of surgical asepsis, discovered by Lord Lister in the 19th century has saved millions of surgical patients from infections transmitted by contaminated hands. However, in the case of SARS-CoV-2 infection, we simply do not know the extent to which enhanced hand and surface washing played a role in limiting viral transmission.

Lessons for measuring the effectiveness of NPIs in the future

There are important lessons for the future. For policymakers and their professional advisers, there is a need to learn from national and international experience of the implementation of NPIs during the COVID-19 pandemic, and to understand in detail the differing national contexts and ways in which NPIs were implemented. National context was an important influence on the outcome of the COVID-19 pandemic.

One key lesson to researchers is to ‘be prepared’. The value of prior preparedness is illustrated by the work of the International Severe Acute Respiratory Infection Consortium (ISARIC)²⁰⁹ that was established in 2011 as a response to emerging respiratory infections such as SARS and avian influenza. As part of its UK work, the consortium developed pre-established protocols for clinical investigation, including draft research ethics committee proposals, so that existing groups of national and international researchers could immediately collaborate to characterise new and emerging viral infectious diseases.

As a result of their preparedness, they were able to start working on COVID-19 within weeks of its identification.

Amidst the rapid and uncertain dynamics of a pandemic, evidence to inform decisions about NPI measures and their implementation is needed in real-time and iteratively, to underpin effective responses and adaptations to fast-moving conditions. Commissioning the kind of research needed and groups to provide it 'from scratch' in such conditions is challenging, and rarely fast enough, as the variable experience of the many rapid response funds and calls launched during COVID-19 indicates. As a complement to open calls for research, which are necessary to develop understanding of a pandemic caused by a novel infectious agent, it is important to use inter-pandemic ('peacetime') periods to pre-position appropriate national and international research consortia and networks, data infrastructures, methodological protocols, and platforms and mechanisms for evidence translation and uptake, so these are ready to be mobilised as needed in real-time as a pandemic unfolds. These should encompass both mechanisms to collect novel data, and to synthesise existing data and studies (including relevant studies from earlier pandemics and inter-pandemic periods) into relevant evidence reviews. As part of this work, it is essential to agree the necessary data to be collected and the data standards to be applied in order to ensure that the protocols that are developed provide for comparability between studies and proper meta-analysis of their data. Studies should be positioned to address both NPI measures and their effectiveness, as well as the social, cultural, and political contexts relevant to their implementation and uptake.

To facilitate balanced decision-making, assessments of the adverse impacts of interventions, in terms of health, society and economy, should be included. Disaggregated studies that can assess implications for different population groups (eg by ethnicity, gender, age, geography) are also important.

Future assessments should also consider the costs as well as the benefits of NPIs, in terms of their impacts on livelihoods, economy, education, social cohesion, physical and mental wellbeing, and potentially other aspects. Drugs regulators are able to make recommendations on the use of drugs based upon evidence of their effects and side effects. Similarly policymakers should be able in the future to make the best policy decisions on NPIs, which are in the main complex social interventions, if they have better evidence on their broader health and societal impacts. They could consider these alongside their effects on reducing the transmission of the infectious agent. The provision of such evidence will require pre-planned protocols, and in some cases prior research, to systematically collect a wide variety of relevant health and social data and, alongside this, an embedded system of expert research advice to assist policymakers in making extremely difficult policy decisions in the face of a pandemic.

However, it could be argued that given the lack of knowledge about the relative effectiveness of the many different individual NPIs, it would in some situations have been ethical and might have been practical to conduct well designed studies to compare the effects of different NPIs. Studies could also be designed to consider ways in which NPI implementation could be optimised eg for quarantine of case contacts, by comparing different durations in isolation, testing regimes or strategies for support.

There is a case that policymakers and researchers should consider the possibility of conducting such studies in advance of the next pandemic – and, if it is considered potentially feasible – for groups of researchers to design the protocols for studies that could be considered for activation, depending on the nature of the next pandemic. But while RCTs should not be discounted, it is highly likely that realistically most information in a future pandemic will continue to be observational. Furthermore, careful consideration should be given – as part of pandemic preparedness – to identifying the information most likely to be needed in the epidemiological models developed in the early stages of outbreaks, well before they become pandemics.

The evidence assembled for the development of this report shows that, in the context of COVID-19, caused by a virus dominantly transmitted by a respiratory route, controlling the transmission of the virus required a clear plan for the stringent application of combinations of NPIs. Such plans are easier to formulate and implement if prepared in advance. Some countries that had experienced recent outbreaks of other emerging respiratory viral infections, including SARS and MERS, were well prepared and already had capacity to implement combinations of NPIs in place.

The question of how to balance the effectiveness of NPIs with their potential adverse individual and societal consequences is a political and not a scientific one. This report examined the effectiveness of the NPIs as a means of reducing the transmission of SARS-CoV-2. Given the extensive social and economic impacts of both the pandemic itself and the NPIs used to slow its transmission, there is a strong case for the development of another report, complementary to this one, based on a series of evidence reviews, examining what has been learnt during the pandemic about the full range of social and economic impacts.

Perhaps the most important lesson of all from the COVID-19 pandemic is the need for government policymakers to consider the balance between the benefits and adverse effects of NPIs in advance of the next pandemic. The next pandemic is likely to be different in important ways from COVID-19 and other previous pandemics. Policymakers should work in partnership with researchers to develop a series of different scenarios for future pandemics. They should also enable researchers to improve our knowledge of the effectiveness of NPIs under laboratory conditions. Protocols should be developed for a future pandemic to find out what works best to reduce the transmission of infection at the same time as causing the least disruption to the normal functioning of society.

For the first time in human history it proved possible to influence the outcome of a pandemic respiratory infection by means of the rapid development, evaluation and implementation at scale of specific treatments and vaccines for COVID-19. The effective application of NPIs ‘buys time’ to allow the development and manufacturing of such therapies and vaccines at scale. So there is every reason to think that the application of combinations of NPIs will be important in future pandemics, particularly at early stages with novel pathogens when there are knowledge gaps and when therapeutics and vaccines are not yet available.

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