Wales COVID-19 Evidence Centre (WCEC)
Rapid Review

Modelling studies used to evaluate the effect of population-level non-pharmaceutical interventions on the reproduction number of Severe Acute Respiratory Syndrome Coronavirus 2 (SARS-CoV-2)

Report number – RR00036 (March 2022)

Rapid Review Details

Review conducted by:

Health Technology Wales

Review Team:

- David Jarrom
- Sasha Barrate
- Jessica Williams
- Jenni Washington
- Elise Hasler
- Tom Winfield

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WCEC Team:

- Adrian Edwards, Alison Cooper, Ruth Lewis, Rebecca-Jane Law, Micaela Gal and Jane Greenwell involved in drafting Topline Summary, review and editing

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Modelling studies used to evaluate the effect of population-level non-pharmaceutical interventions on the Reproduction number of severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2)

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TOPLINE SUMMARY

What is a Rapid Review?

Our rapid reviews use a variation of the systematic review approach, abbreviating or omitting some components to generate the evidence to inform stakeholders promptly whilst maintaining attention to bias. They follow the methodological recommendations and minimum standards for conducting and reporting rapid reviews, including a structured protocol, systematic search, screening, data extraction, critical appraisal, and evidence synthesis to answer a specific question and identify key research gaps. They take one to two months to complete, depending on the breadth and complexity of the research topic/question(s), extent of the evidence base, and type of analysis required for synthesis.

Who is this summary for?

The Welsh Government Technical Advisory Cell (TAC) proposed the question

Background / Aim of Rapid Review

Coronavirus disease 2019 (COVID-19) is a respiratory infectious disease caused by the severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2). The use of non-pharmaceutical interventions has been key in helping to slow down the spread the SARS-CoV-2 virus.

In order to **inform any future 'COVID-19 urgent' situations**, and to **test possible combinations of non-pharmaceutical interventions (NPIs)** that would be required to bring transmission under control again, TAC has developed a **'ready reckoner' NPI tool**. The effectiveness of **population-level NPIs** have predominantly been evaluated using mathematical modelling. The **time-varying reproduction number (Rt)**, which is defined as the expected number of secondary cases arising from a primary case infected at time ('t') provides an important indicator of how fast the virus is spreading at the population level. The NPI tool uses the outcomes of existing modelling studies to directly inform decisions that are pertinent to a specific context or for different NPI bundles. The user enters the current Rt value for their particular setting, chooses a modelling study, and then selects a number of NPIs from the chosen study. A new Rt number is outputted along with a waterfall chart showing the changes in Rt from each individually selected NPI.

The implementation of the NPI tool is **reliant on having a select number of relevant and well-conducted modelling studies upon which to draw**. This Rapid Review documents the **identification, selection, summary and critical appraisal of suitable modelling studies** for use with the tool. The work was carried out to inform the NPI tool, and therefore focuses on reporting the design and characteristics of relevant studies; no modelling outcomes were reported.

Key Findings

Nine modelling studies that evaluated multiple NPIs (NPI bundles) and reported their effect on Rt values were identified; studies published before 2021 were excluded.

Extent of the evidence base

- **Most of the studies reported data from the first wave** (February to August 2020), with only three (Turner et al. 2021, Laydon et al. 2021, Sharma et al. 2021) including second wave data (September 2020 to May 2021). No studies reported data for third wave or later (June 2021 onwards).
- Type of modelling included Bayesian hierarchical models, logistic regression models and Generalised Linear Mixed Models (GLMM). The most common data source for SARS-CoV-2 cases was the Johns Hopkins' Centre for Systems Science and Engineering COVID-19 Dataset, and for NPIs was government sources and news outlets.
- **Eight studies reported data from the UK**; no data specific to Wales were reported.
- The **NPIs were mostly reported in broad categories** and included school closures, workplace closures, closure of public transport, restrictions on gatherings of different sizes and stay at home orders.

Recency of the evidence base

- All included studies were published in 2021.

Critical appraisal

- Modelling studies were appraised based on the assessment of model structure, input data, methods of validation, how uncertainty was addressed, and transparency of the model/methods.
- In all cases, the **model structure was described in sufficient detail,** with reasonable detail of assumptions made and justification given for these assumptions.
- Input parameters were, to a greater or lesser extent, judged to be transparent, justified and reasonable in all studies.
- A common pragmatic approach adopted within included studies was to assume the 'binary' presence or absence of NPIs, which may not reflect their graded introduction and withdrawal in real-world scenarios.
- The approach used in addressing validation and uncertainty, and their documentation, was the most notable variation across studies. All included some form of internal validation, methods for which included validity checks and scenario/sensitivity analysis, but the extent of these and their clear documentation was variable.
- **None of the studies undertook formal external validation**, but the majority (seven out of nine studies) made their code and/or datasets available – meaning replication of their methods should be possible.

Policy Implications

- The NPI tool **can be used to support decisions** during future 'urgent' COVID-19 situations, during which NPIs should be implemented to contain the spread of the virus; it **can be used to project future changes in Rt as a result of specific NPIs**.
- The review identifies nine modelling studies that can be used to implement the NPI tool.
- A summary of the study design and characteristics is provided, which can be used to aid the selection of the most appropriate modelling study when using the NPI. Critical appraisal of these studies identified no major concerns with their design or conduct.

Strength of Evidence

A limited number of well-conducted reviews were selected.

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Abbreviations:

Acronym	Full Description
COVID-19	Coronavirus disease 2019
NPI	Non-pharmaceutical intervention
Rt	Time-specific reproduction number
Rt;l	Time- and location-specific (instantaneous) reproduction number *(The expected number of secondary infections that would arise from a primary infection at time 't' in location 'l', provided conditions remain the same after time)*
R0	Basic reproduction number
R e	Effective reproduction number
SARS-CoV-2	Severe acute respiratory syndrome coronavirus 2

1. BACKGROUND

This Rapid Review is being conducted as part of the Wales COVID-19 Evidence Centre Work Programme. The above question was developed through collaboration with a range of stakeholders including from the COVID-19 Technical Advisory Cell (Welsh Government), the WCEC Core Team, and Health Technology Wales.

1.1 Purpose of this review

Since December 2019, infections with severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) and the respective disease, coronavirus 2019 (COVID-19), have spread worldwide. On 11 March 2020, the World Health Organization (WHO) declared the SARS-CoV-2 outbreak a pandemic. COVID-19 has represented a serious threat to public health reporting 5,960,972 deaths and 437,333,859 confirmed cases globally (World Health Organization 2021).

The latest Welsh Government Coronavirus Control Plan sets out what a 'COVID-19 urgent' scenario could look like for Wales (Welsh Government 2021). It states that in this situation, significant action may need to be taken to protect public health and peoples' lives (Welsh Government 2021). Non-pharmaceutical interventions (NPIs) are one type of measure that may be used to bring the virus back under control. NPIs are also known as public health measures and include, for example, actions such as mask-wearing, physical distancing, school closure, work place closure, public events ban, restrictions on the size of gatherings, and requirements to stay at home (Usher Network for Covid-Evidence Reviews group 2021, Hale T et al. 2020). NPIs to control the COVID-19 pandemic have been mandated at country or regional level, recommended within specific organisations or workplaces, and adopted on an individual level. This rapid review focuses on studies that evaluate the effectiveness of large-scale, population-level NPIs. Some population-level NPIs have high social and economic costs (Angulo MT et al. 2021), which means that policy decisions on which NPIs to implement are not straight forward.

The time-varying Reproduction number (Rt) provides an important measure for tracking the progress of an outbreak and assessing whether NPIs have been effective in controlling transmission. The Rt represents the expected number of secondary cases arising from a primary case infected at a time ('t') (Li et al. 2021).

The Technical Advisory Cell in the Welsh Government has produced a **'ready reckoner' NPI tool** that can be **used in a 'COVID-19 urgent' situation to test possible combinations of NPIs that would be required to bring transmission under control again**. The NPI tool is designed in Python using a streamlit interface. It enables the user to interpret, or translate, the findings of an existing modelling study to inform decisions that are specific to their own circumstance or context. The user is able to enter an Rt for SARS-CoV-2, which reflects their current situation, choose a modelling study, and then select relevant NPI interventions from the chosen study. A new Rt number is outputted along with a waterfall chart showing the changes in Rt from each individually selected NPI.

The accuracy of the estimated reduction to Rt, produced by the NPI tool, are dependent on the robustness of the selected modelling study. It is important that this is based on the most relevant, in addition to well-conducted, modelling study. In order to aid the selection process, a limited number of the best available modelling studies needs to be identified. This Rapid Review documents the identification, selection, and the summary and critical appraisal of suitable studies for use with the tool. The studies were quality-assured by the Wales COVID-19 Evidence Centre and Health Technology Wales.

Research question: What modelling studies can be used to evaluate the effect of population-level non-pharmaceutical interventions on the reproduction number of SARS-CoV-2 studies?

2. RESULTS

We searched for modelling studies that evaluated multiple NPIs (NPI bundles) and reported their effect on Rt values. Our search generated 866 unique articles that were screened against the eligibility criteria (see Methods). Studies published before 2021 were excluded. In total, nine studies met the inclusion criteria and were included in this review (see Table 1). We only included studies that directly reported Rt as a relative change/treatment effect. This led to the exclusion of some studies that reported related outcomes from which it might be possible to calculate or estimate Rt, but which would not be straightforward to do so. For completeness, studies excluded for these reasons are listed in Appendix 1.

3. DISCUSSION

3.1 Summary of the findings

Most of the evidence identified reported data from the first wave (in Europe, February to August 2020), with only three studies (Turner et al. 2021, Daniel et al. 2021, Sharma et al. 2021) including second wave data (September 2020 to May 2021). We did not identify any studies that reported data for third wave or later (June 2021 onwards).

The purpose of the studies varied; some looked at the impact of introducing and relaxing NPI bundles on the transmission of SARS-CoV-2 and some reported on the effectiveness of individual NPIs. However, not all studies reported a clear control or comparison group, and for these studies the absence of NPIs had to be assumed as the control. Two studies (Bo Y et al. 2021, Liu et al. 2021) compared the effectiveness of different types of NPIs against each other and both reported Rt values as the measure of rate of transmission. One study compared first and second wave data for implementing and lifting NPIs (Sharma et al. 2021).

Different models were used across the studies, including Bayesian hierarchical models, logistic regression models and Generalised linear mixed models (GLMM). The Johns Hopkins' Centre for Systems Science and Engineering COVID-19 Dataset was the most common source for confirmed SARS-CoV-2 cases data, whilst data on NPIs were mostly obtained from government sources and news outlets. One study that reported data from the second wave incorporated varying population immunity into their analysis of different NPIs (Turner et al. 2021).

The population or geographic characteristics of the studies identified were mixed, with some using whole population data and some reporting on sample data. Eight out of nine studies reported data on the UK; however, no data specific to Wales were reported. One study used first and second wave data to compare the impact of the different 'tiers' (NPIs and their stringency varying by region depending on metrics such as local incidence) on transmission of SARS-CoV-2 in England (Daniel et al. 2021).

The NPIs were mostly reported in broad categories across all studies and included school closures, workplace closures, closure of public transport, restrictions on gatherings of different sizes and stay at home orders.

3.2 Critical appraisal

Appendix 3 provides detailed judgements based on critical appraisal of each included study. Critical appraisal was based on the methods developed by Burns J et al. (2021) and assessed the model structure, input data, methods of validation, how uncertainty was addressed, and transparency of the model/methods.

In all cases, we judged the **model structure to be described in sufficient detail** with reasonable detail of assumptions made and justification given for these assumptions. Input parameters, to a greater or lesser extent, were also judged to be transparent, justified and reasonable in all studies. One common theme was the use of 'binary' NPIs – either their presence or absence, which may not reflect their graded introduction and withdrawal in real-world scenarios – but we judged this to be a pragmatic approach for the purposes of modelling. Approaches used in addressing validation and uncertainty, and their documentation, were the most notable variations across studies. All included some form of internal validation, methods for which included validity checks and scenario/sensitivity analysis, but the extent of these and their clear documentation was variable. **None of the studies undertook formal external validation**, but most studies (seven out of nine studies) made their code and/or datasets available – meaning **replication of their methods should be possible**.

3.3 Limitations of this Rapid Review

The aim of this rapid review was to systematically identify and summarise studies modelling the effect of multiple NPIs on the SARS CoV-2 Rt. Because this work was carried out to inform the NPI tool described in the Introduction, we only report the design and characteristics of relevant studies. No outcomes were reported on in this review. Most studies reported data from the first wave, with only three studies including second wave data and none from later waves. As many of the study authors acknowledge, behaviours early in the COVID-19 pandemic may not be representative of later behaviours and could influence the effectiveness of many of the NPIs implemented. This assumption led us to pragmatically exclude studies published in 2020 (which by definition would cover the early pandemic period only). This was because the objective of the NPI tool is to project future changes in Rt as a result of NPIs, not to model retrospective changes which are likely to have been greater earlier in the pandemic. However, our findings of relatively few studies beyond the first wave

of the pandemic could limit the applicability of the studies described here to decision making at later stages of the pandemic.

Table 1: Study design and characteristics

Study	Purpose	Analysis	Dates	Participants (population or geographic characteristics)	Interventions (NPIs)	Control/ comparison	Outcomes
Li et al. (2021) Y. Li, H. Campbell, D. Kulkarni et al. (2021). The temporal association of introducing and lifting non-pharmaceutical interventions with the time-varying reproduction number (R) of SARS-CoV-2: a modelling study across 131 countries. The Lancet Infectious Diseases 2021 Vol. 21 Issue 2 Pages 193-202 Accession Number: 33729915 doi: https://dx.doi.org/10.1016/S1473-3099(20)30785-4	Understand the association of introducing and lifting NPIs with the level of transmission of SARS-CoV-2	Logistic regression Utilises linked data – daily county level R data + country specific policies on NPIs. modelling framework accounts for reporting delay between symptom onset and case notification and the delay between onset and infection based on empirical data	First wave January 2020 – July 2020	131 countries (Global)	Country wide NPIs: • closure of schools, • closure of workplaces, • public events bans (e.g., sports, festive, and religious events), • restrictions on the size of gatherings, • closure of public transport, • stay at home orders, • restrictions on internal movement restrictions on international travel	Absence of country wide NPIs	Transmission R ratio: ratio between daily R of each phase and R from the last day of the previous phase (i.e., before the NPI status changed)
Turner et al. (2021) Turner D, Égert B, Guillemette Y, et al. (2021). The tortoise and the hare: The race between vaccine rollout and new COVID variants.	Explore alternative scenarios that differ according to the speed of vaccine rollout and the infectiousness	The framework consists of two equations estimated at high frequency: the first explains the daily evolution of the effective reproduction number, R (representing the spread of the virus), and the	Second wave. Jan 2020-mid May 2021	OECD country	• School closures (Partial closure; Complete) • Workplace closures (Recommend; Require for some sectors/categories of workers; all-but-essential workplaces (e.g. grocery stores, doctors)) • Cancel public events (Recommend; Require)	Absence of NPIs	Effective reproduction number.

Study	Purpose	Analysis	Dates	Participants (population or geographic characteristics)	Interventions (NPIs)	Control/ comparison	Outcomes
doi: https://doi.org/10.1787/4098409d-en	of new variants of the virus	second explains a proxy measure of weekly GDP COVID-19 policy trackers maintained by the Oxford Blavatnik School of Government			• Restrictions on gatherings (>1000; 101-1000; 11-100; ≤10) • Close public transport (Recommend [or significantly reduce transport available]; Require [or prohibit most from using]) • Stay at home requirements (Recommend; Require with exceptions for daily exercise, grocery shopping, and 'essential' trips; Require with minimal exceptions) • Restrictions on internal movement (Recommend not to travel between regions/cities, Internal movement restrictions) • International travel controls (Screening; Quarantine arrivals from high-risk regions; Ban on arrivals from some regions; Ban on all regions or total border closure)		
Sharma et al. (2021) Sharma M, Mindermann S, Rogers-Smith C, et al. (2021). Understanding the effectiveness of government interventions against the resurgence of COVID-19 in Europe. Nature	Estimate the effectiveness of individual NPIs during Europe's second wave of SARS-CoV-2	Semi-mechanistic Bayesian hierarchical model. Chronological NPI data gathered manually; several validation procedures used to ensure high data quality. Data for other model parameters (distributions):	Second wave. NPIs in place 1 Aug 2020 – 9 Jan 2021	7 European countries. Whole country data used for Austria, the Czech Republic, Italy, the Netherlands. For England, Germany, and Switzerland, a stratified random sample of 15	11 broad categories of NPIs included: • Primary schools closed • Secondary schools closed • Universities closed • Night clubs closed • Gastronomy closed • Leisure and entertainment venues closed • Retail and close contact services closed • Night-time curfew	Absence of national/regional NPIs (period prior to second wave) Implementing /lifting NPIs 1st wave outcomes	Percentage reductions in the (instantaneous) reproduction number $R_{t,l}$ (*time and location specific*)

Study	Purpose	Analysis	Dates	Participants (population or geographic characteristics)	Interventions (NPIs)	Control/ comparison	Outcomes
communications. 12(1): 5820. doi: https://dx.doi.org/10.1038/s41467-021-26013-4		generation interval and incubation period from published MA; onset to reported death and onset to case confirmation from Linelist (country specific patient data) Daily case and death data were obtained from government websites.		regions of analysis per country was used. Public data on daily reported cases and deaths were available at the same geographical resolution at which each country implemented NPIs.	• Stricter mask-wearing policy • Public gatherings limited to ≤30, ≤10, 2 people or banned. • Household mixing in private is limited to ≤30, ≤10, 2 people or banned These were further sub-categorised by level of business closure (including closure of all non-essential businesses) and size of public gatherings/household mixing.		
Daniel et al. (2021) Laydon DJ, Mishra S, Hinsley WR, et al. (2021). Modelling the impact of the tier system on SARS-CoV-2 transmission in the UK between the first and second national lockdowns. BMJ Open. 11(4): e050346. doi: https://dx.doi.org/10.1136/bmjopen-2021-050346	Measure the effects of the Tier system on the COVID-19 pandemic in the UK between the first and second national lockdowns, before the emergence of the B.1.1.7 variant of concern.	Semi mechanistic Bayesian hierarchical model with a latent factor analysis Data on NPIs obtained from government websites R_t derived from UK case, death and serological survey data	First and Second Wave 1st July 2020 to 5th November 2020 –	310 lower tier local authorities in the UK (unclear where in the UK)	21 broad categories of NPIs included: • Essential travel (Tier 3) • Table service only in pubs and bars (Tier 3) • Takeaway hospitality only (Tier 3) • Arts venues closed (Tier 3) • Personal care contact services closed (Tier 3) • Public buildings closed • Gyms closed (Tier 3) • Tourist attractions closed (Tier 3) • Organised sport not allowed (Tier 3) • Weddings not allowed (Tier 3) • Places of worship closed (Tier 3) • Schools closed (Tier 3)	Absence of TIER system and then comparison of TIERs 1, 2, and 3.	Change in local time-varying reproduction number R_t - the method estimates transmission by calculating backwards from observed deaths (day of death), cases and serological survey data while simultaneously allowing for the time lag between infection and death.

Study	Purpose	Analysis	Dates	Participants (population or geographic characteristics)	Interventions (NPIs)	Control/ comparison	Outcomes
					• Non-essential retail closed (Tier 3) • Residents cannot leave local area (Tier 3) • Overnight stays discouraged (Tier 2) • No indoor mixing (Tier 2) • Travel discouraged (Tier 2) • Work from home where possible (Tier 1) • Curfew of 10pm for hospitality venues (Tier 1) • Limited to groups of 6 outdoors (Tier 1) Limited to groups of 6 indoors (Tier 1)		
Arroyo-Marioli et al. (2021) Arroyo-Marioli F, Bullano F, Kucinskas S, et al. (2021). Tracking R of COVID-19: A new real-time estimation using the Kalman filter. PLoS ONE [Electronic Resource]. 16(1): e0244474. doi:https://dx.doi.org/10.1371/journal.pone.0244474	Authors developed a new method for estimating the effective reproduction number of an infectious disease and applied this to track the dynamics of COVID-19.	The method is based on the fact that in the SIR model, R is linearly related to the growth rate of the number of infected individuals. This time-varying growth rate is estimated using the Kalman filter from data on new cases. Data on SARS-CoV-2 cases from the John Hopkins CSSE repository. For some of our statistical analyses, we also use data on the number of daily tests per capita collected by Our World in	First wave – exact dates unclear.	Estimates used to assess the effects of non-pharmaceutical interventions (NPIs) in the same sample of 14 European countries. (Austria, Belgium, Denmark, France, Germany, Greece, Italy, Netherlands, Norway, Portugal, Spain, Sweden, Switzerland, and United Kingdom)	Total of five NPIs: • Lockdowns • Bans of public events. • School closures. • Mandated self-isolation when exhibiting symptoms • Social distancing measures.	Absence of NPIs assumed.	Estimates of Rt were used to measure the basic reproduction number R0, i.e., the average number of individuals infected by a single infectious individual when the population is fully susceptible. The authors estimate R0 by the average value of Rt in

Study	Purpose	Analysis	Dates	Participants (population or geographic characteristics)	Interventions (NPIs)	Control/ comparison	Outcomes
		Data, mobility data from Google's "COVID-19 Community Mobility Reports".					the first week of the epidemic.
Banholzer N et al. (2021) Banholzer N, van Weenen E. Lison A. Cenedese (2021). Estimating the effects of non-pharmaceutical interventions on the number of new infections with COVID-19 during the first epidemic wave. PloS one. 16(6): e0252827. doi: https://doi.org/10.1371/journal.pone.0252827	Authors study the effectiveness of seven NPIs in reducing the number of new infections	Semi-mechanistic Bayesian hierarchical model. Reported SARS-CoV-2 cases were obtained from the Johns Hopkins Coronavirus Resource Center. Data on NPIs were collected by the research team. Their implementation dates were systematically obtained from government resources and news outlets	First wave. February 2020 to May 2020	*n* = 20 Western countries during the first epidemic wave: the United States, Canada, Australia, the EU-15 countries (Austria, Belgium, Denmark, Finland, France, Germany, Greece, Ireland, Italy, Luxembourg, the Netherlands, Portugal, Spain, Sweden, and the United Kingdom), Norway, and Switzerland. This amounts to ∼3.3 million reported cases of COVID-19 and covers a population of ∼0.8 billion people.	Seven NPIs: • Ban of large gatherings • School closure • Venue closure • Border closure • Ban of small gatherings • Stay at home order • Work from home order	Absence of NPIs assumed.	Relative reduction in the number of new infections for each NPI.
Brauner et al. (2021) Brauner JM, Mindermann S, Sharma M, et al. (2021).	Authors report on individual effectiveness of each NPI at	Bayesian hierarchical model linking intervention implementation dates to national case and death counts. The model also	First wave. Chronological data	34 European and 7 non-European countries.	NPIs: • Gatherings limited to 1000 people or less • Gatherings limited to 100 people or less	Absence of NPIs assumed.	Percentage reduction in Rt.

Study	Purpose	Analysis	Dates	Participants (population or geographic characteristics)	Interventions (NPIs)	Control/ comparison	Outcomes
Inferring the effectiveness of government interventions against COVID-19. Science. 371(6531): 19. doi:https://dx.doi.org/10.1126/science.abd9338	reducing transmission.	accounts for uncertainty in key epidemiological parameters, such as the average delay from infection to death. Data on confirmed SARS-CoV-2 cases and deaths were taken from the Johns Hopkins CSSE COVID-19 Dataset. NPI final dataset contains primary sources (government websites and/or media articles)	on the implementation of several interventions in 41 countries between 22 January 2022 and 30 May 2020 was collected.	(Albania, Lithuania, Andorra, Malaysia, Austria, Malta, Belgium, Mexico, Bosnia and Herzegovina, Morocco Bulgaria, Netherlands, Croatia New Zealand, Czech Republic, Norway, Denmark, Poland, Estonia, Portugal, Finland, Romania, France, Serbia, Georgia, Singapore, Germany, Slovakia, Greece, Slovenia, Hungary, South Africa, Iceland, Spain, Ireland, Sweden, Israel, Switzerland, Italy, United Kingdom and Latvia)	• Gatherings limited to 10 people or less • Some businesses closed • Most non-essential business closed • Schools closed • Universities closed • Stay at home order		
Bo Y et al. (2021) Bo Y, Guo C. Lin C. Zeng (2021). Effectiveness of non-pharmaceutical interventions on COVID-19 transmission	Authors evaluate and compare the effectiveness of four types of non-pharmaceutical interventions	Model: Generalised linear mixed model (GLMM) Data on the daily number of confirmed COVID-19 cases was extracted from a data repository sourced from Johns Hopkins	First wave 23 January - 13 April 2020.	1,908,197 confirmed COVID-19 cases from 190 countries	NPIs categorised into four types: • Mandatory face marks in public • Isolation or quarantine • Social distancing • Traffic restriction	Authors compared the effectiveness of the different types of NPIs implemented.	Percentage differences in Rt.

Study	Purpose	Analysis	Dates	Participants (population or geographic characteristics)	Interventions (NPIs)	Control/ comparison	Outcomes
in 190 countries from 23 January to 13 April 2020. International journal of infectious diseases. 102: 247-53. doi:https://doi.org/10.1016/j.ijid.2020.10.066	(NPIs) to contain the time-varying effective reproduction number (Rt) of coronavirus disease-2019 (COVID-19).	University Center for Systems Science and Engineering and the Wind Financial database Data pertaining to the implementation of NPIs during the study period were obtained from official webpages of high-circulation newspapers published in the 415 cities/countries.					
Liu et al. (2021) Y. Liu, C. Morgenstern, J. Kelly, R. Lowe, C. C.-W. Group and M. Jit. The impact of non-pharmaceutical interventions on SARS-CoV-2 transmission across 130 countries and territories. BMC Medicine 2021 Vol. 19 Issue 1 Pages 40 doi: https://dx.doi.org/10.1186/s12916-020-01872-8	Authors assessed the effectiveness of NPIs around internal containment and closure, international travel restrictions, economic measures, and health system actions on SARS-CoV-2 transmission in 130 countries and territories.	Gaussian generalised additive model with cubic splines, using stringency index (SI) as the response variable and date as the sole explanatory variable for each World Bank region. Data on COVID-19-related NPI intensity was extracted from version 5 of the Oxford COVID-19 Government Response Tracker (OxCGRT) Median Rt estimates obtained through EpiForecasts [https://epiforecasts.io/], a publicly available repository.	First wave - January to June 2020	130 countries (including European countries, but not the UK)	4 NPI categories: • Internal containment and closure (consists of: School Closures, Workplace Closure, Cancellation of Public Events, Limits on Gathering Sizes, Closure of Public Transport, Stay-at-home Requirement, Internal Movement Requirement) • International travel restrictions • Economic policies (consists of: income Support and Debt/ Contract Relief for Households) • Health System Policies (consists of: Public Information Campaign, Testing Policy, Contact Tracing)	Authors compared different stringency levels of NPIs in different countries	Rate of transmission in populations, represented by Rt

Study	Purpose	Analysis	Dates	Participants (population or geographic characteristics)	Interventions (NPIs)	Control/ comparison	Outcomes
		Authors examined different model specifications to account for the temporal lag between NPIs and changes in Rt, levels of NPI intensity, time-varying changes in NPI effect, and variable selection criteria					

4. REFERENCES

Angulo MT, Castaños F, Moreno-Morton R, et al. (2021). A simple criterion to design optimal non-pharmaceutical interventions for mitigating epidemic outbreaks. Journal of the Royal Society Interface. 18(178). doi: https://doi.org/10.1098/rsif.2020.0803

Arroyo-Marioli F, Bullano F, Kucinskas S, et al. (2021). Tracking R of COVID-19: A new real-time estimation using the Kalman filter. PLoS ONE [Electronic Resource]. 16(1): e0244474. doi: https://dx.doi.org/10.1371/journal.pone.0244474

Banholzer N, van Weenen E, Lison A, et al. (2021). Estimating the effects of non-pharmaceutical interventions on the number of new infections with COVID-19 during the first epidemic wave. PloS one. 16(6): e0252827. doi: 10.1371/journal.pone.0252827

Bendavid E OCBJIJPA. (2021). Assessing Mandatory Stay-at-Home and Business Closure Effects on the Spread of COVID-19. European journal of clinical investigation. e13484. doi: 10.1111/eci.13484

Bo Y, Guo C, Lin C, et al. (2021). Effectiveness of non-pharmaceutical interventions on COVID-19 transmission in 190 countries from 23 January to 13 April 2020. International journal of infectious diseases. 102: 247-53. doi: 10.1016/j.ijid.2020.10.066

Brauner JM, Mindermann S, Sharma M, et al. (2021). Inferring the effectiveness of government interventions against COVID-19. Science. 371(6531): 19. doi: https://dx.doi.org/10.1126/science.abd9338

Burns J, Movsisyan A, Stratil JM, et al. (2021). International travel-related control measures to contain the COVID-19 pandemic: a rapid review. Cochrane Database of Systematic Reviews. 3(CD013717). doi: 10.1002/14651858.CD013717.pub2

Chan LYH, Yuan B, Convertino M. (2021). COVID-19 non-pharmaceutical intervention portfolio effectiveness and risk communication predominance. Scientific Reports. 11(1): 10605. doi: https://dx.doi.org/10.1038/s41598-021-88309-1

Daniel JL, Swapnil M, Wes RH, et al. (2021). Impact of the Tier system on SARS-CoV-2 transmission in the UK between the first and second national lockdowns. Medrxiv. doi: 10.1101/2021.02.23.21252277

Hale T, Webster S, Petherick A, et al. (2020). Coronavirus government response tracker. Available at: https://www.bsg.ox.ac.uk/research/research-projects/covid-19-government-response-tracker [Accessed March 2022].

Hasan A, Putri ERM, Susanto H, et al. (2021). Data-driven modeling and forecasting of COVID-19 outbreak for public policy making. ISA Transactions. 20: 20. doi: https://dx.doi.org/10.1016/j.isatra.2021.01.028

Knock ES, Whittles LK, Lees JA, et al. (2021). Key epidemiological drivers and impact of interventions in the 2020 SARS-CoV-2 epidemic in England. Science Translational Medicine. 13(602): 14. doi: https://dx.doi.org/10.1126/scitranslmed.abg4262

Leonidas S. (2021). On the Effectiveness of COVID-19 Restrictions and Lockdowns: Pan Metron Ariston. SSRN.

Li Y, Campbell H, Kulkarni D, et al. (2021). The temporal association of introducing and lifting non-pharmaceutical interventions with the time-varying reproduction number (R) of SARS-CoV-2: a modelling study across 131 countries. The Lancet Infectious Diseases. 21(2): 193-202. doi: https://dx.doi.org/10.1016/S1473-3099(20)30785-4

Liu Y, Morgenstern C, Kelly J, et al. (2021). The impact of non-pharmaceutical interventions on SARS-CoV-2 transmission across 130 countries and territories. BMC Medicine. 19(1): 40. doi: https://dx.doi.org/10.1186/s12916-020-01872-8

Pozo-Martin F WHCFHJBTSLEBC. (2021). The impact of non-pharmaceutical interventions on COVID-19 epidemic growth in the 37 OECD member states. European journal of epidemiology. 36(6): 629-40. doi: 10.1007/s10654-021-00766-0

Sharma M, Mindermann S, Rogers-Smith C, et al. (2021). Understanding the effectiveness of government interventions against the resurgence of COVID-19 in Europe. Nature Communications. 12(1): 5820. doi: 10.1038/s41467-021-26013-4

Turner D, Égert B, Guillemette Y, et al. (2021). The tortoise and the hare: The race between vaccine rollout and new COVID variants. doi: doi:https://doi.org/10.1787/4098409d-en

Usher Network for Covid-Evidence Reviews group. (2021). Non-Pharmaceutical Interventions (NPIs). Available at: https://www.ed.ac.uk/usher/uncover/our-output/npis-and-r [Accessed February 2022].

Vardavas R, de Lima PN, Baker L. (2021). Modeling COVID-19 Nonpharmaceutical Interventions: Exploring periodic NPI strategies. MedRxiv : the Preprint Server for Health Sciences. 21: 21. doi: https://dx.doi.org/10.1101/2021.02.28.21252642

Welsh Government. (2021). Coronavirus control plan: autumn and winter 2021 update. Available at: https://gov.wales/coronavirus-control-plan-autumn-and-winter-2021-update [Accessed February 2022].

World Health Organization. (2021). WHO Coronavirus (COVID-19) Dashboard. Available at: https://covid19.who.int/ [Accessed February 2021].

Zhao Z, Li X, Liu F, et al. (2021). Stringent Nonpharmaceutical Interventions Are Crucial for Curbing COVID-19 Transmission in the Course of Vaccination: A Case Study of South and Southeast Asian Countries. Healthcare. 9(10): 29. doi: https://dx.doi.org/10.3390/healthcare9101292

5. RAPID REVIEW METHODS

5.1 Eligibility criteria

The aim of this rapid review was to systematically identify and summarise studies modelling the effect of multiple NPIs on the SARS CoV-2 Rt. Because this work was carried out to inform the NPI tool, we only report the design and characteristics (but not outcomes) of relevant studies. Table 2 gives details of the criteria used to select studies for the rapid review.

Table 2: Eligibility Criteria

	Inclusion criteria	Exclusion criteria
Population	General population exposed to/living during the COVID-19 pandemic.	
Settings	Country or region-wide implementation of the intervention – informed by aggregation of data from multiple countries/regions.	We will exclude studies if they meet both of the following criteria: • Data from only one country is included/modelled • The country included or modelled has a population of less than 3 million (chosen as this is approximately the population of Wales) We will also exclude studies that only include data from one region. In this context a 'region' is any geographic/administrative area that does not cover at least one entire country.
Intervention / exposure	Deployment of multiple non-pharmaceutical interventions (NPIs), where these were applied together/concurrently but their effectiveness is studied independently of each other (see notes on outcomes).	Only one NPI considered/used/studied.
Counter intervention	Comparison of different combinations of NPIs to each other, and/or to the absence of NPIs.	We will exclude studies that only report R_t for a single NPI or a single 'bundle' of NPIs – i.e. they do not include a comparison group/counter intervention.
Outcome measures	Change in effective reproduction number (R_t) – reported as a relative change/treatment effect or where absolute effect is reported but relative effect can be calculated. We will only include studies that: • report this outcome for *each* individual intervention (individual NPIs, or bundles of NPIs) considered, and • attempt to control for the confounding effect of other NPIs when estimating this outcome	
Context	COVID-19 Pandemic	Other infectious diseases
Study design	Modelling studies of any design.	

Countries	Any, but we will stratify studies according to countries modelled/countries used to populate the model.	
Language of publication	English language only	
Publication date	2021 onwards	We will exclude studies published in 2020
Publication type	Published and preprint	
Other factors	We will stratify studies according to the time period/wave of the COVID-19 pandemic modelled or from which data was captured. We will categorise studies into the following 'waves' of the epidemic • Wave 1 'Wuhan' Feb – August 2020 • Wave 2 'Wuhan – alpha' Sept 2020 – May 2021 • Wave 3 'Delta' June 2021 – Nov 2021 • Wave 4 'Omicron' Dec 2021 - present	

5.2 Literature search

The search strategy was developed through discussions between Jenni Washington and Elise Hasler, as well as David Jarrom and members of WCEC. Searches were carried out between 17 and 22 December 2021. Databases searched were MEDLINE, Embase, Cochrane Covid-19 study register, Covid-19 L-OVE repository (Epistemonikos), and PROSPERO. Appendix 2 documents the search strategy used for MEDLINE.

No date limit was applied to the literature searches, as it was initially intended to include all studies from the outset of the pandemic, but initial exploratory screening indicated that the majority of the available evidence was from early in the COVID-19 pandemic, and likely of lesser relevance to decision making in 2022. Since, by definition, studies published in 2020 could only include data from the first nine to ten months of the pandemic, we pragmatically applied a date cut-off of 2021 onwards for eligible studies (as detailed in Table 2).

5.3 Study selection process and data extraction

Study screening and selection against the eligibility criteria was carried out by David Jarrom, Sasha Barrate and Jessica Williams. David Jarrom screened the titles and abstracts of all literature search results and selected potentially eligible full texts. Full texts were screened by Sasha Barrate and Jessica Williams, with selection decisions checked by David Jarrom and any disagreements resolved by consensus amongst the three researchers. Data was extracted as documented in Table 1.

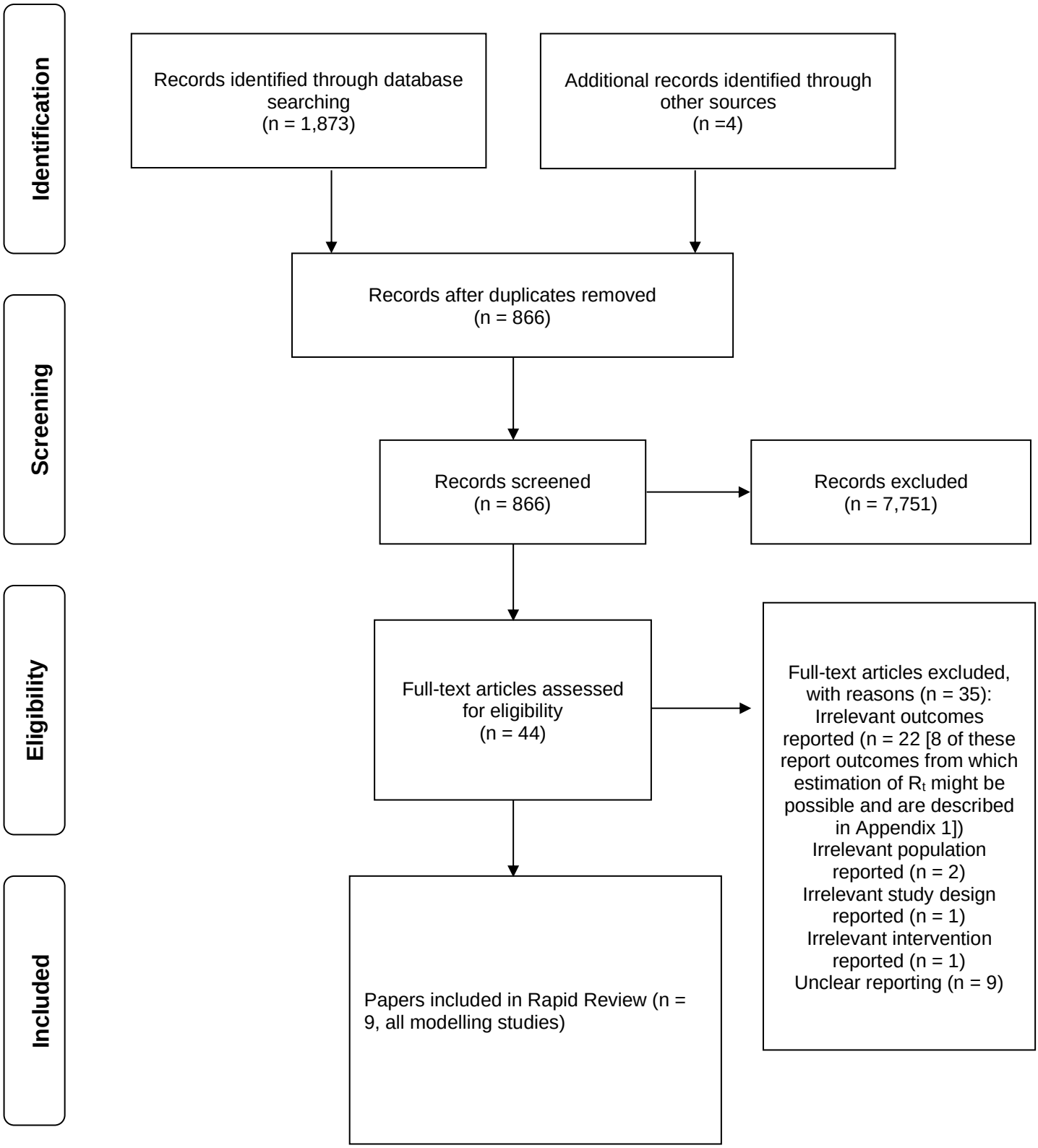
5.4 Critical appraisal

We used initial scoping searches to identify suitable tools for critical appraisal of modelling studies. This identified the checklist used, developed by and reported in Burns J et al. (2021). Use of the checklist was piloted by two authors (David Jarrom and Tom Winfield) who independently checked a sample of studies (n = 3) and reached decisions by consensus. Checklists for the remainder of studies were completed by Tom Winfield and checked by David Jarrom. We used the signalling questions listed within this checklist to

provide narrative summary only and highlight methodological gaps; we did not apply judgements or draw conclusions on risk of bias for each study.

6. EVIDENCE

6.1 Study selection flow chart



7. ADDITIONAL INFORMATION

7.1 Conflicts of interest

The review team declare no conflicts of interest.

7.2 Acknowledgements

The authors would like to thank Brendan Collins, Laura Andrews and Jessica Williams for their contribution in guiding the focus of the review and to interpreting the findings.

8. ABOUT THE WALES COVID-19 EVIDENCE CENTRE (WCEC)

The WCEC integrates with worldwide efforts to synthesise and mobilise knowledge from research.

We operate with a core team as part of Health and Care Research Wales, are hosted in the Wales Centre for Primary and Emergency Care Research (PRIME), and are led by Professor Adrian Edwards of Cardiff University.

The core team of the centre works closely with collaborating partners in Health Technology Wales, Wales Centre for Evidence-Based Care, Specialist Unit for Review Evidence centre, SAIL Databank, Bangor Institute for Health & Medical Research/ Health and Care Economics Cymru, and the Public Health Wales Observatory.

Together we aim to provide around 50 reviews per year, answering the priority questions for policy and practice in Wales as we meet the demands of the pandemic and its impacts.

Director:
Professor Adrian Edwards

Contact Email:
WC19EC@cardiff.ac.uk

Website:
https://healthandcareresearchwales.org/about-research-community/wales-covid-19-evidence-centre

9. APPENDIX

Appendix 1. Excluded studies that did not directly report outcomes of interest, but from which estimation of Rt might be possible.

Study citation	Wave*	Reasons for exclusion
Knock et al. (2021) Knock ES, Whittles LK, Lees JA, et al. (2021). Key epidemiological drivers and impact of interventions in the 2020 SARS-CoV-2 epidemic in England. Science Translational Medicine. 13(602): 14. doi: https://dx.doi.org/10.1126/scitranslmed.abg4262	Waves 1 and 2 (March to December 2020)	R values reported in graphs – unable to data extract outcomes.
Hasan et al. (2021) Hasan A, Putri ERM, Susanto H, et al. (2021). Data driven modeling and forecasting of COVID-19 outbreak for public policy making. ISA Transactions. 20: 20. doi: https://dx.doi.org/10.1016/j.isatra.2021.01.028	Not reported	Reports on Transmission Index – Transmission Index (TI) defined as a ratio between the instantaneous and the maximum value of the effective reproduction number.
Chan et al. (2021) Chan LYH, Yuan B, Convertino M. (2021). COVID-19 non-pharmaceutical intervention portfolio effectiveness and risk communication predominance. Scientific Reports. 11(1): 10605. doi: https://dx.doi.org/10.1038/s41598-021-88309-1	Wave 1 (January to May 2020)	NPI bundles not detailed. Rt values reported in graphs – unable to data extract outcomes.
Bendavid E (2021) Bendavid E OCBJIJPA. (2021). Assessing Mandatory Stay-at-Home and Business Closure Effects on the Spread of COVID-19. European journal of clinical investigation. e13484. doi: https://doi.org/10.1111/eci.13484	Not reported	Outcome is percentage growth rate.
Leonidas (2021) Leonidas S. (2021). On the Effectiveness of COVID-19 Restrictions and Lockdowns: Pan Metron Ariston. SSRN. doi: https://doi.org/10.1101/2021.07.06.21260077	Waves 1 and 2 (February 2020 to April 2021)	Outcome is confirmed case (and death) growth rates.
Pozo-Martin F (2021) Pozo-Martin F WHCFHJBTSLEBC. (2021). The impact of	Wave 2 (October to December 2020)	Outcome is case growth rate.

non-pharmaceutical interventions on COVID-19 epidemic growth in the 37 OECD member states. European journal of epidemiology. 36(6): 629-40. doi: https://doi.org/10.1007/s10654-021-00766-0		
Vardavas et al. (2021) Vardavas R, de Lima PN, Baker L. (2021). Modeling COVID-19 Nonpharmaceutical Interventions: Exploring periodic NPI strategies. MedRxiv : the Preprint Server for Health Sciences. 21: 21. doi: https://dx.doi.org/10.1101/2021.02.28.21252642	Waves 1 and 2 (March 1st to December 31st, 2020)	Rt values reported in graphs – unable to data extract outcomes.
Zhao et al. (2021) Zhao Z, Li X, Liu F, et al. (2021). Stringent Nonpharmaceutical Interventions Are Crucial for Curbing COVID-19 Transmission in the Course of Vaccination: A Case Study of South and Southeast Asian Countries. Healthcare. 9(10): 29. doi: https://dx.doi.org/10.3390/healthcare9101292	Not reported	Outcome is percentage growth rate.
*Categorisation of studies into 'waves': Wave 1 'Wuhan' Feb – August 2020 Wave 2 'Wuhan – alpha' Sept 2020 – May 2021 Wave 3 'Delta' June 2021 – Nov 2021 Wave 4 'Omicron' Dec 2021 - present		

Appendix 2. MEDLINE search strategy

The initial search approach was to search broadly around the main concepts of NPIs and modelling plus the in-built COVID-19 filter. However, this resulted in a large hit rate which would have been unmanageable within the timescale. A third concept was then added to capture the outcomes around reproduction rate/transmission. This still resulted in a large hit rate, so a focused version of the search aiming to identify key high-level modelling papers was developed. The focused search and broad search (minus the focused search) were undertaken separately with priority given to the focused search first for the main sift. To date, it has not been deemed necessary to sift the broad search as the focused search identified enough key high-level modelling papers for the purposes of this review.

Ovid MEDLINE(R) ALL 1946 to December 17, 2021		
Modelling		
1	Models, Theoretical/	158767
2	Models, Statistical/	96998
3	Logistic Models/	148631
4	Models, Biological/	351936
5	Models, Economic/	10868
6	(model* or framework* or dataset*).tw,kf.	3612321
7	or/1-6	3971288
Non-Pharmaceutical Interventions (NPI's)		
8	Policy/	4936
9	Public Policy/	32755
10	Health Policy/	70239
11	Policy Making/	17341
12	Public Health/	88903
13	exp Government/	154290
14	Global Health/	52580
15	Physical Distancing/	1846
16	Quarantine/	5453
17	((non-pharmac* or nonpharmac*) adj3 (intervent* or contain* or control* or measure* or polic* or protocol* or restrict* or strateg*)).tw,kf.	9578
18	NPI*.tw,kf.	4225
19	((government* or public health or public) adj3 (intervention* or polic* or decision*)).tw,kf.	45970
20	((contain* or control* or lockdown* or lock-down* or quarantine* or curfew* or mitigation) adj3 (polic* or strateg* or measure* or scenario*)).tw,kf.	120177
21	(community adj2 containment).tw,kf.	53
22	((social distanc* or physical distanc*) adj3 (polic* or strateg* or measure* or scenario*)).tw,kf.	2207
23	(countermeasure* or counter-measure*).tw,kf.	10918
24	((covid* or vaccin* or immun*) adj2 (pass* or certificate*)).tw,kf.	8407
25	(digital adj2 (pass* or certificate*)).tw,kf.	257
26	or/8-25	561280
Reproduction Rate / Transmission		
27	Basic Reproduction Number/	1580
28	(reproduct* adj2 number*).tw,kf.	5109
29	exp Disease Transmission, Infectious/	76979
30	transmi*.tw,kf.	575063
31	(epidemic adj2 parameter*).tw,kf.	116
32	(attack* adj2 rate*).tw,kw.	5208
33	(communit* adj2 (spread* or circulat*)).tw,kw.	694
34	((virus or viral) adj2 (spread* or circulat*)).tw,kw.	10372
35	United Kingdom/ep or Wales/ep or England/ep or Scotland/ep or Northern Ireland/ep or Ireland/ep or Europe/ep	78580
36	or/27-35	704887

Broad Search		
37	7 and 26 and 36	9072
38	7 and (17 or 18)	2510
39	(17 or 18) and 36	1010
40	(7 or 36) and (24 or 25)	2437
41	or/37-40	13732
42	limit 41 to covid-19	2887
43	limit 42 to english language	2840
44	exp animals/ not exp humans/	4932172
45	43 not 44	2826
Focused Search		
46	(1 or 6) and (17 or 18) and (27 or 28 or 30)	516
47	limit 46 to covid-19	439
48	limit 47 to english language	432
49	exp animals/ not exp humans/	4932172
50	48 not 49	432

Appendix 3. Critical appraisal checklists for all included studies

Appendix 3, Table 1. Critical appraisal: Li et al. (2021)

Aspect	Question	Comments
Model structure	1. Are the structural assumptions transparent and justified?	Yes, Log linear regression model described in detail. Methods described are logical and reflect appropriate assumptions given the assessment.
	2. Are the structural assumptions reasonable given the overall objective, perspective and scope of the model?	Yes, The focus on temporal aspect of NPIs.
Input data	3. Are the input parameters transparent and justified?	Yes – information offered on input parameters. They reflect an appropriate range of NPIs
	4. Are the input parameters reasonable?	Partial - The selection of parameters is reasonable; however, interventions are included as binary variables which restricts the granularity of the assessment (pragmatic approach). The sensitivity analysis investigates the importance of scale.
Validation (external)	5. Has the external validation process been described?	Partial/ unclear. Full transparency of approach is offered as their code is published on Github. Data source reported. Results could be replicated.
	6. Has the model been shown to be externally valid?	No external validation was undertaken.
Validation (internal)	7. Has the internal validation process been described?	Informal – A range of sensitivity analyses were undertaken to assess variables of interest.
	8. Has the model been shown to be internally valid?	Unclear – n o details on validity testing were reported.
Uncertainty	9. Was there an adequate assessment of the effects of uncertainty?	Yes, a range of sensitivity analysis were undertaken. A detailed descriptive review discussed the limitation and uncertainties within the model and results.
Transparency	10. Was technical documentation, in sufficient detail to allow (potentially) for replication, made available openly or under agreements that protect intellectual property?	Yes, detailed descriptive overview of the model was offered in the paper with the addition of all code within Github.

Appendix 3, Table 2. Critical appraisal: Turner et al. (2021)

Aspect	Question	Comments
Model structure	1. Are the structural assumptions transparent and justified?	Yes – Statistical model reported (without great detail), and review of model appropriateness reported – details of which are offered in a footnote (not very transparent). variables described well

	2. Are the structural assumptions reasonable given the overall objective, perspective and scope of the model?	Yes – they log transformed the dependent variable and justified this approach, as this offered an improved goodness of fit. The variables included in the model were stratified in a plausible way. The analysis was undertaken on a 12-day lag to allow for delay in effect. The model assumed fixed country effects.
Input data	3. Are the input parameters transparent and justified?	Yes – The input parameters included an appropriate range of NPI approaches and offered 'stringency' ranges within these interventions. Vaccination is offered in detail.
	4. Are the input parameters reasonable?	Yes. The list of NPIs included in the regression analyses reflected those being undertaken at the point in time during the pandemic.
Validation (external)	5. Has the external validation process been described?	Unclear – there is no mention of external model validation.
	6. Has the model been shown to be externally valid?	Unclear – there is no mention of external model validation.
Validation (internal)	7. Has the internal validation process been described?	Yes/unclear Typical dependant variable appropriateness tests have been undertaken. There is little detail as to the model/alternative models used to assess appropriateness.
	8. Has the model been shown to be internally valid?	No/unclear
Uncertainty	9. Was there an adequate assessment of the effects of uncertainty?	Yes. Effects were reported in detail and uncertainties highlighted. A range of scenario analyses were undertaken which helped to characterise the uncertainty within the model.
Transparency	10. Was technical documentation, in sufficient detail to allow (potentially) for replication, made available openly or under agreements that protect intellectual property?	No/unclear, the model selection and approach was not offered in sufficient detail as to replicate the analysis. Appendix documentation?

Appendix 3, Table 3. Critical appraisal: Sharma et al. (2021)

Aspect	Question	Comments
Model structure	1. Are the structural assumptions transparent and justified?	Yes, the model assumptions are reported and transparent, the model builds on previous work in the area and explains the extension to that model.
	2. Are the structural assumptions reasonable given the overall objective, perspective and scope of the model?	Yes, the model assumptions are discussed and assessed within their sensitivity analysis.
Input data	3. Are the input parameters transparent and justified?	Yes, A comprehensive list of included variables is offered. The Github repository reports all code used in this analysis. The variables are explained and their reason for inclusion is apparent.

	4. Are the input parameters reasonable?	Yes – however, the interventions are mostly included as binary variables which restricts the granularity of the assessment (pragmatic approach).
Validation (external)	5. Has the external validation process been described?	No formal external validation. Bespoke data source, multiple validation steps included in the creation of the data source.
	6. Has the model been shown to be externally valid?	No formal external validation. All code available on Github.
Validation (internal)	7. Has the internal validation process been described?	Yes, the internal validation process included blinding and multiple authors for data collection and dataset assurance. Validation methods undertaken on the model and estimates to assess robustness to assumptions and uncertainty of variables.
	8. Has the model been shown to be internally valid?	Yes, the model validity tests included a range of assumption variability tests – distribution fit checks.
Uncertainty	9. Was there an adequate assessment of the effects of uncertainty?	Yes, there was a range of methods used to characterise the uncertainty of the model.
Transparency	10. Was technical documentation, in sufficient detail to allow (potentially) for replication, made available openly or under agreements that protect intellectual property?	Yes, all code available from Github.

Appendix 3, Table 4. Critical appraisal: Laydon et al. (2021)

Aspect	Question	Comments
Model structure	1. Are the structural assumptions transparent and justified?	Yes, the authors offer a detailed overview of the model of choice with direct reference to the structural assumptions.
	2. Are the structural assumptions reasonable given the overall objective, perspective and scope of the model?	Yes, the model and the assumptions underpinning it are reasonable. The hierarchical model allows for varied effects according to tier level, this approach is used to offer some control for socio-demographic factors.
Input data	3. Are the input parameters transparent and justified?	Yes, the parameters are reported and discussed. Individual interventions are not included – the tier level represents the varied levels of NPI. Authors note that there was an attempt to assess individual NPIs but there was insufficient statistical power to do so.
	4. Are the input parameters reasonable?	Yes – caveat. The paper looks to assess tier level intervention of NPI, this hypothesis is well served by their parameter selection, however there is little information appropriate to granular NPIs.
Validation (external)	5. Has the external validation process been described?	No formal external validation was undertaken. All models – code and dataset are readily available.
	6. Has the model been shown to be externally valid?	No as above.

Validation (internal)	7. Has the internal validation process been described?	Yes – There is mention of internal validation and the role is listed in authors. There was a range of sensitivity analyses undertaken.
	8. Has the model been shown to be internally valid?	Yes, the sensitivity analysis demonstrated that the model was robust to adjustments in the choice of distribution.
Uncertainty	9. Was there an adequate assessment of the effects of uncertainty?	Yes – A range of alternative scales were included, and the results remained robust to these changes.
Transparency	10. Was technical documentation, in sufficient detail to allow (potentially) for replication, made available openly or under agreements that protect intellectual property?	Yes, all code and data is readily available on Github.

Appendix 3, Table 5. Critical appraisal: Arroyo-Marioli et al. (2021)

Aspect	Question	Comments
Model structure	1. Are the structural assumptions transparent and justified?	Yes, The model is well described, all code is reported and there are considerable efforts to minimise the assumptions (non-parametric testing). The modelling approach is well justified and explained in detail.
	2. Are the structural assumptions reasonable given the overall objective, perspective and scope of the model?	Yes, the structural assumptions of the model are reasonable and well explained. The model takes components from prior models to offer an appropriate balance which is bespoke and targets the question.
Input data	3. Are the input parameters transparent and justified?	Yes, the five NPIs are explained with support of a prior paper for detail. Data and code are readily available
	4. Are the input parameters reasonable?	Yes, the NPI selection was pragmatic – The covariates are included as binary variables – limiting the granularity – however, over 14 countries the variability in NPIs may limit any opportunity to observe scale.
Validation (external)	5. Has the external validation process been described?	No – no formal external validation was undertaken – methods are developed from prior publications and all code is available.
	6. Has the model been shown to be externally valid?	No – Same as above, the authors conducted a well described and transparent analysis which would be easily replicable.
Validation (internal)	7. Has the internal validation process been described?	Yes, any unexpected outcomes have been discussed and assessed through rigorous means – with public event effects a sequential inclusion model was undertaken to check for multicollinearity.
	8. Has the model been shown to be internally valid?	Yes – The initial component of the paper is setting up the model, the NPI component is added once the valid model is estimated.
Uncertainty	9. Was there an adequate assessment of the effects of uncertainty?	Yes, the paper assess uncertainty in detail and offers explanation as to the observed findings.

Transparency	10. Was technical documentation, in sufficient detail to allow (potentially) for replication, made available openly or under agreements that protect intellectual property?	Yes, all code is readily available – as is the dataset.

Appendix 3, Table 6. Critical appraisal: Banholzer N (2021)

Aspect	Question	Comments
Model structure	1. Are the structural assumptions transparent and justified?	Yes, a detailed model summary and all modelling choices are offered in their appendix. The model appears to be appropriate for the hypothesis being tested.
	2. Are the structural assumptions reasonable given the overall objective, perspective and scope of the model?	Yes, the model is well documented and supported. Each modelling decision is described in detail in their appendix.
Input data	3. Are the input parameters transparent and justified?	Yes, the parameters are noted, supported, and discussed in detail. There is a high level of transparency associated with this model.
	4. Are the input parameters reasonable?	Yes, The NPI variables were explained well and reasonable. The selection was appropriate given the data limitation of offering such a wide range of included countries.
Validation (external)	5. Has the external validation process been described?	No – no formal external validation was undertaken – methods are developed from prior publications and all code is available.
	6. Has the model been shown to be externally valid?	No – Same as above, the authors conducted a well described and transparent analysis which would be easily replicable.
Validation (internal)	7. Has the internal validation process been described?	Yes, the range of internal validation is extensive. The model parameter review includes variables correlation assessment and an individual variable influence check. The sensitivity analyses assessed subsamples of the data to assess .
	8. Has the model been shown to be internally valid?	Internal validity checks on the model were undertaken and discussed, a more detailed discussion of the modelling was mentioned, and the alternative publication was linked.
Uncertainty	9. Was there an adequate assessment of the effects of uncertainty?	Yes, the uncertainty within the model and the uncertainty around the outcomes were both assessed.
Transparency	10. Was technical documentation, in sufficient detail to allow (potentially) for replication, made available openly or under agreements that protect intellectual property?	Yes, the code was offered, and the documentation was highly detailed.

Appendix 3, Table 7. Critical appraisal: Brauner et al. (2021)

Aspect	Question	Comments
Model structure	1. Are the structural assumptions transparent and justified?	Yes, A detailed model description is offered within the supplementary material. The approach is building on work previously published. The reported detail and Github publishing of code support the transparency. Assumptions are appropriate for the hypotheses being tested.
	2. Are the structural assumptions reasonable given the overall objective, perspective and scope of the model?	Yes, As above.
Input data	3. Are the input parameters transparent and justified?	Yes, The input parameters are appropriate with scales offered where needed.
	4. Are the input parameters reasonable?	Yes, the selected NPIs are reasonable and reflect a pragmatic list given the range of countries being assessed.
Validation (external)	5. Has the external validation process been described?	No formal external validation – all code available and the model builds on externally developed and published works. All code is available on Github.
	6. Has the model been shown to be externally valid?	No, as above.
Validation (internal)	7. Has the internal validation process been described?	Yes, the validation process is described in detail within their companion document. The detail offered is extensive, there is a high amount of validation analysis undertaken.
	8. Has the model been shown to be internally valid?	Yes, this model offers insight into repeated measured with leave-one-out cross validation.
Uncertainty	9. Was there an adequate assessment of the effects of uncertainty?	Yes, a wide range of sensitivity analyses and checks were performed and reported.
Transparency	10. Was technical documentation, in sufficient detail to allow (potentially) for replication, made available openly or under agreements that protect intellectual property?	Yes, there is full transparency to this analysis – Github link available.

Appendix 3, Table 8. Critical appraisal: Bo Y (2021)

Aspect	Question	Comments
Model structure	1. Are the structural assumptions transparent and justified?	Yes, partial. The model is described in terms of the model type and the additional log transformation undertaken to offer a normalised depvar. The underlying structure of the hypothesis is discussed, and it seems justified.
	2. Are the structural assumptions reasonable given the overall objective, perspective and scope of the model?	Yes, the pragmatic approach adopted within this analysis suits the wide scope, the inclusion of 415 sites (countries and cities) means the testing would lose some granularity compared to a more focused study (with a higher degree of detail in explanatory variables and data frequency).

Input data	3. Are the input parameters transparent and justified?	Yes, the variables of interest are described in detail in the companion document – the variables are included as binary (on/off) coding. The binary approach is deemed justified given the data limitation arising from such a range of sites. 4 NPIs are assessed.
	4. Are the input parameters reasonable?	Yes, the 4 NPIs are reasonable given the number of sites. The style of inclusion (1,0) is again a pragmatic approach.
Validation (external)	5. Has the external validation process been described?	No formal external validation was undertaken – however, the simplicity and frequency of adoption of the GLMM model means that there is little doubt as to the validity.
	6. Has the model been shown to be externally valid?	No, as above.
Validation (internal)	7. Has the internal validation process been described?	Yes, partial. A range of appropriate sensitivity analyses were undertaken – initially focused on lag. There are assessments centred on outliers and a detailed view on the age structure of the sites.
	8. Has the model been shown to be internally valid?	Yes, As above, uncertainties within the model are assessed.
Uncertainty	9. Was there an adequate assessment of the effects of uncertainty?	Yes, the discussion and sensitivity analyses appear to be appropriate.
Transparency	10. Was technical documentation, in sufficient detail to allow (potentially) for replication, made available openly or under agreements that protect intellectual property?	Uncertain, the documentation would be insufficient to replicate the analysis. The approach was described but data and code were not readily available.

Appendix 3, Table 9. Critical appraisal: Liu et al. (2021)

Aspect	Question	Comments
Model structure	1. Are the structural assumptions transparent and justified?	Yes, the model is well described and supporting code and documentation offer detail as to the assumptions and the reasoning behind the model choice.
	2. Are the structural assumptions reasonable given the overall objective, perspective and scope of the model?	Yes, the model assumptions are reasonable, the panel approach aligns with the overall objective. Issues associated with time series analysis have been assessed as to identify the most appropriate model.
Input data	3. Are the input parameters transparent and justified?	Yes, the input parameters are transparent and justified – the NPI variables are offered as binary (intervention or not) and maximum level binary (most stringent NPI level or other). The approach includes a wide range of NPIs. The extensive NPI inclusion builds on what has previously been seen.
	4. Are the input parameters reasonable?	Yes, the parameters are reasonable and inline with current literature.
Validation (external)	5. Has the external validation process been described?	No – no formal external validation was undertaken – methods are developed from prior publications and all code is available.

	6. Has the model been shown to be externally valid?	No – Same as above, the authors conducted a well described and transparent analysis which would be easily replicable.
Validation (internal)	7. Has the internal validation process been described?	Yes – the approach has been validated using univariate analysis and forward inclusion variable modelling.
	8. Has the model been shown to be internally valid?	Yes, there are extensive descriptions and discussion around the model and output, uncertainty has been assessed. All the data and code are readily available.
Uncertainty	9. Was there an adequate assessment of the effects of uncertainty?	Yes, a range sensitivity analyses were undertaken including variable selection criteria, temporal lag and the type of NPI coding.
Transparency	10. Was technical documentation, in sufficient detail to allow (potentially) for replication, made available openly or under agreements that protect intellectual property?	Yes, all code and data is readily available.