Supporting information for ***Assessing the effect of school closures on the spread of COVID-19 in Zurich***

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Case data was provided by Gesundheitsdirektion Zürich. This confidential data was provided upon request as the daily number of new COVID-19 cases stratified by age. Our work considers the age groups: 0 to 14 years old (0-14), 15 to 24 years old (15-24), 25 to 44 years old (25-44), 45 to 65 years old (45-65), 66 to 79 years old (66-79), and aged 80 or older (80+). The case data covers the period from first COVID-19 case in Zurich (26th February 2020) until 4th August 2020. The age distribution of the total number of cases (i.e. all cases observed during the study period) does not match the age distribution of people found in the general population, indicating that the disease burden is not the same for all ages. It would seem that younger cases are less represented in the case data.

Non-pharmaceutical countermeasures to increase social distancing such as lockdown, distance learning, and remote working recommendations as well as travel restrictions and border closures have been implemented in Switzerland during the 2019/2020 COVID-19 outbreak. Particularly school closure can be considered a contact matrix-based non-pharmaceutical measure (1). We used the synthetic contact matrices by setting for Switzerland from Mistry et al. (2) and aggregated the contacts by the same age groups as those considered in the case data. This means that we collected data from press releases (3–5) and legislative documents (6–8) published by the Federal Council to harmonise information on policy measures covering the beginning of the pandemic until 27th April 2020. Information on government measures after this date was taken from a list published by Bundesamt für Gesundheit (9). We obtained information on public holidays in Zürich via Bundesamt für Justiz (10), testing via Bundesamt für Gesundheit (11), and temperature via Federal Office of Meteorology and Climatology MeteoSwiss (12). School holiday information was sourced from Kanton Zürich (13). For population offsets, we used the most recent cantonal census counts (2019) from official statistics (14). Testing rates are available at national but not cantonal level.

The weights in the linear combination making up the total contact matrix have been suggested by Mistry et al. (2) to be $w^{\text{household}} = 4.11$ (standard error (SE) 0.41), $w^{\text{work}} = 2.79$ (SE 0.27), $w^{\text{school}} = 11.41$ (SE 0.52), and $w^{\text{other}} = 8.07$ (SE 0.48) for airborne disease. Other authors

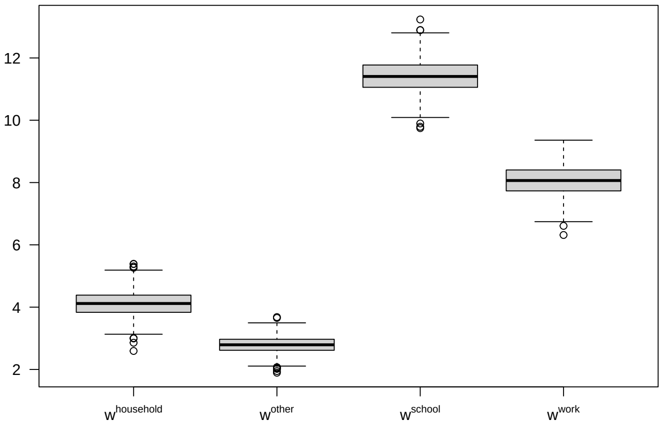

Figure 1: Distribution of samples of Mistry et al. (2) weights

have suggested different weights (15, 16, COVID-19), (17, 18, influenza-like illness, varicella, and parvovirus B19) but without providing any associated uncertainty. While their weights seem different, when applied to our contact matrix, the overall aggregated contact pattern was similar for the different choices of weights, showing the diagonal pattern common to contact matrices. The $n = 1000$ weights sampled and used in our work are illustrated in the supporting information.

1 MODELS

The endemic-epidemic (EE) models considered in this are given by

$$\begin{aligned} Y_{at} \mid Y_{a,t-1}, \dots, Y_{a,t-l} &\sim \text{NegBin}(\lambda_{at}, \psi_a) \\ \lambda_{at} &= \nu_{at} e_a + \phi_{at} \sum_{a'} c_{a,a',t} \sum_{l=1}^{l_{\max}} u_l Y_{a',t-l} \end{aligned} \tag{1}$$

Our simplest log-linear predictors are given by

$$\log(\nu_{at}) = \beta_{\nu a} \mathbb{1}_{\{\text{age group } a\}}(a) + \beta_{\nu_{\text{public holiday}}} \mathbb{1}_{\{t \text{ is a public holiday}\}}(t) + \beta_{\nu_{\text{day of the week}}} \mathbb{1}_{\{\text{weekday } t\}}(t) + \beta_{\nu_{\text{testing rate}}} T_t$$

and

$$\log(\phi_{at}) = \beta_{\phi a} \mathbb{1}_{\{\text{age group } a\}}(a) + \beta_{\phi_{\text{public holiday}}} \mathbb{1}_{\{t \text{ is a public holiday}\}}(t) + \beta_{\phi_{\text{day of the week}}} \mathbb{1}_{\{\text{weekday } t\}}(t) + \beta_{\phi_{\text{testing rate}}} T_t$$

where the daily testing rate T_t is calculated as

$$T_t = \frac{\text{number of tests at time } t}{\text{total population}} \cdot 100000$$

This is considered our reference model. In addition to this reference model we included models that extended the above to include: a centred time trend via $t - \text{median}(t)$ (26th February 2020 takes the value -80 and 4th August 2020 takes the value 80), daily temperature measurement, and a smooth non-linear trend not picked up by other parameters (we call this "seasonality" for shorthand but note that true seasonality cannot be a single year). When we included this trend in our models, we followed the transformations to amplitude and shift following Held and Paul (19), meaning we use

$$\gamma \sin(\omega t) + \delta \cos(\omega t) = A \sin(\omega \cdot t + P)$$

where t is the index for the time series, ω and δ are the coefficients of the sine-cosine curves and $A = \sqrt{\gamma^2 + \delta^2}$ and $P = \arctan(\delta/\gamma)$ are the associated amplitude and phase. ω is additionally an expression containing the frequency of the wave, $\omega = 2\pi/f$, in our models we use $f = 365$. We determined the best model based on Bayesian information criterion (BIC).

The temperature and testing rates used are illustrated in (Figure 2). The time-of-the-week effects (`wkd`) enter with Monday as a reference category.

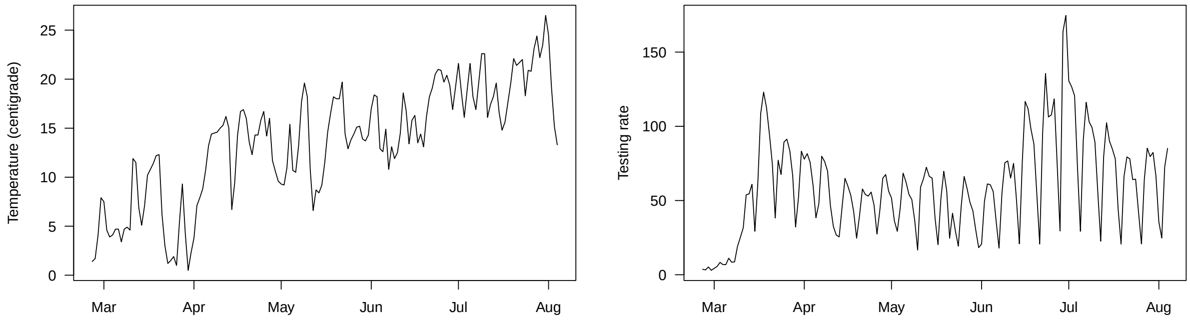

Figure 2: Temperature in Zurich (left) and daily testing rate in Switzerland per 100,000 population (right) during the study period

The naming convention for the models we considered is as follows: the model is named after the effects present in the endemic then epidemic components. For the effects, `S` denotes seasonality, `T` denotes temperature, `L` denotes time, and these are always listed in this ordering. An `x` indicates that the effect is not present in the component. For example, `zh_mod_xTx_xTL` would be the model with an endemic component with temperature and an epidemic component with temperature and time. Seasonality is not present in this example. The reference model is denoted `zh_mod_xxx_xxx`. The corresponding model calls are provided at https://gitlab.switch.ch/suspend/COVID-19-school-ZH. We considered both geometric and shifted Poisson weights u_l in our models. Models with a geometric lag had $u_l = (1-\kappa)^{l-1}, 0 < \kappa < 1$. It has been argued that geometric weights do not make sense for the analysis of daily COVID-19 data as they place most weight on the first lag (whereby the previous day's cases will be weighted highest) and evidence suggests a serial interval of around $2-3$ days (20). BIC values are given in Table 1.

Table 1: All model options considered in the analysis. The names provided respond to the names used (where information on the corresponding model calls is provided)

	Endemic / ν_{at}			Epidemic / ϕ_{at}					
Name	Seasonality	Temperature	Time	Seasonality	Temperature	Time	Lag	BIC	Parameters
`zh_mod_SxL_Sxx`	✓		✓	✓			Poisson	3308	40
`zh_mod_Sxx_xxx`	✓						Poisson	3340	37
`zh_mod_SxL_SxL`	✓		✓	✓		✓	Geometric	3344	41
`zh_mod_SxL_Sxx`	✓		✓	✓			Geometric	3344	40
`zh_mod_Sxx_xxx`	✓						Geometric	3345	37
`zh_mod_Sxx_SxL`	✓			✓		✓	Geometric	3352	40
`zh_mod_SxL_SxL`	✓		✓	✓		✓	Poisson	3352	41
`zh_mod_Sxx_Sxx`	✓			✓			Geometric	3355	39
`zh_mod_Sxx_Sxx`	✓			✓			Poisson	3364	39
`zh_mod_Sxx_SxL`	✓			✓		✓	Poisson	3371	40
`zh_mod_SxL_xxL`	✓		✓			✓	Poisson	3396	39
`zh_mod_xTx_xTL`		✓			✓	✓	Geometric	3397	38
`zh_mod_xTx_xTL`		✓			✓	✓	Poisson	3403	38
`zh_mod_xxL_SxL`			✓	✓		✓	Geometric	3406	37
`zh_mod_xxL_xxL`			✓			✓	Geometric	3406	37
`zh_mod_xxx_Sxx`				✓			Geometric	3406	37
`zh_mod_xxL_xxL`			✓			✓	Poisson	3409	37
`zh_mod_xxL_SxL`			✓	✓		✓	Poisson	3409	37
`zh_mod_SxL_xxL`	✓		✓			✓	Geometric	3411	39
`zh_mod_xxx_xxL`						✓	Geometric	3412	36
`zh_mod_xxx_Sxx`				✓			Poisson	3418	37
`zh_mod_xxx_xxL`						✓	Poisson	3423	36
`zh_mod_xxL_xTL`			✓		✓	✓	Geometric	3444	38
`zh_mod_xTL_xTL`		✓	✓		✓	✓	Geometric	3447	39
`zh_mod_xxL_xTL`			✓		✓	✓	Poisson	3451	38
`zh_mod_xxL_xxx`			✓				Poisson	3468	36
`zh_mod_xxL_xxx`			✓				Geometric	3468	36
`zh_mod_xTL_xTx`		✓	✓		✓		Geometric	3475	38
`zh_mod_xTL_xTx`		✓	✓		✓		Poisson	3475	38
`zh_mod_xxx_xTx`					✓		Geometric	3642	36
`zh_mod_xTx_xTx`		✓			✓		Geometric	3645	37
`zh_mod_xxx_xTx`					✓		Poisson	3647	36
`zh_mod_xTx_xTx`		✓			✓		Poisson	3649	37
`zh_mod_xTx_xxx`		✓					Geometric	3758	36
`zh_mod_xTx_xxx`		✓					Poisson	3767	36
`zh_mod_xxx_xxx`							Geometric	3801	35
`zh_mod_xxx_xxx`							Poisson	3803	35
`zh_mod_xTL_xTL`		✓	✓		✓	✓	Poisson		39
`zh_mod_xTL_xxL`		✓	✓			✓	Poisson		38
`zh_mod_xTL_xxL`		✓	✓			✓	Geometric		38

2 PREDICTED SCENARIOS

To provide a comparison of scenarios B and A we showcase the ratio of cases over time rather than the difference. The differences are small and it is hard to see the patterns based on contact patterns. The ratio between scenarios (cases predicted under scenario B compared to cases predicted under scenario A) shows a different pattern for the youngest age group compared to other age groups. The increase in absolute cases in lower ages is small which is why it takes some time for cases to spread to different age groups. Notably there seems to be a parent delay: 0-14 increases first followed by 25-44. The oldest age group is consistently below the other age groups.

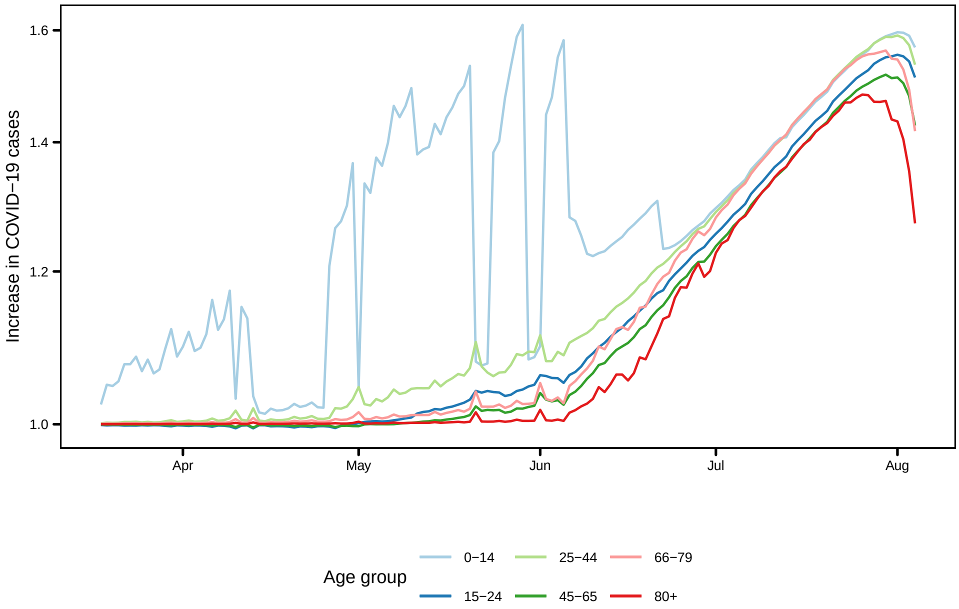

Figure 3: Comparison of predicted counts under scenarios A and B

3 SENSITIVITY ANALYSIS

To assess the sensitivity of our findings, we fit the best fitting model from Table 1 with specific lag distributions u_l more in line with others found in the literature (21, 22), see Figure 4 for the distributions used. Similar patterns are seen under scenarios A and B when predicting using the alternative lag distributions (Table 2). The results found are similar to the original analysis, though the skewness seems to reduce slightly, indicating it may be preferable to use a serial interval distribution from the literature in place of the estimated lag distribution, providing it was estimated in a relevant setting (meaning one similar to the one being modelled).

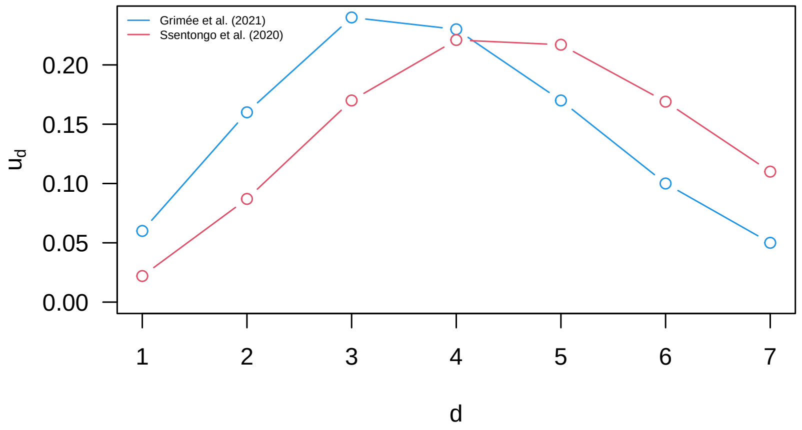

Figure 4: Grimée et al. (21) and Ssentongo et al. (22, Figure S10B) lag distributions

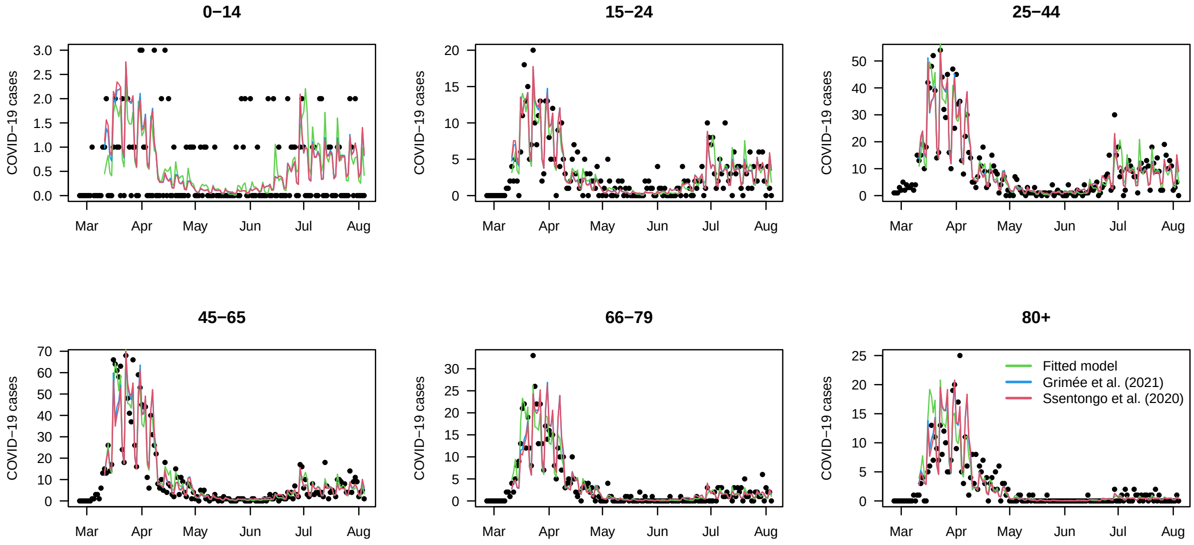

Figure 5: The original model fit as well as the model fit using Grimée et al. (21) and Ssentongo et al. (22) lags

4 EXTENDED DISCUSSION

Analysis of individual case data for Gesundheitsdirektion Zürich (confidential) revealed slight reporting delays which can be rectified through nowcasting (23). We also tried examining two younger age groups, rather than all children of compulsory schooling age. Specifically, we in-

Table 2: Predicted case counts from the same model using Grimée et al. (21) lags in place of the estimated lag distribution (above) and Ssentongo et al. (22) lags (below)

	Scenario A			Scenario B			B - A			B / A		
Age	P_{10}	Median	P_{90}	P_{10}	Median	P_{90}	P_{10}	Median	P_{90}	P_{10}	Median	P_{90}
0-14	58	76	110	65	89	146	6.1	12.5	38.0	1.10	1.17	1.35
15-24	347	400	514	357	423	594	8.1	22.6	80.5	1.02	1.06	1.16
25-44	1197	1336	1619	1234	1409	1856	31.7	74.2	250.3	1.03	1.06	1.16
45-65	1415	1504	1696	1434	1539	1816	12.1	34.5	129.9	1.01	1.02	1.08
66-79	478	518	570	486	528	598	4.5	10.5	33.2	1.01	1.02	1.06
80+	309	348	397	313	353	404	1.1	2.8	10.2	1.00	1.01	1.03
Total (summed)	3877	4163	4826	3956	4324	5302	66.3	159.8	535.2	1.02	1.04	1.11

	Scenario A			Scenario B			B - A			B / A		
Age	P_{10}	Median	P_{90}	P_{10}	Median	P_{90}	P_{10}	Median	P_{90}	P_{10}	Median	P_{90}
0-14	60	78	115	67	92	150	6.4	12.8	37.8	1.10	1.17	1.35
15-24	354	407	526	364	429	603	8.4	22.7	81.2	1.02	1.06	1.16
25-44	1214	1355	1642	1253	1433	1884	33.0	76.2	251.4	1.03	1.06	1.15
45-65	1425	1519	1711	1444	1554	1828	12.3	34.4	128.7	1.01	1.02	1.08
66-79	482	521	575	490	532	603	4.7	10.7	32.5	1.01	1.02	1.06
80+	310	349	399	313	353	406	1.1	2.8	10.2	1.00	1.01	1.03
Total (summed)	3921	4228	4874	3994	4391	5460	68.1	161.4	549.2	1.02	1.04	1.11

cluded a distinction between children aged above or below five years of age, but there were not enough cases available in the very youngest age group for the modelling approach to work well. As seen in Figure 5, the youngest age group in our work (even without further subdivision) has the least cases. Additionally, we note that the policy indicator for school closures also includes closures of tertiary education and so changes to non-compulsory schooling would also be captured in this approach. However, this does not affect the current work as during the study period all levels of school were closed and opened at the same time. Furthermore, we are aware of the existence of complementary behaviour between school and work contacts as school closures are likely to induce an increase in flexible or remote working behavioural changes among parents and guardians as children of certain ages will require more childcare. Similarly, when schools reopen, the desire to work in an office may increase. Such complementary effects would be better captured by empirical longitudinal contact surveys than with the approach used by us.

In this work, we have implicitly assumed contacts in Zürich do not differ from those found at country level. The contact matrix used in this work is a synthetic contact matrix created on the basis of demographic data and compared with empirical contact matrices from other European countries. Ideally, we would liked to have incorporated time-varying contact matrices based on sequential contact surveys as seen elsewhere (e.g. 24–27) but such initiatives were not conducted in Switzerland in the first wave of the 2019/2020 COVID-19 epidemic. One potential drawback of synthetic contact matrices is that the number of contacts in school settings may be slightly inflated if created based on demographic data on school class sizes alone, as not all pupils are to be expected to interact with all of their classmates.

We considered synthetic contact matrices, allowing us to consider contacts in various settings, and adjusted these to reflect social distancing measures, similar to other approaches seen in COVID-19 modelling (28–31). The benefit to using the synthetic contact matrix for Switzerland rather than the single empirical contact diary study which exists (32) is that the sampling approach is well-designed and the sample size is sufficiently large. Regarding changes to the contact matrix, we note that the official date of an intervention's implementation does not necessarily correspond to the exact start of that intervention, as a delay could occur, which is also an implicit assumption made in our modelling approach.

Our model assumes that adults will not experience increased risk by schools opening. We note that certain subgroups of the adult population–namely those that interact with school settings such as teachers and parents–may be at increased risk (33). However, the European Centre for Disease Prevention and Control (34) synthesised evidence on transmission of COVID-19 with regards to children and schools, and found that adults are not at higher risk in schools than in household or community settings, children do not commonly transmit the disease to each other or adults, and adult-to-child transmission primarily occurs outside of school, among other findings. They note that schools being able to remain open depends on low levels of community transmission. Additionally, most of the infections among school-aged children seem to occur in the home rather than in educational settings, which is being examined for Switzerland (35, 36). If such seroprevalence studies were to show low asymptomatic cases in the youngest age group as well as the low number of observed case counts overall, schools may not need close for them. We have not considered within-household effects in this work, such as those examined for influenza (37) as this is out of scope for our work.

Seasonality of the SARS-CoV-2 virus remains to be determined. The framework used in this work is particularly well suited to examining diseases with seasonality (19, 38) and endemic potential, and the widespread use of the EE framework shows its ability to consider both established and novel diseases, such as COVID-19 (39). Furthermore, our models are created in a manner where incorporating daily updates can be done instantaneously which is congruent with the suggestions of Squazzoni et al. (40). Thus, the inclusion of seasonal effects would be easily incorporated if they are determined to be important. For researchers modelling COVID-19 cases with EE approaches in 2021, we recommend incorporating pharmaceutical countermeasures such as vaccines (41). Additional nuances that are not captured in our approach are potential differences in mixing patterns between symptomatic and asymptomatic cases, as seen for influenza (42), and changes to the serial interval distribution following social distancing measures (43). If evidence were available, different contact patterns for asymptomatic and symptomatic groups could be incorporated in the EE modelling framework through an enlarged contact matrix.

5 CODE

The full code used in this work can be accessed via https://gitlab.switch.ch/suspend/COVID-19-school-ZH.

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