Mortality and Longevity

Cause-Specific Excess Mortality During the COVID-19 Pandemic

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A Temporal Correlation Analysis to Disentangle Underreporting, Selection, and Scarring Effects

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Uncertainty remains about the direct and indirect impact of the COVID-19 pandemic on future mortality and morbidity trends. In second quarter 2023, the Society of Actuaries Research Institute's Mortality and Longevity Strategic Research Program Steering Committee (MLPSC) formally released a request to elicit proposals to perform an objective and data-driven study on excess deaths during the COVID-19 pandemic. The study would produce a resource for actuaries and others to aid them in evaluating the impact of COVID-19 and pandemics in general. The request instructed researchers to incorporate findings of the study into a report to be made available on the Society of Actuaries Research Institute Website.

The authors submitted a proposal and were selected by the MLPSC to perform the study. This report is an outcome of their work. In addressing the project objectives, the authors investigated the patterns between COVID-19 mortality and excess mortality from other causes. They also developed a theoretical framework to interpret the results of this analysis and understand potential underlying factors responsible for excess mortality. The opinions expressed and conclusions reached by the authors are their own and do not represent any official position or opinion of the Society of Actuaries Research Institute, the Society of Actuaries, or its members.

Executive Summary

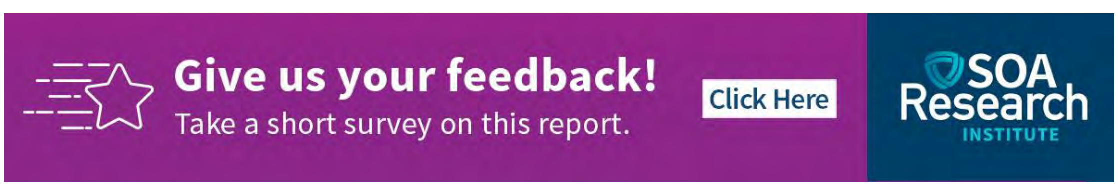
This report presents initial findings from a project investigating the direct and indirect impacts of COVID-19 in the post-acute phase of the pandemic. These findings focused on cause-specific excess mortality in the first three pandemic years, March 2020 to February 2023. In addition, the authors investigated how different mechanisms contributed and could continue to affect mortality rates following the acute pandemic period. The study is based on weekly mortality data by age and cause of death from 2015 to 2023 obtained from the National Center for Health Statistics at the Centers for Disease Control and Prevention, combined with population estimates from the U.S. Census Bureau. Weekly excess deaths by age and cause comparing observed deaths to deaths expected based on pre-pandemic trends were computed. Then the temporal correlation between weekly COVID-19 and excess deaths from other causes at various lags were assessed. The authors developed a theoretical framework to interpret the results of this analysis and understand potential underlying factors responsible for excess mortality.

The main findings of the study are summarized below:

- The authors estimated that a total of 1,465,000 excess deaths occurred between March 2020 and February 2023. COVID-19 contributed the majority of these deaths (969,000), but other natural (376,000) and external (91,000) causes also exhibited elevated mortality.
- Natural causes with elevated mortality include heart disease, cerebrovascular diseases, diabetes, and Alzheimer's disease. Mortality from external causes was also higher than expected, including accidents, substance use, and other external causes.
- In contrast with most other natural causes of death, influenza and other respiratory diseases showed lower mortality than expected. This may reflect a combination of factors, including the effect of COVID-19 mitigation measures and mortality displacement, i.e., at least some individuals

that would have died of influenza and other respiratory diseases died instead of COVID-19. Similarly, no evidence of increased mortality from neoplasms was found. Excess mortality was observed for most external causes of death with the exception of suicide.

- In absolute numbers, older age groups (65–84, 85+) saw the highest rates of excess mortality both from COVID-19 and from other causes. However, in relative terms, the authors found that mid-life adults (45–64) experienced a mortality increase similar to older adults (65+). While showing lower mortality rates compared to older age groups, young adults (25–44) also exhibited elevated mortality rates.
- The analysis of temporal correlation revealed that peaks in COVID-19 mortality coincided with peaks in excess mortality from most natural causes of death excluding influenza and malignant neoplasms. The statistical analysis of these patterns confirmed that same week or past week COVID-19 mortality is strongly associated with excess mortality from natural causes. The authors think that misclassification of COVID-19 deaths is the most likely source for these correlations, with scarring effects, i.e., COVID-19 survivors having a higher risk of dying from other causes, explaining the positive correlation of COVID-19 in the current week with future excess mortality.
- Within natural deaths, deaths from influenza and pneumonia and from malignant neoplasms showed patterns indicating that peaks in COVID-19 mortality were followed by declines in excess mortality for these causes. The authors interpret this pattern as evidence of mortality displacement.
- External deaths, in contrast, showed no systematic temporal correlation with COVID-19 deaths. Since misclassification of COVID-19 deaths could not have been a source of elevated excess mortality from external causes, the authors interpret the absence of correlation as evidence against alternative mechanisms such as healthcare interruptions.
- Taken jointly, these patterns are consistent with substantial underreporting of COVID-19 deaths, particularly in the first year of the pandemic. Misclassification of COVID-19 deaths, thus, likely contributed to high excess in natural causes. Additionally, the authors found evidence that contracting COVID-19 likely increased the likelihood of death from selected natural causes such as diabetes, cardiovascular diseases, and Alzheimer's disease. At the same time, patterns consistent with mortality displacement for influenza and malignant neoplasms were observed, indicating that some individuals who would have died of these causes died instead of COVID-19.
- Finally, the absence of correlation between peaks in external deaths and peaks in COVID-19 mortality suggests that the elevated mortality from external causes was not directly related to the prevalence of COVID-19 infections. Other indirect mechanisms such as behavioral changes might have played a role.



Section 1: Introduction

The COVID-19 pandemic has resulted in a large excess mortality burden in the United States substantially exceeding the number of officially recognized COVID-19 deaths.[1–3] Excess deaths reported to causes other than COVID-19 could represent unrecognized COVID-19 deaths, deaths from pandemic-era health care delays or interruptions, and deaths caused by other social and economic consequences of the pandemic.[4–6] A majority of excess deaths were assigned to natural causes but the number of deaths from external causes including drug poisoning also increased during the COVID-19 pandemic.[7,8]

A recent analysis found that a total of 162,886 excess natural-cause deaths occurred in the United States from March 2020 to August 2022 that were not reported to COVID-19.[9] The same study, as well as another study from California,[10] also examined temporal correlations between natural-cause excess natural causes and reported COVID-19 deaths. In both cases, they found that there was significant temporal correlation between reported COVID-19 deaths and excess deaths, supporting the conclusion that many of those deaths were uncounted COVID-19 deaths. This finding has been supported by qualitative reports of irregularities in certifying COVID-19 deaths in out-of-hospital settings[11] and other literature showing discrepancies in reporting for other causes of death.[12–14] While there appears to be growing consensus in the literature about the existence of unrecognized COVID-19 deaths during the pandemic,[7,9,10] important questions remain around (1) the precise number of unrecognized COVID-19 deaths, (2) what other causes unrecognized COVID-19 deaths were reported to, (3) which other natural and external causes of death, not directly caused by COVID-19, contributed to excess mortality during the pandemic, and (4) which other mechanisms led to excess mortality exceeding COVID-19 mortality beyond underreporting of COVID-19.

Section 2: Data and Methods

For this analysis, publicly available death counts by week and cause of death from the CDC[15,16] were used. For each cause of death and age group, including all ages combined, a seasonal ARIMA model was fitted to observed death counts based on pre-pandemic data on a weekly level (week ending January 10th, 2015 to week ending February 29th, 2020) and then used to predict expected deaths by week for the period March 2020 – February 2023. The authors also did this with monthly data (March 2015 – February 2020) from CDC WONDER[17] for each age group to reduce suppression and noise in the cause-specific and age-specific estimates. Estimates for cause- and age-specific mortality, for which weekly data was only available from 2018 onwards, were adjusted so that the implicit all-cause mortality rates would sum to estimates based on the 2015-2019 baseline. More details are available in the Supplementary Material. Excess mortality was computed as the difference between observed and expected deaths. This methodology has been successfully applied in prior studies.[1,2,10] Having obtained these cause-specific estimates of excess mortality, the authors conducted cause-specific analyses of the temporal relationship between COVID-19 mortality and excess mortality from other causes of death. To do so, ARIMA models were fitted to each pair of series (COVID-19 deaths and cause-specific excess deaths) until reduction to white noise was achieved and then the cross-correlation function between the residuals of the two ARIMA models was computed. This process was repeated separately for each pair of series by cause of death. More details on this analysis are given in the Supplementary Material.

Section 3: Theoretical Framework

The results of the temporal correlation statistical exercise should be interpreted within a theoretical framework with a set of hypotheses that map each configuration of the results with an interpretation. Such a framework is provided in **Table 1**.

Table 1
A THEORETICAL FRAMEWORK TO LINK OBSERVED RESULTS TO HYPOTHESIZED MECHANISMS

	Negative Lag	Contemporaneous	Positive Lag
Positive Correlation	Underreporting (awareness hypothesis)	Underreporting Short-term effects of disruptions in the healthcare system	Scarring Delayed effects of disruptions in the healthcare system
No Correlation	–	Excess not related to COVID-19	–
Negative Correlation	–	Overreporting Substitution	Mortality Selection Underreporting (awareness hypothesis)

Abstracting from the specific positive or negative lag at which a temporal correlation is detected, and abstracting from its strength, results can be divided into one of three categories: those showing a correlation at one or more negative lags (first column), those showing a correlation only at lag zero (second column), and those showing a correlation at one or more positive lags (third column). Furthermore, the correlation can be positive (first row), not statistically significant (second row), or negative (third row). Crossing these two main dimensions results in nine different cells. Of these nine cells, the two corresponding to no correlation at a negative lag and no correlation at a positive lag are not particularly meaningful in isolation and are, thus, left blank.

The remaining seven cells can each be linked to one or more mechanisms creating an association between reported COVID-19 mortality and excess mortality from a particular cause of death. Starting from the first row of **Table 1**, there can be a positive correlation between the two series at a negative, zero, or positive lag. In the authors' view, the most likely mechanism leading to a positive correlation at a negative or zero lag is underreporting of COVID-19 deaths (which, thus, get assigned to other causes of death). If it is believed that underreporting would constitute a fixed proportion of all COVID-19 deaths, then the authors would expect the positive correlation to be observed exclusively at a zero lag. However, it is also possible that underreporting would be declining over time, in which case, depending on the rate of decline, the "transfer" of deaths from COVID-19 to other causes of death could peak before COVID-19 mortality. Finally, it is also possible that underreporting would respond dynamically to peaks in COVID-19 mortality. Underreporting might be higher before a peak in COVID-19, when awareness is lower, and lower after a peak in COVID-19, when awareness is higher. The last two patterns, *declining underreporting* and *awareness underreporting*, would produce a positive correlation at a negative lag in addition to a positive correlation at a zero lag. Awareness underreporting would also imply a negative correlation at a positive lag, as underreporting would be lowest after a peak in COVID-19 mortality, before increasing again. The final cell of the first row, positive correlation at a positive lag, has its most plausible explanation in scarring effects (COVID-19 survivors having a higher risk of dying from other causes) or in delayed effects of the disruption in the healthcare system.

The second row, with only one relevant cell, covers the interpretation of findings of no correlation. If no correlation between cause-specific excess mortality and COVID-19 mortality is detected, then it is likely that the cause-specific excess is not directly related to COVID-19. This lack of correlation does not mean that the indirect effects of COVID-19 did not play a role in the observed excess mortality. It is possible that the economic disruption brought about by the pandemic, as well as behavioral changes, or the public health policies introduced to limit the spread of COVID-19 each led to lower or higher mortality than expected. However, excess mortality associated with these mechanisms would be unlikely to show temporal correlation with COVID-19 mortality and thus lead to null results.

The last row of the table covers the cases in which a negative correlation is observed at a negative, zero, or positive lag. The first cell, negative correlation at a negative lag, is the hardest to explain, and the authors were not able to formulate a plausible explanation for this pattern. However, this pattern was never observed in the results. The second cell, negative correlation at a zero lag, would be consistent with overreporting or mortality displacement. In the case of overreporting, official COVID-19 death counts would partially reflect mortality from other causes, inducing a contemporaneous negative correlation between cause-specific excess and COVID-19 deaths. In the case of mortality displacement, a similar pattern would be observed because COVID-19 is replacing other causes of death, something that likely occurred with influenza and pneumonia. A large role of overreporting and displacement is, however, unlikely when excess deaths exceed COVID-19 by a large margin, as in the United States. In the presence of widespread overreporting or mortality displacement, COVID-19 deaths would be expected to exceed excess deaths, as in France and Belgium[18], with negative excess mortality for a large number of causes of death. The last cell, negative correlation at a positive lag, is consistent either with selection (COVID-19 eliminates the most fragile at time t and, thus, reduces mortality at time t+1) or, as mentioned, is compatible with underreporting under the awareness hypothesis. The Supplementary Material contains a more extensive discussion of different underreporting scenarios.

Section 4: Trends in Cause-Specific and Age-Specific Excess Mortality

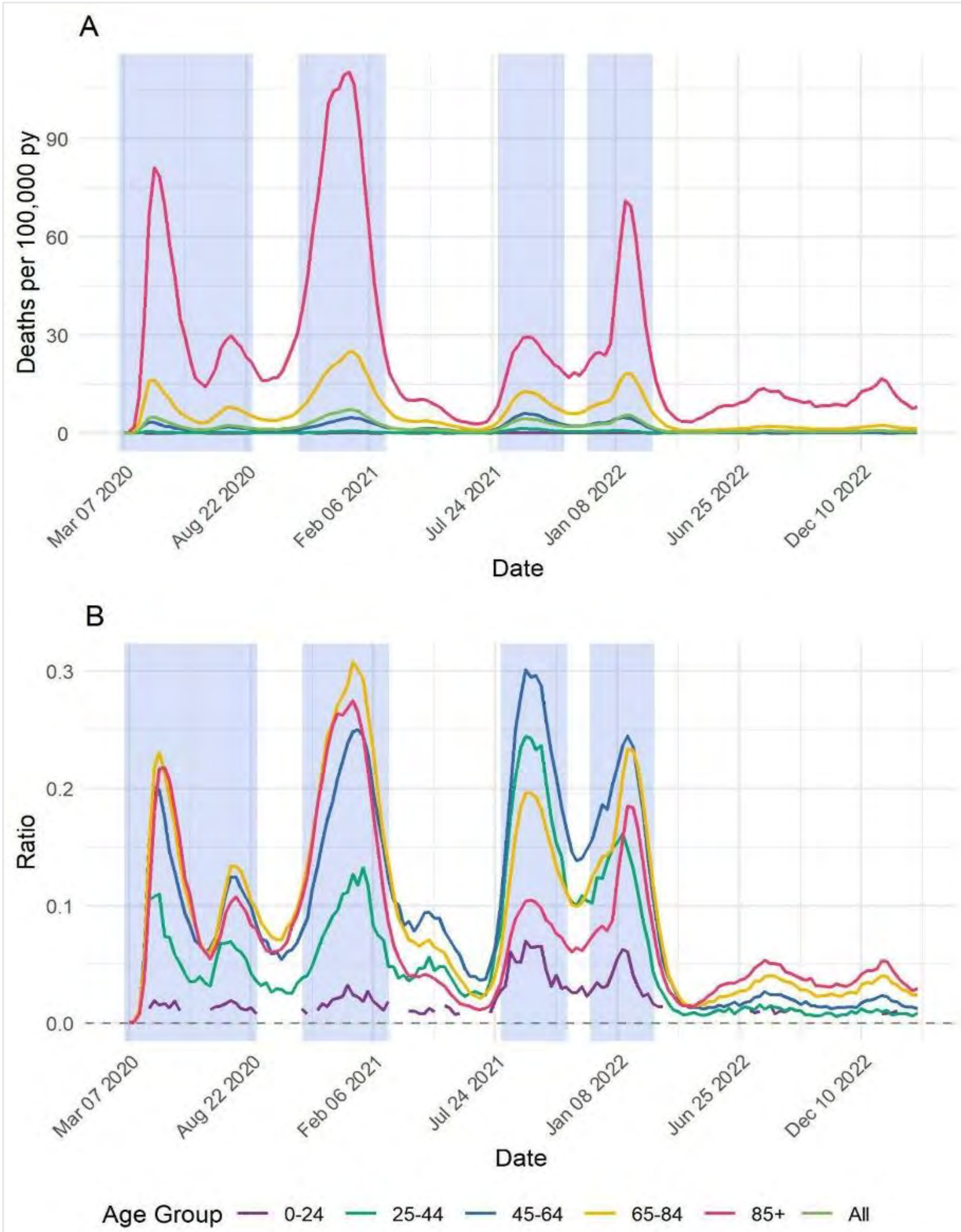
4.1 COVID-19 MORTALITY BY AGE AND TIME, MARCH 2020 – FEBRUARY 2023

Figure 1A shows the number of weekly deaths assigned to COVID-19 for all ages combined and by broad age groups. Several interesting patterns can be observed. First, COVID-19 mortality exhibits a seasonal pattern that can parsimoniously be described as the sum of a winter peak in November–January (which was more of a spring peak in the first year) and a summer peak in August–October (which occurred a bit earlier in the first year). The size of the peaks changed during the pandemic, with the deadliest winter peak occurring between November 2020 and January 2021 and the deadliest summer peak occurring between August and October 2021. In each period, the winter peak shows higher mortality compared to the summer peak. It is also notable that both peaks can be observed also in the third and fourth years of the pandemic (March 2022 – February 2023 and March 2023 – February 2024), when the level of COVID-19 mortality was substantially lower.

COVID-19 mortality showed a strong positive age gradient when measured as deaths per 100,000 residents (death rates). The gradient can be observed throughout the pandemic, though both the absolute and relative gap between age groups narrowed over time. When looking at mortality rates, ages 85+ had the highest COVID-19 death rates, followed by ages 65–84, and ages 45–64 and 25–44. The presence of an age gradient is not surprising given that most infectious diseases, and all-cause mortality more generally, show a similar age distribution. It is, thus, natural to go one step further and ask whether COVID-19 mortality showed a steeper age gradient than anticipated based on expected all-cause mortality. To answer this question, the number of age-specific COVID-19 deaths in each week can be divided by the corresponding number of expected all-cause deaths and mortality rate ratios or P-scores can be computed. The results of this exercise are presented in Figure 1B. They show that, in relative terms (i.e., as a proportion of expected all-cause mortality) and with the exception of the second summer peak (related to the Delta variant), mortality increased similarly in age groups 45–64, 65–84, and 85+, with age groups 0–24 and 25–44 showing more moderate excess. As documented elsewhere, the peak related to the Delta variant shows a very different age pattern, with a negative age gradient (except for age group 0–24). Overall, these findings suggest that, at least as a first approximation, COVID-19 was as selective as all-cause mortality before the pandemic but showed less selectivity during the Delta wave. In other words, individuals dying of COVID-19 likely had a similar number of remaining years of life compared to those dying of all causes before the pandemic, but likely had a higher number of remaining years of life during the Delta wave. This gives evidence against strong selection effects.

Figure 1

WEEKLY COVID-19 DEATH RATES FOR ALL AGES AND BY AGE GROUP (A) AND MORTALITY RATIOS BY AGE GROUP (B)

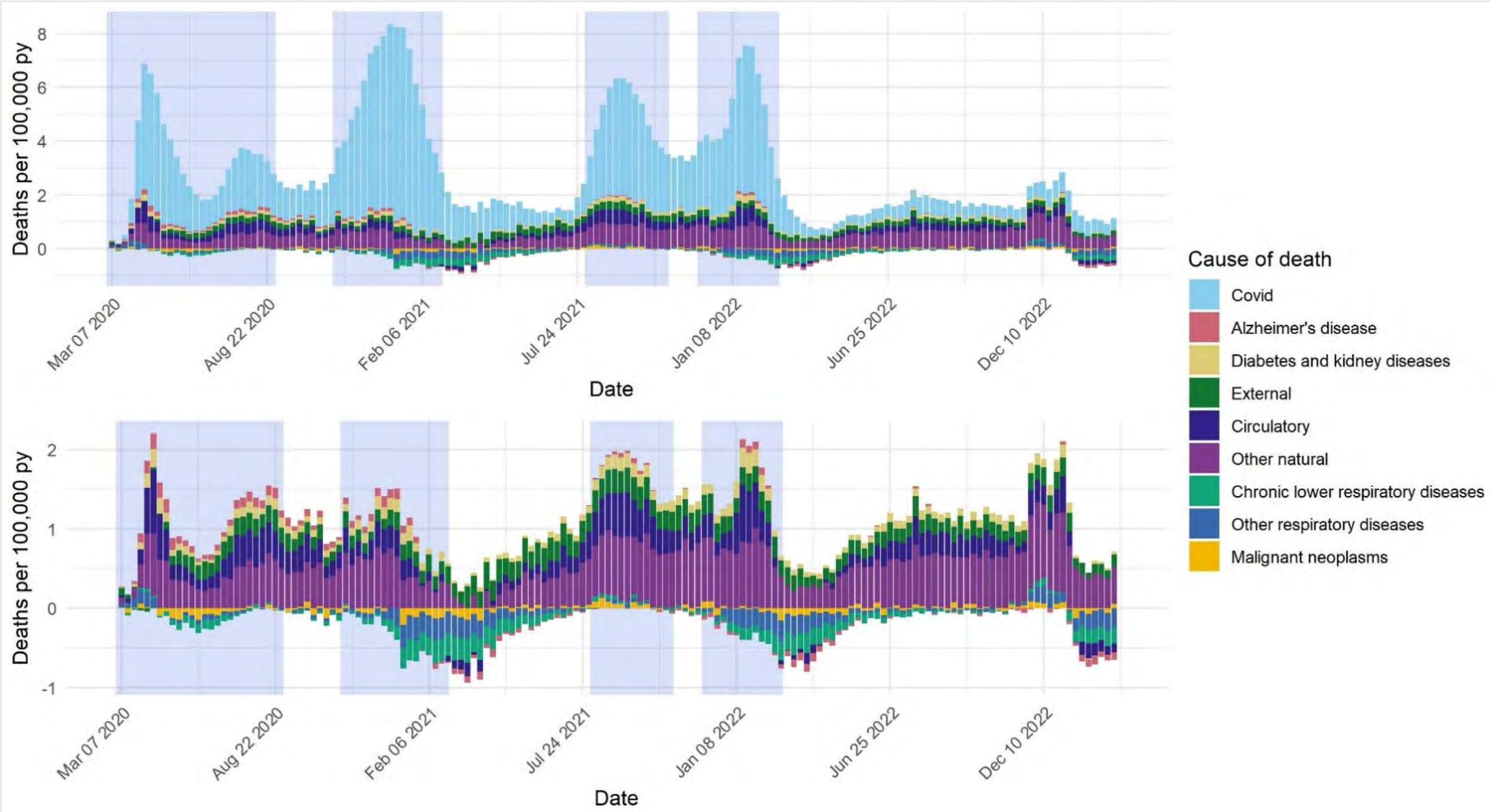


Notes. Observed death counts under 10 were censored. ARIMA models were fitted to weekly observed all-cause death rates from the week ending January 10th, 2015, to the week ending February 29th, 2020, and projected from the week ending March 7th, 2020, to the week ending February 25th, 2023, to estimate all-cause expected death rates for each age group and all ages combined. In panel B, the ratio is calculated as: (observed covid rate) / (expected all-cause death rate).

4.2 TRENDS IN CAUSE-SPECIFIC EXCESS MORTALITY FOR ALL AGES COMBINED

Figure 2 shows the contribution of different causes of deaths to excess mortality. Looking at Figure 2A, COVID-19 contributed the highest number of deaths per capita, though the proportion of all excess deaths contributed by COVID-19 declined over time. Excess deaths assigned to causes other than COVID-19 show less variability than COVID-19 deaths but similar patterns (peaks and troughs) over time. Figure 2B, which highlights the role of causes other than COVID-19, shows that most natural and external causes of death had higher mortality rates than expected. The notable exceptions are deaths from respiratory diseases, showing negative excess, and deaths from malignant neoplasms, showing little excess. Cardiovascular diseases, Alzheimer's disease, and diabetes and kidney diseases, represented less than half of all deaths from natural causes, indicating that excess mortality occurred across most natural causes and not just within selected ones. As noted, mortality from external causes was also elevated throughout the period. Cause-specific excess and expected mortality rates are summarized in Table 2 for each pandemic year.

Figure 2
WEEKLY EXCESS DEATH RATES BY CAUSE OF DEATH



Notes. The two panels display the same data but the bottom panel zooms-in on causes of death other than COVID-19. Observed death counts under 10 were censored. ARIMA models were fitted to weekly observed all-cause death rates from the week ending January 10th, 2015, to the week ending February 29th, 2020, and projected from the week ending March 7th, 2020, to the week ending February 25th, 2023, to estimate all-cause expected death rates for each age group and all ages combined.

Table 2

EXCESS AND EXPECTED DEATH RATES BY CAUSE OF DEATH AND PANDEMIC YEAR

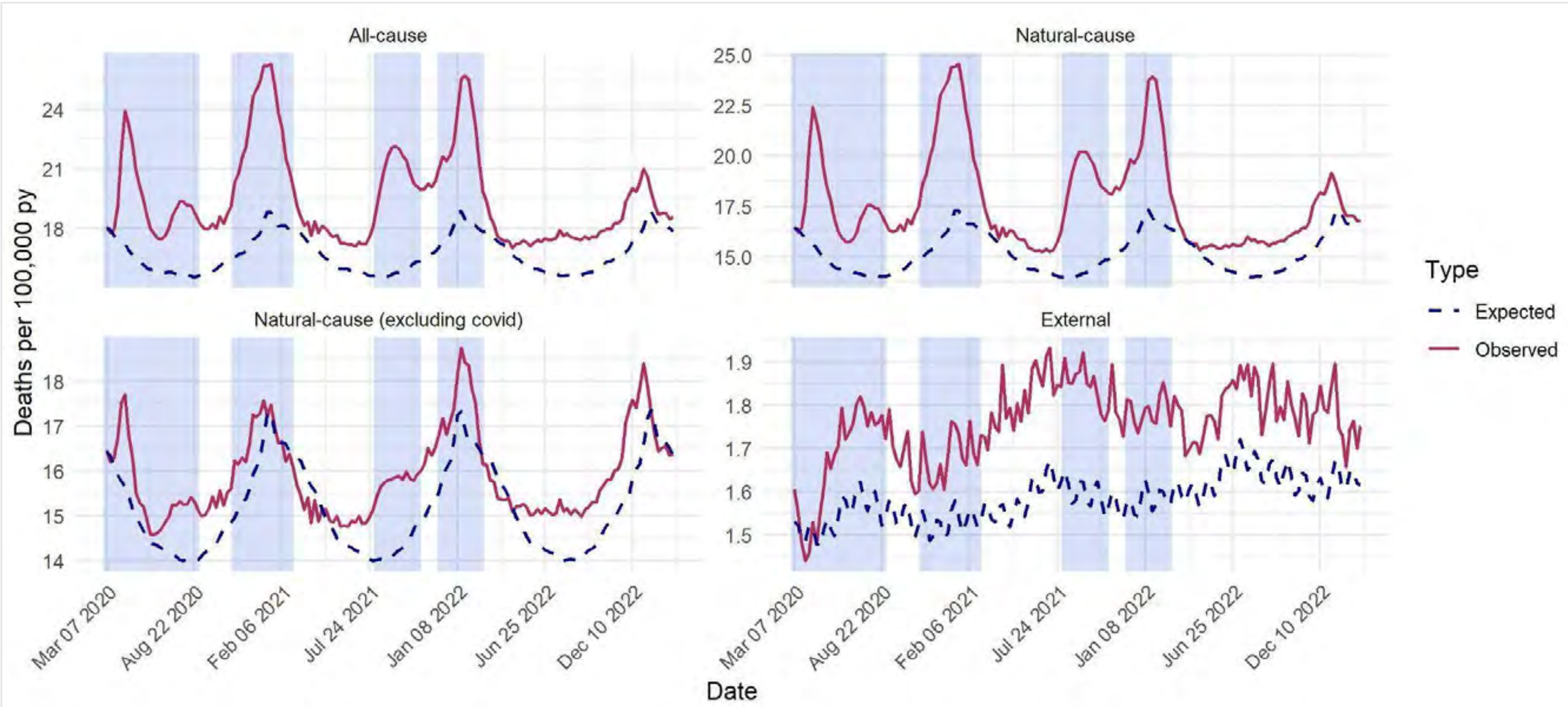
	Year 1 March 2020 – February 2021		Year 2 March 2021 – February 2022		Year 3 March 2022 – February 2023	
	Expected Rate (95% CI)	Excess Rate (95% CI)	Expected Rate (95% CI)	Excess Rate (95% CI)	Expected Rate (95% CI)	Excess Rate (95% CI)
All-cause, Natural-cause & External cause						
All-cause	869.4	193.0	868.4	172.6	868.4	75.6
Natural-cause (including COVID-19)	790.0	185.3	789.0	157.7	789.0	62.0
Natural-cause (excluding COVID-19)	790.0	37.8	789.0	40.2	789.0	35.1
External	80.0	7.2	82.4	11.9	84.8	8.2
Specific Causes						
COVID-19	–	147.5	–	117.5	–	26.9
Heart diseases	176.8	10.0	176.7	9.4	176.7	4.0
Accidents	54.9	7.2	56.5	11.6	58.2	9.7
Diabetes mellitus	26.6	5.0	26.6	4.6	26.6	2.9
Alzheimer's disease	36.5	4.2	36.6	-0.6	36.6	-1.6
Cerebrovascular diseases	45.6	3.0	45.6	3.8	45.6	3.1
Septicemia	11.5	0.5	11.5	1.0	11.5	1.1
Ill-defined	9.8	0.5	9.8	0.7	9.8	0.0
Kidney diseases	15.6	0.3	15.6	1.1	15.6	1.4
External substances	1.9	0.2	2.0	0.1	2.0	-0.2
Other respiratory diseases	14.2	-0.8	14.6	-0.6	15.0	-0.5
Suicide	14.8	-1.0	15.3	-0.6	15.7	-0.7
Malignant neoplasms	182.3	-2.1	182.3	0.0	182.3	-0.3
Influenza and pneumonia	17.0	-2.4	16.9	-4.1	16.9	-2.5
Chronic lower respiratory diseases	48.1	-4.0	48.2	-4.7	48.2	-4.2
Other natural	207.3	169.8	207.3	144.5	207.3	55.4
Other external	8.4	1.7	8.6	1.7	8.9	0.3

Notes. Rates are calculated as deaths per 100,000 person-years. Midyear population values: Year 1 – 331,660,758; Year 2 – 332,294,082; Year 3 – 333,133,413

Figure 3 and **Figure 4** examine expected and observed deaths by week and selected causes for the period March 2020 – February 2023. In **Figure 3,** deaths are presented by four broad groups of causes of death: all causes combined, natural causes (including COVID-19), natural causes (excluding COVID-19), and external causes. Each broad group displays significant excess mortality, which manifest as a larger number of observed than expected deaths. The temporal trend in total excess mortality is dominated by COVID-19 in the first two years of the pandemic, as can be seen by comparing the temporal patterns with those in **Figure 1** but becomes progressively less related. This is not surprising given that in the first two pandemic years, COVID-19 accounted for 76.4% and 68.1% of all excess deaths, respectively, but for only 35.6% in the third year. Overall, excess mortality for all natural causes combined excluding COVID-19 also shows a temporal pattern similar to COVID-19 mortality with two important differences: 1) the height of the peaks shows less variability, and 2) there is no clear ranking between summer and winter peaks. There are two exceptions to this general picture. The first is cancer mortality, shown in **Figure 4**, for which, as noted, there is little excess mortality. The second is mortality from influenza and pneumonia,[19] shown in **Figure 4**, for which negative excess is observed for most of the period, except for the first few months of the pandemic, and an early influenza season starting in November 2023. It is worth noting that the seasonality of influenza mortality during the pandemic deviates from the pre-pandemic patterns and seems to align more closely with that of COVID-19 deaths, suggesting that some COVID-19 deaths might have been incorrectly assigned to influenza and pneumonia. The seasonality in excess mortality from natural causes can be explained by three types of mechanisms: 1) deaths from natural causes exhibited a marked seasonality even before the pandemic, so that an additional force of mortality acting multiplicatively would produce excess deaths with the same seasonal pattern as pre-pandemic deaths, 2) it is likely that some COVID-19 deaths have been erroneously attributed to natural causes, which, given the seasonality of COVID-19, would produce a similar seasonality in excess deaths from natural causes,[20] and 3) it is possible that surviving a COVID-19 infection would increase the risk of dying from other natural causes, which would produce a similar seasonality in excess deaths from natural causes. The temporal correlation analysis will allow us to understand the relative importance of these three mechanisms.

Mortality from external causes (see **Figure 3** for all deaths combined and **Figure 4** for more detailed causes) was also higher than expected throughout the pandemic but exhibits no clear seasonal pattern, rather remaining approximately constant. Within external causes, while accidents mortality and mortality from other external causes were above expected levels, mortality from suicides, and external substance-related deaths showed no systematic excess (**Figure 4**). The authors were unable to examine substance-related deaths assigned to natural causes (ICD-10 codes F10-F16, F19, K70, K73-K74), which likely increased during the pandemic.[21] A key difference between substance-related natural deaths and substance-related external deaths is that the former are mostly attributable to alcohol consumption, while the latter are mostly attributed to other substances, particular opioids. The finding of little excess mortality for external substance-related deaths suggests that the overall increase in substance-related deaths is likely due to an increase in alcohol consumption, rather than to higher consumption of other substances. The lack of seasonality in excess mortality from external causes is not very surprising given that 1) external deaths before the pandemic did not show a marked seasonality, 2) compared to natural causes it is less likely that COVID-19 deaths might have been erroneously attributed to an external cause, and 3) it less likely that surviving a COVID-19 infection would increase the risk of dying from an external cause.

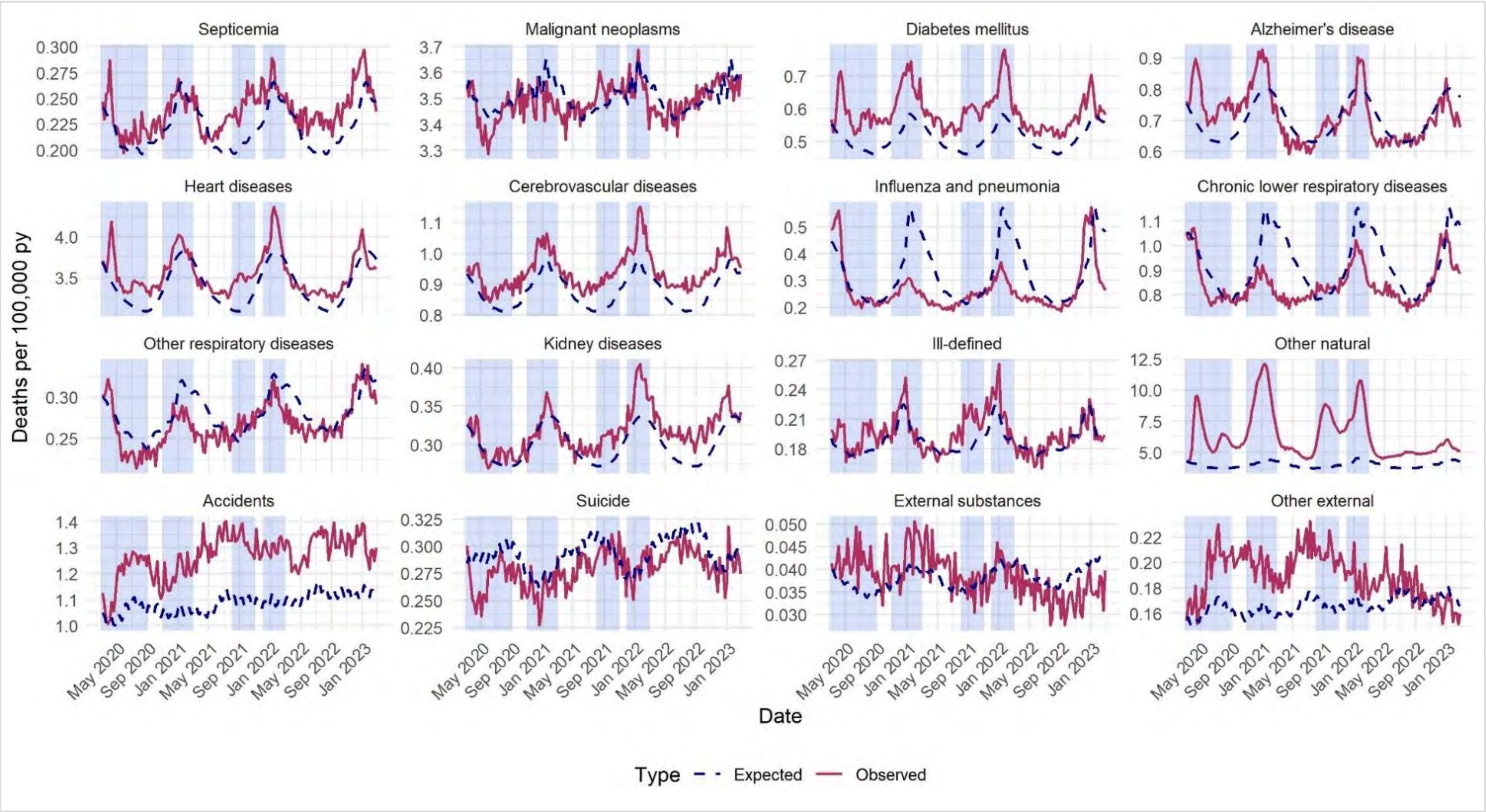
Figure 3
WEEKLY OBSERVED AND EXPECTED DEATH RATES BY CAUSE OF DEATH (BROAD CAUSES)



Notes. Rates are calculated as deaths per 100,000 person-years. ARIMA models were fitted to weekly observed cause-specific death rates from the week ending January 10th, 2015, to the week ending February 29th, 2020, and projected from the week ending March 7th, 2020, to the week ending February 25th, 2023, to estimate expected death rates for each cause of death for all ages combined. Excess is calculated as [(observed rate) - (expected rate)].

Figure 4

WEEKLY OBSERVED AND EXPECTED DEATH RATES BY CAUSE OF DEATH (DETAILED CAUSES)



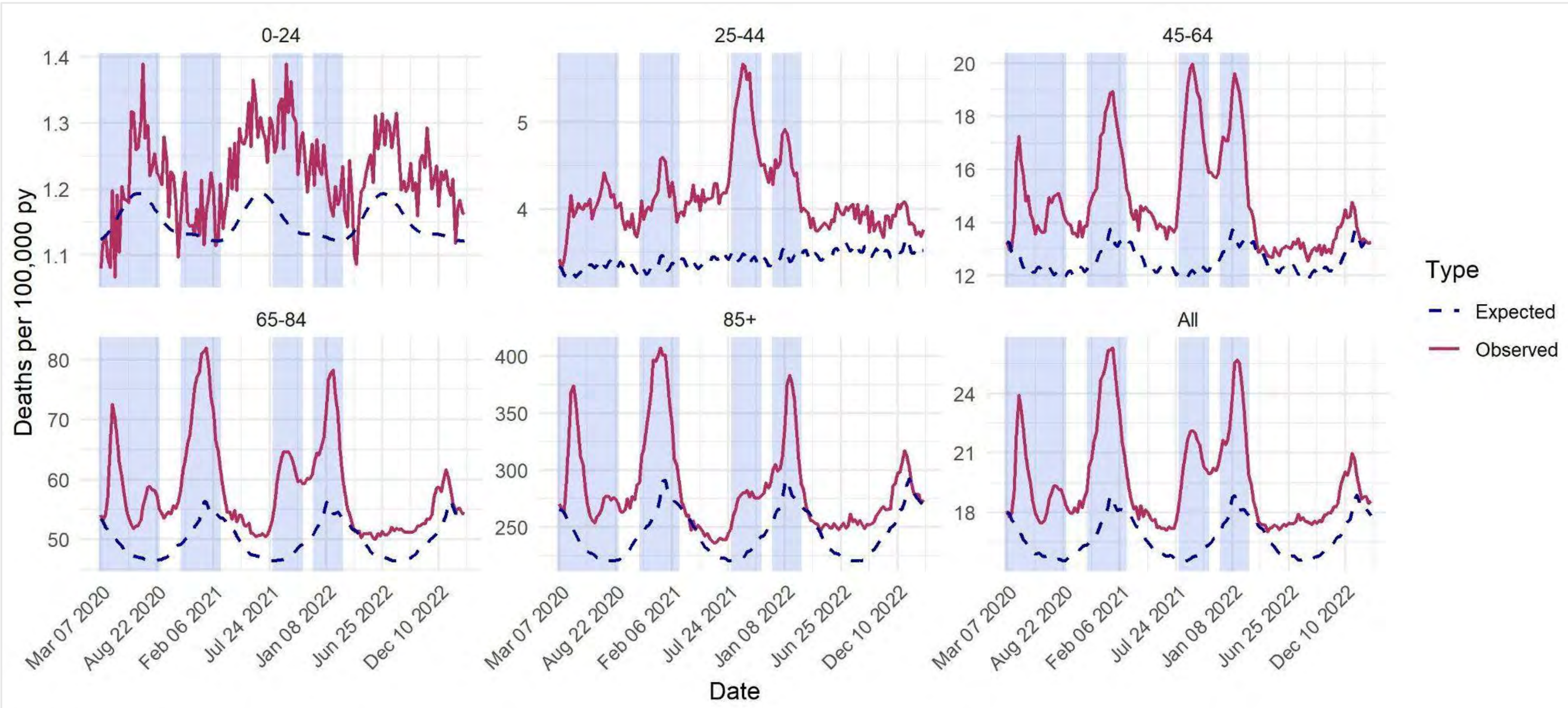
Notes. Rates are calculated as deaths per 100,000 person-years. ARIMA models were fitted to weekly observed cause-specific death rates from the week ending January 10th, 2015, to the week ending February 29th, 2020, and projected from the week ending March 7th, 2020, to the week ending February 25th, 2023, to estimate expected deaths for each cause of death for all ages combined. Excess is calculated as [(observed rate) - (expected rate)].

4.3 TRENDS IN AGE-SPECIFIC EXCESS MORTALITY BY BROADER GROUPS OF CAUSES

Figure 5 presents age-specific rates of expected and observed mortality for all causes combined. Figure 6 focuses on excess mortality and presents age-specific ratios of excess to expected mortality or P-scores. Values larger than zero indicate positive excess (as a proportion of expected deaths), while negative values indicate lower than expected mortality. The panel for all causes combined shows age-specific ratios similar to the ones for COVID-19 mortality in Figure 1B. Ages 85+, 65–84, and 45–64 have similar relative excess, except between March 2021 and December 2021 when relative excess for ages 85+ was lower (and even negative between March and June). Once external causes were removed (from both the numerator and denominator), it was found that ages 24–44 had the highest relative excess in all months, except during the second winter peak when they were tied with the other groups (excluding ages 0–24). The relative disadvantage of the 25–44 group is even more pronounced after removing deaths assigned to COVID-19 from the numerator. Age-specific excess and expected rates for each pandemic year are summarized in Table 3.

Figure 5

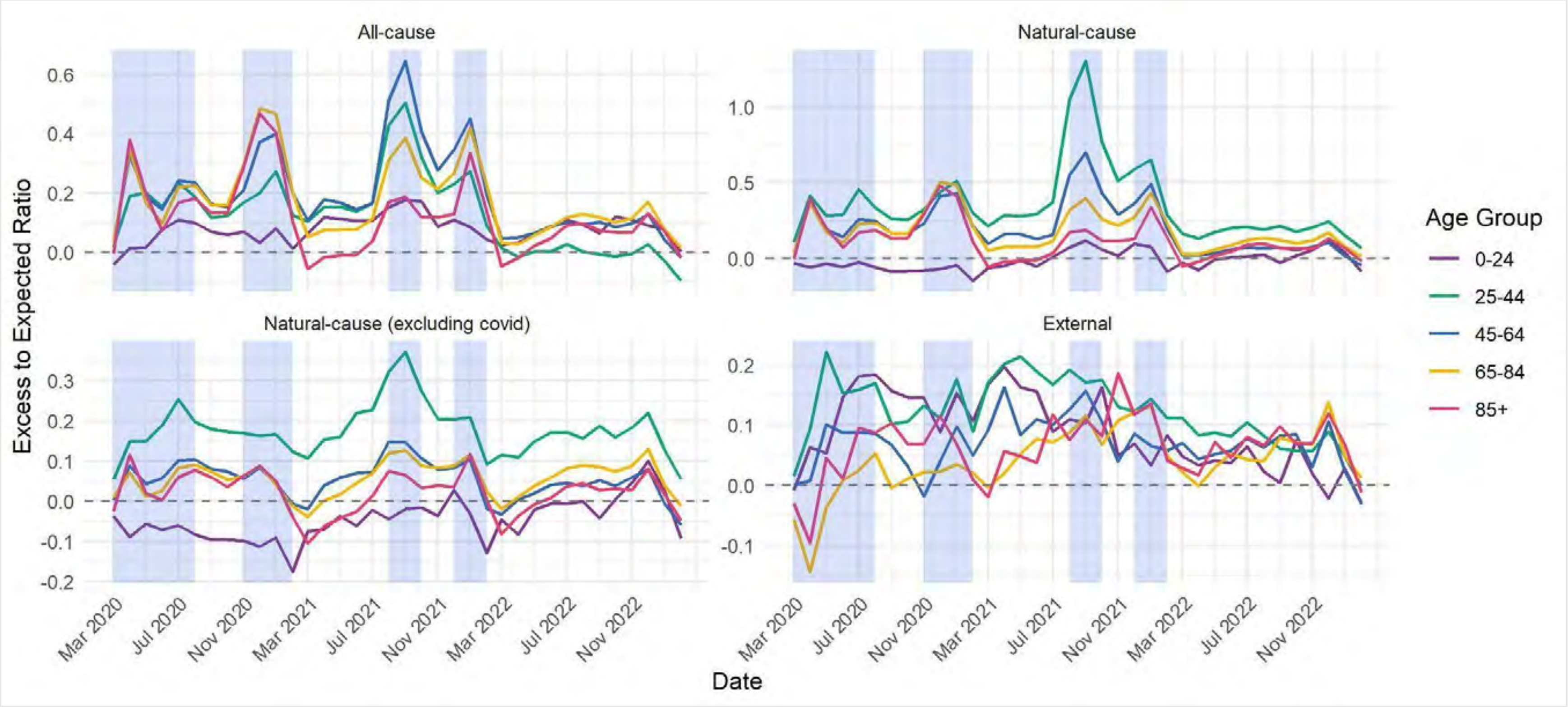
WEEKLY OBSERVED AND EXPECTED ALL-CAUSE DEATH RATES BY AGE-GROUP



Notes. Rates are calculated as deaths per 100,000 person-years. ARIMA models were fitted to weekly observed cause-specific death rates from the week ending January 10th, 2015, to the week ending February 29th, 2020, and projected from the week ending March 7th, 2020, to the week ending February 25th, 2023, to estimate expected all-cause death rates for each age-group. Excess is calculated as [(observed rate) - (expected rate)].

Figure 6

MONTHLY EXCESS TO EXPECTED RATIOS BY CAUSE OF DEATH AND AGE CATEGORY



Notes. Rates are calculated as deaths per 100,000 person-years. ARIMA models were fitted to monthly observed cause-specific death rates from March 2015 to February 2020 and projected from March 2020 to March 2023 to estimate expected deaths for each cause of death for each age group. Excess to expected ratios are calculated as [(excess rate)/(expected rate)].

Table 3

EXPECTED AND EXCESS DEATH RATES BY CAUSE OF DEATH AND AGE CATEGORY

	Year 1 March 2020 – February 2021			Year 2 March 2021 – February 2022			Year 3 March 2022 – February 2023		
	Expected Rate (95% CI)	Excess Rate (95% CI)	Population	Expected Rate (95% CI)	Excess Rate (95% CI)	Population	Expected Rate (95% CI)	Excess Rate (95% CI)	Population
All-cause									
0–24	59.8	2.2	104,507,600	59.8	5.7	103,974,398	59.8	3.6	103,757,480
25–44	172.7	36.2	88,354,248	177.5	57.4	88,770,334	182.4	19.8	89,277,285
45–64	653.2	134.4	83,679,345	653.2	183.1	83,009,008	653.2	38.0	82,435,561
65–84	2,595.1	625.2	48,618,163	2,595.2	505.5	50,055,230	2,595.2	177.4	51,633,688
85+	12,740.1	3,298.0	6,501,402	12,739.1	1,712.8	6,485,112	12,739.0	1,065.9	6,533,452
Natural-cause (including COVID-19)									
0–24	31.1	-2.6	104,507,600	31.1	0.0	103,974,398	31.1	-0.3	103,757,480
25–44	80.6	20.4	88,354,248	82.9	35.1	88,770,334	85.1	4.4	89,277,285
45–64	566.4	124.6	83,679,345	566.4	163.6	83,009,008	566.4	17.5	82,435,561
65–84	2,497.4	620.7	48,618,163	2,497.5	490.5	50,055,230	2,497.5	162.4	51,633,688
85+	12,349.2	3,257.7	6,501,402	12,348.3	1,651.9	6,485,112	12,348.2	1,010.6	6,533,452
Natural-cause (excluding COVID-19)									
0–24	31.1	-3.2	104,507,600	31.1	-1.7	103,974,398	31.1	-0.6	103,757,480
25–44	80.6	7.5	88,354,248	82.9	9.3	88,770,334	85.1	2.3	89,277,285
45–64	566.4	24.2	83,679,345	566.4	31.0	83,009,008	566.4	3.7	82,435,561
65–84	2,497.4	117.5	48,618,163	2,497.5	119.6	50,055,230	2,497.5	78.4	51,633,688
85+	12,349.2	990.5	6,501,402	12,348.3	577.4	6,485,112	12,348.2	510.1	6,533,452
External									
0–24	28.6	4.8	104,507,600	28.7	5.6	103,974,398	28.7	3.9	103,757,480
25–44	92.0	15.9	88,354,248	94.7	22.3	88,770,334	97.3	15.4	89,277,285
45–64	86.8	9.8	83,679,345	86.8	19.5	83,009,008	86.8	20.6	82,435,561
65–84	97.7	4.5	48,618,163	97.7	15.0	50,055,230	97.7	15.0	51,633,688
85+	390.9	40.3	6,501,402	390.8	60.9	6,485,112	390.8	55.3	6,533,452
COVID-19									
0–24	–	0.7	104,507,600	–	1.8	103,974,398	–	0.3	103,798,222
25–44	–	12.9	88,354,248	–	25.8	88,770,334	–	2.1	89,139,125
45–64	–	100.4	83,679,345	–	132.6	83,009,008	–	13.7	82,548,114
65–84	–	503.2	48,618,163	–	370.9	50,055,230	–	84.0	51,171,146
85+	–	2,267.2	6,501,402	–	1,074.5	6,485,112	–	500.5	6,476,806

Notes. Rates are calculated as deaths per 100,000 person-years. Observed death counts under 10 were censored. ARIMA models were fitted to weekly observed all-cause death rates from the week ending January 10th, 2015, to the week ending February 29th, 2020, and natural-cause and external death rates from the week ending January 6th, 2018, to the week ending February 29th, 2020, and projected from the week ending March 7th, 2020, to the week ending February 25th, 2023, to estimate expected death rates for each age group and all ages combined. Natural-cause and external estimates were scaled by historical age-specific distribution to aggregate to age-specific all-cause estimates.

Looking at the more detailed causes in **Supplementary Figure 1**, it can be seen that this pattern is driven by CVD mortality and by causes of death in the residual category. Also notice a sudden peak in excess mortality from Influenza and Pneumonia for ages 25–44 in September 2021, which coincides with the Delta wave of COVID-19 mortality. Taken together, these observations suggest that an underreporting of COVID-19, higher mortality risk from CVD following a COVID-19 infection, and possible healthcare interruptions lie behind the more pronounced disadvantage for ages 25–44 in excess mortality excluding COVID-19. Individuals in ages 25–44 were also at an increased risk of death from external causes (**Figure 6**), driven by both accidents and substance use (**Supplementary Figure 1**). However, the proportional increase in mortality from external causes, for this and other age groups, was small in comparison with the proportional increase in mortality from natural causes.

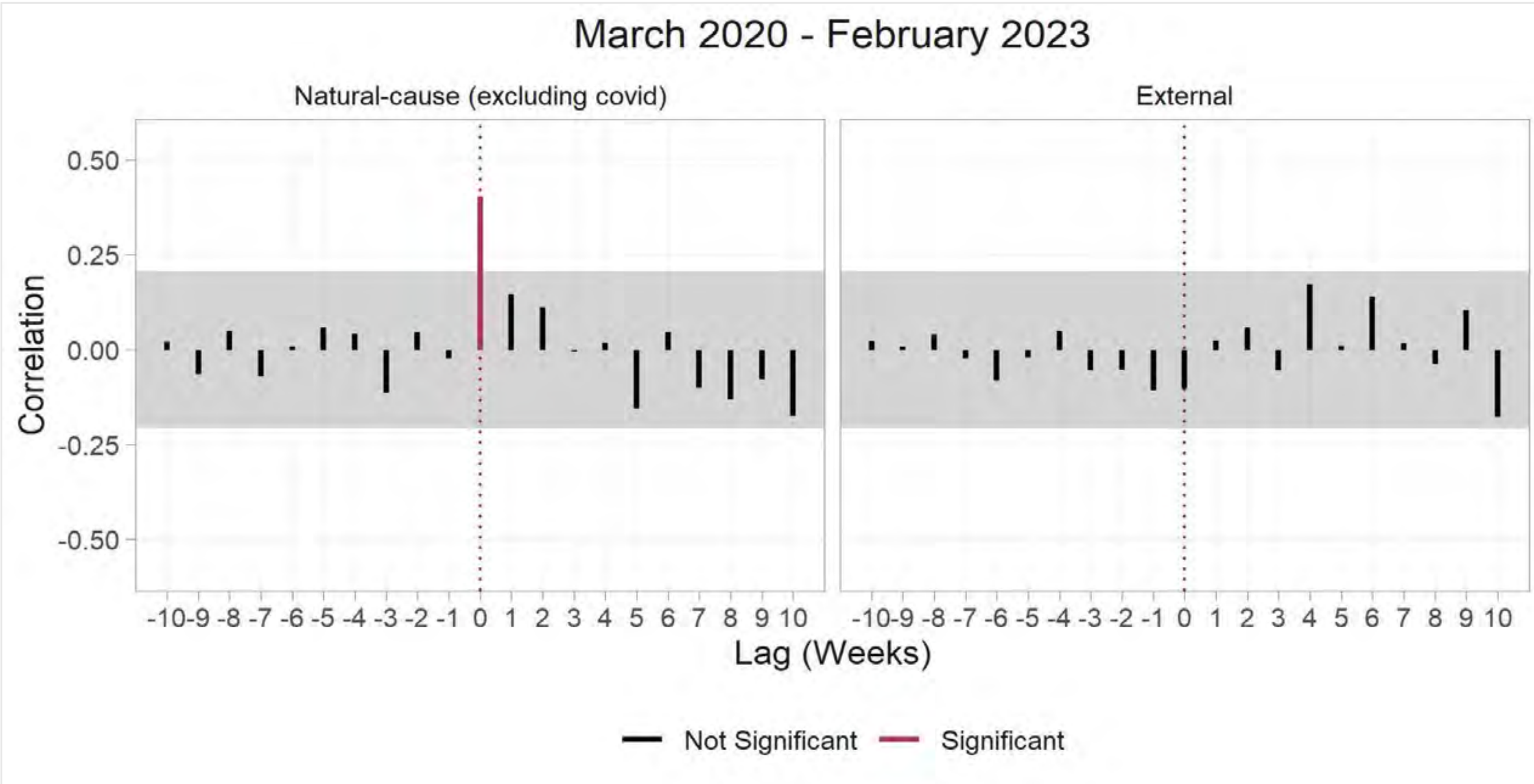
Section 5: Temporal Correlation between Excess Mortality and COVID-19 Mortality

5.1 TEMPORAL CORRELATION BETWEEN COVID-19 MORTALITY AND CAUSE-SPECIFIC EXCESS MORTALITY

Figure 7 shows the results of the temporal correlation analysis by broad and detailed causes of death. For all natural causes combined, the authors find a positive correlation between COVID-19 mortality and the cause-specific excess mortality series at lag zero (same week). Based on our theoretical framework, this is most consistent with a mix of underreporting and increased mortality due to stress on the healthcare system.

Figure 7

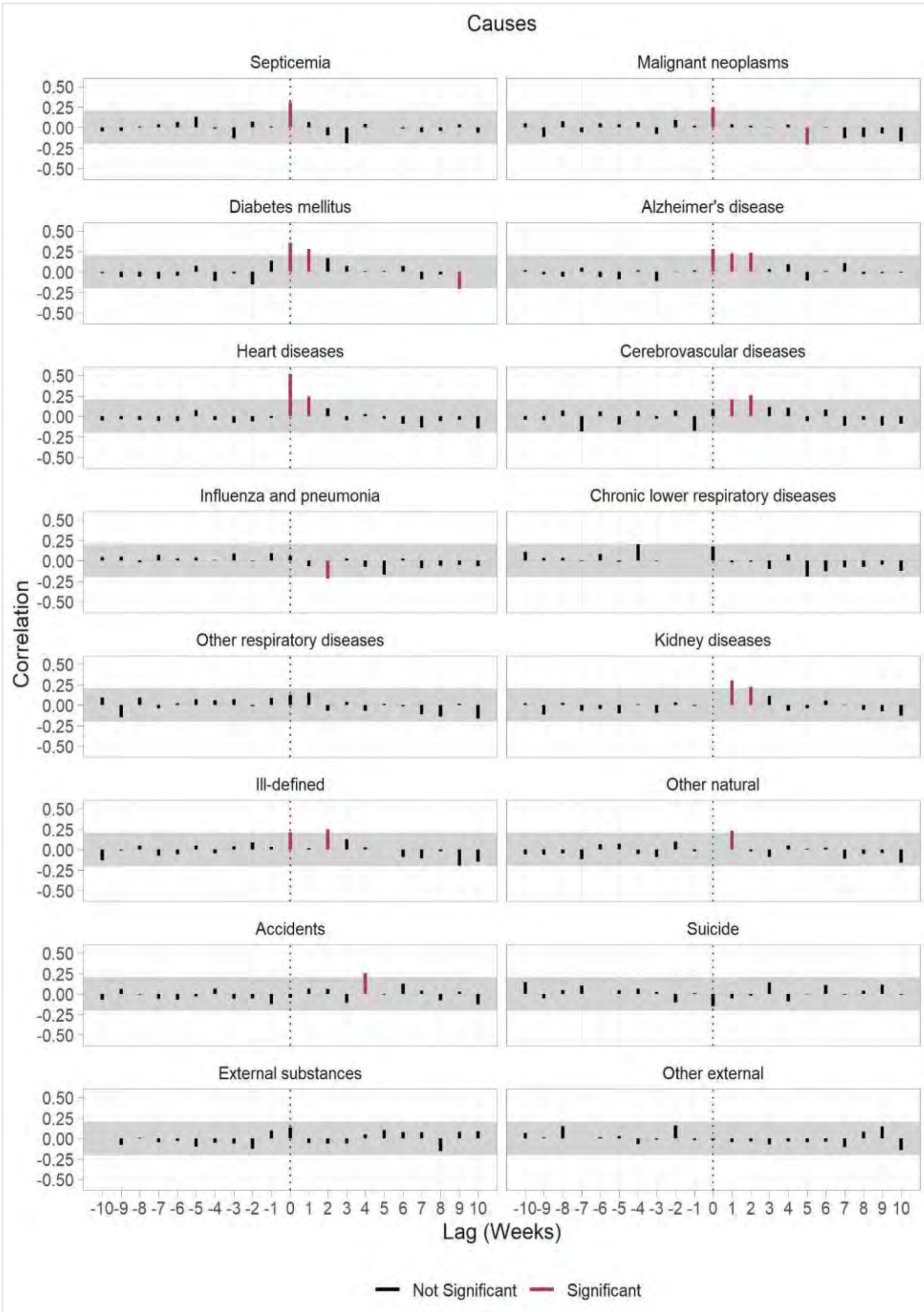
WEEKLY CROSS-CORRELATIONS BETWEEN COVID-19 DEATHS AND EXCESS DEATHS, WEEK ENDING MARCH 7TH, 2020 – WEEK ENDING FEBRUARY 25TH, 2023



Notes. Cross-correlation plots examining temporal correlations between the weekly time series for reported COVID-19 deaths converted to rates and the weekly time series for excess deaths reported to causes other than COVID-19 converted to rates, week ending March 7th, 2020, through week ending February 25th, 2023. Increases in reported COVID-19 deaths may correlate with increases (positive correlation coefficient) or decreases (negative correlation coefficient) in excess deaths reported to non-COVID-19 causes. The x axis indicates the time lag in weeks. Increases in reported COVID-19 deaths may correlate with changes in excess deaths reported to non-COVID-19 causes in the same month (lag 0), in future months (lag greater than 0), and/or in previous months (lag less than 0). Correlation coefficients that are outside the gray shaded area indicate significance at alpha = 0.01 and are colored red to assist with interpretation.

Figure 8

WEEKLY CROSS-CORRELATIONS BETWEEN COVID-19 DEATHS AND EXCESS DEATHS BY SELECT CAUSES OF DEATH, WEEK ENDING MARCH 7TH, 2020 – WEEK ENDING FEBRUARY 25TH, 2023

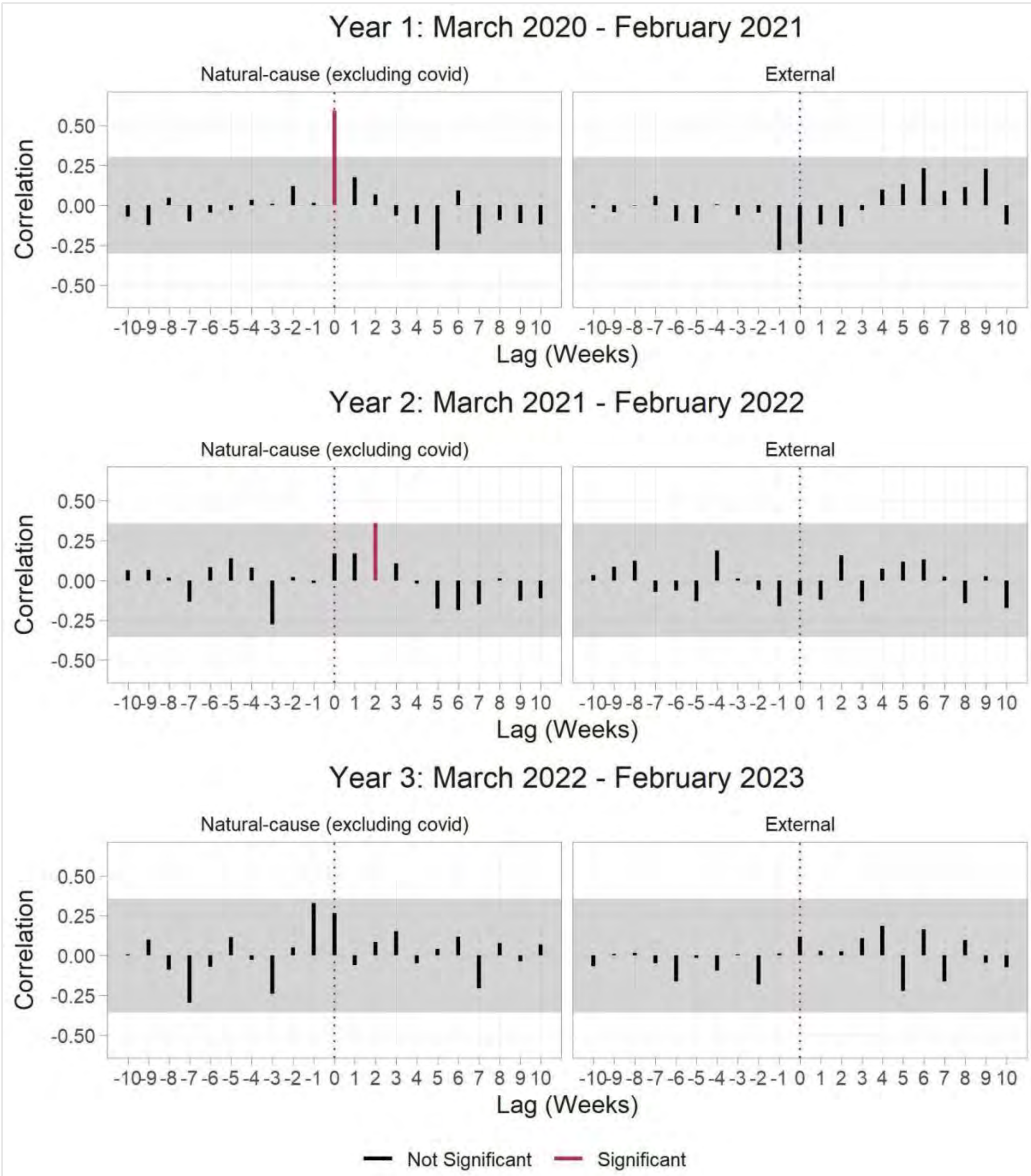


Notes. Cross-correlation plots examining temporal correlations between the weekly time series for reported COVID-19 deaths converted to rates and the weekly time series for excess deaths reported to causes other than COVID-19 converted to rates, week ending March 7th, 2020, through week ending February 25th, 2023. Increases in reported COVID-19 deaths may correlate with increases (positive correlation coefficient) or decreases (negative correlation coefficient) in excess deaths reported to non-COVID-19 causes. The x-axis indicates the time lag in weeks. Increases in reported COVID-19 deaths may correlate with changes in excess deaths reported to non-COVID-19 causes in the same month (lag 0), in future months (lag greater than 0), and/or in previous months (lag less than 0). Correlation coefficients that are outside the gray shaded area indicate significance at alpha = 0.01 and are colored red to assist with interpretation.

Looking at the more detailed causes in Figure 8 helps us shed more light on the relative importance of these explanations. The positive correlation at zero is visible for heart diseases, diabetes, malignant neoplasm, Alzheimer's disease, and septicemia. A positive correlation at a positive lag (indicating that peaks in COVID-19 are followed by increased excess) is visible for Alzheimer's disease, heart disease and other CVDs, and kidney diseases. The fact that the positive correlation at positive lags is present for CVD and diabetes, for both of which COVID-19 is a risk factor, suggests that scarring might be playing a role. The residual category shows a positive correlation at lag zero, but not at positive lags. Cancer mortality also shows a positive correlation at lag zero, but it appears to be weak. Interestingly, influenza and pneumonia show a negative correlation at lag two, suggesting that COVID-19 displaced influenza and pneumonia deaths. Taken together, these findings suggest that some scarring likely took place for CVD and diabetes, while an underreporting of COVID-19 is likely for most natural causes of death. It is harder to reach a conclusion regarding the role of healthcare interruptions. This question can be illuminated by looking at deaths from external causes. Neither external deaths as an aggregate nor the more detailed causes show any correlation with COVID-19 mortality. This provides some evidence against a sizable role of healthcare interruptions. If healthcare interruptions were an important explanation for the lag zero and lag one correlation between COVID-19 and natural causes, the same correlation would be expected to show up for some of the external causes, particularly accidents, for which a rapid intervention is crucial. The absence of such a correlation does suggest that to the extent to which healthcare interruptions did play a role in causing excess mortality, they were of secondary importance relative to the underreporting of COVID-19 and scarring.

Figure 9

WEEKLY CROSS-CORRELATIONS BETWEEN COVID-19 DEATHS AND EXCESS DEATHS BY PANDEMIC YEAR, WEEK ENDING MARCH 7, 2020 – WEEK ENDING FEBRUARY 25, 2023



Notes. Cross-correlation plots examining temporal correlations between the weekly time series for reported COVID-19 deaths converted to rates and the weekly time series for excess deaths reported to causes other than COVID-19 converted to rates, week ending March 7th, 2020, through week ending February 25th, 2023. Increases in reported COVID-19 deaths may correlate with increases (positive correlation coefficient) or decreases (negative correlation coefficient) in excess deaths reported to non-COVID-19 causes. The x axis indicates the time lag in weeks. Increases in reported COVID-19 deaths may correlate with changes in excess deaths reported to non-COVID-19 causes in the same month (lag 0), in future months (lag greater than 0), and/or in previous months (lag less than 0). Correlation coefficients that are outside the gray shaded area indicate significance at alpha = 0.01 and are colored red to assist with interpretation.

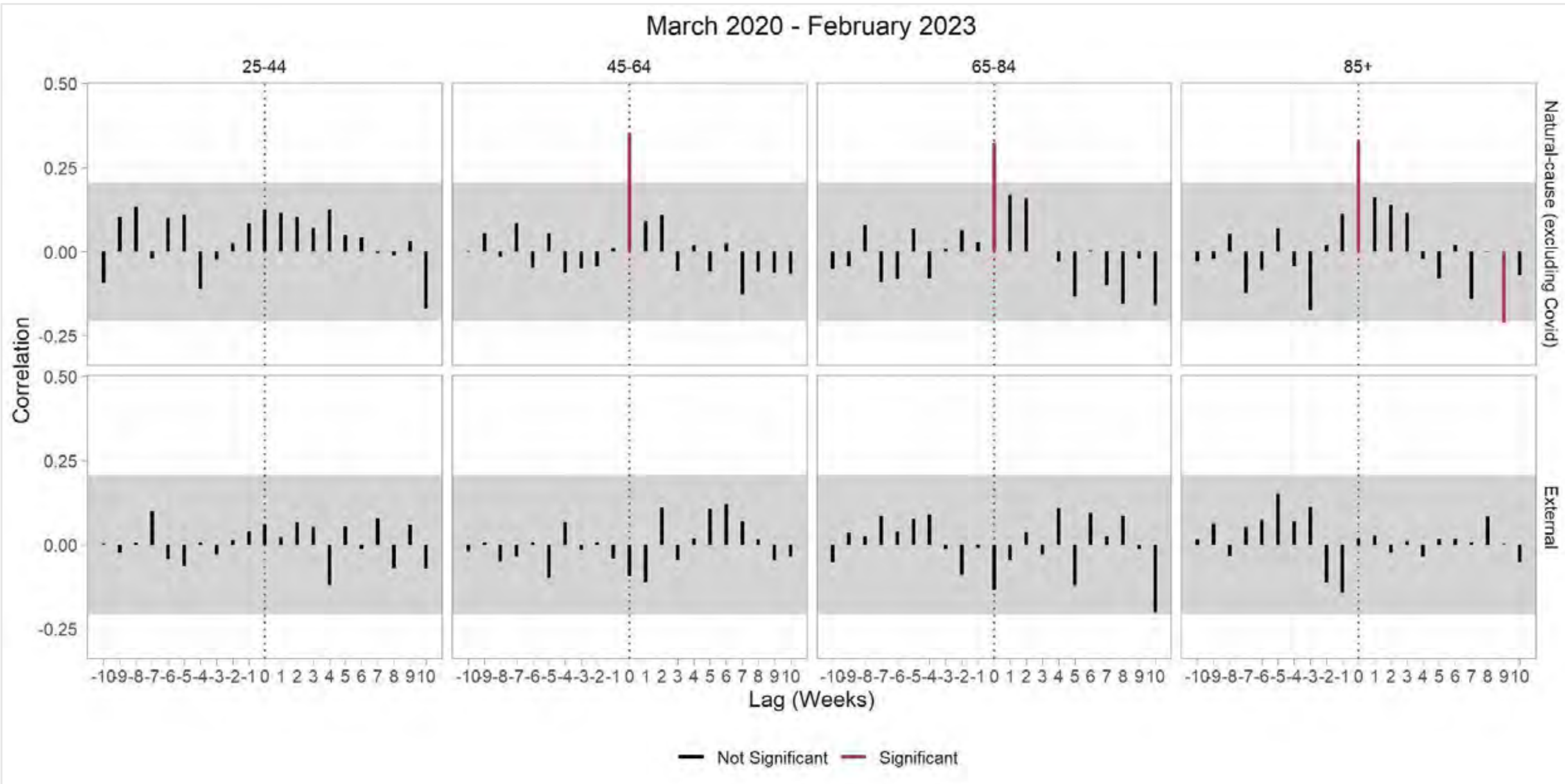
Figure 9 examines the cross-correlation separately for each pandemic year and shows that the positive correlation at lag zero between excess mortality in natural causes and COVID-19 mortality was present only in the first year, when underreporting was more likely due to limited testing capacity. The second year is instead dominated by a positive correlation at a positive lag, possibly suggesting that scarring became more important. No correlation is detectable in the third year, which the authors think indicates the diminished importance of COVID-19 as a driver of excess mortality. This is consistent with the lower proportion of all excess deaths contributed by COVID-19 (35.6%) in the last period.

5.2 TEMPORAL CORRELATION BETWEEN AGE-SPECIFIC COVID-19 MORTALITY AND EXCESS MORTALITY

Our last exhibit, Figure 10, repeats the temporal correlation analysis by age. It is important to understand whether the main correlations can be observed in different age groups because most of our mechanisms, scarring, selection, and underreporting, would only operate within groups and not across them. An incorrect assignment of COVID-19 deaths to other causes of death can only happen within age groups, similarly, scarring should manifest as a correlation between COVID-19 mortality today in a given age group and excess mortality in a future period within the same age group. The only exception to this pattern is for deaths related to healthcare interruptions, which could happen across groups and not only within the groups with high COVID-19 mortality. Looking at Figure 10, it can be seen that the positive correlation at lag zero is observed for all age groups except for individuals aged 25–44 (for which both excess and COVID-19 mortality were low in absolute numbers). This reinforces the conclusion that underreporting and scarring are the most plausible explanations for excess mortality not assigned to COVID-19.

Figure 10

WEEKLY CROSS-CORRELATIONS BETWEEN COVID-19 DEATH RATES AND AGE-SPECIFIC EXCESS DEATH RATES (ALL CAUSES COMBINED, EXCLUDING COVID-19), WEEK ENDING MARCH 7, 2020 – WEEK ENDING FEBRUARY 25, 2023



Notes. Cross-correlation plots examining temporal correlations between the age-specific weekly time series for reported COVID-19 deaths converted to rates and the age-specific weekly time series for excess deaths reported to Non-COVID-19 natural causes and non-COVID-19 external causes converted to rates, week ending March 7th, 2020, through week ending February 25th, 2023. Age group 0–24 is excluded due to missingness in COVID-19 time series. Increases in reported COVID-19 deaths may correlate with increases (positive correlation coefficient) or decreases (negative correlation coefficient) in excess deaths reported to non-COVID-19 causes. The x axis indicates the time lag in weeks. Increases in reported COVID-19 deaths may correlate with changes in excess deaths reported to non-COVID-19 causes in the same month (lag 0), in future months (lag greater than 0), and/or in previous months (lag less than 0). Correlation coefficients that are outside the gray shaded area indicate significance at alpha = 0.01 and are colored red to assist with interpretation

Section 6: Conclusion

This research provides valuable insights into patterns of excess mortality by cause of death and underlying mechanisms responsible for excess deaths. While a substantial body of literature documents the former, few studies have evaluated why specific causes of death were elevated during the pandemic and whether direct or indirect mechanisms were responsible. In this report, testable hypotheses are developed grounded in theory regarding the mechanisms of excess mortality. Then these hypotheses are tested by assessing the cross-correlation between COVID-19 and excess deaths from other causes across weekly data points. The findings revealed that misclassification of COVID-19 deaths appeared to be an important mechanism driving excess deaths from other causes. However, the analyses also indicated the possibility of an additional role for other mechanisms including scarring effects and displacement of influenza and pneumonia. Notably, the authors found no strong evidence of selection. Future research should continue to elucidate these patterns, drawing on other types of data and methodologies.

The analysis in this report has some limitations. Regarding data, the authors were not able to obtain weekly series of death counts by both age and cause of death for a reasonably long baseline periods (2015–2019) and, thus, had to rely on a more complex procedure based on using a shorter baseline period (2018–2019) and, subsequently, adjusted the expected deaths counts so that they would sum to the cause-specific and age-specific totals from models trained on the longer baseline period. This procedure could potentially produce inconsistent results. To confirm the plausibility of the results, the total estimates were benchmarked against those presented in several other publications and the authors found no statistically significant discrepancies. Similarly, the cause-specific estimates were compared with others in the literature and no major differences were found.

Previous research has documented a large gap between excess deaths estimated to have occurred during the COVID-19 pandemic and official counts of COVID-19 deaths in the United States. While several observers have suggested that excess deaths not assigned to COVID-19 might be the product of widespread underreporting, only limited evidence existed to support this claim. In this report, by combing insights from different methods, and by testing multiple implications of different potential mechanisms, the authors found strong evidence that underreporting of COVID-19 was the main explanation for excess mortality exceeding COVID-19 mortality, particularly in the first pandemic year.

Section 7: Acknowledgments

The authors' deepest gratitude goes to those without whose efforts this project could not have come to fruition: the volunteers who generously shared their wisdom, insights, advice, guidance, and arm's-length review of this study prior to publication. Any opinions expressed may not reflect their opinions nor those of their employers. Any errors belong to the authors alone.

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Appendix A: Supplementary Material

A.1 DETAILS ON CAUSE OF DEATH SCALING

Due to data availability, certain weekly estimates had baseline periods of January 6th, 2018, to February 29th, 2020. This includes age-specific natural cause and external cause, as well as all-age specific external deaths: suicide, accidents, external substances and other external. To account for differences in the baseline period, expected age-specific natural cause and external cause estimates were proportionally scaled to add up to the expected age-specific all-cause estimates, and expected specific external estimates were proportionally scaled to add up to the expected external estimates.

A.2 DETAILS ON THE CROSS-CORRELATION ANALYSIS

The goal of the cross-correlation analysis described in the Data and Methods section is to recover the data generating model relating contemporaneous values of the series of excess deaths a given cause (X_1) to values of the series of COVID-19 deaths (X_2). This type of analysis allows us to investigate the temporal relationship between these two series. Below we describe the detailed steps involved in this approach.

The procedure to estimate the cross-correlation between X_1 and X_2 follows the one outlined in Example 11.2.1 of Brockwell and Davis (1987)[22] The procedure consists in first pre-whitening the two series, which we will do by fitting appropriate ARIMA models, and then computing the cross-correlation on the pre-whitened series. To find the most appropriate ARIMA model for each series, we select the model with the smallest Bayesian Information Criterion (BIC) using the auto.arima function from the forecast package, setting the differencing parameter to 1 so that first differences is taken before fitting the models and searching over all models (rather than stepwise selection). Reduction to stationary series is required as the cross-correlation can be meaningfully computed only for stationary series. The pre-whitening step is needed to ensure that the cross-correlations are asymptotically normal with mean 0 and variance $n^{1/2}$, where n is the length of the two time series. This result, proven in theorem 11.2.2 in Brockwell and Davis (1987), ensures that standard statistical tests can be performed based on the critical values of a standard normal distribution.

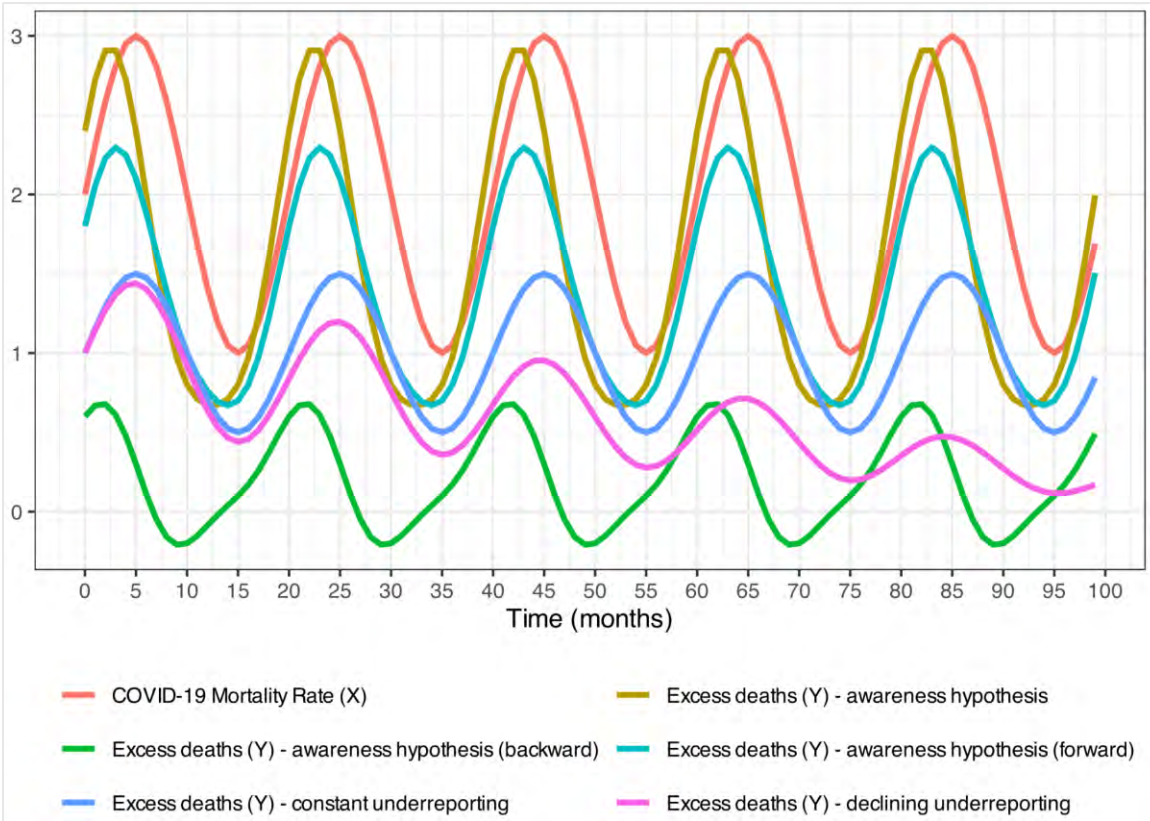
A.3 FOUR MODELS OF UNDERREPORTING

In a real-world scenario, it is likely that some of the mechanisms described in Table 1 might be acting at the same time, making the results harder to interpret. However, we can work with a model first to make sure that the mechanisms we hypothesized produce the expected effects.

In Supplementary Figure 1, we investigate four different types of underreporting. We use the following simplifying assumptions. First, denoting with Y excess deaths for a given cause, we assume that excess is only caused by misclassification of cause of death on death certificates, which transfers some COVID-19 deaths to this cause. Second, we assume that the excess for all causes can be written as $Y(t) = u(t, X) \cdot X(t)$, where $X(t)$ is COVID-19 mortality at time t, and $u(\cdot)$ is the underreporting function, that might or might not depend on time t and on X. This equation implicitly assumes that excess $Y(t)$ is proportional to COVID-19 mortality in the same period. However, the proportion of misclassified deaths can vary over time and possibly depend on past, present, or future values of X.

Supplementary Figure 1

THE RELATIONSHIP BETWEEN EXCESS MORTALITY AND COVID-19 MORTALITY UNDER FOUR UNDERREPORTING SCENARIOS



Supplementary Table 1 describes four types of underreporting. The simplest case is that of constant underreporting, in which a constant proportion c of COVID-19 deaths gets assigned to a different cause. The second most simple case is that of declining underreporting, in which the proportion of underreported deaths declines over time (here linearly for simplicity). The last two cases introduce a more complex relationship between the level of COVID-19 mortality and underreporting and both correspond to the awareness hypothesis. In the first case, underreporting depends (negatively) on past values of COVID-19 mortality. It, thus, decreases after COVID-19 peaks but increases after COVID-19 troughs. We can call this backward-looking underreporting. In the last case, underreporting depends (positively) on future values of COVID-19 mortality. It, thus, increases in anticipation of COVID-19 peaks but begins declining before COVID-19 mortality has peaked. It is important to distinguish, at least theoretically, between these two cases because they give rise to different temporal correlation patterns.

Supplementary Table 1

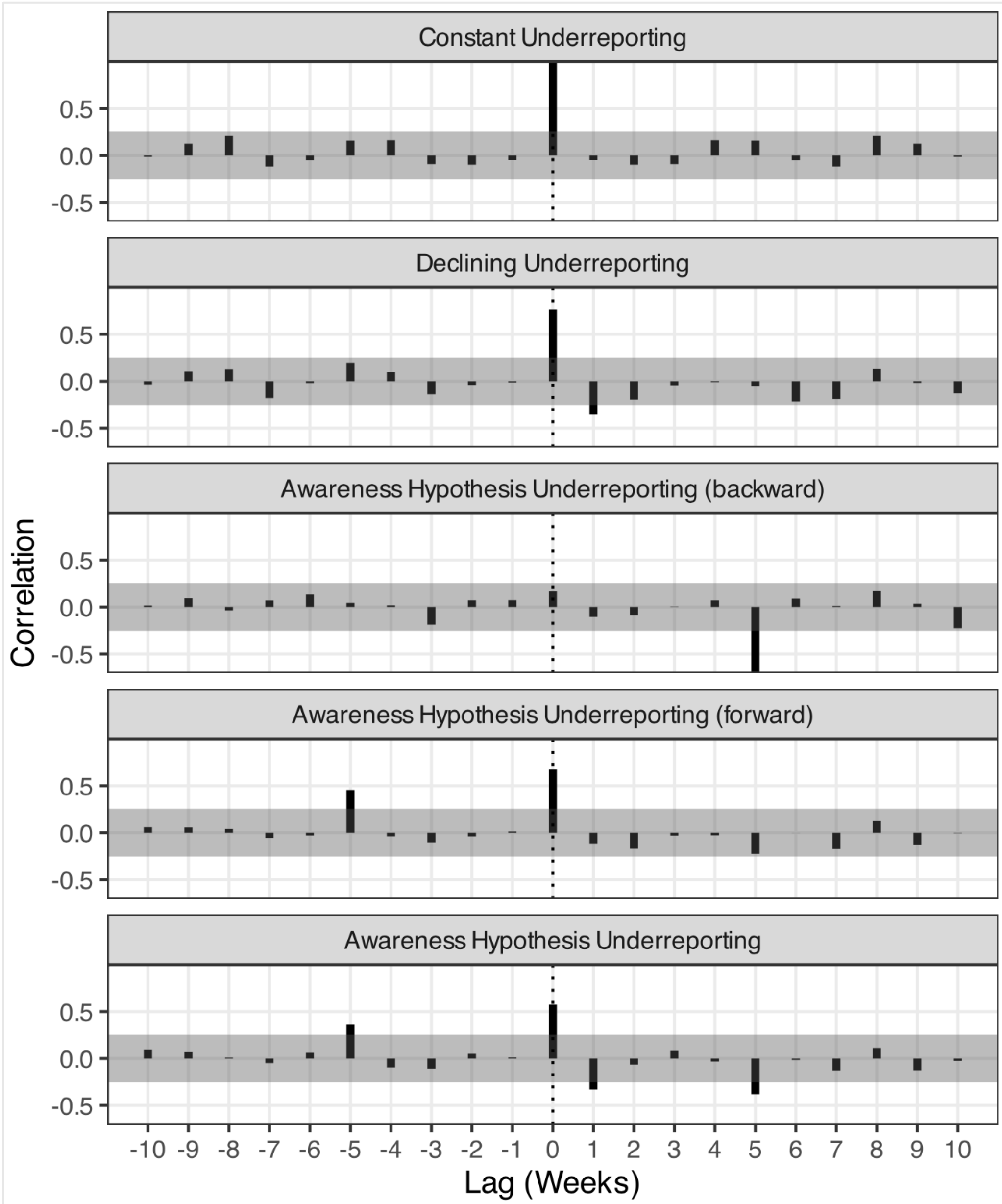
FOUR TYPES OF UNDERREPORTING FUNCTIONS

Underreporting Type	Description	Underreporting Function
Constant	Constant underreporting over time	$u(t, X) = c$
Declining	Declining rate of underreporting over time	$u(t, X) = c - a \cdot t$ (such that $u(t, X) > 0$)
Awareness (backward-looking)	Underreporting declines after peaks in COVID-19 mortality	$u(t, X) = c - b \cdot X(t - n)$ (such that $u(t, X) > 0$)
Awareness (forward-looking)	Underreporting increases in anticipation of COVID-19 peaks	$u(t, X) = c + d \cdot X(t + n)$ (such that $u(t, X) > 0$)
Awareness	Underreporting is highest before COVID-19 peaks (low awareness) and decreases after COVID-19 peaks (high awareness)	$u(t, X) = c + d \cdot X(t + n) - b \cdot X(t - n)$ (such that $u(t, X) > 0$)

Supplementary Figure 1 shows how excess deaths $Y(t)$ look under each underreporting function with simulated data. Supplementary Figure 2 shows the results of the temporal correlation analysis applied to the simulated data in each of the scenarios. We can see that in the constant underreporting scenario, excess mortality follows exactly the same pattern as COVID-19 mortality but scaled down, the temporal correlation between the two series is exclusively at lag zero. In the declining underreporting scenario, we can see that the peaks in excess mortality tend to slightly precede those in COVID-19 mortality, which will induce, in some cases, a positive correlation at a negative lag in addition to a positive correlation at zero. The correlation will also tend to be smaller. In both the backward-looking and the forward-looking awareness scenarios, excess mortality peaks before COVID-19 mortality (though for different reasons). In the backward-looking awareness scenario, the cross-correlation analysis will detect a negative correlation at a positive lag (because the analysis is executed from the point of view of X). In the forward-looking awareness scenario, the cross-correlation analysis will detect a positive correlation at a negative lag. If we combine the two, the cross-correlation analysis will detect both a positive correlation at a negative lag and a negative correlation at a negative lag, as we wrote in Table 1.

Supplementary Figure 2

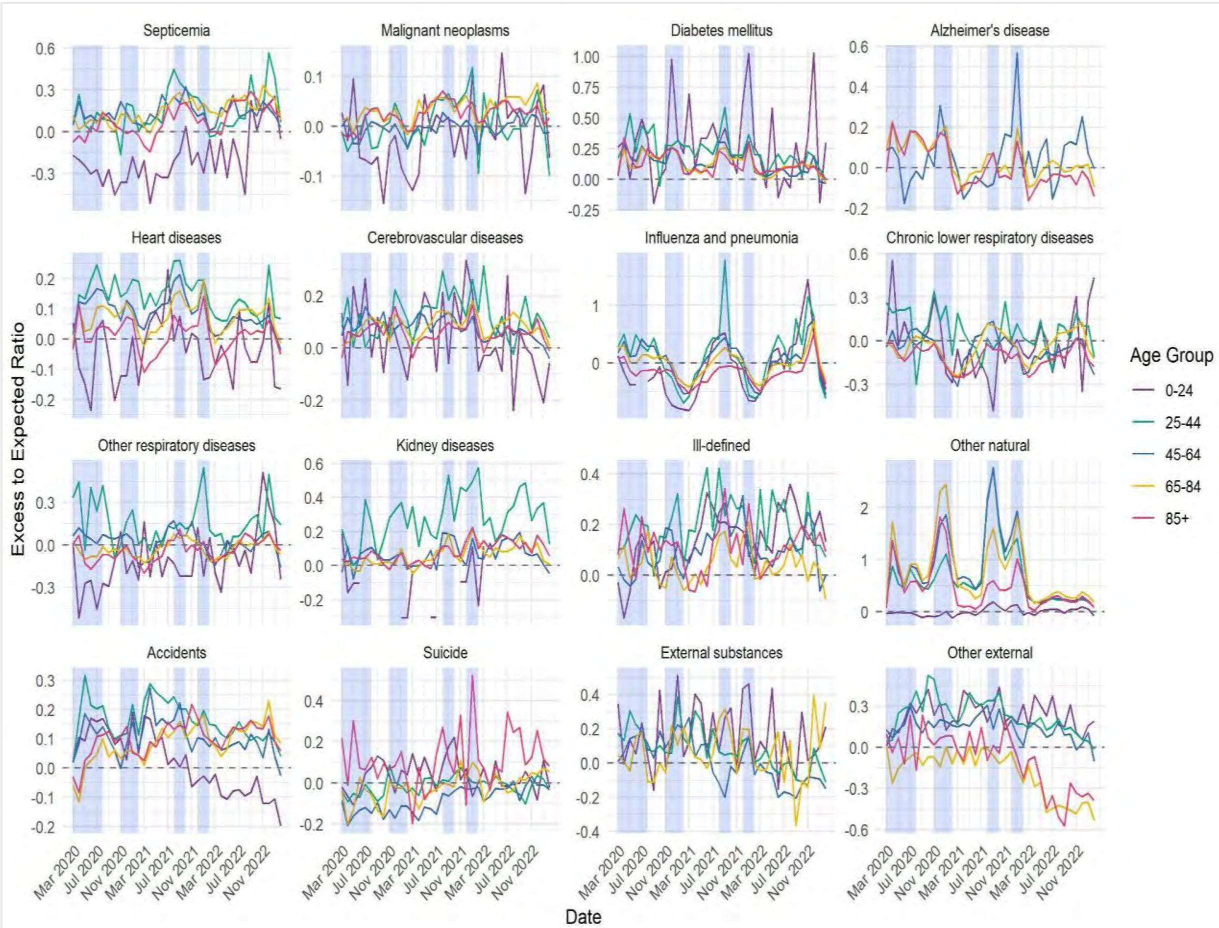
TEMPORAL CORRELATION BETWEEN EXCESS MORTALITY AND COVID-19 MORTALITY UNDER FOUR UNDERREPORTING SCENARIOS



Notes. The relevant lags in the simulations are always +5 and -5, as can be seen by the significant lags. In the temporal correlation analysis, we introduced some noise to the X series.

Supplementary Figure 3

MONTHLY EXCESS TO EXPECTED RATIOS BY CAUSE OF DEATH AND AGE GROUP



Notes. Rates are calculated as deaths per 100,000 person-years. ARIMA models were fitted to monthly observed cause-specific death rates from March 2015 to February 2020 and projected from March 2020 to December 2022 to estimate expected deaths for each cause of death for each age group. Excess to expected ratios are calculated as [(excess rate)/(expected rate)].

Supplementary Table 2

CAUSES OF DEATH GROUPINGS AND ICD-10 CODES

Aggregate Group	Condensed Causes	Expanded Causes	ICD-10 Codes
Natural causes (A00–R99, U04–U07)	Circulatory	Heart diseases	I00–I09,I11,I13,I20–I51
		Cerebrovascular diseases	I60–I69
	Diabetes and kidney diseases	Diabetes mellitus	E10–E14
		Kidney diseases	N00–N07,N17–N19,N25–N27
	Other respiratory diseases	Influenza and pneumonia	J10–J18
		Other respiratory diseases	J00–J06,J30–J39,J67,J70–J98
	Chronic lower respiratory diseases	Chronic lower respiratory diseases	J40–J47
	Alzheimer's disease	Alzheimer's disease	G30
	Malignant neoplasms	Malignant neoplasms	C00–C97
	Other natural	Septicemia	A40–A41
		Ill-defined	R00–R99
		COVID-19	U07.1
		Other natural	Natural residual
External causes (U01–U03, V01–Y89)	External cause	Accidents	V01–V99,W00–X59,Y85,Y86
		Suicide	U03,X60–X84,Y87
		Substances	X40,X45,X85,Y10–Y15
		Other external	External residual

Supplementary Table 3

EXCESS AND EXPECTED DEATH RATES BY CAUSE OF DEATH AND PANDEMIC YEAR WITH CONFIDENCE INTERVALS

	Year 1 March 2020 – February 2021		Year 2 March 2021 – February 2022		Year 3 March 2022 – February 2023	
	Expected Rate (95% CI)	Excess Rate (95% CI)	Expected Rate (95% CI)	Excess Rate (95% CI)	Expected Rate (95% CI)	Excess Rate (95% CI)
All-cause, Natural-cause, & External cause						
All-cause	869.4 (823.0 – 915.7)	193.0 (146.6 – 239.4)	868.4 (809.5 – 927.3)	172.6 (113.8 – 231.5)	868.4 (800.0 – 936.9)	75.6 (7.1 – 144.0)
Natural-cause (including COVID-19)	790.2 (749.1 – 831.2)	185.1 (144.0 – 226.1)	789.1 (744.5 – 833.7)	157.6 (113.0 – 202.2)	789.1 (742.4 – 835.9)	61.9 (15.1 – 108.6)
Natural-cause (excluding COVID-19)	790.2 (749.1 – 831.2)	37.6 (-3.5 - 78.6)	789.1 (744.5 - 833.7)	40.1 (-4.6 - 84.7)	789.1 (742.4 - 835.9)	35.0 (-11.8 - 81.7)
External	80.0 (75.4 - 84.6)	7.2 (2.5 - 11.8)	82.4 (75.8 - 89.0)	11.9 (5.3 - 18.6)	84.8 (76.7 - 92.9)	8.2 (0.1 - 16.3)
Specific Causes						
Heart diseases	176.8 (158.2 - 195.4)	10.0 (-8.6 - 28.6)	176.7 (149.3 - 204.1)	9.4 (-18.1 - 36.8)	176.7 (142.9 - 210.5)	4.0 (-29.8 - 37.8)
Accidents	54.9 (51.7 - 58.0)	7.2 (4.0 - 10.4)	56.5 (52.0 - 61.1)	11.6 (7.1 - 16.2)	58.2 (52.6 - 63.7)	9.7 (4.1 - 15.3)
Diabetes mellitus	26.6 (24.1 - 29.2)	5.0 (2.4 - 7.5)	26.6 (22.9 - 30.3)	4.6 (0.9 - 8.4)	26.6 (22.0 - 31.2)	2.9 (-1.7 - 7.4)
Alzheimer's disease	36.5 (32.7 - 40.3)	4.2 (0.4 - 8.1)	36.6 (32.1 - 41.0)	-0.6 (-5.0 - 3.8)	36.6 (31.7 - 41.4)	-1.6 (-6.4 - 3.3)
Cerebrovascular diseases	45.6 (42.9 - 48.4)	3.0 (0.3 - 5.7)	45.6 (42.5 - 48.8)	3.8 (0.7 - 7.0)	45.6 (42.1 - 49.1)	3.1 (-0.4 - 6.6)
Septicemia	11.5 (10.2 - 12.9)	0.5 (-0.8 - 1.9)	11.5 (9.9 - 13.1)	1.0 (-0.6 - 2.6)	11.5 (9.7 - 13.3)	1.1 (-0.7 - 2.9)
Ill-defined	9.8 (8.6 - 10.9)	0.5 (-0.7 - 1.6)	9.8 (8.3 - 11.3)	0.7 (-0.8 - 2.2)	9.8 (8.0 - 11.5)	0.0 (-1.7 - 1.7)
Kidney diseases	15.6 (14.4 - 16.8)	0.3 (-0.9 - 1.5)	15.6 (14.4 - 16.8)	1.1 (-0.1 - 2.3)	15.6 (14.4 - 16.8)	1.4 (0.2 - 2.6)
External substances	1.9 (1.8 - 2.0)	0.2 (0.1 - 0.4)	2.0 (1.8 - 2.1)	0.1 (-0.1 - 0.2)	2.0 (1.8 - 2.2)	-0.2 (-0.4 - 0.0)
Other respiratory diseases	14.2 (12.9 - 15.4)	-0.8 (-2.1 - 0.4)	14.6 (12.9 - 16.2)	-0.6 (-2.3 - 1.0)	15.0 (13.0 - 16.9)	-0.5 (-2.4 - 1.5)
Suicide	14.8 (14.0 - 15.7)	-1.0 (-1.8 - -0.1)	15.3 (14.0 - 16.5)	-0.6 (-1.8 - 0.7)	15.7 (14.2 - 17.2)	-0.7 (-2.2 - 0.8)
Malignant neoplasms	182.3 (177.5 - 187.1)	-2.1 (-6.9 - 2.6)	182.3 (177.1 - 187.4)	0.0 (-5.2 - 5.1)	182.3 (176.8 - 187.7)	-0.3 (-5.8 - 5.2)
Influenza and pneumonia	17.0 (9.3 - 24.7)	-2.4 (-10.1 - 5.3)	16.9 (8.8 - 25.0)	-4.1 (-12.2 - 4.0)	16.9 (8.8 - 25.0)	-2.5 (-10.6 - 5.6)
Chronic lower respiratory diseases	48.1 (43.9 - 52.2)	-4.0 (-8.1 - 0.2)	48.2 (44.0 - 52.4)	-4.7 (-8.9 - -0.4)	48.2 (44.0 - 52.4)	-4.2 (-8.4 - 0.1)
Other natural	207.3 (187.4 - 227.3)	169.8 (149.8 - 189.8)	207.3 (172.1 - 242.5)	144.5 (109.3 - 179.7)	207.3 (162.0 - 252.7)	55.4 (10.1 - 100.8)
Other external	8.4 (7.9 - 8.9)	1.7 (1.2 - 2.2)	8.6 (8.0 - 9.3)	1.7 (1.0 - 2.4)	8.9 (8.1 - 9.8)	0.3 (-0.6 - 1.1)

Notes. Rates are calculated as deaths per 100,000 person-years. Midyear population values: Year 1 – 331,660,758; Year 2 – 332,294,082; Year 3 – 333,133,413

Supplementary Table 3

EXPECTED AND EXCESS DEATH RATES BY CAUSE OF DEATH AND AGE CATEGORY WITH CONFIDENCE INTERVALS

	Year 1 March 2020 – February 2021			Year 2 March 2021 – February 2022			Year 3 March 2022 – February 2023		
	Expected Rate (95% CI)	Excess Rate (95% CI)	Population	Expected Rate (95% CI)	Excess Rate (95% CI)	Population	Expected Rate (95% CI)	Excess Rate (95% CI)	Population
All-cause									
0–24	59.8 (54.5 - 65.1)	2.2 (-3.1 - 7.6)	104,507,600	59.8 (52.6 - 66.9)	5.7 (-1.5 - 12.8)	103,974,398	59.8 (51.2 - 68.3)	3.6 (-5.0 - 12.1)	103,757,480
25–44	172.7 (161.6 - 183.8)	36.2 (25.1 - 47.4)	88,354,248	177.5 (161.7 - 193.4)	57.4 (41.6 - 73.3)	88,770,334	182.4 (163.0 - 201.8)	19.8 (0.3 - 39.2)	89,277,285
45–64	653.2 (601.1 - 705.2)	134.4 (82.4 - 186.5)	83,679,345	653.2 (563.4 - 742.9)	183.1 (93.4 - 272.9)	83,009,008	653.2 (538.0 - 768.4)	38.0 (-77.1 - 153.2)	82,435,561
65–84	2,595.2 (2,329.7 - 2,860.6)	625.2 (359.7 - 890.7)	48,618,163	2,595.2 (2,120.6 - 3,069.9)	505.5 (30.8 - 980.1)	50,055,230	2,595.2 (1,982.5 - 3,208.0)	177.3 (-435.4 - 790.1)	51,633,688
85+	12,740.0 (10,680.8 - 14,799.1)	3,298.1 (1,238.9 - 5,357.2)	6,501,402	12,739.0 (9,063.3 - 16,414.7)	1,712.9 (-1,962.8 - 5,388.6)	6,485,112	12,738.9 (7,995.7 - 17,482.1)	1,066.0 (-3,677.1 - 5,809.2)	6,533,452
Natural-cause (including COVID-19)									
0–24	40.9 (37.4 - 44.4)	15.5 (11.9 - 19.0)	104,507,600	40.9 (37.4 - 44.4)	19.5 (16.0 - 23.1)	103,974,398	40.9 (37.4 - 44.4)	20.2 (16.7 - 23.7)	103,757,480
25–44	109.9 (101.1 - 118.7)	79.3 (70.5 - 88.1)	88,354,248	112.9 (103.0 - 122.9)	97.2 (87.2 - 107.2)	88,770,334	116.0 (105.0 - 127.0)	60.9 (49.9 - 71.9)	89,277,285
45–64	606.7 (582.1 - 631.2)	675.0 (650.4 - 699.5)	83,679,345	606.7 (582.1 - 631.3)	720.7 (696.1 - 745.3)	83,009,008	606.7 (582.1 - 631.3)	547.3 (522.7 - 571.9)	82,435,561
65–84	2,545.4 (2,275.3 - 2,815.4)	3,187.6 (2,917.5 - 3,457.7)	48,618,163	2,545.4 (2,083.5 - 3,007.3)	3,059.5 (2,597.6 - 3,521.5)	50,055,230	2,545.4 (1,953.7 - 3,137.1)	2,690.3 (2,098.6 - 3,281.9)	51,633,688
85+	12,541.5 (9,972.7 - 15,110.3)	-11,983.7 (-14,552.4 - -9,414.9)	6,501,402	12,540.6 (7,954.2 - 17,126.9)	-12,026.1 (-16,612.4 - -7,439.8)	6,485,112	12,540.5 (6,620.8 - 18,460.2)	-12,037.2 (-17,956.9 - -6,117.5)	6,533,452
Natural-cause (excluding COVID-19)									
0–24	40.9 (37.4 - 44.4)	14.8 (11.2 - 18.3)	104,507,600	40.9 (37.4 - 44.4)	17.8 (14.3 - 21.3)	103,974,398	40.9 (37.4 - 44.4)	19.9 (16.4 - 23.4)	103,757,480
25–44	109.9 (101.1 - 118.7)	66.4 (57.6 - 75.2)	88,354,248	112.9 (103.0 - 122.9)	71.4 (61.5 - 81.4)	88,770,334	116.0 (105.0 - 127.0)	58.8 (47.8 - 69.8)	89,277,285
45–64	606.7 (582.1 - 631.2)	574.6 (550.1 - 599.1)	83,679,345	606.7 (582.1 - 631.3)	588.1 (563.5 - 612.7)	83,009,008	606.7 (582.1 - 631.3)	533.5 (508.9 - 558.1)	82,435,561
65–84	2,545.4 (2,275.3 - 2,815.4)	2,684.4 (2,414.3 - 2,954.5)	48,618,163	2,545.4 (2,083.5 - 3,007.3)	2,688.6 (2,226.7 - 3,150.6)	50,055,230	2,545.4 (1,953.7 - 3,137.1)	2,606.3 (2,014.6 - 3,198.0)	51,633,688
85+	12,541.5 (9,972.7 - 15,110.3)	-14,250.8 (-16,819.6 - -11,682.0)	6,501,402	12,540.6 (7,954.2 - 17,126.9)	-13,100.6 (-17,686.9 - -8,514.3)	6,485,112	12,540.5 (6,620.8 - 18,460.2)	-12,537.7 (-18,457.4 - -6,618.0)	6,533,452
External									
0–24	18.9 (16.9 - 20.8)	14.6 (12.6 - 16.5)	104,507,600	18.9 (16.9 - 20.9)	15.4 (13.4 - 17.4)	103,974,398	18.9 (16.9 - 20.9)	13.7 (11.7 - 15.7)	103,757,480
25–44	62.8 (57.5 - 68.1)	45.1 (39.8 - 50.4)	88,354,248	64.6 (57.0 - 72.3)	52.4 (44.8 - 60.1)	88,770,334	66.4 (56.8 - 76.0)	46.3 (36.6 - 55.9)	89,277,285
45–64	46.5 (41.1 - 51.9)	50.1 (44.7 - 55.5)	83,679,345	46.5 (38.7 - 54.3)	59.8 (52.0 - 67.5)	83,009,008	46.5 (37.0 - 56.0)	60.9 (51.4 - 70.3)	82,435,561
65–84	49.8 (45.6 - 54.0)	52.5 (48.3 - 56.7)	48,618,163	49.8 (45.4 - 54.2)	63.0 (58.6 - 67.3)	50,055,230	49.8 (45.3 - 54.3)	62.9 (58.3 - 67.4)	51,633,688
85+	198.5 (175.5 - 221.5)	-190.2 (-213.2 - -167.2)	6,501,402	198.4 (169.1 - 227.8)	-189.8 (-219.1 - -160.5)	6,485,112	198.4 (164.0 - 232.9)	-189.9 (-224.3 - -155.4)	6,533,452
COVID-19									
0–24	-- (-- - --)	0.7 (-- - --)	104,507,600	-- (-- - --)	1.8 (-- - --)	103,974,398	-- (-- - --)	0.26 (-- - --)	103,798,222
25–44	-- (-- - --)	12.9 (-- - --)	88,354,248	-- (-- - --)	25.8 (-- - --)	88,770,334	-- (-- - --)	2.1 (-- - --)	89,139,125
45–64	-- (-- - --)	100.4 (-- - --)	83,679,345	-- (-- - --)	132.6 (-- - --)	83,009,008	-- (-- - --)	13.7 (-- - --)	82,548,114
65–84	-- (-- - --)	503.2 (-- - --)	48,618,163	-- (-- - --)	370.9 (-- - --)	50,055,230	-- (-- - --)	84.0 (-- - --)	51,171,146
85+	-- (-- - --)	2,267.2 (-- - --)	6,501,402	-- (-- - --)	1,074.5 (-- - --)	6,485,112	-- (-- - --)	500.5 (-- - --)	6,476,806

Notes. Rates are calculated as deaths per 100,000 person-year

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