Supplementary Information of Impact of the Euro 2020 championship on the spread of COVID-19

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S1 Data sources

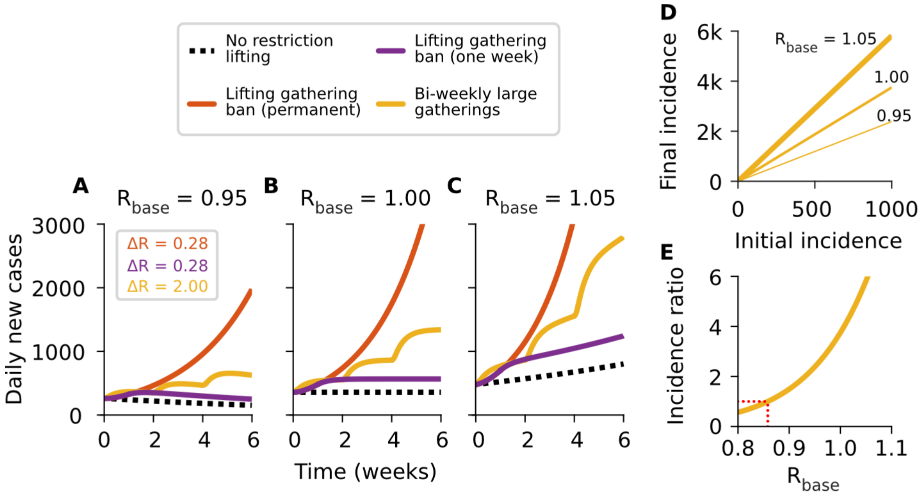
We used the daily COVID-19 case numbers, resolved by age and country, as reported publicly by the state health institute or equivalent of each country covered in this work. The data was retrieved either directly or taken from COVerAGE-DB [1]:

- Germany: Robert Koch Institut
  `https://www.arcgis.com/home/item.html?id=f10774f1c63e40168479a1feb6c7ca74`
- France: Santé publique France
  `https://www.data.gouv.fr/fr/datasets/taux-dincidence-de-lepidemie-de-covid-19`
- England: National Health Service
  `https://coronavirus.data.gov.uk/details/download`
- Scotland: Public Health Scotland
  `https://www.opendata.nhs.scot/dataset/covid-19-in-scotland`
- Austria: Österreichische Agentur für Gesundheit und Ernährungssicherheit GmbH
  `https://covid19-dashboard.ages.at/`
- Belgium: Sciensano
  `https://epistat.wiv-isp.be/covid/`
- The Czech Republic: Ministerstvo zdravotnictví
  `https://onemocneni-aktualne.mzcr.cz/covid-19`
- Italy: Istituto Superiore di Sanità
  Aggregated by COVerAGE-DB from
  `https://www.epicentro.iss.it/coronavirus/sars-cov-2-sorveglianza-dati`
- The Netherlands: National Institute for Public Health and the Environment
  `https://data.rivm.nl/covid-19/`
- Slovakia: The Institute for Healthcare Analyses (IZA) of the Ministry of Health
  Aggregated by COVerAGE-DB from
  `https://github.com/Institut-Zdravotnych-Analyz/covid19-data`
- Spain: Ministry of Public Health
  Aggregated by COVerAGE-DB from
  `https://cnecovid.isciii.es/covid19/`

To estimate the deaths associated with the Euro 2020 cases we calculate the case fatality risk by using the number of deaths and number of cases as reported by Our World in Data (OWD) [2].

For showcasing the stringency of governmental measures (panel C in Fig. S24-S36), we used data from the Oxford COVID-19 Government Response Tracker [3] and the public health and social measures (PHSM) severity index [4] from the World Health Organization (WHO). For our correlational analysis of cases and human mobility (Fig. 3B and S4), we used data from the COVID-19 Community Mobility Reports [5] provided by Google. For correlation with pre-Euro 2020 incidences (Fig.S6B) we use case numbers as reported by the Johns Hopkins University (JHU) [6]. Lastly, we used data from Google Trends [7] to investigate people's interest in the Euro 2020 (Fig. S20).

S2 Supplementary analysis: our results in context



Supplementary Figure S1: **Our results in context: How much of an effect do short but strong increases of transmission have? A–C:** Understanding Euro 2020 matches as point interventions where the reproduction number is allowed to increase drastically from its base level R_{base} for one day ($\Delta R = 2.0$, yellow curve), we compare its cumulative effect with different scenarios of lifting restrictions. These effects are in the order of magnitude of those reported in the literature [8]. The purple lines represent the same effect as a single increase but distributed over one week ($\Delta R = 0.28 \approx 2/7$), while the red curve represents a permanent lifting of those restrictions. The effect of the yellow and purple interventions is similar for $t \leq 2$ weeks because the product between ΔR and the duration of the intervention is the same. **D:** We observe long-term effects of consecutive interventions even when R_{base} is lower than one (red dotted line). The impact of these effects increases exponentially with R_{base}. **E:** Similarly, the final incidence (after six weeks) increases with R_{base}. The red dotted line indicates that an incidence ratio larger than one can already result from values of R_{base} smaller than one. Altogether, the cumulative effect of short but strong interventions (such as Euro 2020 matches) can be compared to lifting all bans on gatherings for a certain period of time. Curves were generated using a linear SEIS model without immunity for illustrative purposes.

To put our results in context, we compare the impact that different hypothetical scenarios of lifting of restrictions would have on case numbers (Fig. S1). Using a linear SEIS model for illustrative purposes, we evaluate three scenarios: i) Recurrent, bi-weekly (period $T = 2$ weeks) large events that strongly increase the reproduction number over its base level R_{base} for one day by $\Delta R_s = 2.0$ (yellow curves). This effect size is comparable to what we inferred for some heated matches (e.g., Scotland - England for Scotland: $\Delta R_{\text{match}} = 3.5\,[2.9, 4.2]$, England - Italy for England: $\Delta R_{\text{match}} = 2.0\,[1.6, 3.5]$, England - Italy for Italy: $\Delta R_{\text{match}} = 0.9\,[-0.7, 4.4]$, and the Czech Republic - Denmark for the Czech Republic: $\Delta R_{\text{match}} = 2.7\,[0.8, 4.4]$). ii) A temporary one-week lifting of restrictions, with an effect equal to a single-day large event by distributing the increase in R_{base} over a week: $\Delta R_w = 0.28 \approx 2/7$ (purple curves). iii) A permanent lifting of restrictions to the level of the second scenario: $\Delta R_p = 0.28$ for the considered time span (red curves). The value for ΔR_s in the first scenario is comparable to the largest effects found for the England-Scotland matches, while those in the second and third scenarios are similar to the effect of banning all private gatherings of 2 people or more as reported in [8].

The effect of interventions is comparable whenever the products between ΔR and the duration of the interventions are the same (e.g., yellow and purple curves for $t \leq 2$ weeks in Fig. S1A, B). In other words, the cumulative effect of short but strong interventions (such as Euro 2020 matches), can be compared to lifting all bans on gatherings for a certain period of time. However, for regularly recurring interventions of size ΔR_s, we observe permanent long-term effects when $R_{\text{base}} + \Delta R_s/T \geq 1$; the impact of recurring interventions increases disproportionately over time (Fig. S1A–C). Controlling the long-term effect of recurrent increases of the reproduction number is possible if the underlying reproduction number R_{base} is small enough. Small changes of R_{base} substantially impact the outcome, even below the $R_{\text{base}} = 1$ threshold, and in an exponential manner (Fig. S1D, E). This underlines the importance of control strategies if large-scale events are expected to temporally increase the spread of COVID-19.

On the other hand, quantitatively, the expected size z of an infection chain depends on the effective reproduction number R_{eff}. As long as R_{eff} is larger than one, the infection chains can become arbitrarily large. But even if $R_{\text{eff}} < 1$, one single infection is expected to cause $z = (1 - R_{\text{eff}})^{-1}$ infections before the chain dies out. For example, if $R_{\text{eff}} = 0.9$, a single infection caused by the Euro 2020 implies $z = 10$ infections in the total chain. Thus, in comparison, the primary cases have only a small contribution; the majority of the impact of an event like the Euro 2020 is the spread of subsequent infections into the general population (e.g., Fig. 2A).

S3 Supplementary Tables

Country	Median percentage of primary cases	Median percentage of subsequent cases	Median percentage of primary and subsequent cases	Probability that football increased cases
Avg.	3.2% [1.3%, 5.2%]	-	-	> 99.9%
England	12.4% [5.6%, 22.5%]	36.0% [27.9%, 44.7%]	47.8% [36.0%, 62.9%]	> 99.9%
Czech Republic	9.7% [3.3%, 16.2%]	47.8% [24.2%, 58.7%]	57.7% [28.7%, 72.6%]	> 99.9%
Scotland	3.3% [1.3%, 8.1%]	36.6% [28.6%, 43.9%]	40.8% [30.9%, 50.3%]	> 99.9%
Spain	2.8% [-1.1%, 9.2%]	24.1% [-16.3%, 60.6%]	26.9% [-16.9%, 69.2%]	91.8%
Italy	2.1% [-5.8%, 10.9%]	16.1% [-230.2%, 69.5%]	18.7% [-235.6%, 78.4%]	74.1%
Slovakia	1.6% [-7.7%, 10.2%]	15.5% [-88.2%, 50.6%]	17.3% [-95.7%, 60.0%]	70.8%
Germany	1.4% [-1.8%, 4.2%]	22.1% [-36.3%, 44.8%]	23.6% [-38.0%, 48.6%]	86.7%
Austria	1.2% [-2.2%, 4.8%]	24.0% [-62.9%, 60.8%]	25.2% [-65.0%, 65.2%]	79.4%
Belgium	0.6% [-2.3%, 4.2%]	9.2% [-60.0%, 47.9%]	9.8% [-62.2%, 51.8%]	67.6%
France	0.5% [-0.2%, 1.4%]	23.1% [-8.4%, 45.8%]	23.6% [-8.6%, 47.0%]	94.1%
Portugal	0.3% [-2.6%, 2.7%]	-4.4% [-55.1%, 24.5%]	-4.1% [-57.4%, 26.9%]	60.6%
The Netherlands	-1.5% [-3.3%, -0.2%]	-49.1% [-111.7%, -1.4%]	-50.6% [-114.6%, -1.7%]	1.5%

Supplementary Table S1: **Credible intervals from the posterior distribution** of the number of football related cases divided by the total number of cases during the championship. CI denotes 95% credible interval.

Country	Primary cases per mil. people (male)	Primary cases per mil. people (female)	Primary and subsequent cases per mil. people
Avg.	-	-	2228 [986, 3308]
England	3595 [2661, 5729]	1686 [1143, 3453]	10600 [8185, 13875]
Czech Republic	94 [40, 142]	65 [22, 108]	459 [229, 577]
Scotland	1352 [940, 1758]	351 [222, 517]	7897 [6136, 9529]
Spain	594 [-217, 1722]	387 [-160, 1346]	4518 [-2840, 11595]
Italy	55 [-121, 227]	27 [-77, 131]	319 [-4001, 1335]
Slovakia	8 [-30, 38]	4 [-19, 25]	57 [-313, 196]
Germany	15 [-16, 36]	7 [-11, 24]	174 [-280, 359]
Austria	42 [-70, 141]	23 [-45, 100]	642 [-1646, 1661]
Belgium	34 [-112, 198]	18 [-81, 155]	411 [-2611, 2174]
France	43 [-12, 95]	27 [-8, 76]	1515 [-552, 3008]
Portugal	41 [-331, 340]	25 [-247, 251]	-449 [-6294, 2960]
Netherlands	-186 [-328, -31]	-98 [-222, -13]	-4805 [-10851, -166]

Supplementary Table S2: **Cases attributed to the Euro 2020 per million inhabitants** and related 95 % credible intervals in the male and female population. Primary and primary plus secondary cases are shown separately. Subsequent cases are almost gender-symmetric in all countries (see also Fig. S2). This indicates that also possible unobserved characteristics of the primary football-related infections in terms of other factors – such as age – are most likely distributed over the whole population in the course of subsequent infections.

Country	Primary cases (male)	Primary cases (female)	Primary and subsequent cases	Estimated deaths associated with primary and subsequent cases
England	93619 [69591, 145127]	43872 [29946, 87030]	567280 [436870, 747399]	1227 [945, 1616]
Czech Republic	494 [215, 753]	346 [116, 558]	4920 [2455, 6182]	60 [30, 75]
Scotland	3478 [2444, 4481]	908 [574, 1320]	41720 [31766, 50146]	90 [69, 108]
Spain	13570 [-4463, 40212]	8870 [-3339, 31389]	211952 [-122694, 546650]	503 [-291, 1298]
Italy	1535 [-3399, 6718]	750 [-2219, 3824]	17810 [-243916, 79338]	170 [-2327, 757]
Slovakia	21 [-87, 100]	11 [-47, 67]	320 [-1809, 1087]	4 [-24, 14]
Germany	618 [-629, 1460]	306 [-440, 944]	14626 [-23538, 29644]	304 [-489, 616]
Austria	178 [-308, 626]	97 [-179, 436]	6078 [-15534, 15387]	34 [-86, 85]
Belgium	191 [-600, 1091]	101 [-441, 834]	5352 [-31477, 24778]	14 [-84, 66]
France	1357 [-331, 2920]	857 [-219, 2325]	95929 [-40644, 190114]	423 [-179, 838]
Portugal	202 [-1683, 1667]	122 [-1229, 1255]	-5205 [-72249, 29231]	-22 [-300, 121]
Netherlands	-1573 [-2756, -277]	-838 [-1859, -106]	-82805 [-181983, -3149]	-75 [-164, -3]
Total	114769 [81915, 167796]	56781 [36247, 100400]	844609 [396860, 1253494]	1689 [794, 2507]

Supplementary Table S3: **Total cases attributed to the Euro 2020** and related 95 % credible intervals. The associated deaths are calculated under the assumption that the cases were equally distributed among age-groups and using the case fatality risk for the respective country in the time window of the Euro 2020.

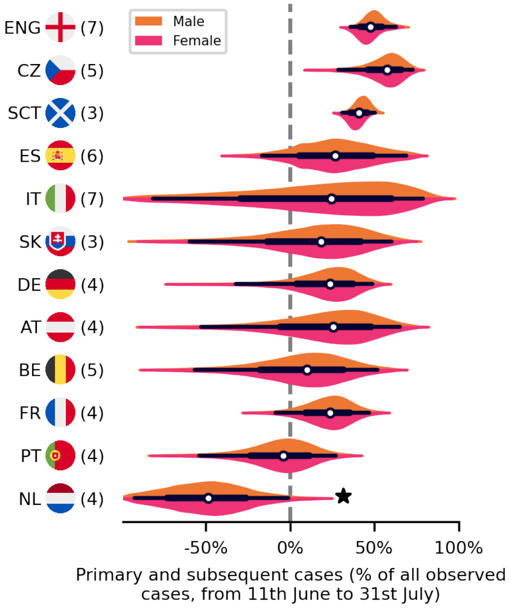
Country	$\Delta R_{\text{match}}^{\text{mean}}$	Delay D
Avg.	0.46 [0.18, 0.75]	
England	0.75 [0.01, 1.66]	4.55 [4.36, 4.94]
Czech Republic	1.26 [-0.50, 3.19]	5.53 [4.75, 6.32]
Scotland	1.09 [-2.77, 4.69]	3.52 [3.35, 3.74]
Spain	0.37 [-0.72, 1.83]	6.91 [5.43, 7.82]
Italy	0.28 [-1.11, 1.79]	5.51 [3.96, 7.11]
Slovakia	0.32 [-2.27, 2.56]	5.00 [3.67, 7.28]
Germany	0.33 [-0.62, 1.12]	6.82 [5.69, 8.43]
Austria	0.28 [-0.90, 1.45]	4.58 [3.46, 6.37]
Belgium	0.11 [-0.61, 0.92]	5.09 [3.71, 6.69]
France	0.30 [-0.46, 0.97]	3.68 [3.13, 4.46]
Portugal	-0.02 [-1.33, 1.34]	5.49 [4.30, 6.55]
Netherlands	-0.74 [-3.30, 1.36]	5.70 [4.28, 6.00]

Supplementary Table S4: **Average effect of Euro 2020 matches on the spread of COVID-19, per country.**

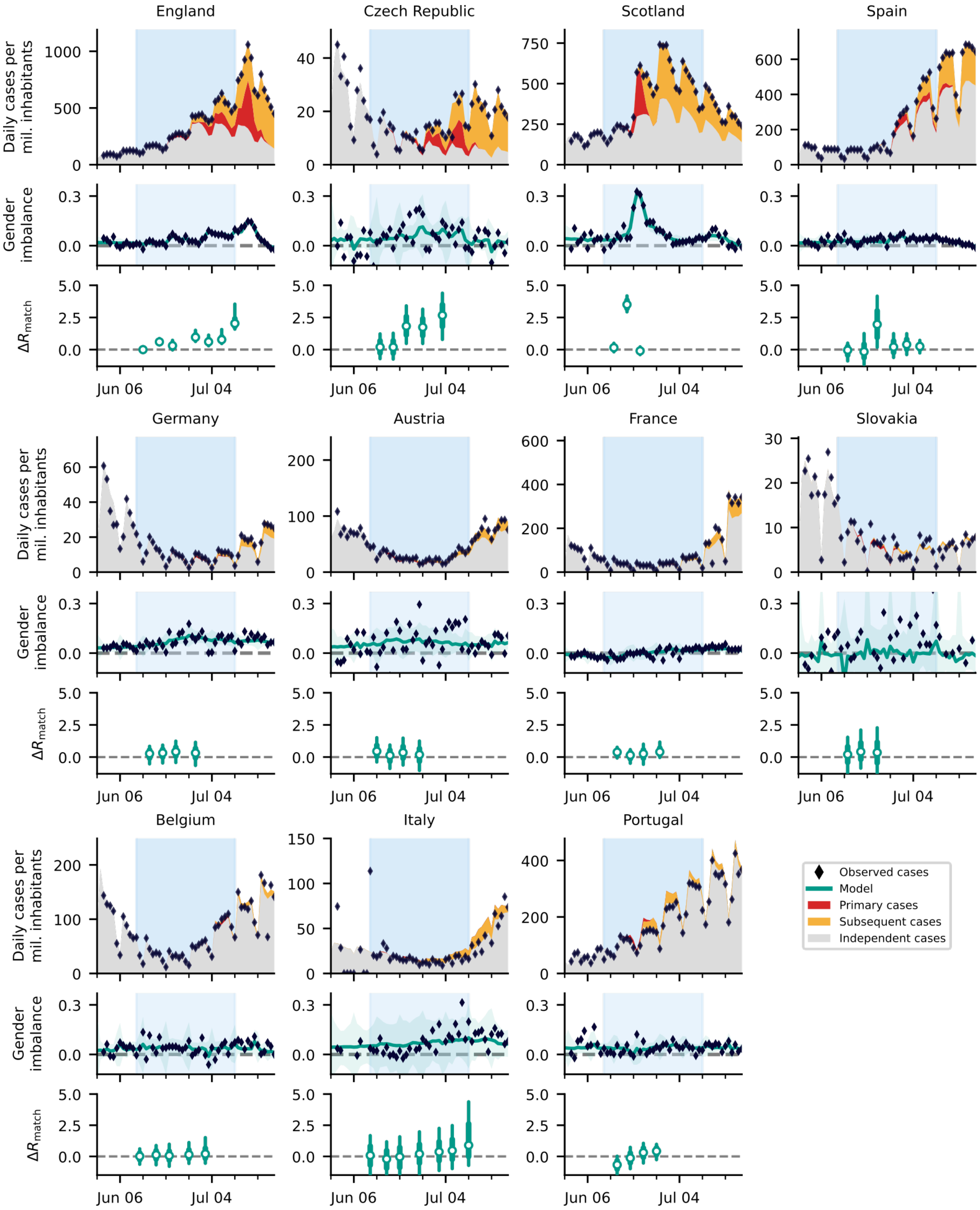
Country	Matches played	Matches hosted	Union	Time between first and last match of the country (days)
England	7	8	9	28
Czech Republic	5	0	5	19
Scotland	3	4	5	8
Spain	6	4	7	22
Italy	7	4	8	30
Slovakia	3	0	3	9
Germany	4	4	5	14
Austria	4	0	4	13
Belgium	5	0	5	20
France	4	0	4	13
Portugal	4	0	4	12
Netherlands	4	4	5	14

Supplementary Table S5: **Number of matches** played by the national team in the Euro 2020, matches played in the country and the union of the two categories. The union denotes the sum of the first two numbers without the overlapping matches.

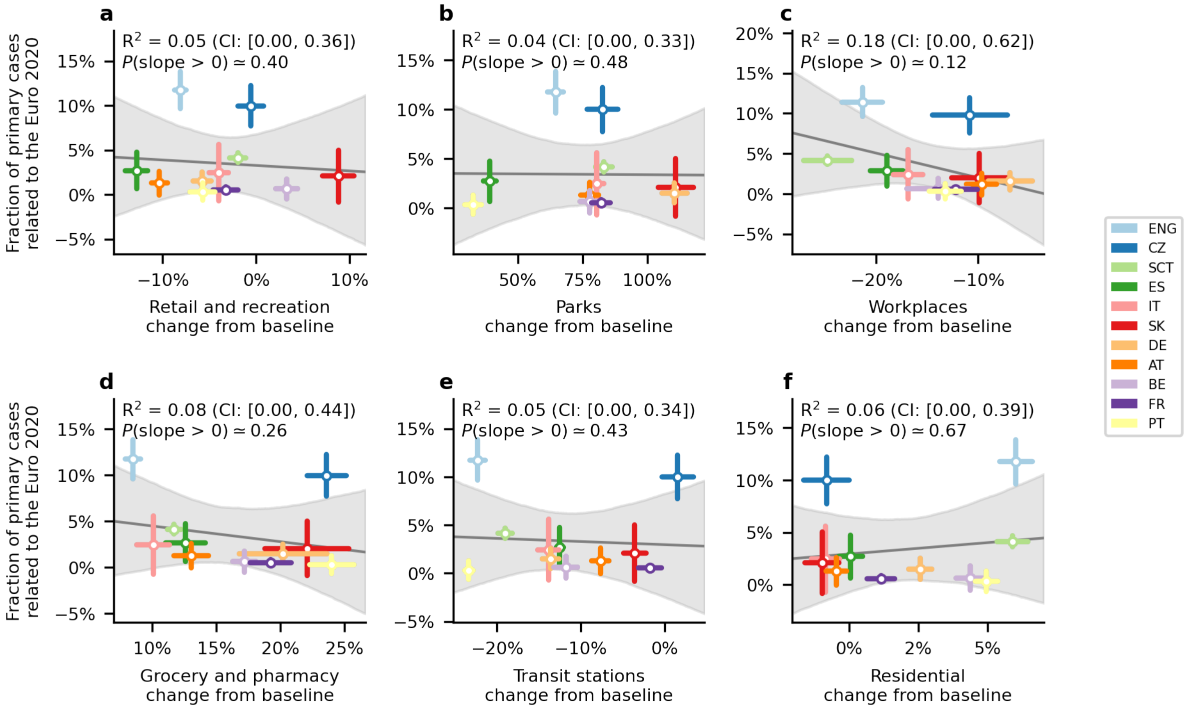
S4 Supplementary Figures



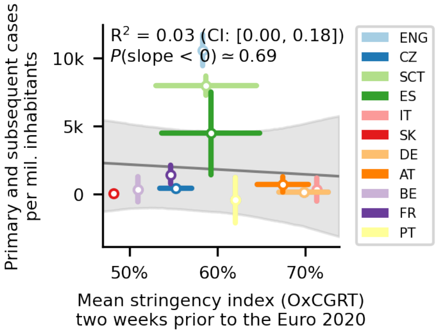
Supplementary Figure S2: **Overview of the sum of primary and subsequent cases accountable to the Euro 2020**. Calculations account for cases until July 31st, i.e., about three weeks after the championship finished. In the Netherlands ($\star$) the "freedom day" occurred on the same time as the Euro 2020. This effect also had a gender imbalance, thus, making it hard for our model to extract the Euro 2020 effect (see. Fig. S31). White dots represent median values, black bars and whiskers correspond to the 68% and 95% credible intervals (CI), respectively, and the distributions in color (truncated at 99% CI) represent the differences by gender ($n = 12$ countries).



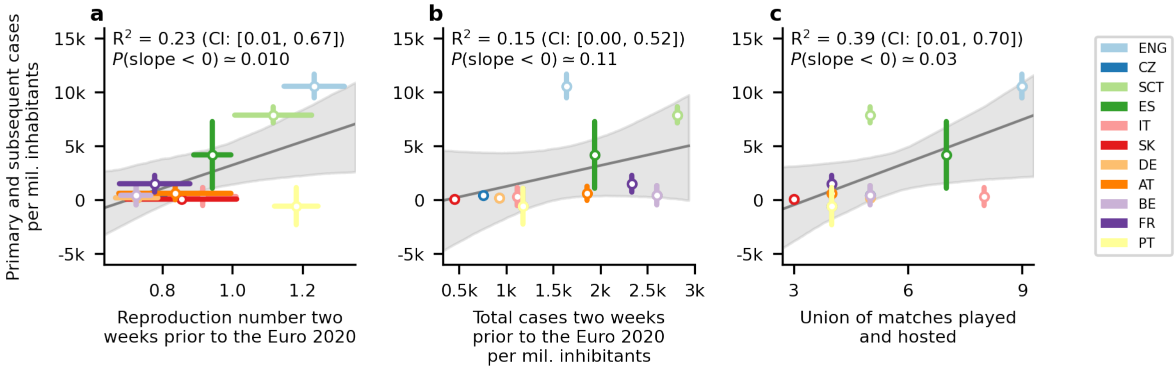
Supplementary Figure S3: **Overview of cases in all considered countries apart from the Netherlands** We split the observed incidence (black diamonds) of the three countries with the largest effect size into i) cases independent of Euro 2020 matches (gray area), ii) primary cases (directly associated with Euro 2020 matches, red area), and ii) subsequent cases (additional infection chains started by primary cases, orange area). See Figure 2 for more details. The turquoise shaded areas correspond to 95% CI. In the box plots, white dots represent median values, turquoise bars and whiskers correspond to the 68% and 95% credible intervals (CI), respectively.



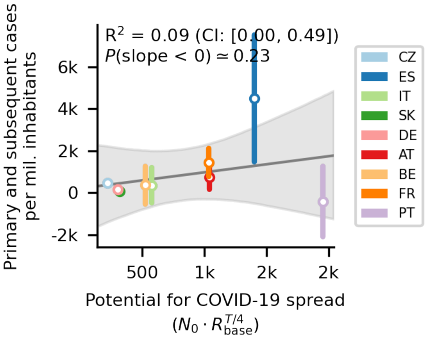
Supplementary Figure S4: **We found no significant correlation between cases arising from the Euro 2020 and human mobility.** Using mobility data from the “Google COVID-19 Community Mobility Reports” [5], we tested for correlation against the fraction of Euro 2020 related cases. Using the different categories (**A**-**F**) from the Mobility Report we found no significant correlation in either. The gray line and area are the median and 95% credible interval of the linear regression ($n = 11$ countries; The Netherlands was excluded for this analysis). Whiskers denote one standard deviation.



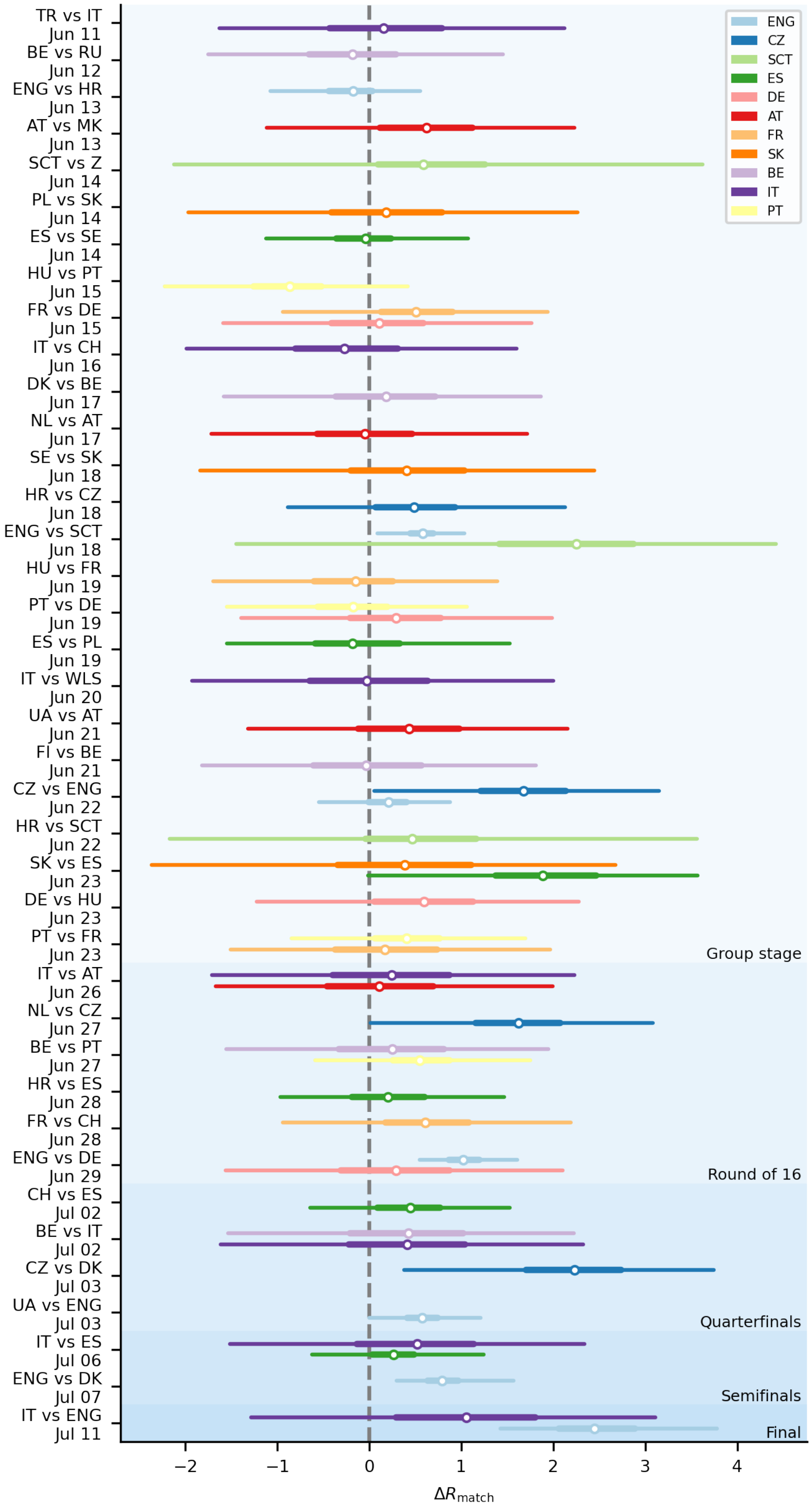
Supplementary Figure S5: **We found no significant correlation between cases arising from the Euro 2020 and the stringency of governmental interventions.** We correlated the average Oxford governmental response tracker [3] in the two weeks before the championship with the total number of cases per million inhabitants related to football gatherings. The gray line and area are the median and 95% credible interval of the linear regression ($n = 11$ countries; The Netherlands was excluded for this analysis). Whiskers denote one standard deviation.



Supplementary Figure S6: **We found slight trends in the correlations between the impact of Euro 2020 and the base reproduction number and country popularity.** While these correlations are below the classical significance threshold of 0.05, they are less explanatory than the potential for spread (defined in Fig. 3). There was no significant correlation between the initial COVID-19 incidence and the impact of the Euro 2020. The gray line and area are the median and 95% credible intervals of the linear regression (n = 11 countries; The Netherlands was excluded for this analysis). Whiskers denote one standard deviation.

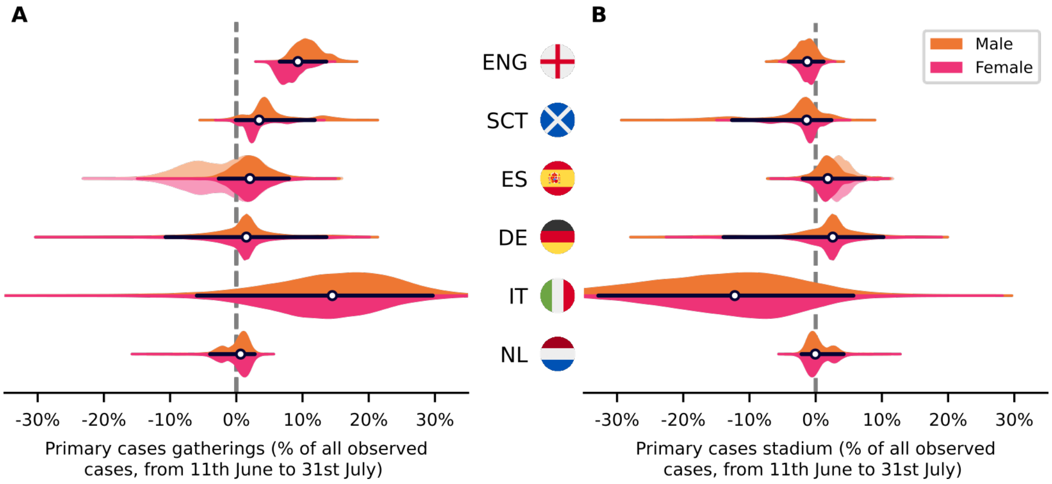


Supplementary Figure S7: **Prediction of the impact of Euro 2020 matches without the two most significant countries in the main model (England and Scotland).** The potential for spread, i.e., the number of COVID-19 cases that would be expected during the time T a country is playing in the Euro 2020 ($N_0 \cdot R_{\text{pre}}^{T/4}$) is still correlated with the number of Euro 2020-related cases after removing the two most significant entries from the analysis but not significantly. The observed slope without the most significant countries (median: 0.76, 95% CI: [-1.46, 3.04]) is consistent within its uncertainties with the slope including all countries (median: 1.62, 95% CI: [1.0, 2.26])). Due to the post-hoc nature of the removal of the most significant entries, this result is only shown for information. The gray line and area are the median and 95% credible interval of the linear regression (n = 9 countries; The Netherlands, England and Scotland were excluded for this analysis). Whiskers denote one standard deviation.



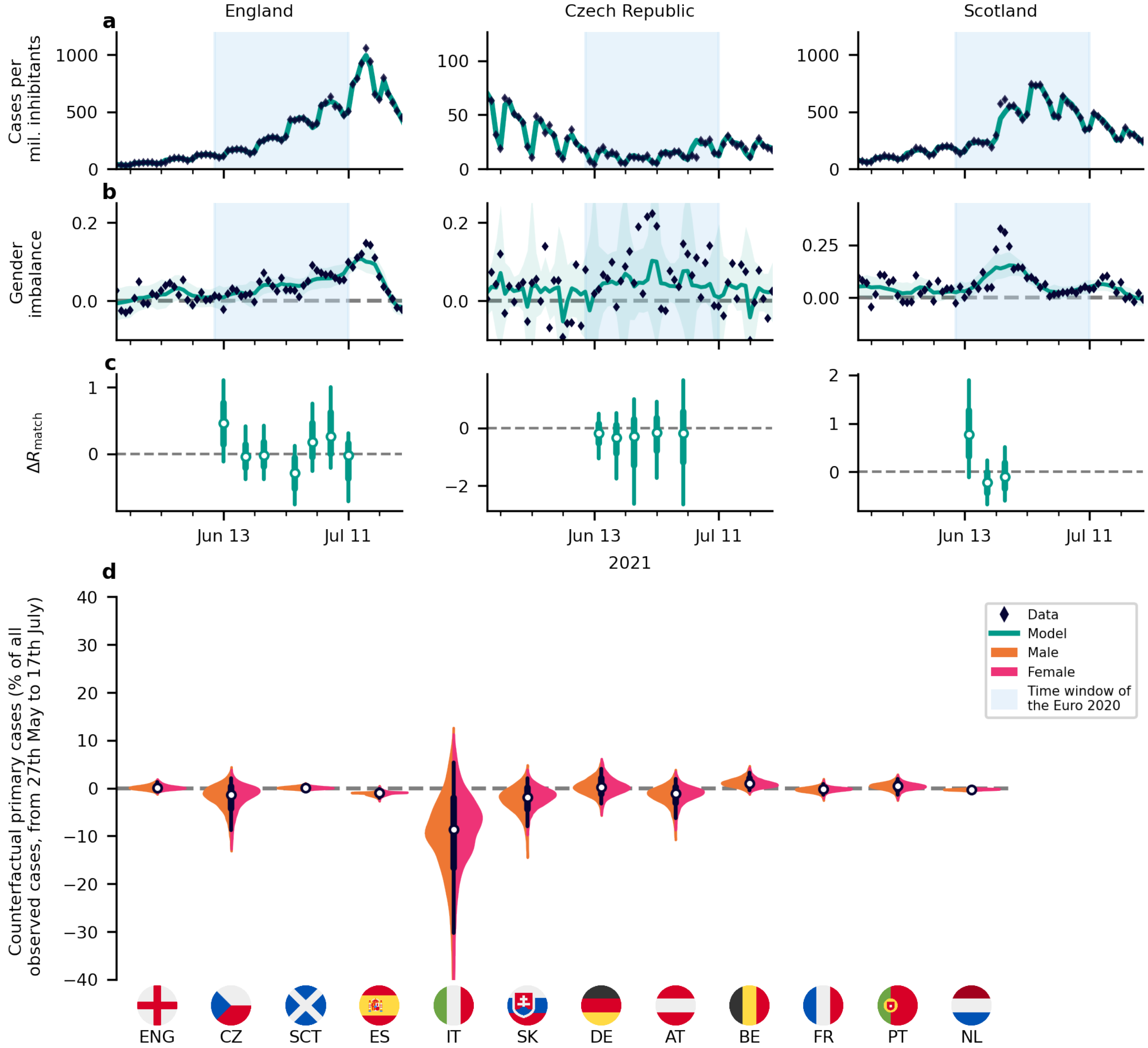
Supplementary Figure S8: **Effect of single Euro 2020 matches on the spread of COVID-19 across competing countries.** White dots represent median values, colored bars and whiskers correspond to the 68% and 95% credible intervals (CI).

S4.1 Model including the effect of stadiums

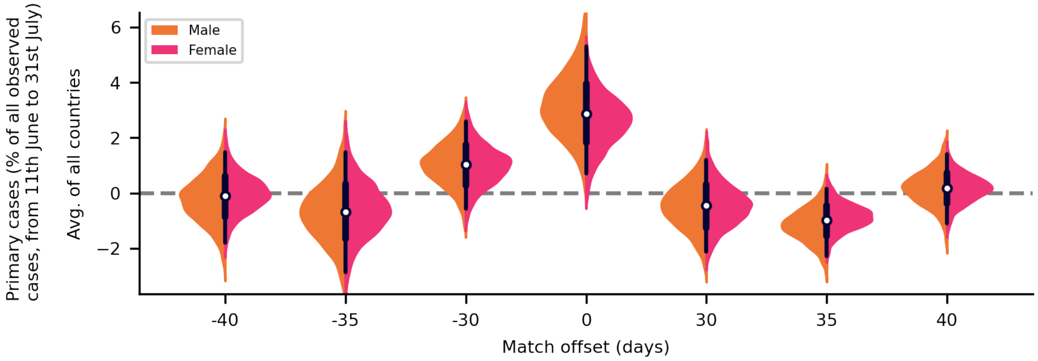


Supplementary Figure S9: **Including in our model the potential local transmission around the stadium where the matches occur does not significantly increase the overall effect.** In addition to the effect of football-related gatherings (**A**), we extended our model to include an additive effect on the reproduction number when a country hosted a match (**B**) (for those countries that hosted matches, i.e. $n = 6$ countries). We assume that local transmissions in and around the stadium would be detected mainly in the venue's country. However, football-related cases in a country where matches have a significant contribution to COVID-19 spread are tied to the dates of matches played by the country's team (A) and not to the country of the stadium venue (B), which is especially visible for England and Scotland. This also explains why previous attempts at measuring Euro 2020-related cases focusing on stadium venues were inconclusive. For Spain, an increase in the base reproduction number close to the date of a match makes the model inconclusive. In transparent is the region of the posterior of which we suppose that the model identifies the increase incorrectly; that is, where the posterior delay is smaller than 5.5 days. White dots represent median values, black bars and whiskers correspond to the 68% and 95% credible intervals (CI), respectively, and the distributions in color (truncated at 99% CI) represent the differences by gender.

S4.2 Testing the detection of a null-effect

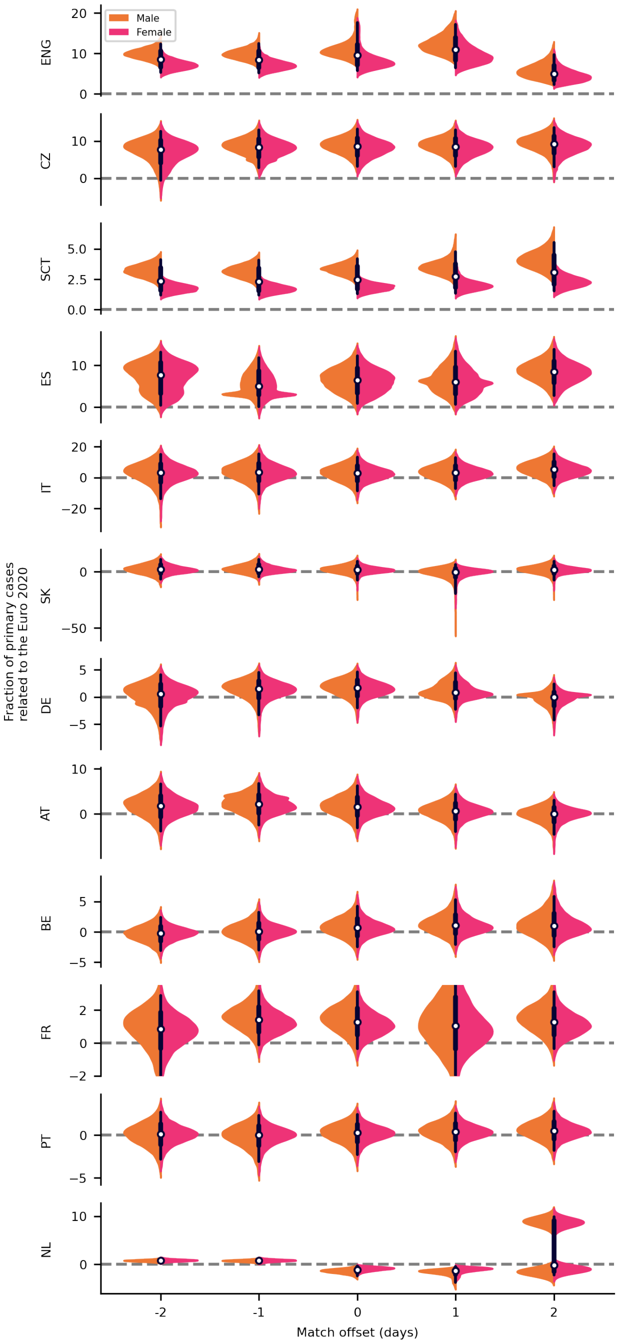


Supplementary Figure S10: **A temporal offset of 14 days leads to no inferred effect.** An artificial offset of the match data of 14 days decouples the gender ratio changes and the matches. This leads to no inferred effect of the championship – even in the three countries with the largest effect sizes in the main model (**A-C**). White dots represent median values, black bars and whiskers correspond to the 68% and 95% credible intervals (CI) (n = 12 countries). Shaded turquoise area denotes 95% CI.

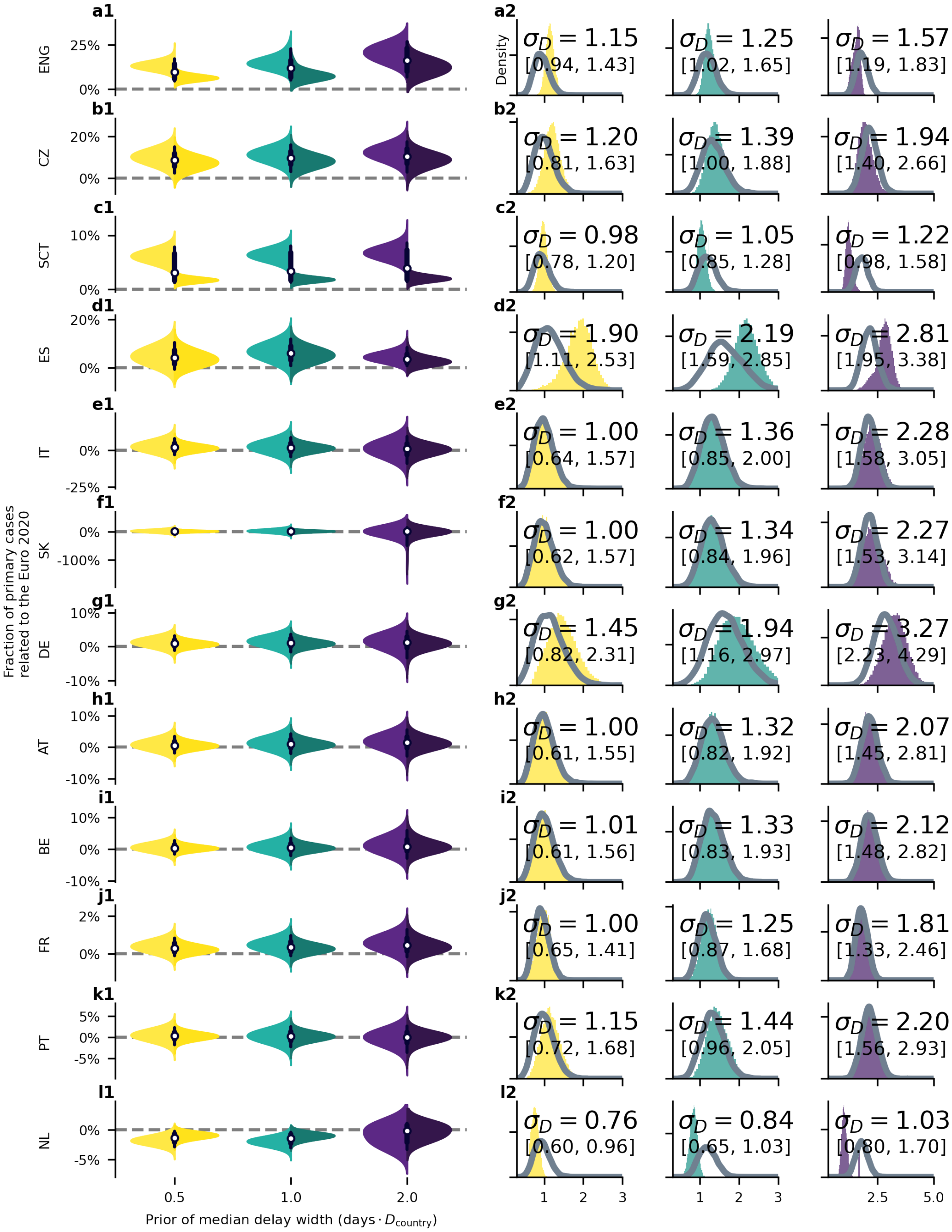


Supplementary Figure S11: **Changing the days of the match by a large offset results in a non-significant effect.** To test the reliability of our results, we ran counterfactual scenarios where the date of the matches was moved to lie outside the championship period. As expected, such offsets lead non-significant results of the average effect size across countries. White dots represent median values, black bars and whiskers correspond to the 68% and 95% credible intervals (CI) ($n = 11$ countries, The Netherlands was excluded for this analysis).

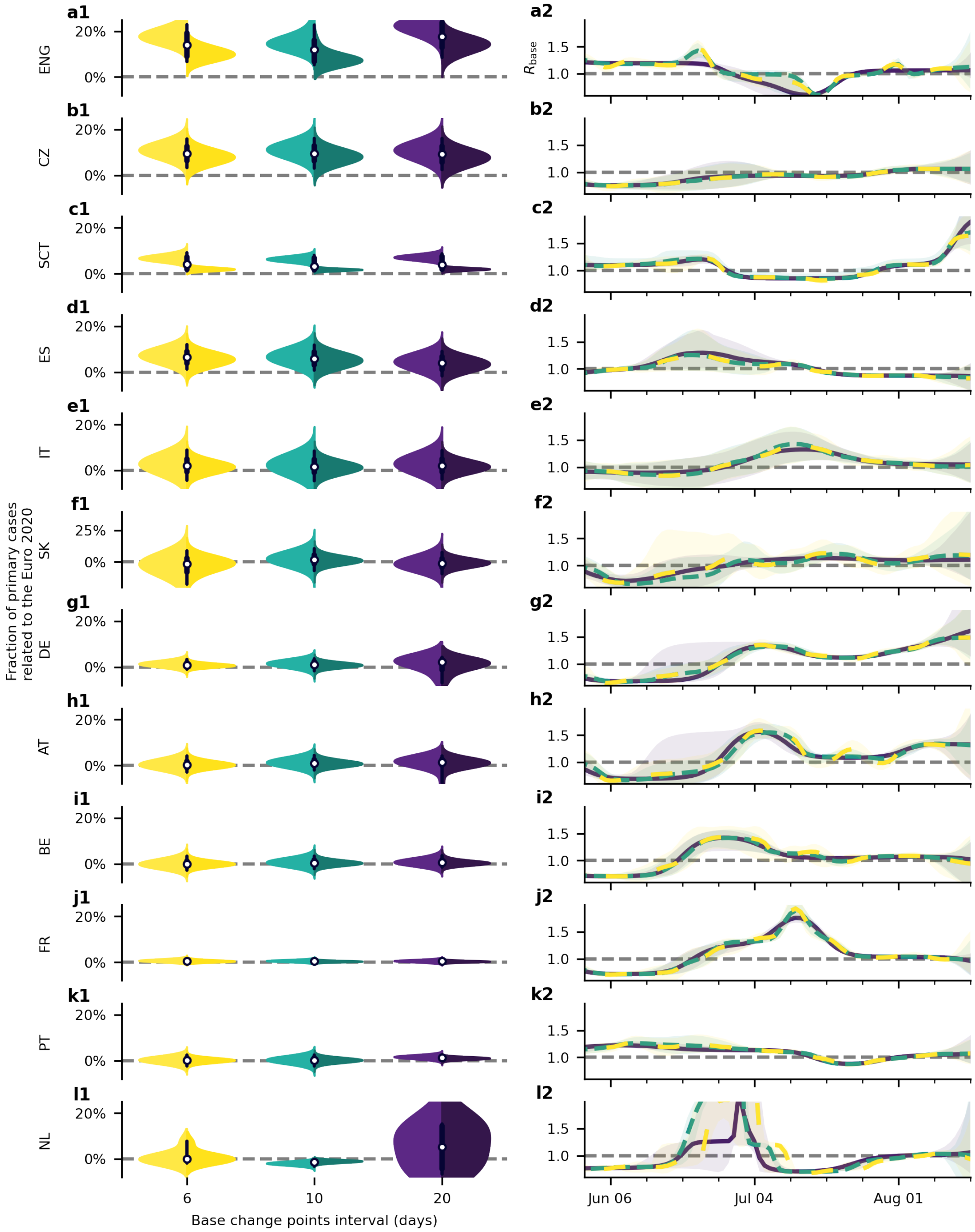
S4.3 Robustness of parameters



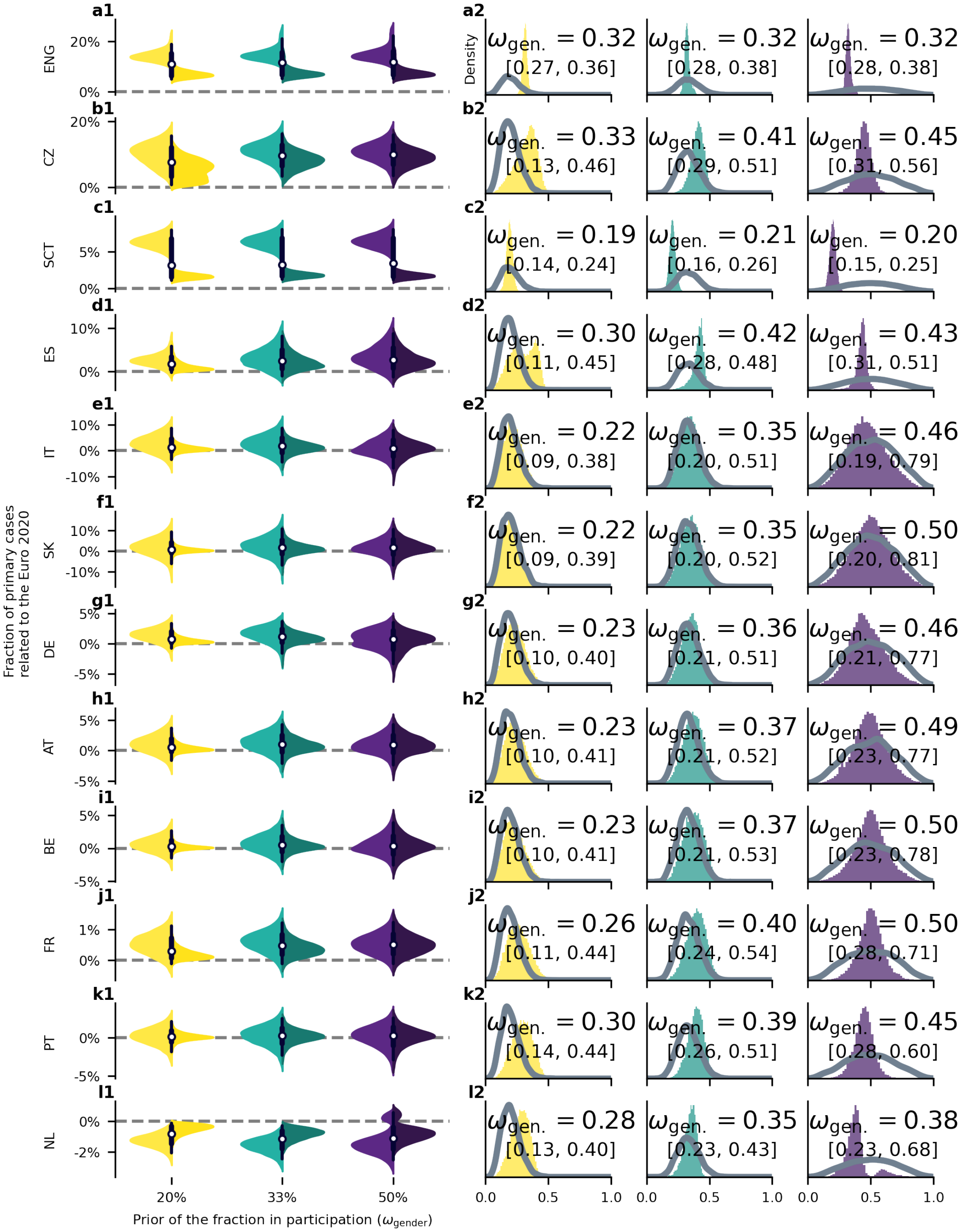
Supplementary Figure S12: **Robustness test for the effect of the temporal association between matches and cases by varying the effective delay.** We applied an artificial variation of all match days in a positive or negative direction. Under these relatively small variations of the delay, the gender imbalance is strong enough to lead to a stable effect size as the prior of the delay still allows for a sufficient shift of the posterior delay. The model run for France with a 1-day offset is missing because of an unknown, sampling-based error. White dots represent median values, black bars and whiskers correspond to the 68% and 95% credible intervals (CI), respectively, and the distributions in color (truncated at 99% CI) represent the differences by gender ($n = 11$ countries, The Netherlands was excluded for this analysis).



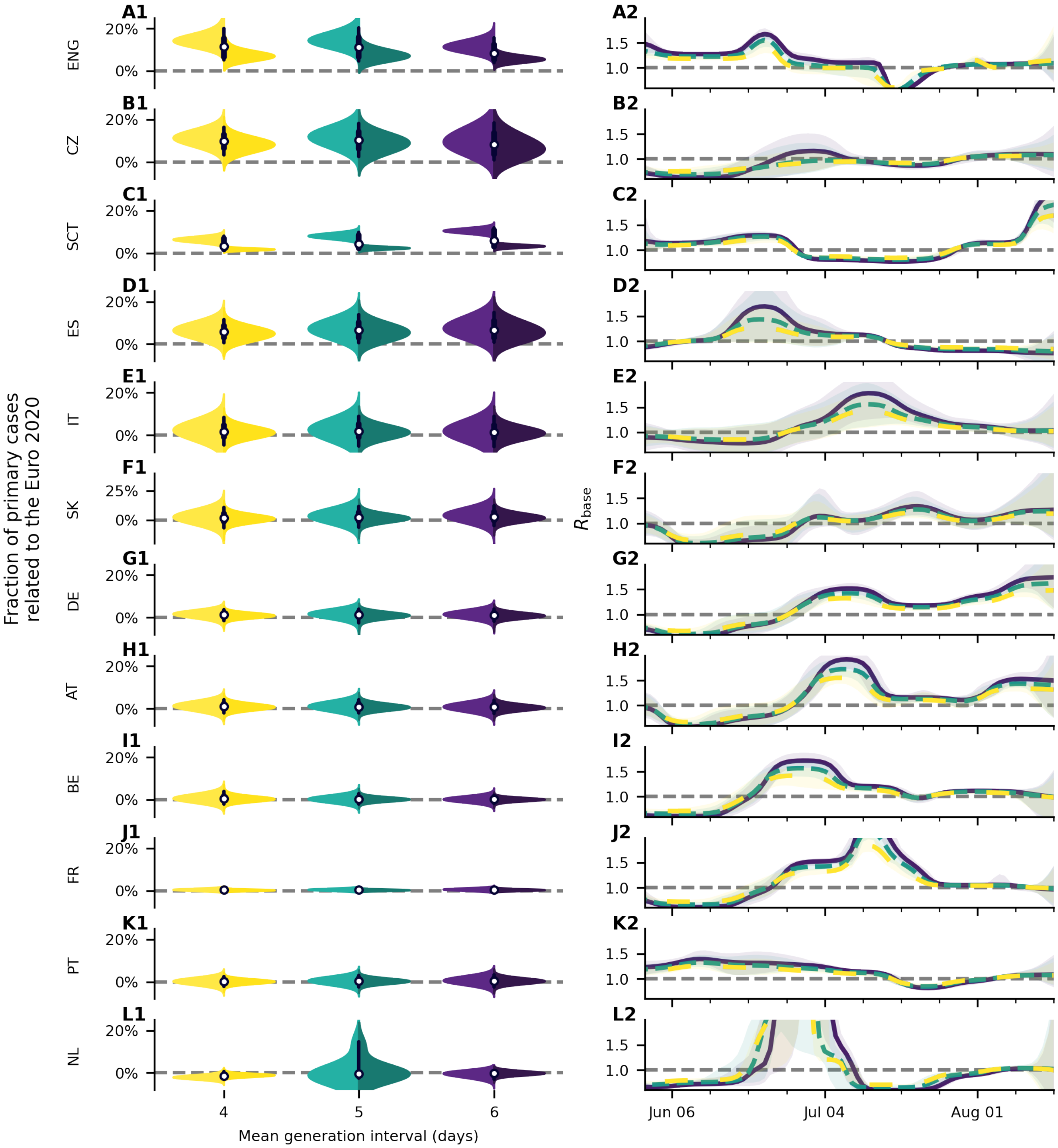
Supplementary Figure S13: **Robustness test for the effect of the width of the delay kernel.** In this robustness test, we varied the prior for the width of the delay kernel from the country-specific default (green) towards smaller (yellow) and larger (purple) widths (left column). In the violin plots, the left side is the prior for men; the right side for women. The right column shows the priors and resulting posterior of the standard deviation of the delay kernel σ_D. Except for England and Scotland (**A2, D2**), the data does not constrain this parameter. The results are not significantly modified in any country by changing the prior assumptions on this parameter (left column). On average, allowing for larger widths increases the effect size over the reported results. White dots represent median values, black bars and whiskers correspond to the 68% and 95% credible intervals (CI), respectively, and the distributions in color (truncated at 99% CI) represent the differences by gender.



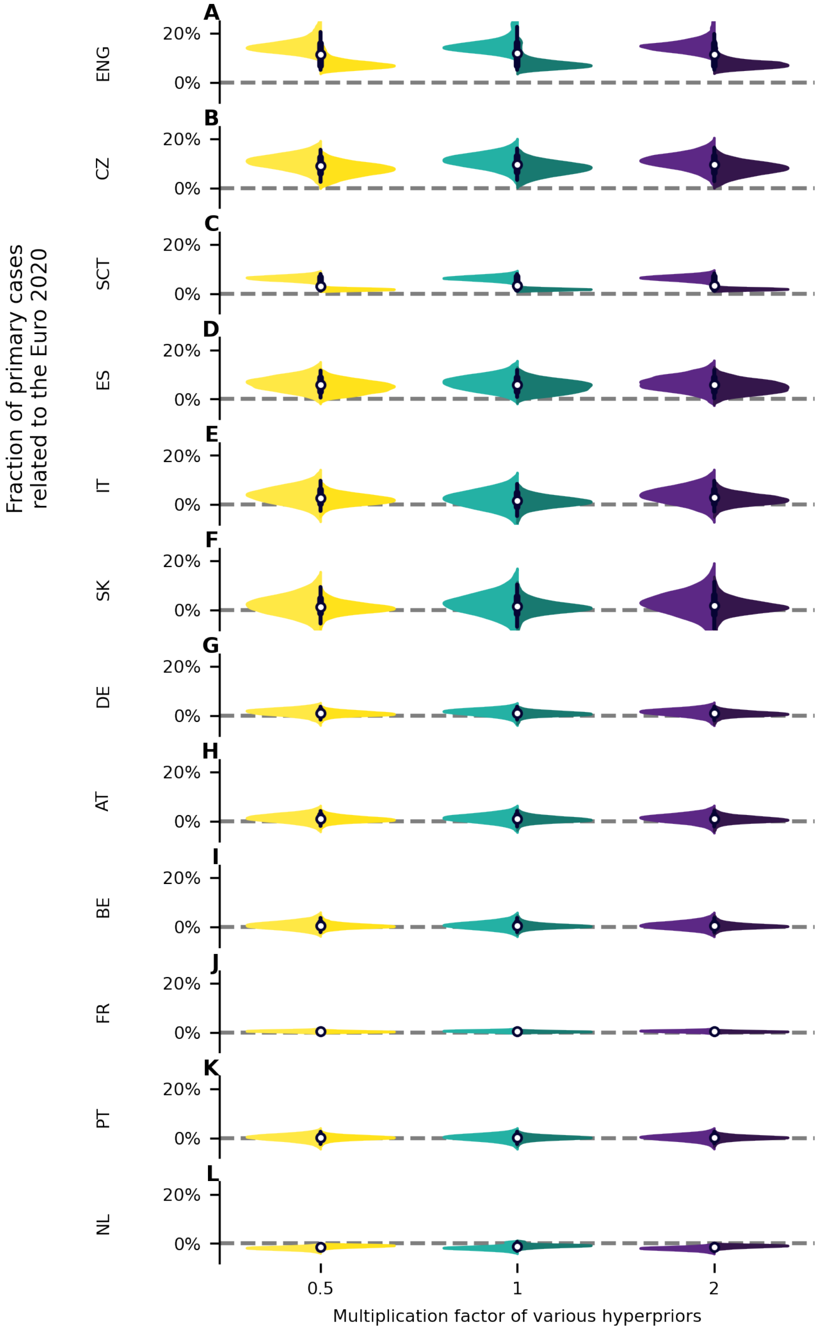
Supplementary Figure S14: **Robustness test for the effect of the allowed base reproduction number variability.** We propose models with three different base change point intervals: 6 days (yellow), 10 days (green), and 20 days (purple). In the violin plots, the left side is the distribution for men; the right side for women. We do not find significant differences in the fraction of football-related cases (left column) nor in the base reproduction numbers R_{base} (right column). On average, allowing less variation in R_{base} – i.e., removing the freedom of the model to absorb potential gender-symmetric and non-time-resolved cases related to football matches into short-timescale variations of R_{base} – increases the effect size over the reported baseline results. Shaded areas in panels ***2** correspond to 95% CI. White dots represent median values, black bars and whiskers correspond to the 68% and 95% credible intervals (CI), respectively, and the distributions in color (truncated at 99% CI) represent the differences by gender.



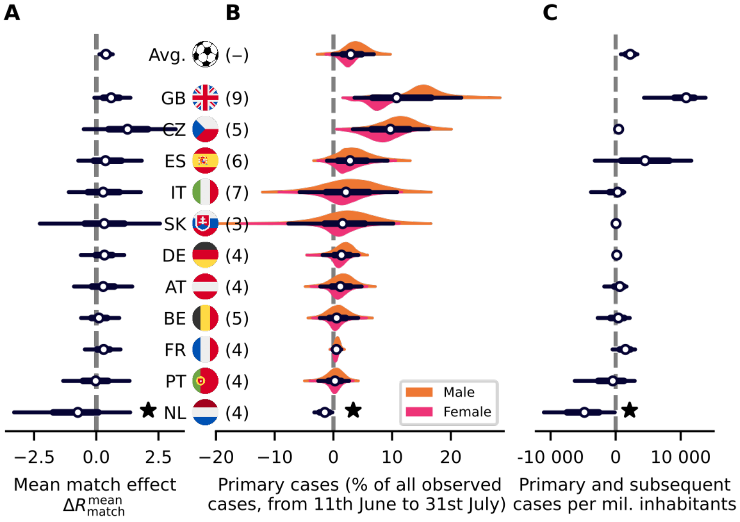
Supplementary Figure S15: **Robustness test for the effect of the fraction of female participation in football related gatherings** The default model employs a relatively constraining prior for the fraction of female participation in football-related gatherings (green) motivated by [9]. To check for the influence of this assumption, in an alternative model, we assume a more uninformative prior with mean female participation of 50% participation (purple) instead of 20% (green) (**A2-G2**). We do not find large differences in the results. On average, the total fraction of cases attributed to football matches grows when allowing the assumption of larger female participation in the fan gatherings. Hence, more cases are attributed to the Euro 2020 overall than in the baseline model. At the same time, a constraint used by the model for associating cases and matches is relieved. Thus, on average, the uncertainty of the posterior slightly grows (**A1-G1**). White dots represent median values, black bars and whiskers correspond to the 68% and 95% credible intervals (CI), respectively, and the distributions in color (truncated at 99% CI) represent the differences by gender.



Supplementary Figure S16: **Robustness test for the effect the generation interval.** We propose models with three different generation intervals: with a mean of 4 days (yellow), 5 days (green), and 6 days (purple). The lack of significant difference in the fraction of football-related cases (left column) shows that if we assume a longer generation intervals than our base assumption of 4 days our conclusions do not change. One remarks that the the base reproduction numbers R_{base} (right column) increases with a longer assumed generation interval, which is expected because a the increase of cases that needs to be modeled stays fixed. In the violin plots, the left side is the distribution for men; the right side for women. Shaded areas in the right column correspond to 95% CI. White dots represent median values, black bars and whiskers correspond to the 68% and 95% credible intervals (CI), respectively, and the distributions in color (truncated at 99% CI) represent the differences by gender.

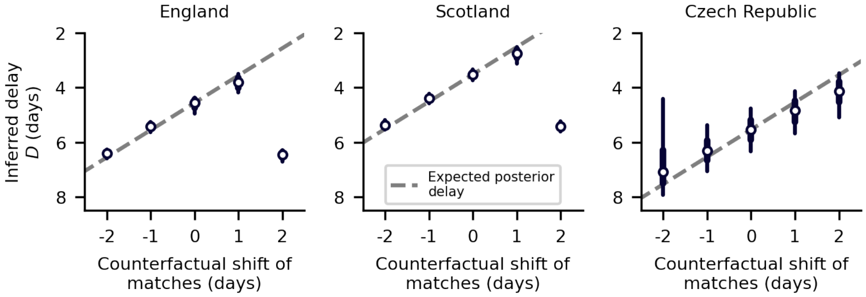


Supplementary Figure S17: **Robustness test for the remaining priors not studied in the previous figures.** Many of the priors in the model are relatively uninformative for the model. In these runs, we increased and decreased the prior value of the equations (16), (26), (35), (51), (52) and (54) by a factor of 2. In the violin plots, the left side is the distribution for men; the right side for women. White dots represent median values, black bars and whiskers correspond to the 68% and 95% credible intervals (CI), respectively, and the distributions in color (truncated at 99% CI) represent the differences by gender.

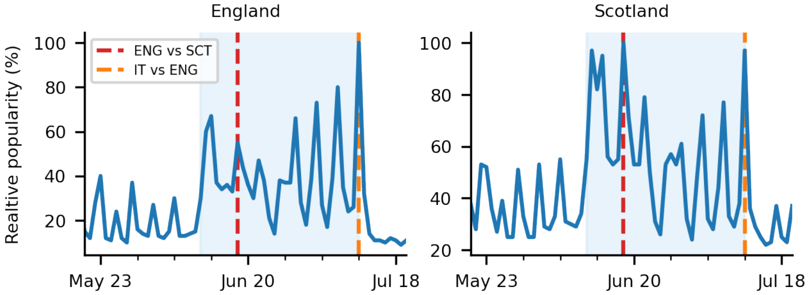


Supplementary Figure S18: **The combination of the case numbers of England and Scotland leads to similar results.** Because England and Scotland had each a team participating in the Euro 2020 we analyzed them separately, even if both are part of the United Kingdom. Here we added the case numbers of both (denoted as GB) and combined their matches for a new model run. The overall results do not change much in this alternative parametrization. White dots represent median values, black bars and whiskers correspond to the 68% and 95% credible intervals (CI), respectively, and the distributions in color (truncated at 99% CI) represent the differences by gender ($n = 11$ countries).

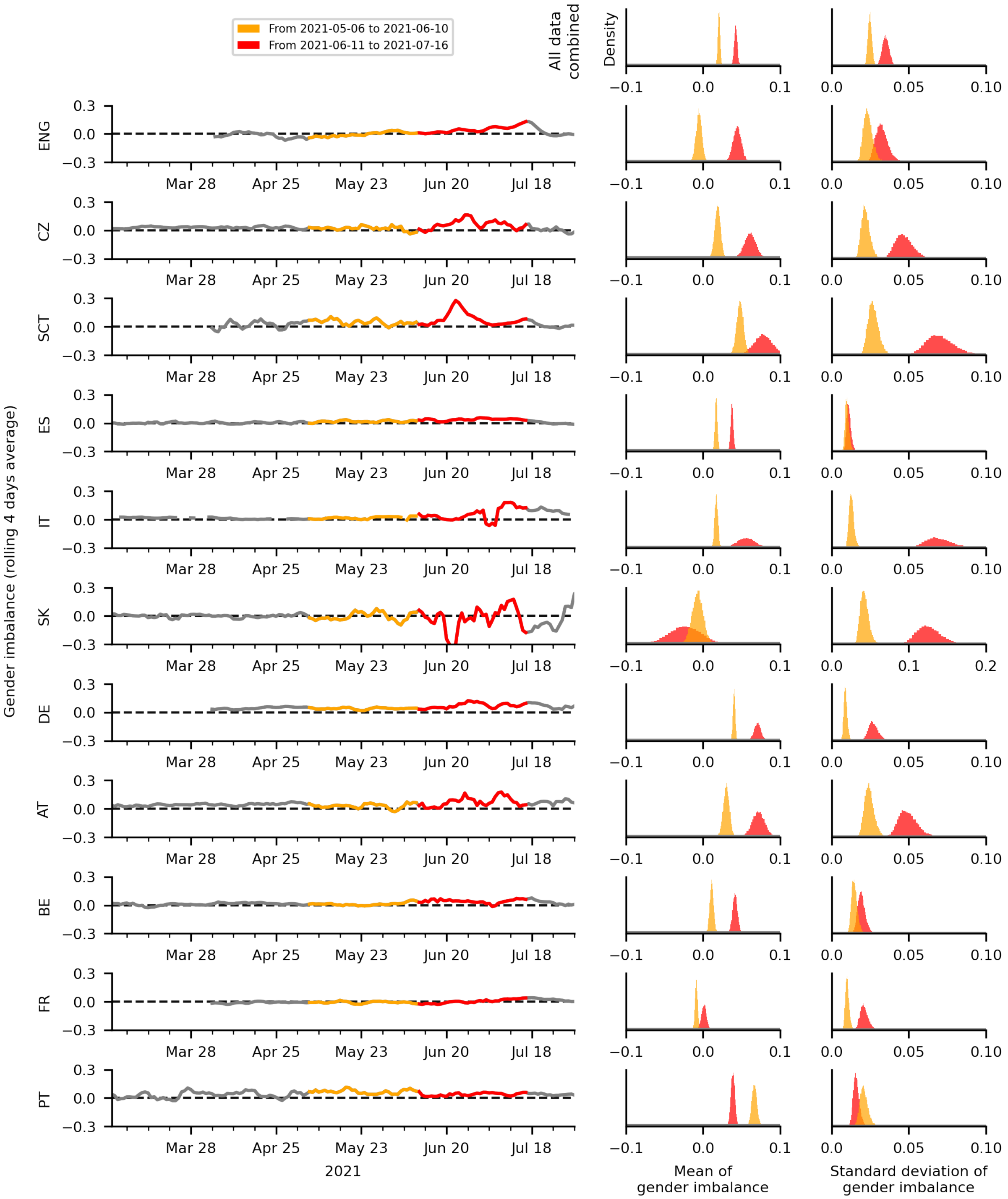
S4.4 Further analyses



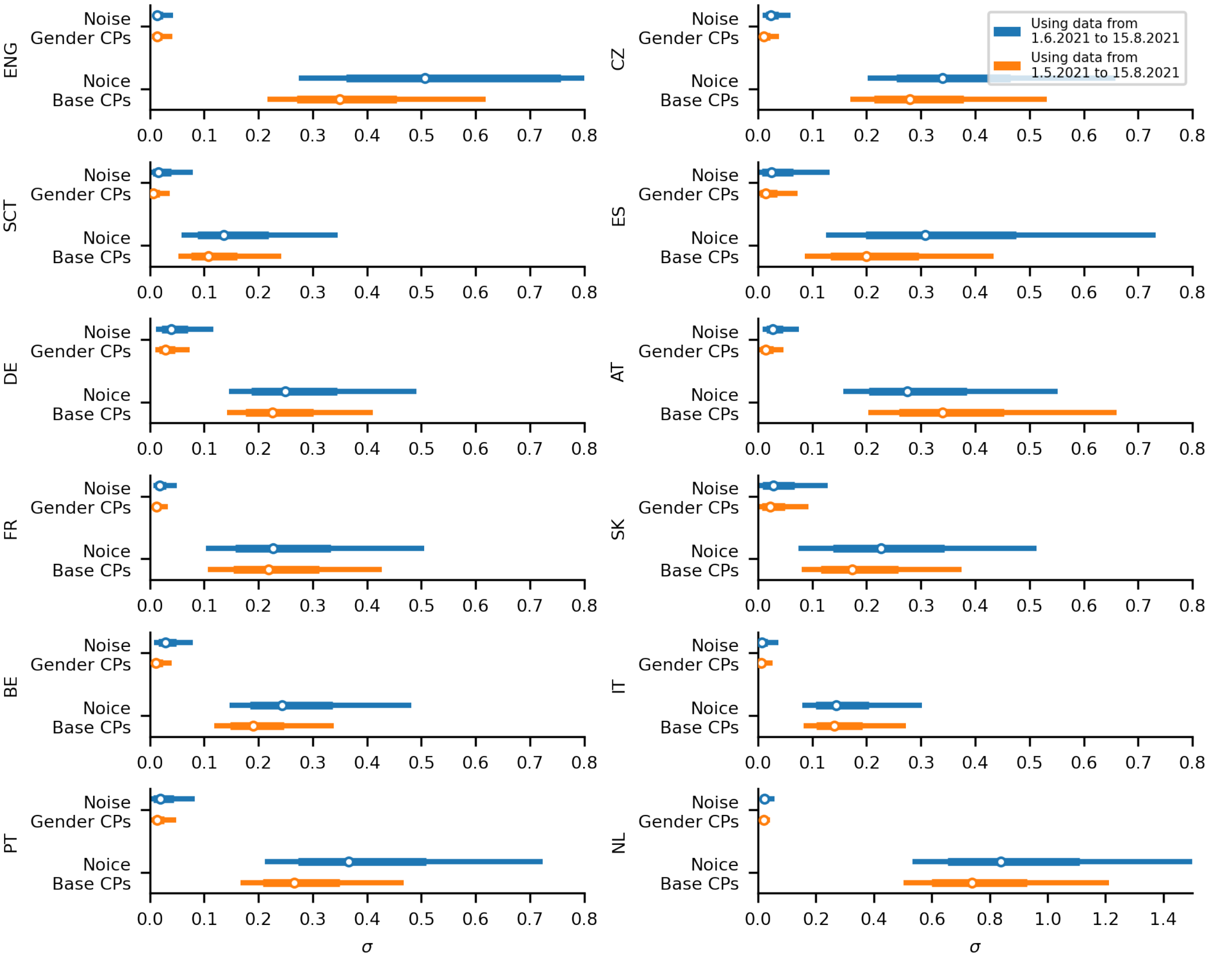
Supplementary Figure S19: **Our model is able to identify the delay between infection and reporting of it.** We tested counterfactual scenarios for England, Scotland and the Czech Republic where the dates of the matches were changed. Despite the same prior delay, the model managed to adapt the inferred delay to match the expected delay from the original model. White dots represent median values, black bars and whiskers correspond to the 68% and 95% credible intervals (CI).



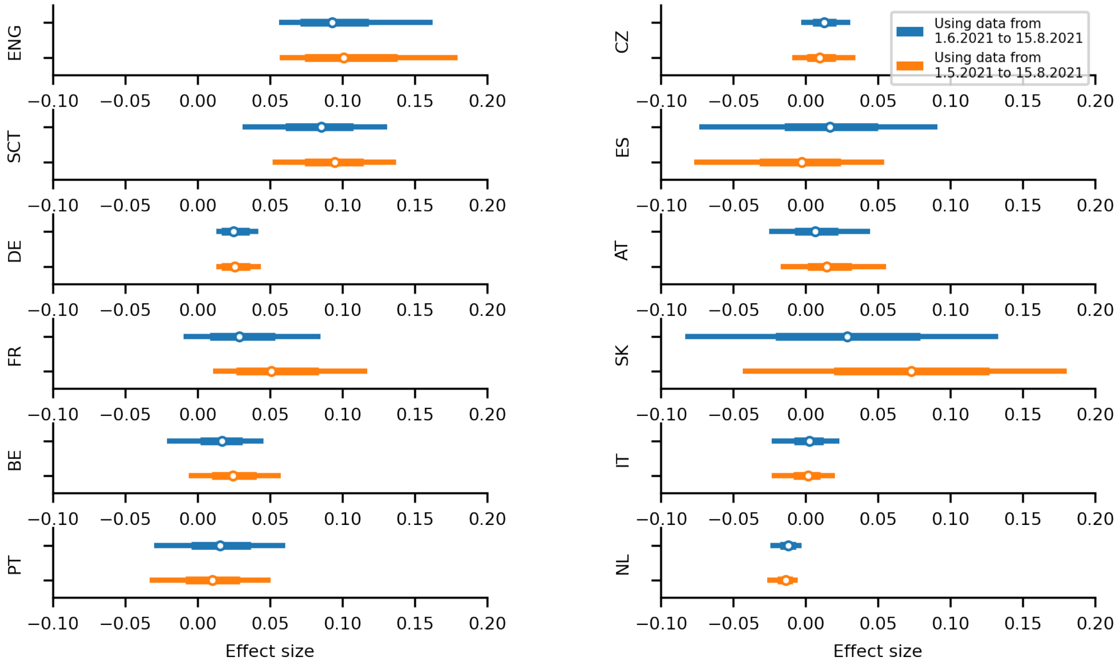
Supplementary Figure S20: **Relative popularity of the search term “football” in England and Scotland** measured using “Google Trends” [7] in the category “sport news”. Vertical red lines represent the final and match of Scotland vs England, respectively.



Supplementary Figure S21: **Male-female imbalance over time shows the largest deviations during championship.** We plotted the gender imbalance directly from our data (left column). All countries which showed significant effects had their largest imbalance change during or slightly after the championship (red), and also a number of non-significant countries display this behavior. In addition, the standard deviation of the imbalance during the championship (red) was on average larger than before the championship (orange, right column). This indicates that the large changes in imbalance during the championship were highly unusual and can't be attributed to chance alone. The red time period are the 30 days of the tournament plus the 5 days after and the orange time period the ones up to 35 days before the tournament.

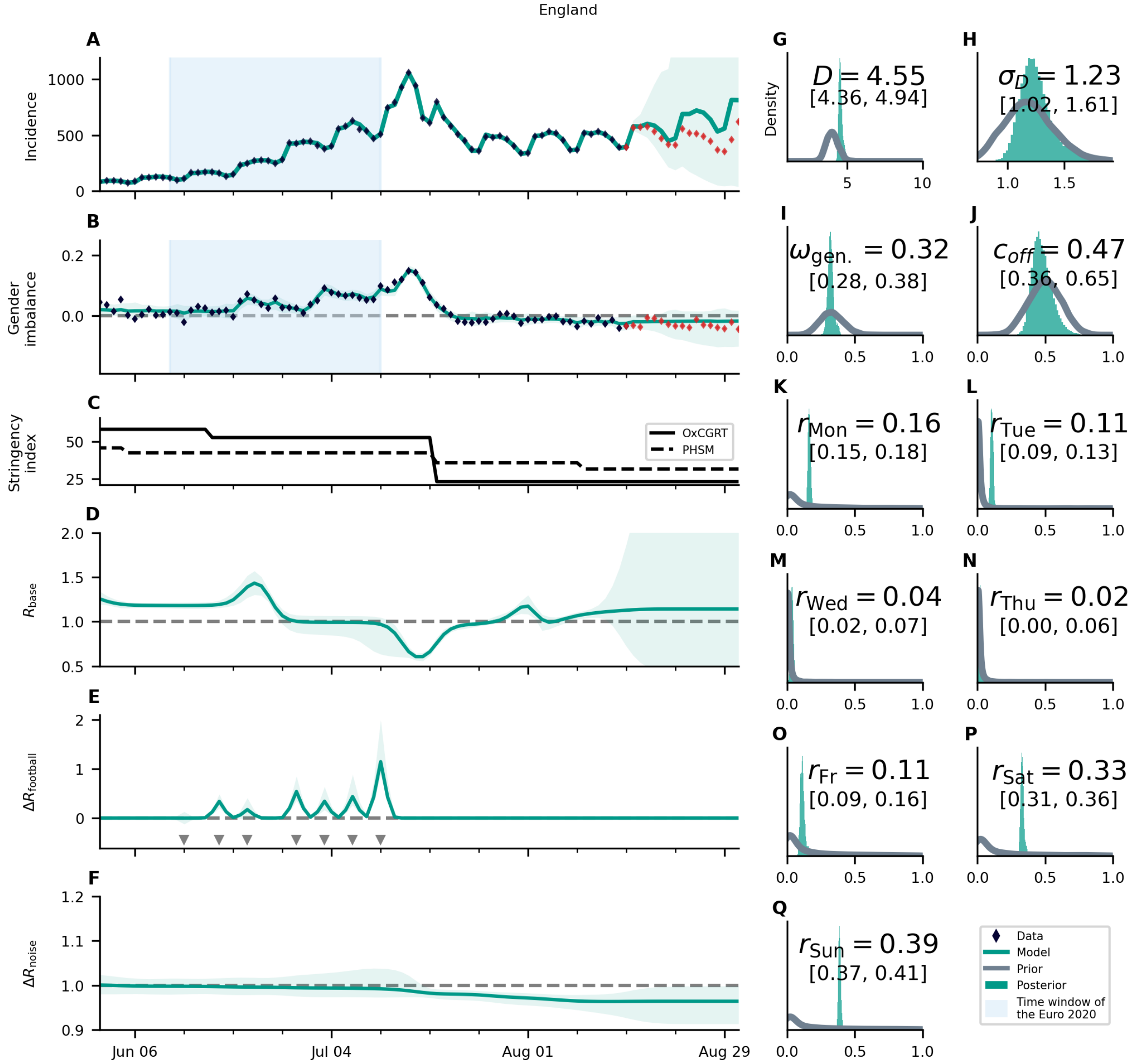


Supplementary Figure S22: **The inferred noise terms do not depend strongly on the length of the analyzed time-period.** We plotted the size of our gender noise term $\sigma_{\Delta\tilde{\gamma}}$ and the size of the change-points of the base reproduction number $\sigma_{\Delta\gamma}$. When beginning the run of our model a month earlier (blue), the noise terms do not change significantly compared to our base model (orange). White dots represent median values, colored bars and whiskers correspond to the 68% and 95% credible intervals (CI).

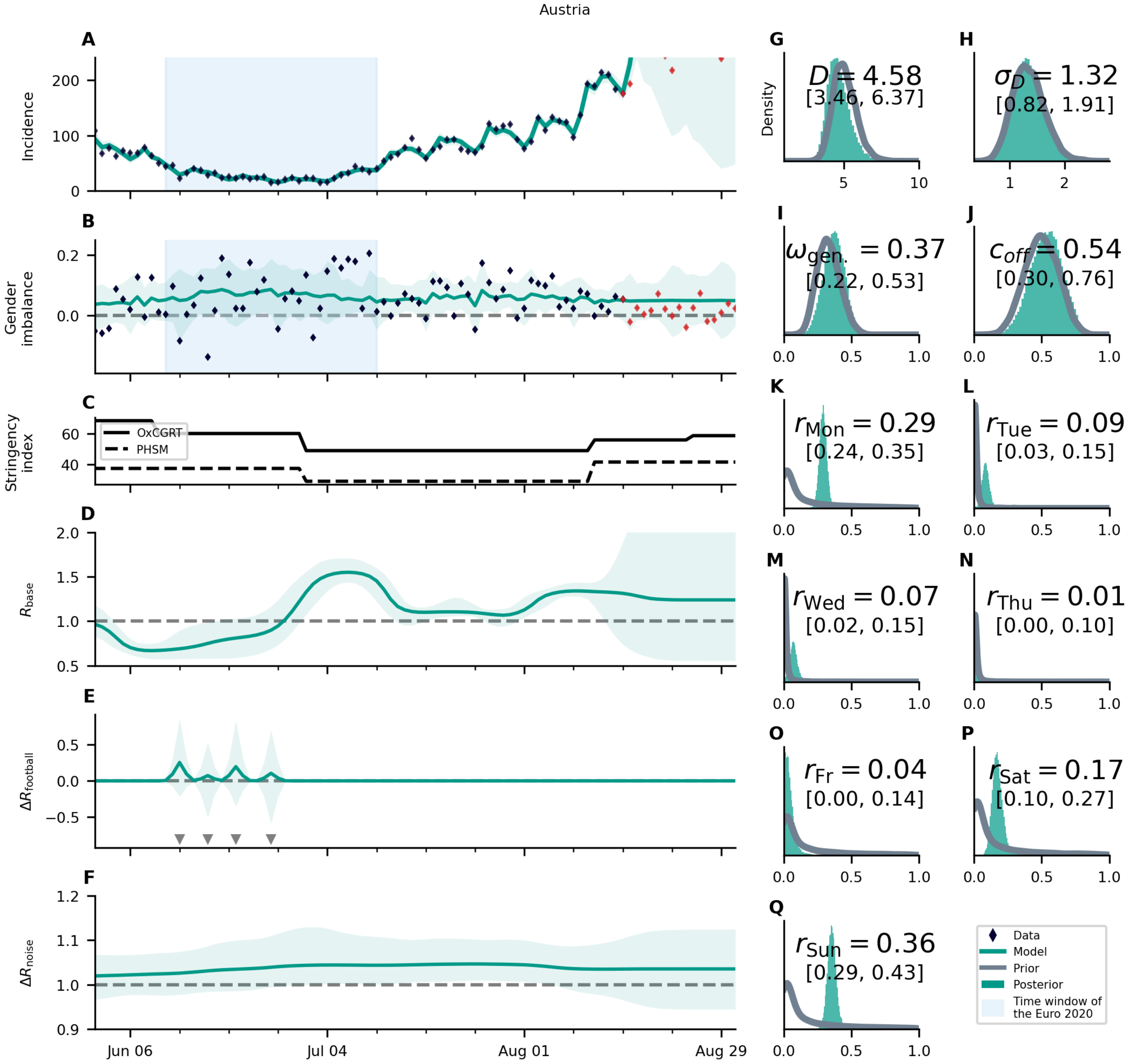


Supplementary Figure S23: **The inferred effect size (percentage of football-related primary infections) do not depend strongly on the length of the analyzed time-period.** To showcase that the total length of the analyzed period doesn't change significantly our results, we compare the percentage of football-related primary infections one-month-longer runs (blue) compared to our base model (orange). White dots represent median values, colored bars and whiskers correspond to the 68% and 95% credible intervals (CI).

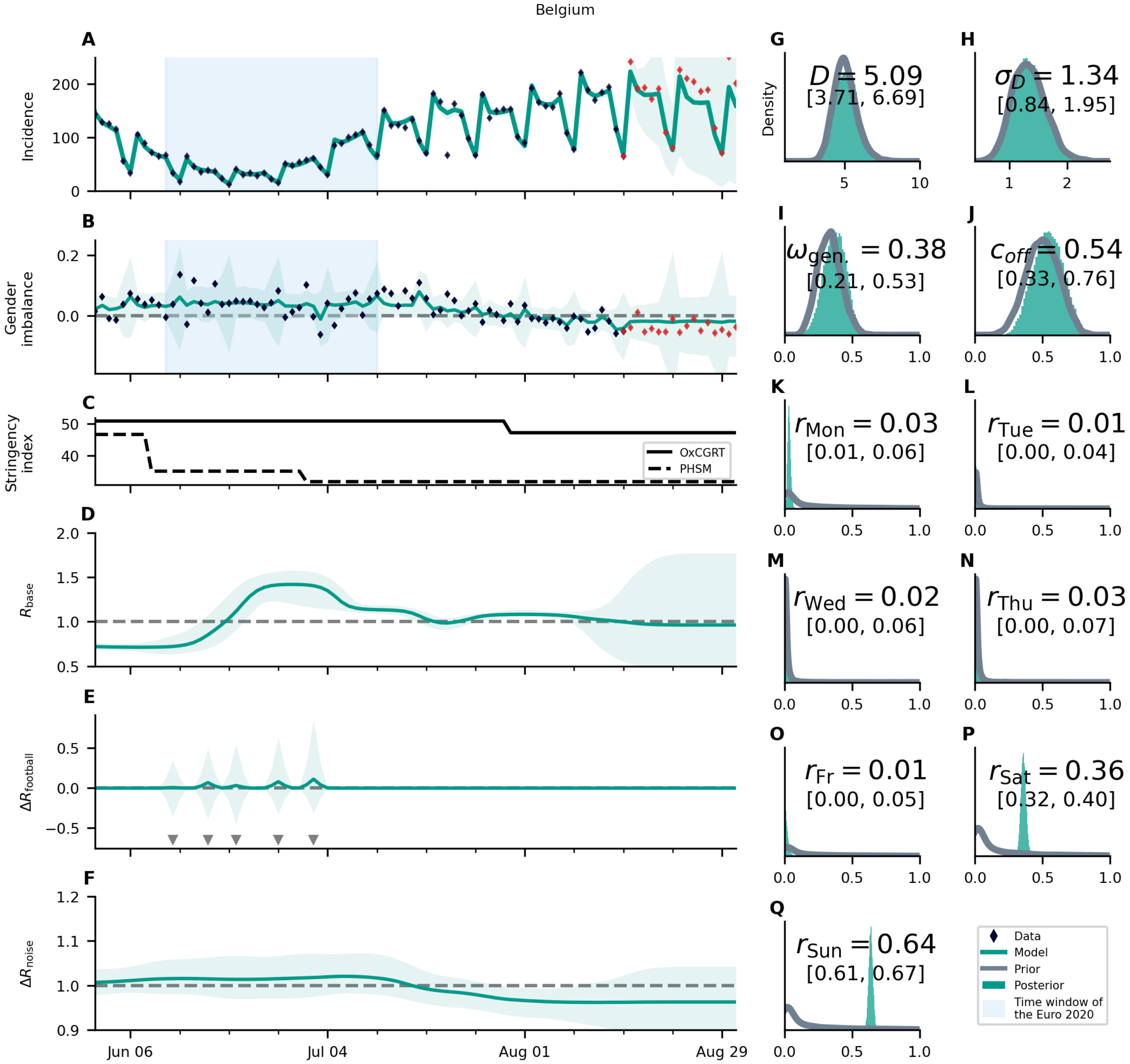
S4.5 Posterior of parameters



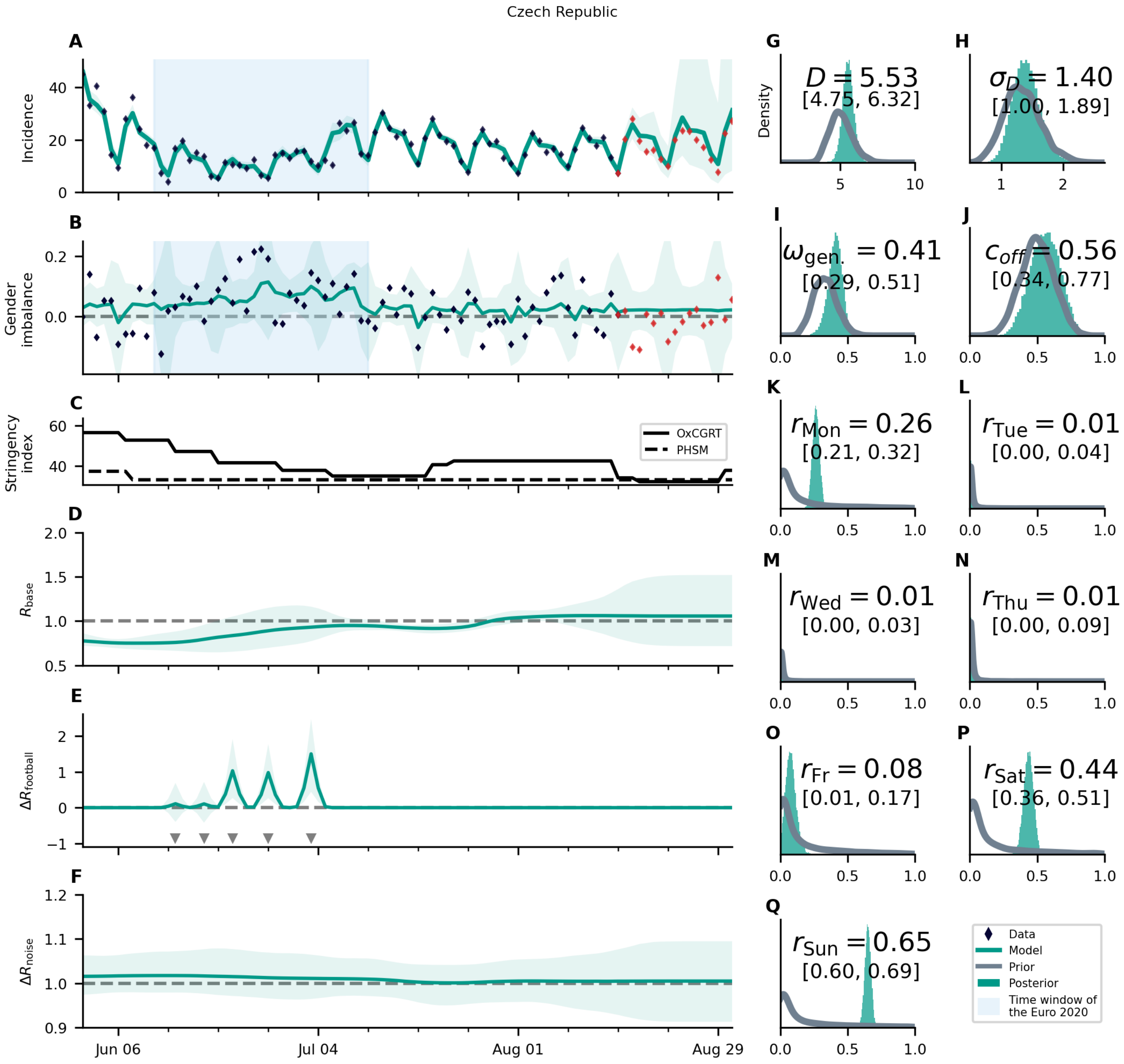
Supplementary Figure S24: **Overview of the posterior for England.** We compare (**A**) the time-dependence of the incidence before, during (blue shaded area) and after the championship; (**B**) the gender imbalance of observed cases; (**C**) Oxford governmental response tracker (OxCGRT) [3] and public health and social measures severity index (PHSM) [4] (not part of the model); (**D**) the gender-symmetric base reproduction number R_{base}; (**E**) the gender-asymmetric football reproduction number R_{football}; (**F**) gender-asymmetric noise related reproduction number R_{noise}; and (**G**) to (**Q**) the prior and posterior of various parameters. In mid July the incidence starts dropping. In contrast, the number of deaths continues to increase. Together, this indicates that the testing policy was changed around that time. England is one of the two countries where the delay D and the female participation in fan activities dominating the additional transmission can be measured and significantly constrained with the data compared to the prior distribution (**G** and **I**). Red diamonds show data not used for the analysis. This comes with an increase in the uncertainty in the model prediction. One notes two slight bumps of the base reproduction number: one during and one after the end of the championship. The first bump may indicate that our model is not able to fully attribute a part of the effective reproduction number to $\Delta R_{\mathrm{football}}$ and is attributing the effect of England's matches in the group phase to the base reproduction number instead. The second bump might be explained hereby: During the championship there may be generally more social contacts, which are not in temporal synchronization with the matches, and therefore not explained by $\Delta R_{\mathrm{football}}$ but by R_{base} instead. Hence, after the championship the base reproduction number decreases and increases again when measures are lifted (**C**). The turquoise shaded areas correspond to 95% credible intervals.



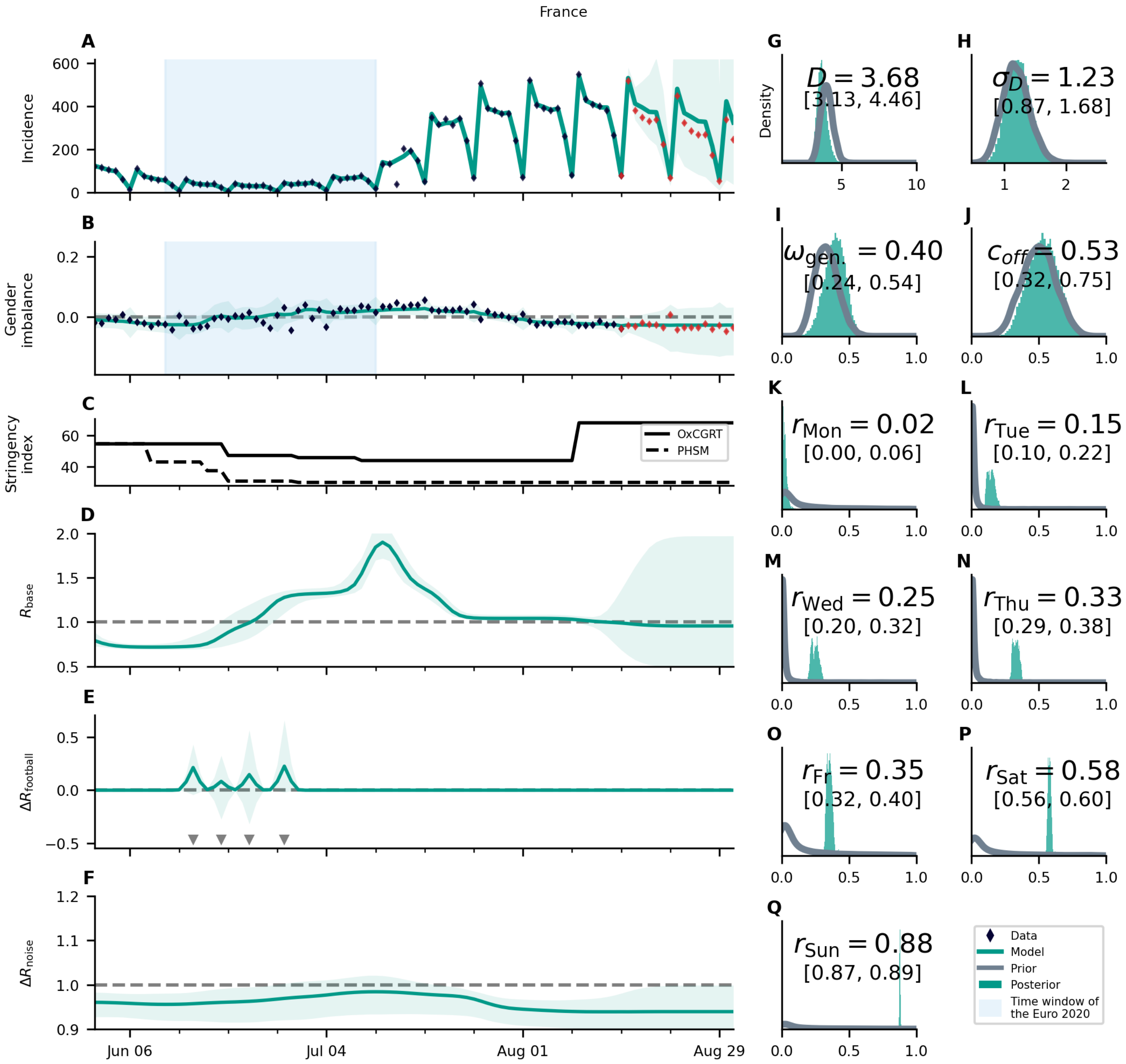
Supplementary Figure S25: **Overview of the posterior for Austria.** For an explanation of the panel structure, see supplementary Fig. S24. Austria shows a low significance for assigning cases to matches. The increase of R_{base} coincides with the relaxation of restrictions **C**, but the subsequent decrease is not explained. The turquoise shaded areas correspond to 95% credible intervals.



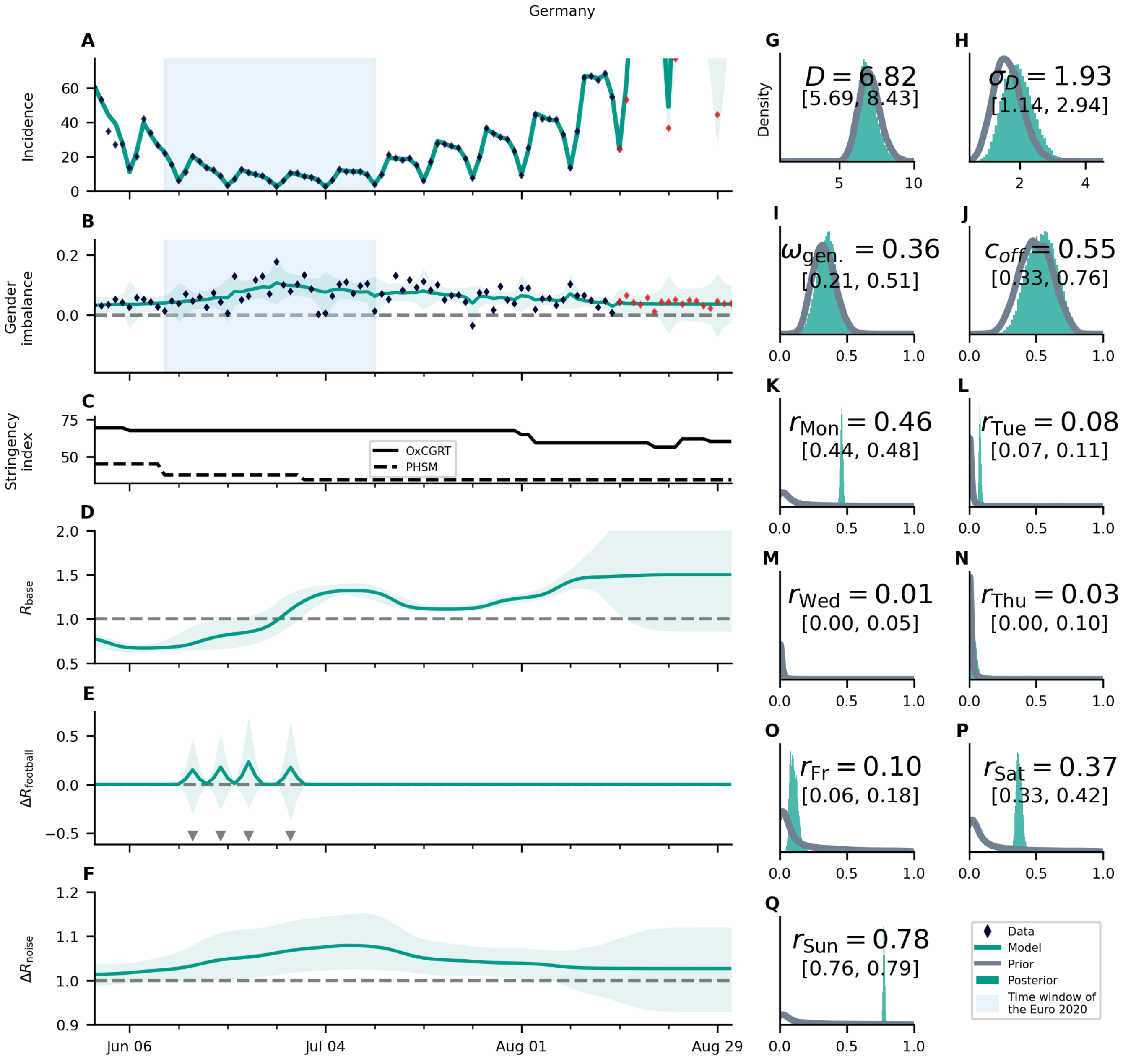
Supplementary Figure S26: **Overview of the posterior for Belgium.** For an explanation of the panel structure, see supplementary Fig. S24. Belgium shows a low significance for assigning cases to matches, but an intermittent increase of R_{base} during the championship. The turquoise shaded areas correspond to 95% credible intervals.



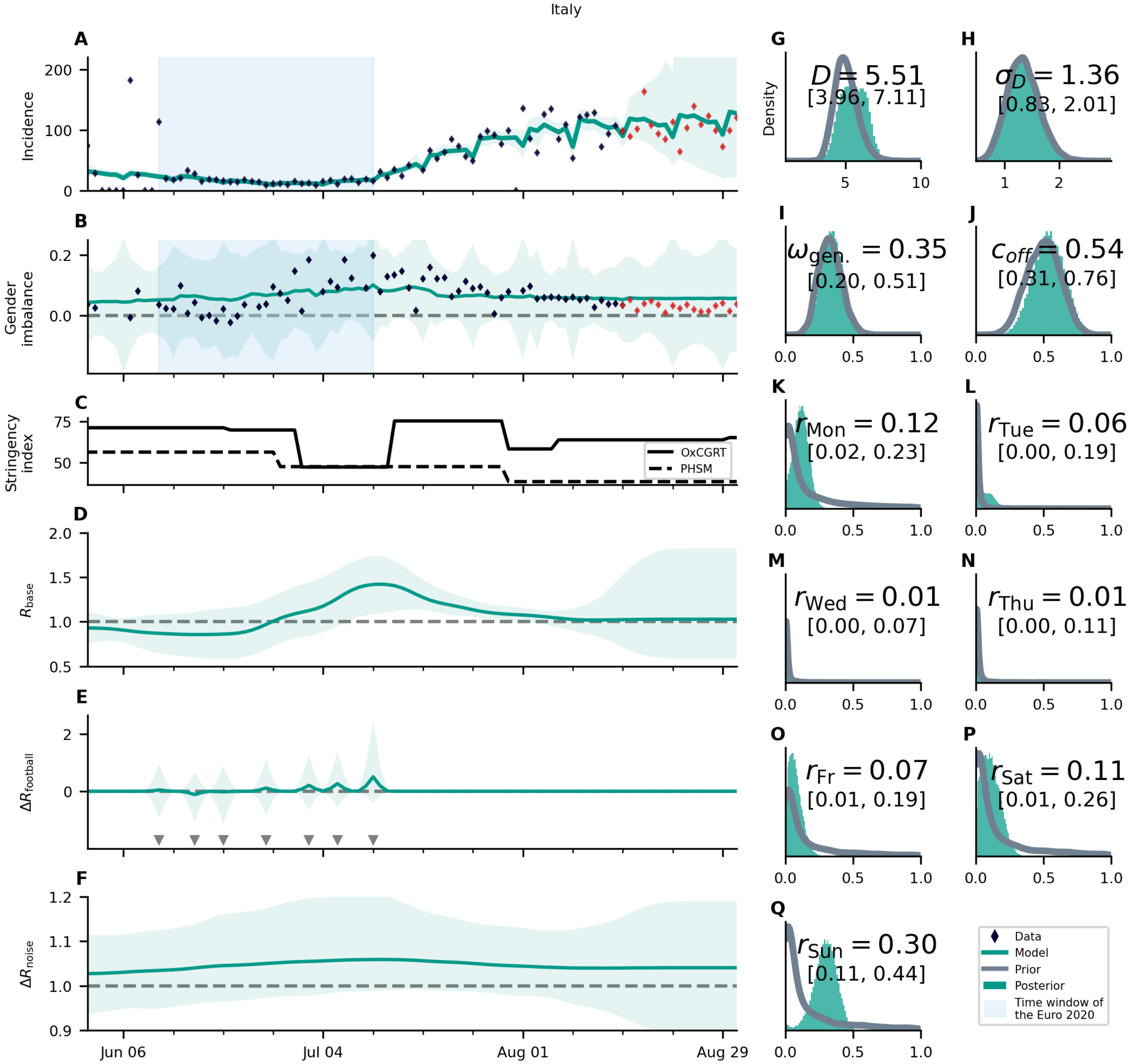
Supplementary Figure S27: **Overview of the posterior for the Czech Republic.** For an explanation of the panel structure, see supplementary Fig. S24. The overall incidence is relatively low, which increases the noisiness of the data. This is especially apparent in the gender imbalance (**B**). The base reproduction number is slowly increasing during the analyzed time-period, which can be partially explained by a decrease of the stringency index (**C**). The match effects are greater for later matches, beginning from the last group match until the quarterfinals (**E**), which is the expected variation. The turquoise shaded areas correspond to 95% credible intervals.



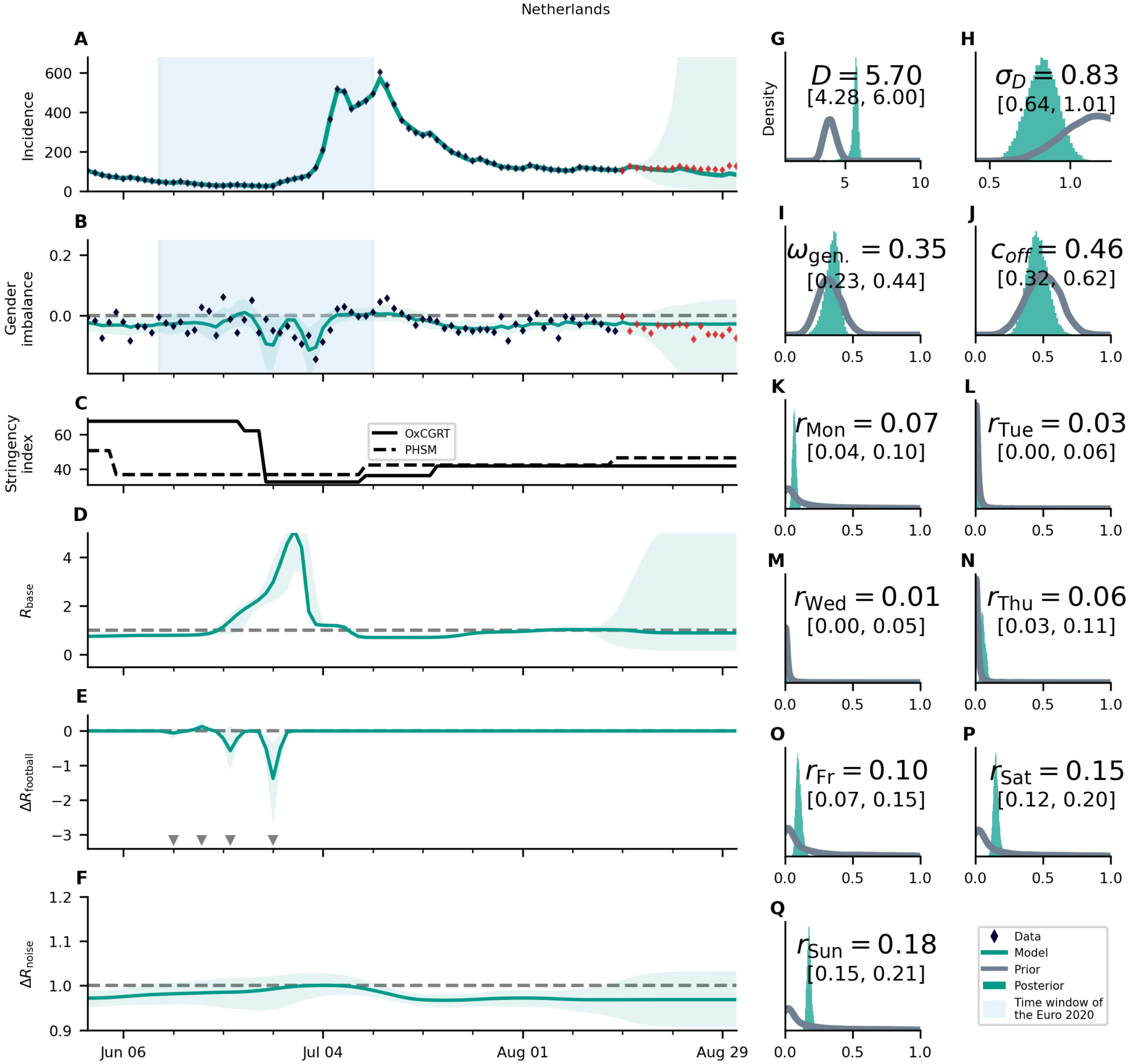
Supplementary Figure S28: **Overview of the posterior for France.** For an explanation of the panel structure, see supplementary Fig. S24. France shows a very pronounced increase of R_{base} over the course of the championship and a very small fraction of cases assigned to matches of the French team. This hints at a rather gender-neutral effect of match-induced infections in France, in agreement with the results shown in Fig. S15. The peak of R_{base} occurs on July 11th when clubs etc re-opened. It is unclear why the base reproduction number decreases this much again afterwards. The turquoise shaded areas correspond to 95% credible intervals.



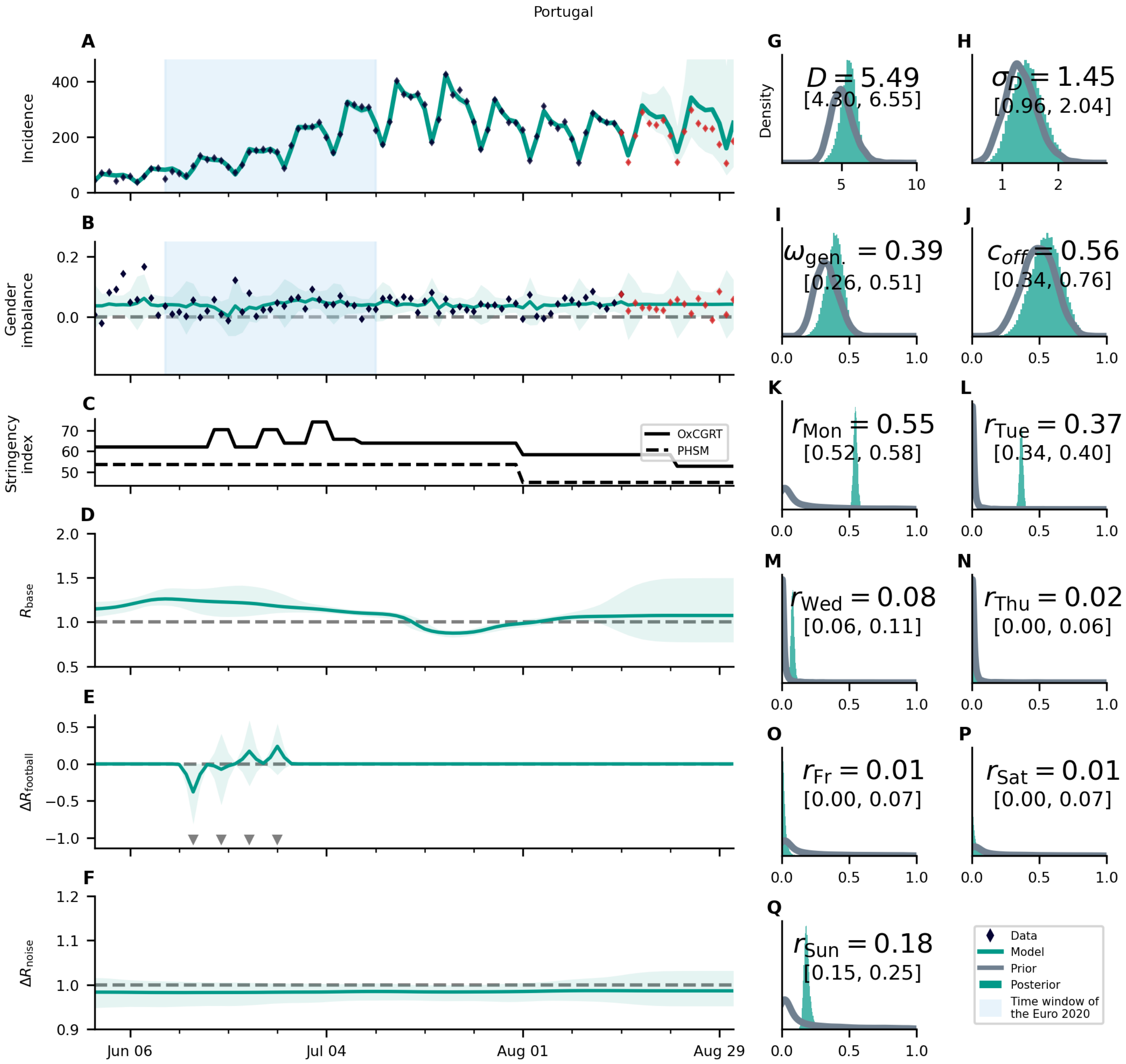
Supplementary Figure S29: **Overview of the posterior for Germany.** For an explanation of the panel structure, see supplementary Fig. S24. Germany shows an increase of R_{base} and of the gender imbalance over the course of the championship (**B**). It might be the case that the Euro 2020 contribution is not tightly tied to matches of the German team, prohibiting the model to explain the observed gender imbalance via the individual matches (**E**), leading to an increase of ΔR_{noise} instead (**F**). The turquoise shaded areas correspond to 95% credible intervals.



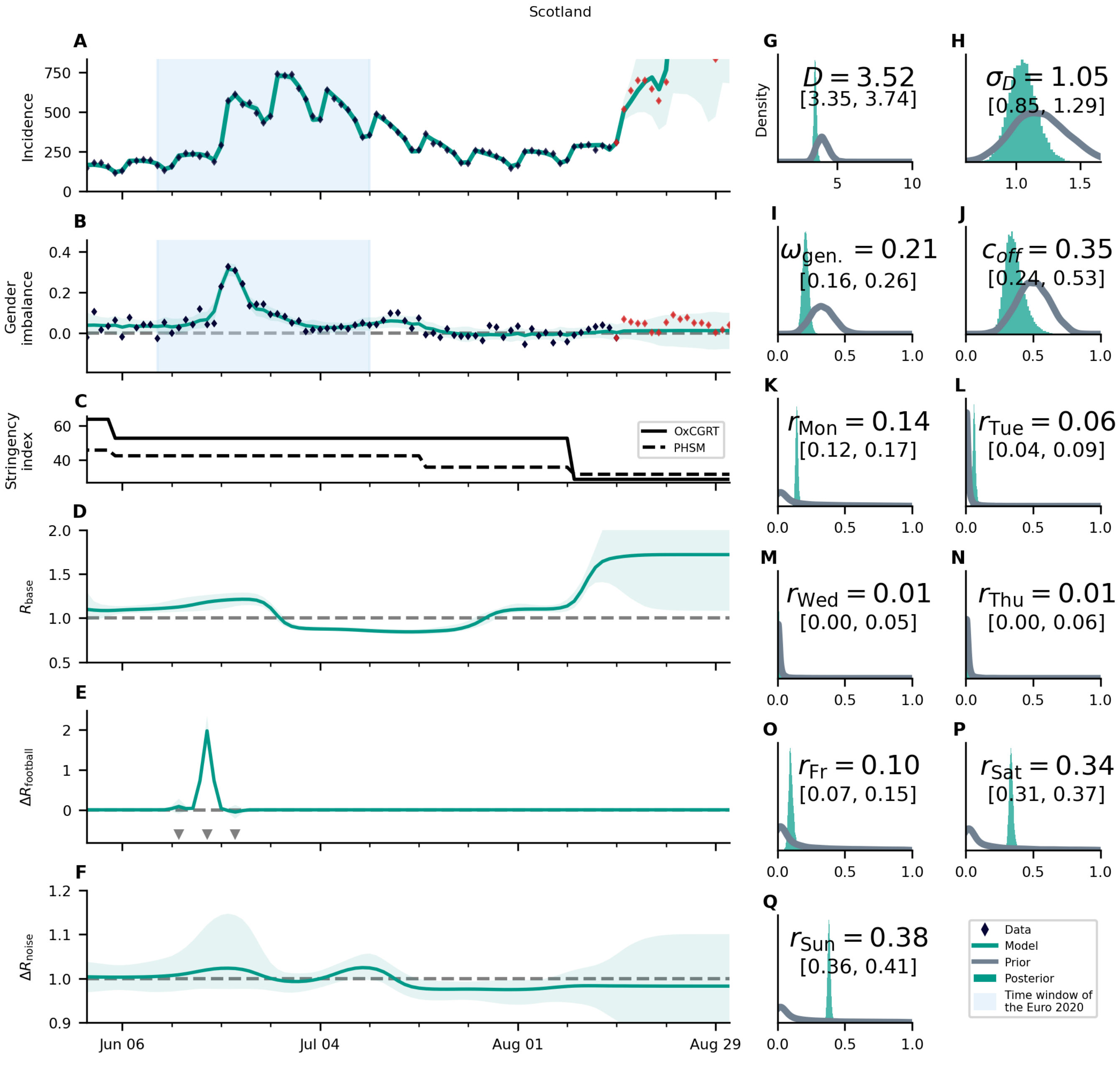
Supplementary Figure S30: **Overview of the posterior for Italy.** For an explanation of the panel structure, see supplementary Fig. S24. Italy is one of the countries where an intermittent increase in R_{base} is observed (**D**). The development of the base reproduction number also coincides well with the relaxations and reinstatement of restrictions (**C**). Match-related football effects are not clearly visible (**E**). The turquoise shaded areas correspond to 95% credible intervals.



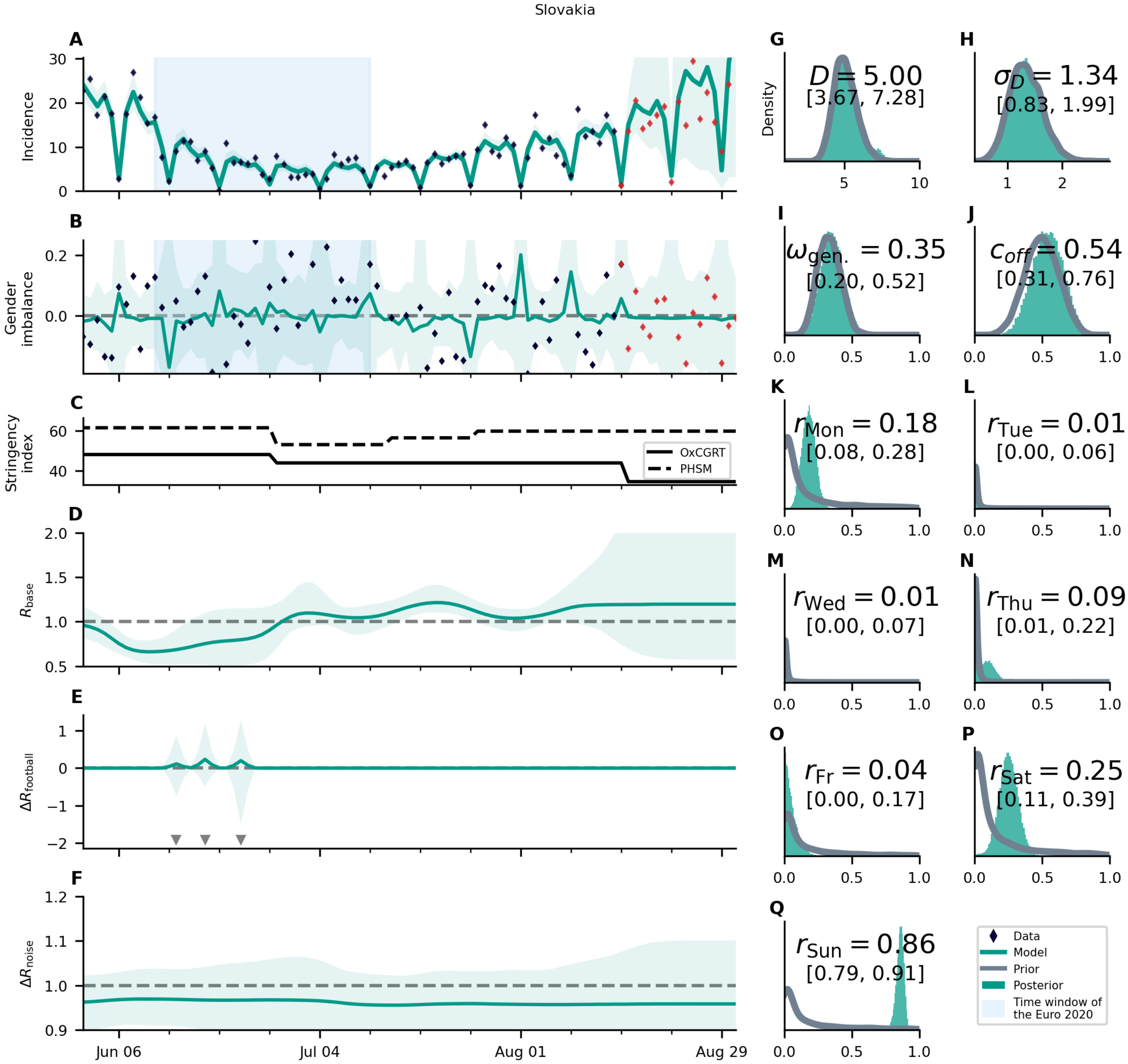
Supplementary Figure S31: **Overview of the posterior for the Netherlands.** For an explanation of the panel structure, see supplementary Fig. S24. The country wide “freedom day” on June 26th [10] is clearly visible in the incidence numbers **A** as well as the posterior base reproduction number **B**. Its effects overshadow possible effects from the Euro 2020 and we removed this country from subsequent analyses. The turquoise shaded areas correspond to 95% credible intervals.



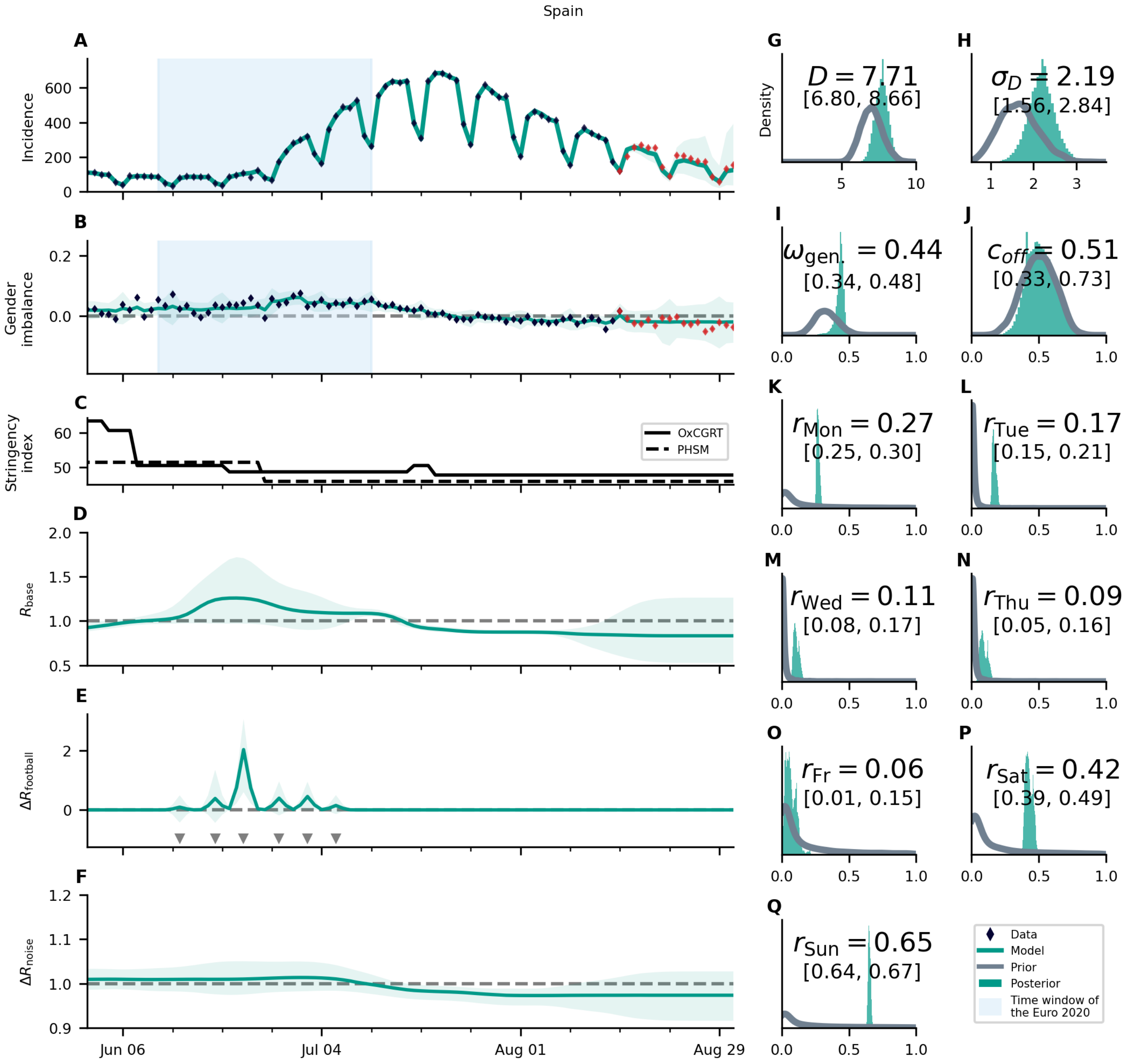
Supplementary Figure S32: **Overview of the posterior for Portugal.** For an explanation of the panel structure, see supplementary Fig. S24. Together with England, Portugal has the highest R_{base} before the championship. It is the only country in which a decrease of R_{base} over the course of the championship is observed. The fact that R_{base} remains low after the championship could be a hint that the possible increase of cases due to the Euro 2020 in Portugal is small compared to the reduction stemming from unrelated changes. The turquoise shaded areas correspond to 95% credible intervals.



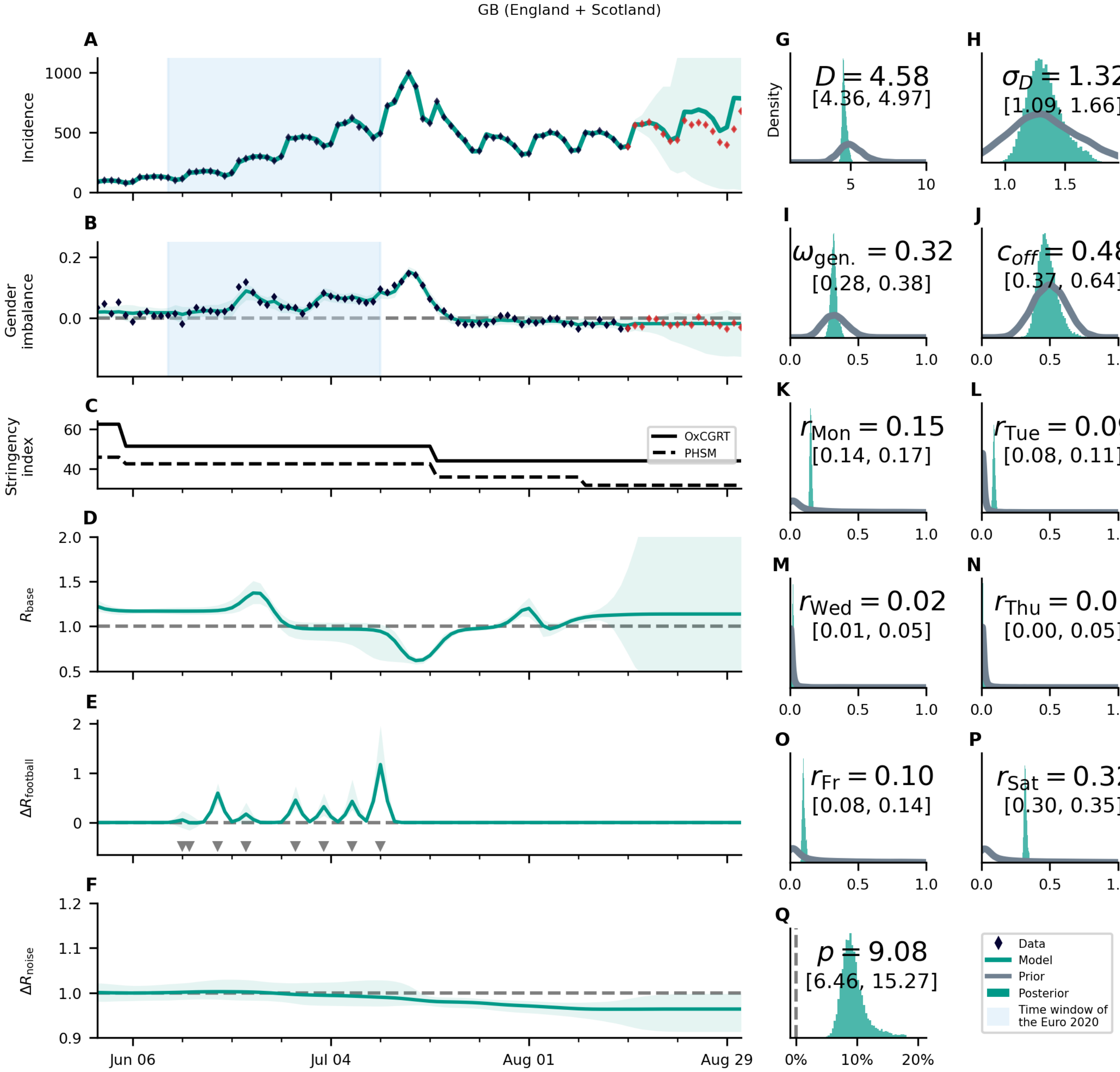
Supplementary Figure S33: **Overview of the posterior for Scotland.** For an explanation of the panel structure, see supplementary Fig. S24. Scotland is the country with the most significant effect of a single match, in this case against England. While this is in full agreement press reports (see also Fig. S20), the prior assumption of an exceptional large effect of this game is not built into the model. This clear association, thus, is a successful validation of the model functionality. The relaxation of governmental restrictions on August 9th is also well reflected in the development of the base reproduction number. The turquoise shaded areas correspond to 95% credible intervals.



Supplementary Figure S34: **Overview of the posterior for Slovakia.** For an explanation of the panel structure, see supplementary Fig. S24. Hardly any significant effects, apart from a small but long-lasting increase in R_{base}, are observed. The turquoise shaded areas correspond to 95% credible intervals.

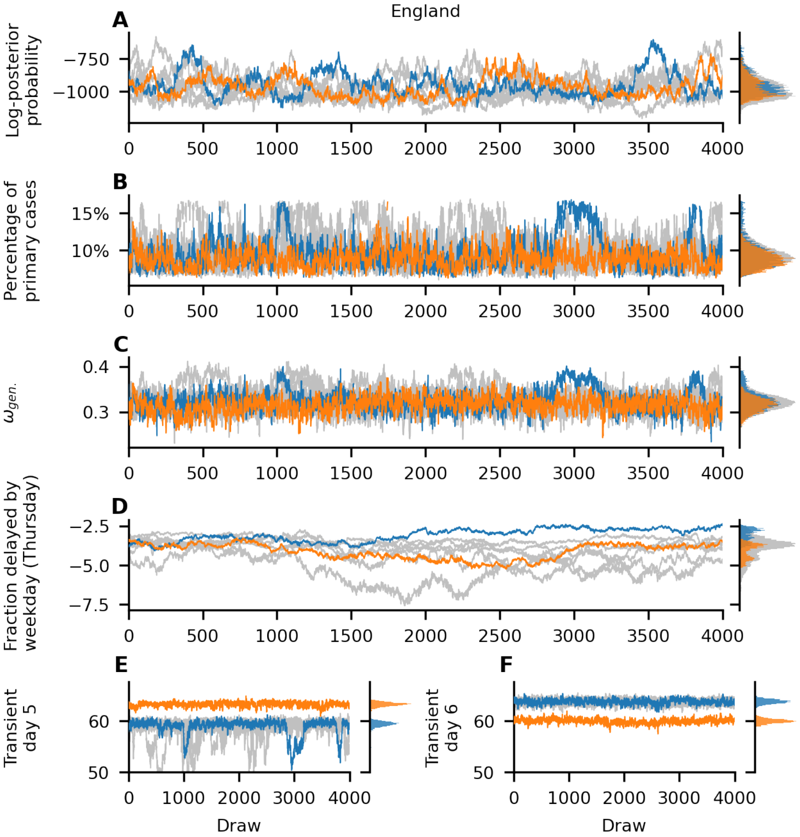


Supplementary Figure S35: **Overview of the posterior for Spain.** For an explanation of the panel structure, see supplementary Fig. S24. The national state of emergency ended in Spain on June 21st, in the middle of the championship. The model has therefore some difficulty to separate the effect of the relaxation of restrictions and the one of the matches, which translates into wide credible intervals in R_{base} (**C**) and $\Delta R_{\text{football}}$ (**D**). The turquoise shaded areas correspond to 95% credible intervals.

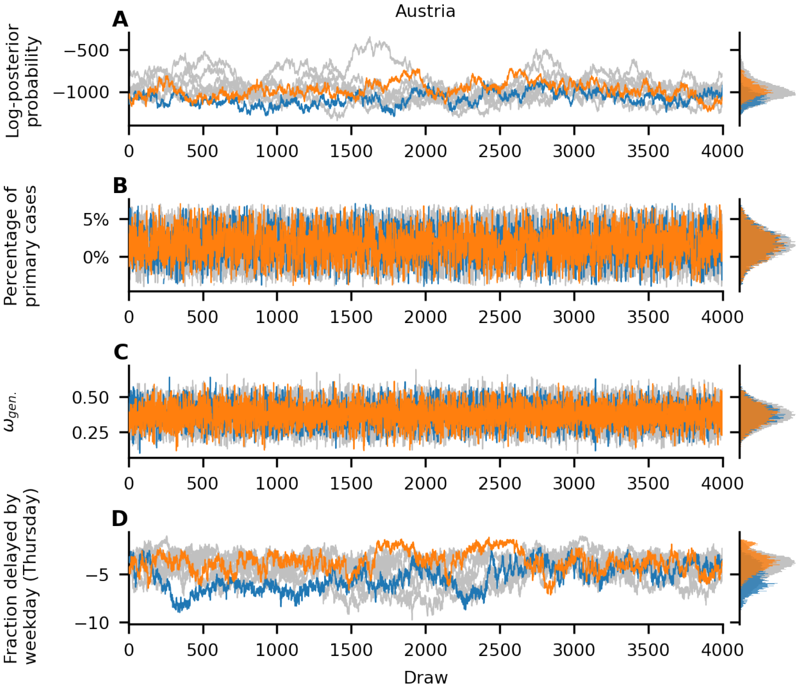


Supplementary Figure S36: **Overview of the posterior for the combined data of England and Scotland** For an explanation of the panel structure, see supplementary Fig. S24. The turquoise shaded areas correspond to 95% credible intervals.

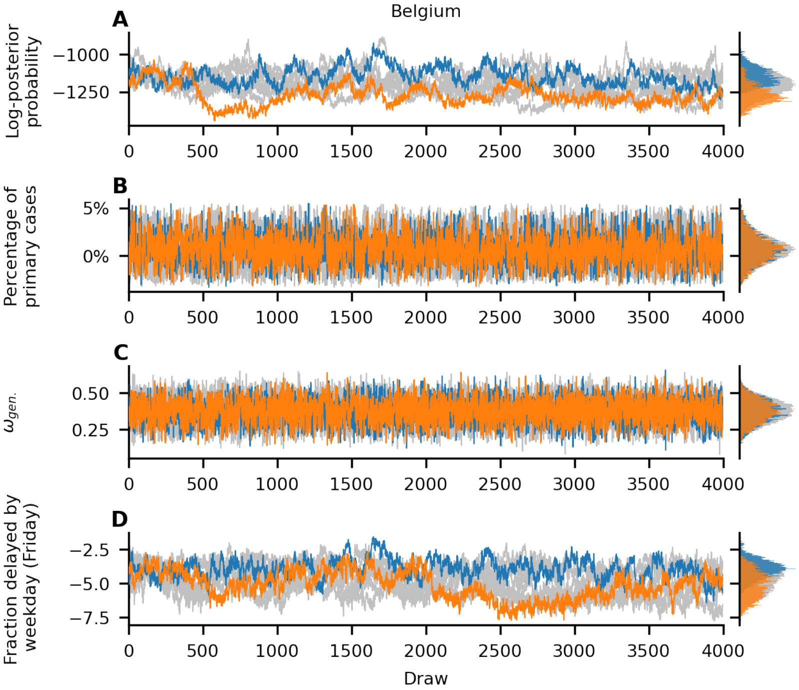
S4.6 Chain mixing of selected parameters



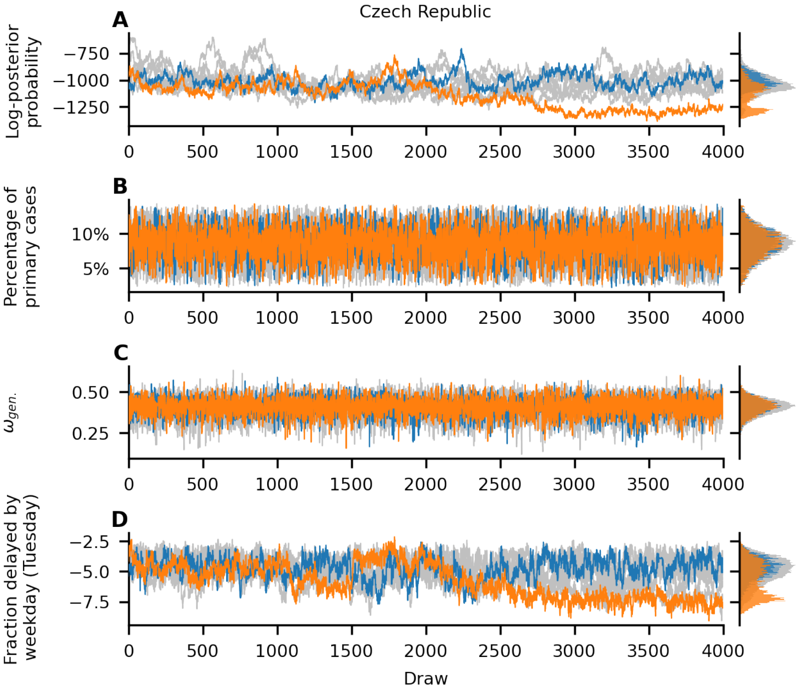
Supplementary Figure S37: **Chain mixing of selected parameters for England** Here we plot the unnormalized log-posterior probability (**A**) and selected parameters (**B** – **F**) as function for each draw and MCMC chain. Orange and blue depict two chains with the highest between-chain variance, the two least converging chains. The gray lines and histogram represent the ensemble of all chains. For our parameters of interest (**B**, **C**) the posterior distribution mixes well, even if the individual chains do not mix well in some other parameters (**D** – **F**), indicating that despite the degeneracy of some parameters, the inference of our parameters of interest is not affected. Panel **D** is a plot of the parameter with the worst mixing (the highest $\mathcal{R}$-hat value). Panels **E** and **F** show that the non-converging behavior can be explained as the exchange between two nearly degenerate solutions in two of the auxiliary parameters.



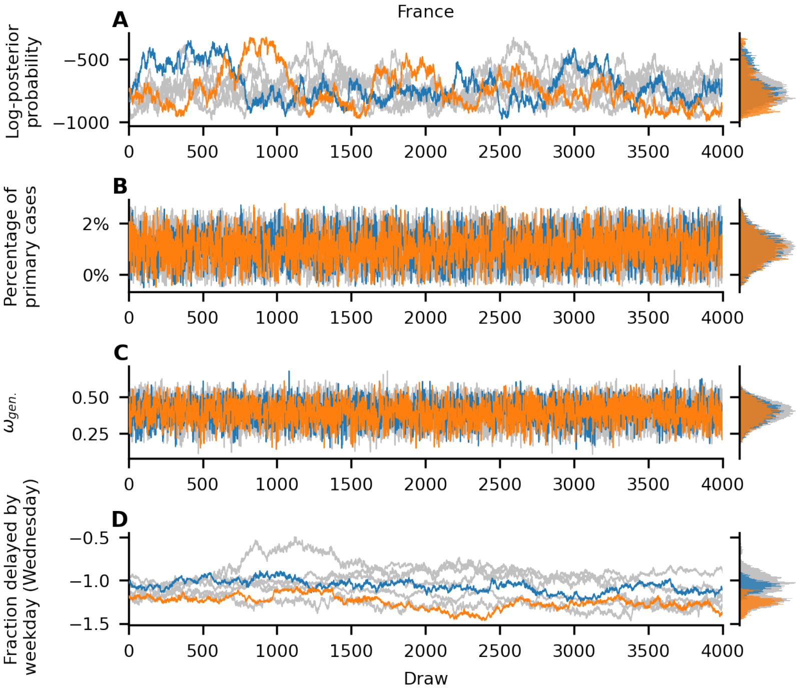
Supplementary Figure S38: **Chain mixing of selected parameters for Austria** Here the fraction of cases delayed by weekday on Thursdays is the parameter with the highest $\mathcal{R}$-hat values as seen in panel **D**. For a further detailed description of the panels see supplementary Fig. S37.



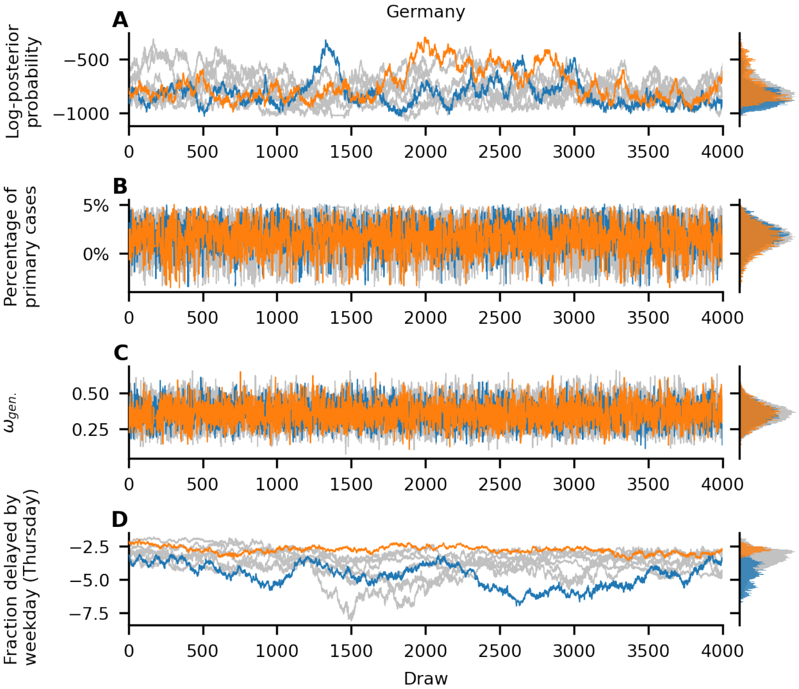
Supplementary Figure S39: **Chain mixing of selected parameters for Belgium** Here the fraction of cases delayed by weekday on Fridays is the parameter with the highest $\mathcal{R}$-hat values as seen in panel **D**. For a further detailed description of the panels see supplementary Fig. S37.



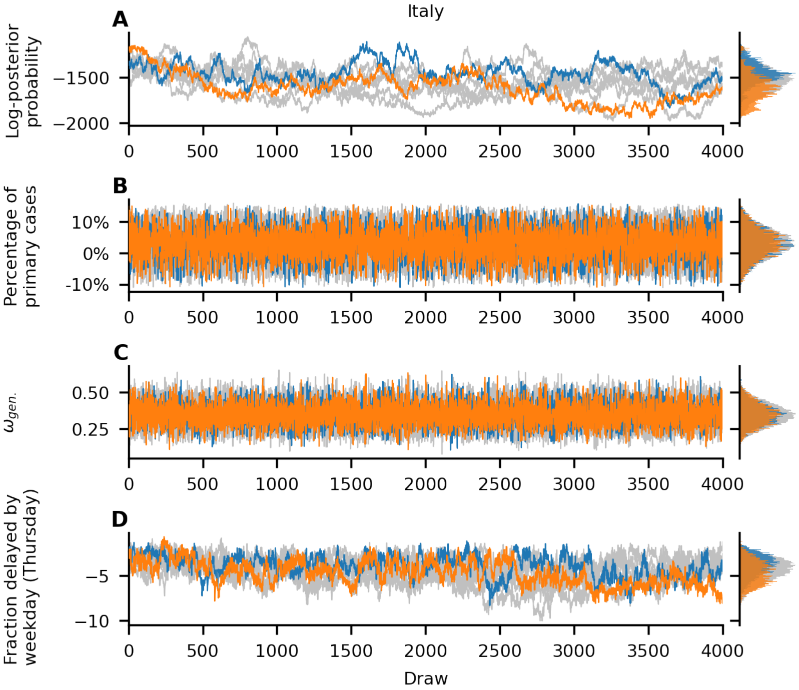
Supplementary Figure S40: **Chain mixing of selected parameters for Czech Republic** Here the fraction of cases delayed by weekday on Thursdays is the parameter with the highest $\mathcal{R}$-hat values as seen in panel **D**. For a further detailed description of the panels see supplementary Fig. S37.



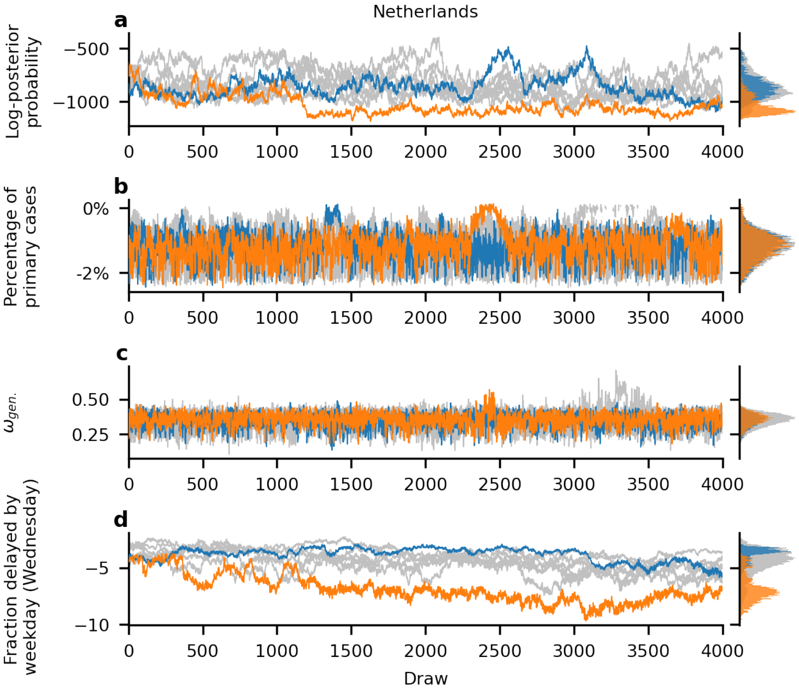
Supplementary Figure S41: **Chain mixing of selected parameters for France** Here the fraction of cases delayed by weekday on Wednesdays is the parameter with the highest $\mathcal{R}$-hat values as seen in panel **D**. For a further detailed description of the panels see supplementary Fig. S37.



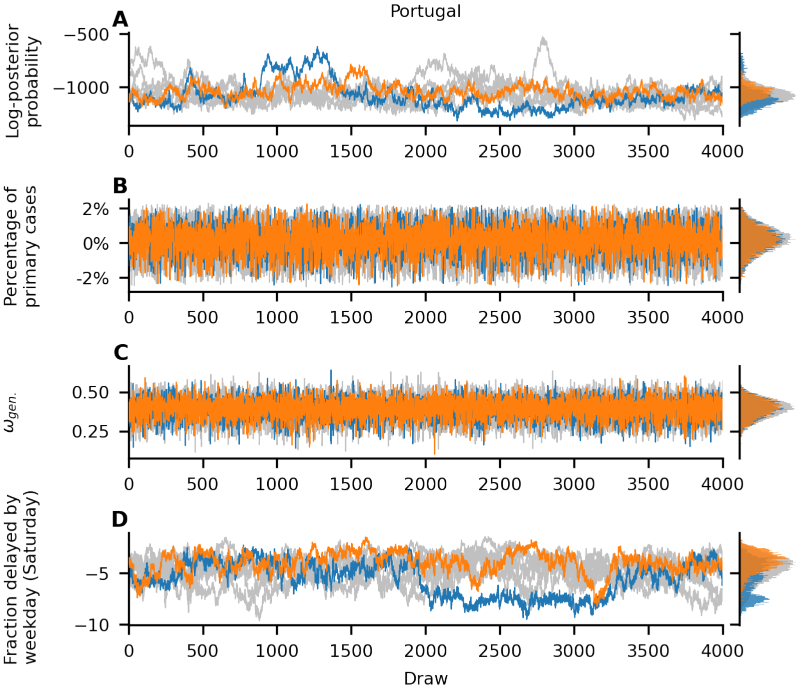
Supplementary Figure S42: **Chain mixing of selected parameters for Germany** Here the fraction of cases delayed by weekday on Thursdays is the parameter with the highest $\mathcal{R}$-hat values as seen in panel **D**. For a further detailed description of the panels see supplementary Fig. S37.



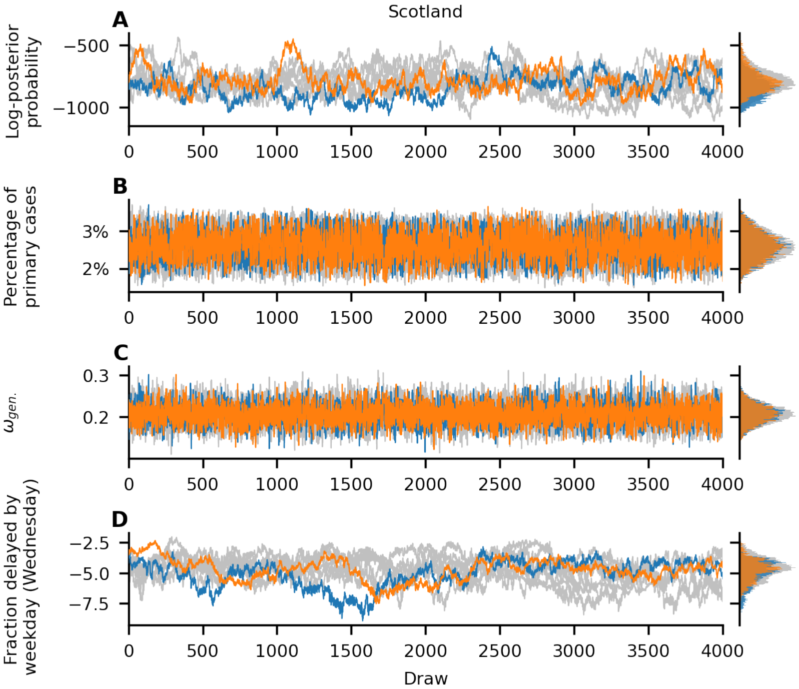
Supplementary Figure S43: **Chain mixing of selected parameters for Italy** Here the fraction of cases delayed by weekday on Thursdays is the parameter with the highest $\mathcal{R}$-hat values as seen in panel **D**. For a further detailed description of the panels see supplementary Fig. S37.



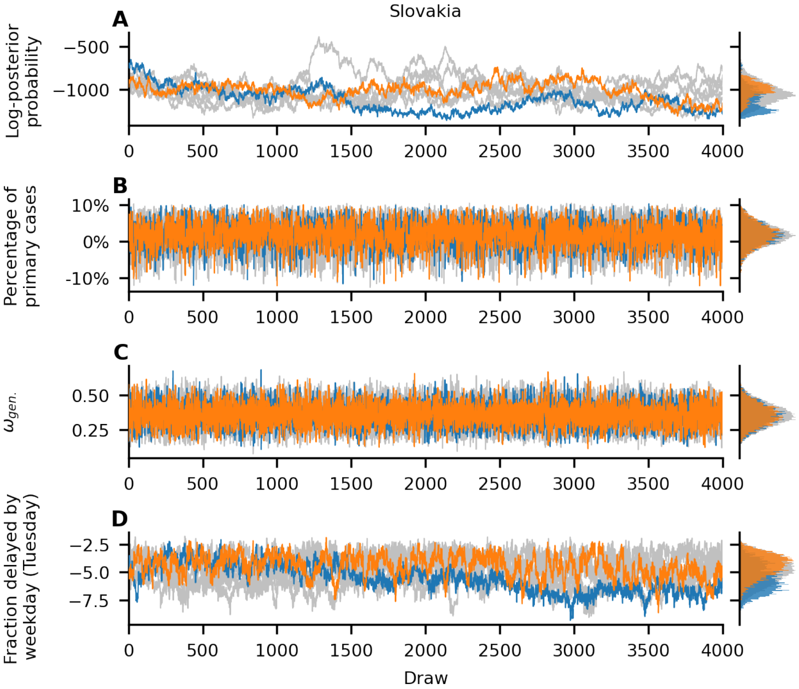
Supplementary Figure S44: **Chain mixing of selected parameters for Portugal** Here the fraction of cases delayed by weekday on Wednesdays is the parameter with the highest $\mathcal{R}$-hat values as seen in panel **D**. For a further detailed description of the panels see supplementary Fig. S37.



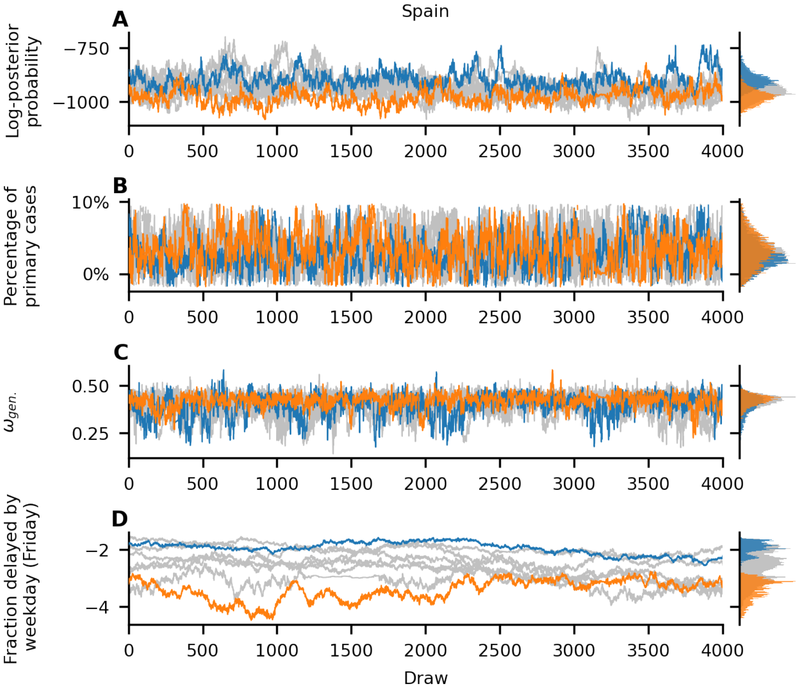
Supplementary Figure S45: **Chain mixing of selected parameters for Portugal** Here the fraction of cases delayed by weekday on Saturdays is the parameter with the highest $\mathcal{R}$-hat values as seen in panel **D**. For a further detailed description of the panels see supplementary Fig. S37.



Supplementary Figure S46: **Chain mixing of selected parameters for Scotland** Here the fraction of cases delayed by weekday on Wednesdays is the parameter with the highest $\mathcal{R}$-hat values as seen in panel **D**. For a further detailed description of the panels see supplementary Fig. S37.



Supplementary Figure S47: **Chain mixing of selected parameters for Slovakia** Here the fraction of cases delayed by weekday on Thursdays is the parameter with the highest $\mathcal{R}$-hat values as seen in panel **D**. For a further detailed description of the panels see supplementary Fig. S37.



Supplementary Figure S48: **Chain mixing of selected parameters for Spain** Here the fraction of cases delayed by weekday on Fridays is the parameter with the highest $\mathcal{R}$-hat values as seen in panel **D**. For a further detailed description of the panels see supplementary Fig. S37.

Supplementary References

[1] T. Riffe, E. Acosta, Data Resource Profile: COVerAGE-DB: a global demographic database of COVID-19 cases and deaths, *International Journal of Epidemiology* **50**, 390–390f (2021).

[2] E. O.-O. Max Roser, Hannah Ritchie, J. Hasell, Coronavirus Pandemic (COVID-19), *Our World in Data* (2020). `https://ourworldindata.org/coronavirus`, (Europe, America, and Oceania and Asia).

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Peer Review File

Impact of the Euro 2020 championship on the spread of COVID-19

REVIEWER COMMENTS

Reviewer #1 (Remarks to the Author):

This article presents a Bayesian model to appreciate the impact of isolated events, here "football matches" on the dynamics
of transmission of a communicable disease, here "COVID-19". A model is built where extra transmission surrounds football matches,
implicating 2 teams, and the country hosting the match. Sex imbalance in cases helps estimating increases in transmission.

1-The authors claim (line 27) that euro 2020 is a "randomized trial" between countries and that this help them making cuasal conclusions.
I do not see how their analysis uses this fact, nor how it could inform causality.
In randomized trials, randomization generally ensure that all units are exchangeable between treatment arms,
so that effect is obtained by simple differences.
Here a model is fit without any reference to the random nature of EURO2020. The justification is not clear in the introduction
and furthermore this aspect is not mentionned again in the discussion nor to justify causal interpretation.
If the authors believe that the randomization can really help in their study, this should be argued much more convincingly.
Otherwise, it should be removed.

2-The authors make a strong assumption that part of sex imbalance in cases is due to EURO2020; and estimate the effect of football matches conditional on this assumption.
The model assumes that effects are only seen in either countries having a match, or in hosting countries.
It could be that the effect of matches are seen in every countries for every match.
Did the author try to fit such a model and would it be feasible ?

3-In Fig 3A, it's not clear how Rbase is defined. It is varying with time. Furthermore,
given how the number of secondary cases is computed in the model, which is a function of Rbase(t) and generation interval,
it seems obvious that it should scale with R^(T/4). Could it be shown that this conclusion is not foregone?

4-Is omega_gender really a measure of "as likely to attend football related"? It seems more related to the composition of
the population with 33% women and that women are 50% as likely to attend.

5-I'm not convinced that the lack of convergence of the daily parameters as indicated by the H statistics is not relevant.
Since the authors build on the precise timing of events to infer parameters, this may on the contrary have a strong effect.
It is customary to report the traces of estimated parameters to illustrate convergence;
this could be done here in the supplementary material.

6-Is the unspecific contact matrix for sex imbalance really with a -1 ? is this for centering? a few words may be of use.

7-The authors report the Oxford tracker. Could they find a relationship between the stringency of measures and the effect of matches?
maybe a correlation between stringency at the time of the match and estimated match effect?
Mobility was discussed in this respect, but I couldn't find summary measures.

Reviewer #2 (Remarks to the Author):

Main Comments:

1) A number of the conclusions appear to rely heavily on the fact that England and Scotland saw large gender imbalances in Covid-19 cases, with other countries contributing substantially less to the conclusions. This is particularly true in Figure 3A, where the points corresponding to England and Scotland have very high leverage and so will dominate the slope of the line of best fit. To what extent therefore are these results internationally applicable - is it possible that cultural differences in the United Kingdom are uniquely responsible for football matches causing a gender imbalance in case numbers? What would the results (including Figure 3A) look like if the UK (i.e. England and Scotland) were excluded? What issues arise from treating England and Scotland as independent, despite them being part of the same country, subject to the same national-level measures?

2) The authors' justification for removing the Netherlands from the analysis is reasonable, but it is concerning to see the extent to which there was a gender imbalance in cases towards women. Under the model used in this paper, what is the probability that such a large deviation occurred due to random noise alone? Moreover, if this probability is small, is it possible that there is insufficient noise assumed in the model, and hence that some of the significance of the results in countries which saw a gender imbalance towards men has been over-stated?

3) In equations (22) and (31), it appears that the sums are over all n - assumedly the sum should only be over those n such that the changepoint associated with n has already occurred?

4) Prior distributions are chosen throughout (e.g. equations (9), (16), (21)...) without justification. To what extent are the results dependent on these choices? It is important that the sensitivity of the conclusions is explored sufficiently to inform readers (and indeed referees) of their strength. This should not be avoided citing "environmental reasons".

5) If environmental concerns, as cited in Figures S9 and S10, are valid, then can the authors determine computational efficiencies that would make the investigation more feasible without unreasonable environmental costs?

6) Would it be possible to run the same analysis, but to initialise the model significantly before the start of the championship? This would provide a good examination of the interaction between the base and noise terms.

7) Why are the p-values given for one-sided, rather than two-sided, tests? [For example, in Figure S6.] Indeed Figure S6(C) looks like the two-sided p-value should be considerably greater than 0.06. Also why is the central line so near the top of the shaded area? This would appear to be an error which makes me concerned about all of the graphs with such shading.

8) Do the linear regression models plotted in Figure 3 (and elsewhere) allow for heteroscedasticity? If not, then this should be allowed for given the considerable variability in uncertainty associated with the plotted estimates. The methods section should make 100% clear what how linear regressions have been estimated and what is plotted.

Editorial Comments:
1) Be consistent with decimal / comma notation (e.g. 10.000 is used in the abstract to mean what is given as 10000 elsewhere)
2) Line 29: There is potentially some link between pandemic state and team progression (e.g. Billy Gilmour was forced to isolate for Scotland).
3) Line 166: Should be "FIFA World Cup" instead of "World Championship"
4) Table S2, row 5: Typo - you have R_{b}ase instead of R_{base}
5) Line 389: alpha_{prior,m} is acting as a function of m rather than a matrix (also in Table S1)
6) Why is beta_{prior,m} not listed in Table S1?
7) Inconsistency throughout between "The Czech Republic" and "Czechia"
8) In Figure S7, the terms "Quarter-finals" and "Semifinal" are fine, but there is only one "Final" – it is not "Finals". The terms are not "quarter finale" [Fig S19] or "finale" [Fig S15]. Further, the

paper should not switch between “final match” and “finals”. The text (line 98) is confusing when it refers to “final matches” since there is only one “final match”.
9) Line 442: Should be “eq. (44)” – i.e. the brackets are needed.
10) Table S10: “Time in championship” should really be time between first and last match, shouldn’t it?
11) In all cases the figure captions need to clearly define the shading as well as any lines that have been plotted. For example, it would appear that Fig S5 shows linear regression model estimates and 95% confidence intervals, but this is not stated.

Reviewer #3 (Remarks to the Author):

This study aims to quantify the impact of the UEFA Euro 2020 Football Championship on the spread of COVID-19 among 12 countries to influence public health policy.

This is an interesting paper that exemplifies the importance of public health policies regarding large-scale sporting events. I found one major limitation in the estimation of the number of deaths associated with the analyzed events and a set of other relatively easily addressable points.

- Line 37, “disease transmission rates” -> “infection transmission rates”. The disease cannot be transmitted; the infection (or the pathogen) is transmitted.

- Line 47. “Basic” should be “base” (according to the nomenclature used in the rest of the manuscript).

- Line 64. Primary cases are defined as “infections occurring at gatherings on match days.” How are these primary cases identified? And how do you differentiate 1) between primary and subsequent cases and 2) cases that occur from different matches?

- In lines 66-67, you mention “We included all subsequent until July 31…”. Were subsequent cases for all participating countries analyzed until July 31 or was that only for the countries involved in the final match? If yes, how do you justify that countries participating only in early matches are still contributing to subsequent COVID-19 cases long after the matches? If all countries were not included until July 31, were subsequent cases two weeks after the country’s final match included in the analysis?

- Line 78. First, it is SARS-CoV-2 infections and not COVID-19 infections. Second, these are “reported SARS-CoV-2 infections”, which are large underestimations of the true number of infections. Please rephrase and add a comment on this in the Discussion.

- Line 79. First, that is a “case fatality ratio”, not a rate. Rates are expressed in time^-1, while you are using that as a ratio instead. Second, exactly as there is a gender imbalance in the population affected by Euro 2020, there very likely is an age imbalance as well. Specifically, we exact that population to be much younger than the general population of the country. As such, for a disease like COVID-19 where the fatality is much higher in the elderly, applying an age-independent case fatality ratio provides hardly credible results. I strongly encourage the authors to either to rely on age-dependent estimates of the case fatality ratio or to entirely drop the estimates of the number of deaths.

- Connected to the previous point, it is possible that the case reporting rate has temporarily increased right after each match. This should be discussed as a study limitation.

- Line 122. A generation interval of 4 days appears to be very short. That could be a reasonable estimate for a Chinese setting with very isolation policies in dedicated facilities, but rather short for a European context with very loose household isolation policies. 6 days would be a more sensible choice (see for instance Manica et al, Estimation of the incubation period and generation time of SARS-CoV-2 Alpha and Delta variants from contact tracing data, medrxiv).

- Lines 145-147 and 148-150. These sentences are speculative. It might well be the case that such events should be entirely banned during certain epidemic phases and/or mass gatherings avoided altogether. Moreover, the authorities “should” not do anything based on a manuscript. Each authority should make the decision based on its specific targets and priorities (which may not be aligned with those considered in this manuscript).

- Line 150-151. I agree with this point, but it is phrased rather badly. The incubation period has a wide distribution, and its mean is not representative of the whole phenomenon. Moreover, not only the mean of the incubation period but also the mean of the generation time is in line with the interval between matches.

- In Figures 2 and S4, base cases are named “independent cases” in the figure, but the captions and main text all refer to them as “base cases”. I suggest keeping these labels consistent throughout the paper and figures.

- In general, there is quite a bit of confusion between cases and infections that the authors appear to be used interchangeably, while they are two clearly defined and different epidemiological concepts. Please carefully revise the wording throughout the manuscript.

October 21, 2022

Revision of our manuscript to *Nature Communications*

Dear reviewers,

thank you very much for the helpful comments!

Following the suggestions, we added additional analyses and clarifications to the manuscript and the Supplementary Information. To summarize the main points:

- We ran additional robustness checks on a number of priors (Supplementary Fig. S18) and the generation interval (Supplementary Fig. S17)
- For the already existing robustness checks, we added runs of the remaining countries (Supplementary Fig. S13–18)
- We added a consistency check by offsetting the matches by ±30, ±35, and ±40 days to show that during time-periods where we do not expect an effect, our model does not infer an effect (Supplementary Fig. S12).
- We added plots to illustrate the sampling of our Markov Chain Monte Carlo chains and to show that the chains are well mixed in for our variables of interest, even if individual degenerate parameters of our model do not showcase good mixing (Supplementary Fig. S38–S49).
- We added a new figure showing an analysis of the mean and standard deviation of the gender imbalance before and during the Euro 2020 (Supplementary Fig. S22). Here we clearly show that during the Euro 2020 the mean and variance increased on average.

We once again thank you for your valuable input and are looking forward to your reply,

Viola Priesemann and Philip Bechtle
(on behalf of all authors)

Reviewer 1

> This article presents a Bayesian model to appreciate the impact of isolated events, here football matches on the dynamics of transmission of a communicable disease, here COVID-19. A model is built where extra transmission surrounds football matches, implicating 2 teams, and the country hosting the match. Sex imbalance in cases helps estimating increases in transmission.

We thank you for your helpful comments and suggestions, which led us to expand our manuscript, especially the controls and consistency checks. Below we address them point by point.

> **1** The authors claim (line 27) that euro 2020 is a randomized trial between countries and that this help them making causal conclusions. I do not see how their analysis uses this fact, nor how it could inform causality. In randomized trials, randomization generally ensure that all units are exchangeable between treatment arms, so that effect is obtained by simple differences. Here a model is fit without any reference to the random nature of EURO2020. The justification is not clear in the introduction and furthermore this aspect is not mentioned again in the discussion nor to justify causal interpretation. If the authors believe that the randomization can really help in their study, this should be argued much more convincingly. Otherwise, it should be removed.

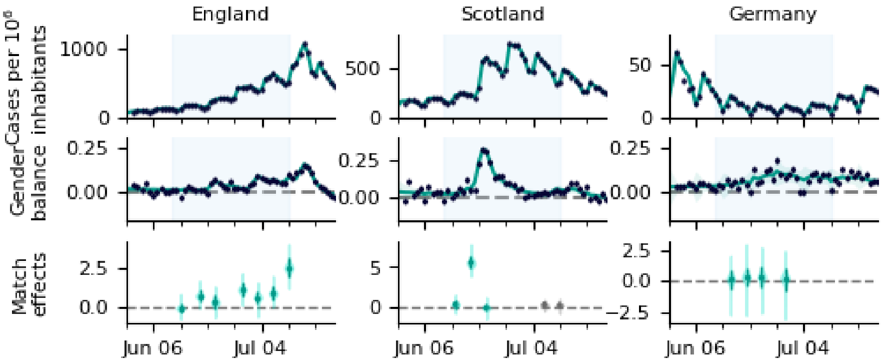
Thank you for pointing this out. We agree that our study is not a "controlled randomized trial" in the strict sense. However, our study benefits from a specific kind of randomization that enables us to at least approximately extract a causal effect. Other typical studies that infer the effect of social gatherings by quantifying, e.g. non-pharmaceutical interventions (NPIs), have the bias that the NPIs are typically correlated with the incidence (e.g., with increasing incidence, the NPIs become stronger as well). In our case the time points of the matches do not depend on the incidence in the countries or their change. Moreover, a team's success in a match is, in principle, independent of the incidence in the given country (see also our reply to comment **E2** of Reviewer 2). Thus overall, randomization in that sense is present and, thereby, the source of bias present in said other studies is eliminated.

To enable us to refer to this benefit of (approximate) randomization, we changed the phrasing in our text to call it a "randomized study" to distinguish it from controlled randomized trials, and we make explicit what we mean by it. Moreover, we removed the reference to Banerjee et al. 2016. The introduction paragraph (lines 27–33) reads now:

> “ Two facts make the Euro 2020 especially suitable for the quantification. First, the Euro 2020 resembles a randomized study across countries: The time-points of the matches in a country do not depend on the state of the pandemic in that country and how far a team advances in the championship has a random component as well [20]. This independence between the time-points of the match and the COVID-19 incidence allows quantifying the effect of football-related social gatherings without classical biasing effects. This is advantageous compared to classical inference studies quantifying the impact of non-pharmaceutical interventions (NPIs) on COVID-19 where implementing NPIs is a typical reaction to growing case numbers [Dehning2020, Brauner2020, Sharma2021]. ”

2 The authors make a strong assumption that part of sex imbalance in cases is due to EURO2020; and estimate the effect of football matches conditional on this assumption. The model assumes that effects are only seen in either countries having a match, or in hosting countries. It could be that the effect of matches are seen in every countries for every match. Did the author try to fit such a model and would it be feasible?

Thank you for the interesting idea. However, we would not be able to successfully fit such a model because there would be too many matches (51) for the duration the tournament (30 days) and the number of days with matches (22) to have statistical power. In a slightly earlier version of the model, we concentrated on the potentially strongest effect, namely testing whether we see the effect of the final and semi-final of England in the Scottish case numbers, but there was no significant effect that our model could find (see below in gray):



To test for the potential effect on gender-imbalance, we compare the time before and during the tournament. One expects a larger gender imbalance and a larger variance of the gender imbalance during during the tournament, compared to the time before. Specifically, we estimated the mean and the standard deviation of the gender imbalance during the 30 days of the tournament (plus the 5 days after) and for the 35 days before the tournament; we see on average a clear difference: Both, the mean and the variance of gender imbalance, were typically much larger during the tournament, indicating that the matches induced strong fluctuations in gender imbalance. This is shown in the figure that we now added to the manuscript (Supplementary Fig. S22, right column).

Regarding the remark "The authors make a strong assumption that part of sex imbalance in cases is due to EURO2020". The main assumption we are making is that we *allow* differing reproduction numbers on the day of the matches: We find similar effect sizes even if we choose an alternative prior assumption, namely that the female and male fraction are equal (Supplementary Figure S16, purple histograms, gray is the prior). Even for this case, the posterior distribution of the female participation converge for the three significant countries to median values between 20% – 45%. We now make this clear in lines 200–202:

> " Furthermore, when using wider prior ranges for the gender imbalance, football-related COVID-19 cases remain unchanged but the uncertainty increases (Supplementary Fig. S16), thus validating our choice. Even for the case of prior symmetric gender imbalance assumptions, the posterior distribution of the female participation converge for the three most significant countries to median values between 20% – 45%. "

> **3** In Fig 3A, its not clear how R_{base} is defined. It is varying with time. Furthermore, given how the number of secondary cases is computed in the model, which is a function of $R_{base}(t)$ and generation interval, it seems obvious that it should scale with $R^{(T/4)}$. Could it be shown that this conclusion is not foregone?

Thank you for this remark. We agree that the notation was a bit confusing. We now specifically named the "R_{base} directly before the championship" R_{pre} and made sure to clarify that is is the reproduction number prior to the championship lines 125-127:

> " From theory, we expect the absolute number of infections generated by Euro 2020 matches to depend non-linearly on a country's base incidence N_0, which determines the probability to meet an infected person, and on the effective reproduction number prior to the championship R_{pre}, as a gauge for the underlying infection dynamics generating the subsequent cases, which determines how strongly an additional infection spreads in the population. "

And also in lines 136-140:

> “ Altogether, our data suggest that a favorable pandemic situation (low R_{pre} and low N_0) before the gatherings, and low R_{base} during the period of gatherings jointly minimize the impact of the Euro 2020 on community contagion. A prerequisite for this is that the known preventive measures, such as reducing group size, imposing preventive measures, and minimizing the number of encounters remain encouraged. ”

We agree that some degree of correlation with R_{pre} is not surprising. However, it is only observable as long as not the primary infections at the gatherings but the chains of subsequent cases dominate the overall impact of the championship. The fact that the quantitative effect of the pandemic situation before the championship (R_{pre}) has a clear impact is an important finding for preventive mitigation practices.

4 Is ω_{gender} really a measure of as likely to attend football related? It seems more related to the composition of the population with 33% women and that women are 50% as likely to attend.

Thank you for pointing this out. Our description of the normalization was not precise. We expanded the definition in Supplementary Table S2, and changed line 412ff to make it more clear:

> “ ω_{gender} | The fraction of female participation in football related gatherings compared to the total participation ”

> “ $\mathbf{C}_{\text{match}}$ describes the contact behavior in the context of the Euro 2020 football matches (right purple box in Supplementary Fig. S1). Here, we assume as a prior that the female participation in football-related gatherings accounts for $\simeq 33\%$ (95% percentiles [18%,51%] of the total participation. ”

5 Im not convinced that the lack of convergence of the daily parameters as indicated by the H statistics is not relevant. Since the authors build on the precise timing of events to infer parameters, this may on the contrary have a strong effect. It is customary to report the traces of estimated parameters to illustrate convergence; this could be done here in the supplementary material.

Thank you for raising this point. We now report the traces to illustrate convergence (see Supplementary Figures S38–S49). We show that for the parameters of interest the lack of convergence by the $\mathcal{R}$-hat statistics is not relevant. The remaining non-convergent chains are due to interchanging degenerate solutions in auxiliary parameters, as exemplified in Supplementary Figure S38. We observe good mixing of the chains for the parameters of interest. Even if some chains are more biased in some parameters, the effect on our parameters of interest is small. The lack of convergence of daily parameters are due to some degeneracy in the parameters: We could in principle create a model without daily reporting delay, which would have no degenerate solutions for auxiliary parameters but would also be less realistic.

6 Is the unspecific contact matrix for sex imbalance really with a -1 ? is this for centering? a few words may be of use.

Thank you for the feedback. We agree that the paragraph explaining C_{noise} was lacking. We included a sentence explaining the centering (lines 420–421):

> " $\mathbf{C}_{\text{noise}}$ describes the effect of an additional noise term, which changes gender balance without being related to football matches (middle purple box in Supplementary Fig. S1). For simplicity, it is implemented as
>
> $$\mathbf{C}_{\text{noise}} = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}, \tag{1}$$
>
> whereby we center the diagonal elements, such that the cases introduced by the noise term sum up to zero, i.e. $\sum_{i,j} R_{\text{noise}} \cdot C_{\text{noise},i,j} = 0$. "

7 The authors report the Oxford tracker. Could they find a relationship between the stringency of measures and the effect of matches? maybe a correlation between stringency at the time of the match and estimated match effect? Mobility was discussed in this respect, but I couldnt find summary measures.

This is indeed an interesting question. We have already looked into the stringency measures before submission of the manuscript, and have included it in the analysis in the manuscript now (see Supplementary Figure S6) . We made this clear by including the following sentence in lines 146–147:

> " Moreover, we found no relationship between the effect size and the Oxford governmental response tracker [Hale2021] (Supplementary Fig. S6). "

This can also be seen by comparing panels A and C in the Supplementary Figures S25–S37.

Reviewer 2

> **1** A number of the conclusions appear to rely heavily on the fact that England and Scotland saw large gender imbalances in Covid-19 cases, with other countries contributing substantially less to the conclusions. This is particularly true in Figure 3A, where the points corresponding to England and Scotland have very high leverage and so will dominate the slope of the line of best fit. To what extent therefore are these results internationally applicable - is it possible that cultural differences in the United Kingdom are uniquely responsible for football matches causing a gender imbalance in case numbers? What would the results (including Figure 3A) look like if the UK (i.e. England and Scotland) were excluded? What issues arise from treating England and Scotland as independent, despite them being part of the same country, subject to the same national-level measures?

Indeed we assume that there are unknown cultural aspects at play in each country. Therefore, our model makes no assumption about the cultural background of the strongly varying gender imbalances within countries. We do not dare speculate in the paper as to which specific cultural effects cause the observed strongly differing gender imbalances. E.g. we observe potentially different gender imbalances between England (0.32 [0.28,0.38]) and Czech Republic (0.41 [0.29,0.51]), showing that the model can indeed attribute soccer related cases for different ranges of observed gender imbalances, even if this range includes 50 % at the 95 % confidence level. Since the model has this freedom independently in each country, we believe that separating the countries by observed effect size post-hoc is not necessarily statistically representative.

Nonetheless, it is of course interesting to look at such a split model. Fig. 3A specifically is now shown without the UK in Supplementary Fig. S8.

As expected when removing the most significant data points, the overall significance is reduced. However, the regression parameters are consistent between all data points (1.62 [1.0, 2.26]) and the result without the UK (0.76 [-1.46, 3.04]). We now mention this in the document in lines 130-133:

> “ The strong significance of this correlation relies mainly on England and Scotland. However, the observed trend in an analysis without these two countries, while not significant at the 95% confidence level, is consistent with the findings including all countries. This is shown in Supplementary Fig. S8. ”

We also reran our analysis not assuming England and Scotland as independent: We added the case numbers of both constituent countries and combined their matches on this run. We found overall similar results (Supplementary Fig. S19 and S37).

2 The authors justification for removing the Netherlands from the analysis is reasonable, but it is concerning to see the extent to which there was a gender imbalance in cases towards women. Under the model used in this paper, what is the probability that such a large deviation occurred due to random noise alone? Moreover, if this probability is small, is it possible that there is insufficient noise assumed in the model, and hence that some of the significance of the results in countries which saw a gender imbalance towards men has been over-stated?

We appreciate the feedback. As you have already noticed the opposite effect in the Netherlands is quite an interesting phenomenon. The observed effect is very likely due to the simultaneously occurring freedom day. We were told that with opening dancing locations (clubs), especially women made use of that opportunity - and hence got infected with higher probability. However, we have no scientific sources that confirm this effect around the freedom day. It is also well possible that further phenomena affected the male and female population in a different way.

Nevertheless, we can estimate the probability that such an event solely occurred due to random noise under our model. Our model estimates the noise on the gender imbalance $\sigma_{\Delta\tilde{\gamma}}$ to be about 0.02 (95% CI: [0.007, 0.06]). In order to obtain an imbalance such that the deviation can be explained, one needs a change of ΔR_{noise} of about 0.17. Using the upper estimate of the $\sigma_{\Delta\tilde{\gamma}}$, such a change requires a deviation of about 2.8σ, which corresponds to a (two-sided) probability of 0.5%.

Hence, we do not interpret this occurrence as an event due to random noise as parameterized in R_{noise}. However, in this case, your follow-up question on the possible occurrence of such events at other times during the championship is of high relevance.

Therefore, we perform the following test: Assuming the noise to be under-represented in the model, a counterfactual shift of the date of the matches would lead to the random occurrence of some significant results in the effect size. This is not the case for delays of 14, ± 30, ± 35, ± 40 days (see Supplementary Figure S11 and S12). Here, the counterfactual results always include an effect size of zero within a 95% CI in contrast to the factual result (The largest deviation at 35 days is at the 93.7th percentile). Hence, we can exclude that the significance of the result is due to under-represented noise. Please also note that the offset results do not all show the exact same result, but do vary within the credible interval of the result. This is expected since the model can randomly attribute variations of case numbers and gender imbalances on a timescale of the average time span between games or shorter to R_{soccer}. The indicative agreement between the range of variation between offset results and the CI in this low statistics sample of 6 experiments hints at the correctness of the statistical result.

Related to this discussion is answer **2** to Reviewer 1. There we show the variance of the changes in the gender imbalance in two time slices: once in the 35 days directly before the championship, and once in the 30 days of the championship plus one generation interval of 5 days for all analyzed countries. One observes that the variance is larger during the championship in most countries, supporting the hypothesis that the gender imbalance varied more than usually during the championship.

> **3** In equations (22) and (31), it appears that the sums are over all n - assumedly the sum should only be over those n such that the changepoint associated with n has already occurred?

Thank you for this question. It pointed us to an error in equation (25): Instead of

$$\Delta\gamma_n \sim \mathcal{N}\left(\Delta\gamma_{n-1}, \sigma_{\Delta\gamma}\right) \quad \forall n$$

it should have been

$$\Delta\gamma_n \sim \mathcal{N}\left(0, \sigma_{\Delta\gamma}\right) \quad \forall n.$$

We also added an explanatory sentence to these equations (lines 436ff):

> “The idea behind this parameterization is that $\Delta\gamma_n$ models the change of R-value, which occurs at times d_n. These changes are then summed in equation (24). Change points that have not occurred yet at time t do not contribute in a significant way to the sum as the sigmoid function tends to zero for $t << d_n$. ”

We hope this makes our choice in the equations a bit clearer.

> **4** Prior distributions are chosen throughout (e.g. equations (9), (16), (21)) without justification. To what extent are the results dependent on these choices? It is important that the sensitivity of the conclusions is explored sufficiently to inform readers (and indeed referees) of their strength. This should not be avoided citing environmental reasons.

Most priors are chosen to be rather uninformative, having little influence on our results. To show that, we multiplied the values of all those priors by a factor of 0.5 and 2 and show that the results do not change (Supplementary Fig. S18). In the methods text below, we added the respective equation when the robustness of the prior choices are investigated. The influence of equation (9) had already been investigated in Supplementary Fig. S16. In addition, for priors for which the parameterization makes it difficult to assess what the numbers represent, we added the 95% CI as information. Concretely this concerns equation (6) lines 408–412:

> “ Here, we have the prior assumption that contacts between women, contacts between men, and contacts between women and men are equally probable. Hence, we chose the parameters for the Beta distribution such that c_{off} has a mean of 50% with a 2.5th and 97.5th percentile of [27%, 77%]. This prior is chosen such that it is rather uninformative. As shown in Supplementary Fig. S18, this and other priors of auxiliary parameters do not affect the parameter of interest if their width is varied within a factor of 2 up and down. ”

We also added the following text for equations (49) and (50) which parameterize the fraction of delayed cases during the week (lines 476 – 480).

> “ We chose the prior of $r^{\dagger}_{\mathrm{base},d}$ for Tuesday, Wednesday and Thursday such that only a small fraction of cases are delayed during the week. The chosen prior in equation (48) corresponds to a 2.5th and 97.5th percentile of r_d of [0%; 5%]. For the other days (Friday, Saturday, Sunday, Monday), the chosen prior leaves a lot of freedom, equation (49) corresponds to a 2.5th and 97.5th percentile of r_d of [0%; 72%]. ”

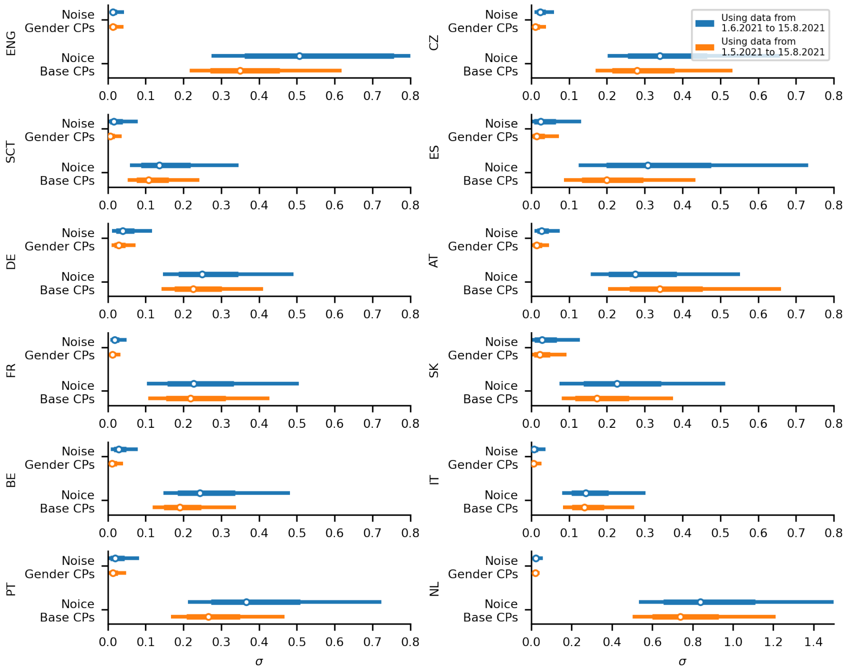
These three priors (eqs. (6), (49) and (50)) were excluded from the robustness analysis of Supplementary Fig. S18 because their parameterization makes it difficult to multiply it by a single number. However they encode reasonable assumptions. For instance, for equation (49) the assumption that cases do not have an additional delay during the week is the canonical choice. It would have been the same assumption if we would have chosen to model the delay on different weekdays in the same way.

> **5** If environmental concerns, as cited in Figures S9 and S10, are valid, then can the authors determine computational efficiencies that would make the investigation more feasible without unreasonable environmental costs?

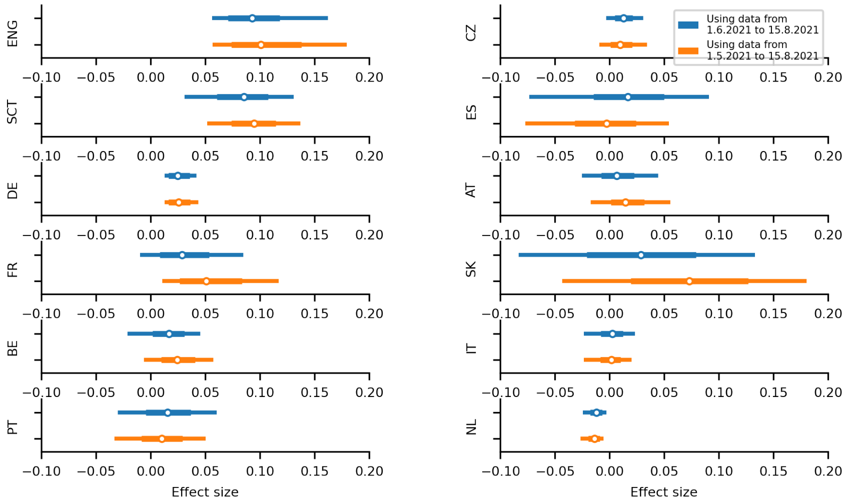
We ran our robustness analyses (Supplementary Figures S13 to S18) for the missing countries, however with half the length of the MCMC chains. This reduces the quality of the posterior distribution estimation for these countries a little.

> **6** Would it be possible to run the same analysis, but to initialise the model significantly before the start of the championship? This would provide a good examination of the interaction between the base and noise terms.’

Thank you for the idea. We have run our analysis starting one month earlier, and added the figures to the manuscript (Supplementary Fig. S23 and S24). We can not see a significant difference in noise terms using the longer time period (see below).



Moreover the effect size is not altered in any significant way (see below).



7 Why are the p-values given for one-sided, rather than two-sided, tests? [For example, in Figure S6.] Indeed Figure S6C looks like the two-sided p-value should be considerably greater than 0.06. Also why is the central line so near the top of the shaded area? This would appear to be an error which makes me concerned about all of the graphs with such shading.

Thank you very much for noticing! We found a small error in the computation of the CI. Instead of the lower bound of 2.5% we computed the 0.25% bound. This is fixed now in all figures and is displayed correctly.

The tests are one-sided, because we don't exactly use p-values, but the Bayesian counterpart the "Probability of Direction" (see e.g. [Makowski2019]). It is simply the proportion of the posterior distribution that corroborates the hypothesis (or support the alternative hypothesis when used similarly to the p-value) and it is therefore one-sided.

8 Do the linear regression models plotted in Figure 3 (and elsewhere) allow for heteroscedasticity? If not, then this should be allowed for given the considerable variability in uncertainty associated with the plotted estimates. The methods section should make 100% clear what how linear regressions have been estimated and what is plotted.

The regression indeed has heteroscedastic errors since it includes the individual posterior uncertainties of the effect size individually for each data point. Beyond this, the Bayesian parameterization of the regression adds one parameter which models the consistency of the data with a linear dependence. It is chosen as a constant value for each entry, since it characterizes the applicability of the chosen functional dependence and is not a property of each measurement. We added the following explanation in the methods (lines 539–543):

> " Therefore our regression model includes the "measurement error" $\hat{\sigma}_c$ which models the heteroscadistic effect size of every country, and an additional model error τ which models the homoscedastic deviations of the country effect sizes from the linear model. In the plots, we plot the regression line $\hat{Y}_c$ with its shaded 95% CI, and data points $(\hat{X}_c, Y_c^\dagger)$ where the whiskers correspond to the one standard deviation, modeled here by ϵ_c and $\hat{\sigma}_c$. "

Editorial comments:
E1 Be consistent with decimal / comma notation (e.g. 10.000 is used in the abstract to mean what is given as 10000 elsewhere)

Thank you for noticing the inconsistency. We now consistently use commas in the text.

> **E2** Line 29: There is potentially some link between pandemic state and team progression (e.g. Billy Gilmour was forced to isolate for Scotland).

This is a good point. We rewrote the corresponding paragraph in the introduction, stating that the relation has a random component (lines 27f):

> " First, the Euro 2020 resembles a randomized study across countries: The time-points of the matches in a country do not depend on the state of the pandemic in that country and how far a team advances in the championship as a random component as well [20]. "

However, we believe that this link will not be strong because most teams should have training (camps) before and during the tournament where additional tests and measures helped to partially decouple the pandemic situation from the home country. Social and physical distancing were strongly encouraged by relevant authorities, see e.g. the statement from UEFA Euro 2020 chief medical officer Dr Zoran Bahtijarevi and UEFA Euro 2020 medical advisor Dr Daniel Koch:

"If the teams respect our recommendations, they are actually travelling from their base camp, which is a bubble and which should be a protected environment. They will be travelling using their own group of vehicles in which all the drivers have been tested, and most of them are vaccinated too. They will fly on their own charter flight, and at the airport theyre using special boarding procedures, which is also actually limiting their contact with the population. When they arrive in a country, they have a special disembarkation procedure, they use their own vehicles and travel to a protected environment at the hotel. Id like to take this opportunity to congratulate the teams on qualifying for the last 16... and would call on them once again to respect the measures in place, because they are there for their benefit."

A listing of the observed COVID-19 cases of players during the isolation period before the championship (see Reuters Article) displays sufficiently low statistics to assume no direct connection. Moreover, for three of the twelve teams, the team base was not in their home country.

Although all of this does not guarantee that there is no potential link between the pandemic state and team progression, it greatly reduces its likelihood.

We added a few sentences about this in the discussion (lines 184–189):

> “ Our results might further be biased if the incidence and the teams’ progression in the Euro 2020 are correlated. It is conceivable that high incidence would negatively correlate with team progression through ill or quarantined team members. However, there were only few such cases during the Euro 2020 [Reuters Article], and the correlation might also be positive: At higher case numbers the team might be more careful. Hence, the correlation is unclear and probably negligible. ”

E3 Line 166: Should be FIFA World Cup instead of World Championship

Indeed, thank you. We have corrected it accordingly.

E4 Table S2, row 5: Typo - you have R_base instead of R_{base}

Thank you for noticing. We have corrected it.

E5 Line 389: $\alpha_{\text{prior},m}$ is acting as a function of m rather than a matrix (also in Table S1)

We are sorry for the unclear notation and definition. We clarified the object as (line 423f):

> “ $\alpha_{\text{prior},m}$ is the m-th element of the vector that encodes the prior expectation of the effect of a match on the reproduction number. ”

E6 Why is $\beta_{\text{prior},m}$ not listed in Table S1?

Thank you for noticing that we forgot to put in there. We have now listed it in the table.

E7 Inconsistency throughout between The Czech Republic and Czechia

Thank you for pointing us to the inconsistency. We have corrected all instances of “Czechia” to “Czech Republic”.

> **E8** In Figure S7, the terms Quarter-finals and Semifinal are fine, but there is only one Final it is not Finals. The terms are not quarter finale [Fig S19] or finale [Fig S15]. Further, the paper should not switch between final match and finals. The text (line 98) is confusing when it refers to final matches since there is only one final match.’

Thank you for pointing this out. We have corrected “finals” to “final”, “final matches” to “last matches of the championship” and “quarter finale” to “quarterfinals” in the text and also in Supplementary Figure S9.

> **E9** Line 442: Should be eq. (44) i.e. the brackets are needed.

Thank you for noticing. We corrected it (line 467).

> **E10** Table S10: Time in championship should really be time between first and last match, shouldnt it?

You are completely right. We rephrased the column name to “Time between first and last match of the country (days)” to clarify.

> **E11** In all cases the figure captions need to clearly define the shading as well as any lines that have been plotted. For example, it would appear that Fig S5 shows linear regression model estimates and 95% confidence intervals, but this is not stated.

Thank you for noticing this inconsistency. Throughout the manuscript, we always use 95%, 68% credible intervals or one standard deviation. We have added the missing definitions to the figure captions.

Reviewer 3

> This study aims to quantify the impact of the UEFA Euro 2020 Football Championship on the spread of COVID-19 among 12 countries to influence public health policy.This is an interesting paper that exemplifies the importance of public health policies regarding large-scale sporting events. I found one major limitation in the estimation of the number of deaths associated with the analyzed events and a set of other relatively easily addressable points.

We thank you for your detailed comments and suggestions, which led us to improve our manuscript. Below we address them point by point.

> **1** Line 37, disease transmission rates → infection transmission rates. The disease cannot be transmitted; the infection (or the pathogen) is transmitted.

Thank you for pointing this out. According to the definition in cancer.gov, we understand an infection as a process, i.e. nothing that can be transmitted. We are glad about your second suggestion and corrected it to "pathogen transmission rates" (line 36f).

> **2** Line 47. Basic should be base (according to the nomenclature used in the rest of the manuscript).

Thank you for noticing. We have corrected it accordingly.

> **3** Line 64. Primary cases are defined as infections occurring at gatherings on match days. How are these primary cases identified? And how do you differentiate 1) between primary and subsequent cases and 2) cases that occur from different matches?

Thank you for noticing the lack of a definition of primary and subsequent cases. We added a subsection in the method section which reads (lines 497–501):

> " We compute the number of primary football related infected $I_{\text{primary},g}(t)$ as the number of infections happening at football related gathering. The percentage of primary cases f_g is than computed by dividing by the total number of infected $I_g(t)$.

$$I_{\text{primary},g}(t) = \frac{S(t)R_{\text{football}}(t)}{N} \sum_{g'} I_{g'}(t)\mathbf{C}_{\text{football},g',g} \tag{2}$$

$$f_g = \sum_t \frac{I_{\text{primary},g}(t)}{I_g(t)} \quad t \in [\text{11th June}, \text{31st July}] \tag{3}$$

To obtain the subsequent infected $I_{\text{subsequent},g}(t)$ we subtract infected obtained from a hypothetical scenario without football games $I_{\text{none},g}(t)$ from the total number of infected.

$$I_{\text{subsequent},g} = I_g(t) - I_{\text{primary},g}(t) - I_{\text{none},g}(t) \tag{4}$$

$$\tag{5}$$

Specific, we consider a counterfactual scenario, where we sample from our model leaving all inferred parameters the same expect for the football related reproduction number $R_{\text{football},g}(t)$, which we set to zero. ”

4 In lines 66-67, you mention “We included all subsequent until July 31...”. Were subsequent cases for all participating countries analyzed until July 31 or was that only for the countries involved in the final match? If yes, how do you justify that countries participating only in early matches are still contributing to subsequent COVID-19 cases long after the matches? If all countries were not included until July 31, were subsequent cases two weeks after the countrys final match included in the analysis?

Thank you very much for these considerations. There is a lot of freedom of choice at that point. One could also argue that the time of the first match of each country should be the one that determines until when the subsequent cases are considered. For enhanced clarity, we decided to go with fixed dates. We are also comparing the absolute case and deaths numbers. For this comparison we need to use common fixed dates.

5 Line 78. First, it is SARS-CoV-2 infections and not COVID-19 infections. Second, these are reported SARS-CoV-2 infections, which are large underestimations of the true number of infections. Please rephrase and add a comment on this in the Discussion.

Thank you for pointing this out. We have corrected our wording where applicable, and discussed further on the effect of possible additional testing and reporting. In the discussion, lines 210–211 now read:

> “However, we expect that some individuals would actively get tested right after a match, thereby increasing the case finding and reporting rates. ”

Moreover, in response to your comment **12** we emphasize the definition of a case in the introduction lines 29–41:

In the following, we use “case” to refer to a confirmed case of a SARS-CoV-2 infections in a human and “case numbers” to refer to the number of such cases. Not all infections are reported and represented in the cases and cases come with a delay after the actual infections.

A likely underestimation of the true pandemic state as seen only by confirmed cases does not alter the key findings of our analysis, since we attribute *observed* cases to championship-related fan activity and make no statement about additional unreported cases.

> **6** Line 79. First, that is a case fatality ratio, not a rate. Rates are expressed in $time^{-1}$, while you are using that as a ratio instead. Second, exactly as there is a gender imbalance in the population affected by Euro 2020, there very likely is an age imbalance as well. Specifically, we exact that population to be much younger than the general population of the country. As such, for a disease like COVID-19 where the fatality is much higher in the elderly, applying an age-independent case fatality ratio provides hardly credible results. I strongly encourage the authors to either to rely on age-dependent estimates of the case fatality ratio or to entirely drop the estimates of the number of deaths.

Thank you for pointing this out. We have replaced "case fatality rate" for "case fatality risk" everywhere in our manuscript, so that it is clear that it does not have units and it refers to the chances of an individual dying given infection.

Furthermore, the strong coupling in cases between age groups – exemplified by the lack of success in Sweden to protect the elderly in care homes (see bmj Article) – hints at a strong coupling of infections between age groups. Since the total football-related cases are dominated by subsequent cases, we can assume that the primary cases spread rapidly over age groups. We have added a word of caution to the manuscript in lines 83–87:

This is likely slightly overestimated because the age groups most at risk from COVID-19 related death are probably underrepresented in football-related social activities and thus more unlikely to be affected by primary championship-related infections. However, the overall number of primary and subsequent cases attributed to the championship is dominated by the subsequent cases, and the mixing and infections between age-groups then mitigates this bias.

We did also remove the estimate of the number of deaths from the abstract and the conclusion paragraph of the discussion to not overemphasize this result.

7 Connected to the previous point, it is possible that the case reporting rate has temporarily increased right after each match. This should be discussed as a study limitation.

Thank you for pointing this out. We have now included both this phenomenon when discussing testing before as well as after a match (and associated gatherings) and its implications for our results. Now lines 210–214 read:

> “ However, we expect that some individuals would actively get tested right after a match, thereby increasing the case finding and reporting rates. This can slightly affect our estimates for the delay distribution D and would require additional information to be corrected. Altogether, analyzing large-scale events with precise timing and substantial impact on the spread presents a promising, resource-efficient complement to classical quantification of delays. ”

8 Line 122. A generation interval of 4 days appears to be very short. That could be a reasonable estimate for a Chinese setting with very isolation policies in dedicated facilities, but rather short for a European context with very loose household isolation policies. 6 days would be a more sensible choice (see for instance Manica et al, Estimation of the incubation period and generation time of SARS-CoV-2 Alpha and Delta variants from contact tracing data, Medrxiv).

Thank you for pointing us to this. We investigated the impact of a longer generation interval on our results and found out that the differences are negligible (Supplementary Fig. S17). It mainly changes the inferred base reproduction number, but the total impact of the championship remains mostly the same. Therefore we kept our current model as the base model.

9 Lines 145-147 and 148-150. These sentences are speculative. It might well be the case that such events should be entirely banned during certain epidemic phases and/or mass gatherings avoided altogether. Moreover, the authorities should not do anything based on a manuscript. Each authority should make the decision based on its specific targets and priorities (which may not be aligned with those considered in this manuscript).

Thank you, this is an important point. We have rephrased these sentences to be rather explanatory than demanding (lines 158–163):

> “ To prevent the impacts of these events, measures, such as promoting vaccination, enacting mask mandates, and limiting gathering sizes, can be helpful. Besides, the effectiveness of such interventions has already been quantified in different settings (e.g., [Brauner2020, Sharma2021]) so that policymakers can weigh them according to specific targets and priorities. Furthermore, focused measures that aim to mitigate disease spread *in situ*, such as testing campaigns and requiring COVID passports to attend sport-related gatherings and viewing parties, present themselves as helpful options. ”

10 Line 150-151. I agree with this point, but it is phrased rather badly. The incubation period has a wide distribution, and its mean is not representative of the whole phenomenon. Moreover, not only the mean of the incubation period but also the mean of the generation time is in line with the interval between matches.

Thank you for pointing this out. We have rephrased the whole passage to be clearer. Now lines 164 – 168 read:

Moreover, the championship distribution of matches every 4 to 5 days coincides with the mean incubation period and generation interval of COVID-19. This means that individuals who get infected watching a match can turn infectious by the subsequent while potentially pre-symptomatic. Such resonance effects between gathering intervals and incubation time can increase the spread considerably [Zierenberg2021].

11 In Figures 2 and S4, base cases are named independent cases in the figure, but the captions and main text all refer to them as base cases. I suggest keeping these labels consistent throughout the paper and figures.

Thank you for noticing this. We have removed every instance of “base case” to restore consistency.

12 In general, there is quite a bit of confusion between cases and infections that the authors appear to be used interchangeably, while they are two clearly defined and different epidemiological concepts. Please carefully revise the wording throughout the manuscript.

Thank you for noticing this inconsistency. As mentioned in our reply to your comment **5**, we added a remark in the introduction (lines 39–41), which reads:

In the following, we use “case” to refer to a confirmed case of a SARS-CoV-2 infections in a human and “case numbers” to refer to the number of such cases. Not all infections are reported and represented in the cases and cases come with a delay after the actual infections.

Additionally, we replaced instances of infections with cases where we found it to be more accurate.

REVIEWERS' COMMENTS

Reviewer #1 (Remarks to the Author):

The authors have satisfactorily answered to my comments.

Reviewer #2 (Remarks to the Author):

It is useful that Figure S8 has been added to demonstrate the impact of excluding England and Scotland. However, I don't feel that this text:
"The strong significance of this correlation relies mainly on England and Scotland. However, the observed trend in an analysis without these two countries, while not significant at the 95% confidence level, is consistent with the findings including all countries. This is shown in supplementary Fig. S8."
puts enough information into the main text. The R^2 is 0.09 when England and Scotland are excluded, with a 95% CI of (0.00, 0.49). It would be useful if the slope estimates and 95% CIs were given in the text as well - I only know them because they were included in the response:
"However, the regression parameters are consistent between all data points (1.62 [1.0, 2.26]) and the result without the UK (0.76 [-1.46, 3.04])."
This statement makes clear that without England and Scotland, there is almost no information.

Finally, it is not helpful that the x-axis numbers for Fig S8 are "500", "1k", "2k" and again "2k". There is plenty of space to make this figure larger so 500, 1000, 1500 and 2000 can be used rather than having "2k" representing both 1500 and 2000.

Reviewer #3 (Remarks to the Author):

The authors have adequately addressed my comments. Please find below a short list of very minor comments.

Line 44: "infections" -> "infection"

Line 94: "[…] mixing of infections between age-groups then […]" -> "[…] mixing between individuals of different age groups then […]"

Line 408: Ref. 46 does not provide estimates of the generation interval.

Lines 408 and 409: "[…] but shorter than the estimated serial interval of the original strain.". First, a reference is missing here. Second, why do the authors refer to the serial interval here since estimates of the generation interval for the ancestral lineages of SARS-CoV-2 are available in the literature? See for instance, https://www.nature.com/articles/s41467-021-21710-6 and https://www.science.org/doi/full/10.1126/science.abb6936 .

December 2, 2022

Revision of our manuscript to *Nature Communications*

Dear reviewers,

thank you very much for all the helpful comments during the review period. We addressed the last comments as detailed below.

Viola Priesemann and Philip Bechtle
(on behalf of all authors)

Reviewer 1

> The authors have satisfactorily answered to my comments.

Thank you again for your helpful comments.

Reviewer 2

> It is useful that Figure S8 has been added to demonstrate the impact of excluding England and Scotland. However, I don't feel that this text: "The strong significance of this correlation relies mainly on England and Scotland. However, the observed trend in an analysis without these two countries, while not significant at the 95% confidence level, is consistent with the findings including all countries. This is shown in supplementary Fig. S8." puts enough information into the main text. The R^2 is 0.09 when England and Scotland are excluded, with a 95% CI of (0.00, 0.49). It would be useful if the slope estimates and 95% CIs were given in the text as well - I only know them because they were included in the response: "However, the regression parameters are consistent between all data points (1.62 [1.0, 2.26]) and the result without the UK (0.76 [-1.46, 3.04])." This statement makes clear that without England and Scotland, there is almost no information.

Indeed, it is helpful to be more informative here. We added to the main text the slope estimates:

> " Indeed, we find a clear correlation between the observed and the expected incidence Fig. **??**a, $R^2 = 0.77$ (95% CI [0.39,0.9]), p<0.001, with a slope of 1.62 (95% CI [1.0, 2.26]). The strong significance of this correlation relies mainly on England and Scotland. However, the observed slope in an analysis without these two countries (0.76, 95% CI: [-1.46, 3.04]), while not significant at the 95% confidence level, is consistent with the findings including all countries. This is shown in supplementary Fig. S7. "

And also added these slope estimate to the caption of supplementary Fig. S7 and emphasized that the correlation is not significant:

> " The potential for spread, i.e., the number of COVID-19 cases that would be expected during the time T a country is playing in the Euro 2020 ($N_0 \cdot R_{\text{pre}}^{T/4}$) is still correlated with the number of Euro 2020-related cases after removing the two most significant entries from the analysis but not significantly. The observed slope without the most significant countries (median: 0.76, 95% CI: [-1.46, 3.04]) is consistent within its uncertainties with the slope including all countries (median: 1.62, 95% CI: [1.0, 2.26])). "

> Finally, it is not helpful that the x-axis numbers for Fig S8 are "500", "1k", "2k" and again "2k". There is plenty of space to make this figure larger so 500, 1000, 1500 and 2000 can be used rather than having "2k" representing both 1500 and 2000.

Thank you for spotting this. We corrected the x-axis numbers as suggested.

Reviewer 3

> Line 44: “infections” -> “infection”
> Line 94: “[...] mixing of infections between age-groups then [...]” -> “[...] mixing between individuals of different age groups then [...]”

We corrected it as suggested.

> Line 408: Ref. 46 does not provide estimates of the generation interval.
> Lines 408 and 409: “[...] but shorter than the estimated serial interval of the original strain.”. First, a reference is missing here. Second, why do the authors refer to the serial interval here since estimates of the generation interval for the ancestral lineages of SARS-CoV-2 are available in the literature? See for instance, https://www.nature.com/articles/s41467-021-21710-6 and https://www.science.org/doi/full/10.1126/science.abb6936 .

Indeed, the literature references are not suitable, and refering to the serial interval instead of the generation interval isn’t appropriate. We replaced the previous reference 46 which only estimated the serial interval by [47] W. S. Hart, et al. (2022) (https://www.thelancet.com/journals/laninf/article/PIIS1473-3099(22)00001-9) and added the two proposed references for the generation interval of the original strain ([48, 49]). We also added here a reference to the robustness check figure of the generation interval:

> “ This generation interval (between infections) is modeled by a Gamma distribution $G(\tau)$ with a mean μ of four days and standard deviation σ of one and a half days. This is a little longer than the estimates of the generation interval of the Delta variant [45, 46], but shorter than the estimated generation interval of the original strain [47, 48]. The impact of the choice of generation interval has negligible impact on our results (supplementary Fig. S7). ”

nature portfolio

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Last updated by author(s): Sebastian B. Mohr, Jonas Dehning

Reporting Summary

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For all statistical analyses, confirm that the following items are present in the figure legend, table legend, main text, or Methods section.

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□	☒	The exact sample size (*n*) for each experimental group/condition, given as a discrete number and unit of measurement
☒	□	A statement on whether measurements were taken from distinct samples or whether the same sample was measured repeatedly
☒	□	The statistical test(s) used AND whether they are one- or two-sided *Only common tests should be described solely by name; describe more complex techniques in the Methods section.*
□	☒	A description of all covariates tested
□	☒	A description of any assumptions or corrections, such as tests of normality and adjustment for multiple comparisons
□	☒	A full description of the statistical parameters including central tendency (e.g. means) or other basic estimates (e.g. regression coefficient) AND variation (e.g. standard deviation) or associated estimates of uncertainty (e.g. confidence intervals)
☒	□	For null hypothesis testing, the test statistic (e.g. *F*, *t*, *r*) with confidence intervals, effect sizes, degrees of freedom and *P* value noted *Give P values as exact values whenever suitable.*
□	☒	For Bayesian analysis, information on the choice of priors and Markov chain Monte Carlo settings
□	☒	For hierarchical and complex designs, identification of the appropriate level for tests and full reporting of outcomes
□	☒	Estimates of effect sizes (e.g. Cohen's *d*, Pearson's *r*), indicating how they were calculated

Our web collection on statistics for biologists contains articles on many of the points above.

Software and code

Policy information about availability of computer code

Data collection	For the collection of data we used only publicly available data. See SI 'S1 Data sources' for more information.
Data analysis	We use pymc3 version 3.11.2 for MCMC sampling and model definition. Our code is available at: https://github.com/Priesemann-Group/covid19_soccer (DOI: 10.5281/zenodo.7386313)

For manuscripts utilizing custom algorithms or software that are central to the research but not yet described in published literature, software must be made available to editors and reviewers. We strongly encourage code deposition in a community repository (e.g. GitHub). See the Nature Portfolio guidelines for submitting code & software for further information.

Data

Policy information about availability of data

All manuscripts must include a data availability statement. This statement should provide the following information, where applicable:

- Accession codes, unique identifiers, or web links for publicly available datasets
- A description of any restrictions on data availability
- For clinical datasets or third party data, please ensure that the statement adheres to our policy

The data from our model runs, i.e., from the sampling is available on G-node https://gin.g-node.org/semohr/covid19_soccer_data. The daily case numbers stratified by age and gender were acquired from the local health authorities (see also Supplementary Information "S1 Data sources') from the following sources: https://www.arcgis.com/home/item.html?id=f10774f1c63e40168479a1feb6c7ca74 , https://www.data.gouv.fr/fr/datasets/taux-dincidence-de-lepidemie-de-covid-19 , https://coronavirus.data.gov.uk/details/download , https://covid19-dashboard.ages.at , https://epistat.wiv-isp.be/covid , https://onemocneni-aktualne.mzcr.cz/covid-1 , https://data.rivm.nl/covid-19 , https://www.coverage-db.org

Human research participants

Policy information about studies involving human research participants and Sex and Gender in Research.

Reporting on sex and gender	Our study takes into account the gender of people infected by SARS-CoV-2. However, only the aggregated count of reported cases is being used. We do not possess individual level data. The gender information has been collected by the health authorities of the European countries included in this study.
Population characteristics	We use publicly available data of the number of COVID-19 cases that doesn't include individual level data nor population characteristics except for the gender
Recruitment	No research participants were recruited
Ethics oversight	As we didn't recruit participants and used only publicly available data, no ethics oversight was present.

Note that full information on the approval of the study protocol must also be provided in the manuscript.

Field-specific reporting

Please select the one below that is the best fit for your research. If you are not sure, read the appropriate sections before making your selection.

☒ Life sciences □ Behavioural & social sciences □ Ecological, evolutionary & environmental sciences

For a reference copy of the document with all sections, see nature.com/documents/nr-reporting-summary-flat.pdf

Life sciences study design

All studies must disclose on these points even when the disclosure is negative.

Sample size	We analyze all countries which reported the gender of COVID-19 cases on a daily basis and participated in the Euro 2020.
Data exclusions	We excluded The Netherlands from the average effect and correlation calculations because the relaxation of governmental interventions occured within the period of the Championship and had a large effect on case numbers and their gender imbalance.
Replication	We conducted extensive robustness tests of our results, see Supplementary Figures S11-S19.
Randomization	We performed no randomization ourself. Our study has a random part because the dates and participant countries of the Euro 2020 matches depended on the draw performed by the UEFA and the subsequent success of the teams during the championship. This allocation of matches is nearly independent of the state of the pandemic and therefore doesn't influence our results.
Blinding	There is no group allocation and thus no blinding.

Reporting for specific materials, systems and methods

We require information from authors about some types of materials, experimental systems and methods used in many studies. Here, indicate whether each material, system or method listed is relevant to your study. If you are not sure if a list item applies to your research, read the appropriate section before selecting a response.

Materials & experimental systems

n/a	Involved in the study	
☒	□	Antibodies
☒	□	Eukaryotic cell lines
☒	□	Palaeontology and archaeology
☒	□	Animals and other organisms
☒	□	Clinical data
☒	□	Dual use research of concern

Methods

n/a	Involved in the study	
☒	□	ChIP-seq
☒	□	Flow cytometry
☒	□	MRI-based neuroimaging