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Original Article

Age-specific mortality patterns across influenza pandemics: evidence from all-cause mortality data across multiple populations

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Abstract

Background: **Understanding age-specific mortality patterns across historic influenza pandemics is crucial for future pandemic preparedness. Prior research shows that, while the 1918 pandemic caused unprecedented mortality in younger adults, subsequent pandemics in 1957, 1968, and 2009 displayed varying mortality patterns, with elevated risks in some younger populations and elderly populations. However, cross-national comparative analyses of these patterns using harmonized all-cause mortality data remain lacking but are critical for informing public health strategies.**

Methods: **We analysed age-specific all-cause absolute and percentage excess mortality patterns across 48 populations during the 1918, 1957, 1968, and 2009 influenza pandemics by using data from the Human Mortality Database.**

Results: **While the 1918 pandemic consistently showed a peak in positive absolute excess mortality at younger ages (5–39 years), age-specific mortality patterns in 1918 also varied substantially across the populations, particularly at older and early-childhood ages; subsequent pandemics lacked this peak and revealed varied mortality patterns across the age groups, including inconsistent excess mortality rates among the elderly. The percentage of excess mortality also differed by country and pandemic, highlighting the complexity of age-based mortality risks.**

Conclusion: **This work demonstrates that reports of increased severity among young people as a universal feature of all historical influenza pandemics may have been exaggerated, influenced by the exceptional mortality among the young during the 1918 pandemic.**

Keywords influenza pandemics, age-specific mortality, pandemic preparedness

Key Messages

- This research aimed to understand the impact of age on mortality risk across four influenza pandemics in multiple populations.
- We found that the absolute and percentage mortality patterns emphasized different aspects of age-specific risk across pandemics, illustrating that the metric choice influences how age patterns are interpreted.
- By comparing mortality data across multiple populations, this research challenges prior assumptions based on US-centric data and highlights the heterogeneity of age-specific risk across pandemics.

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Introduction

Understanding historic viral pandemics is essential for future pandemic preparedness. The 1918 H1N1 influenza pandemic—the deadliest influenza pandemic on record—caused an estimated 50–100 million deaths worldwide [1]. Younger adults, aged 20–40 years, experienced higher excess mortality than other age groups [2], with a mean age of death of ∼27 years [3]. Since then, three further influenza pandemics have occurred: the 1957 H2N2 and 1968 H3N2 events, each causing 1–4 million deaths [4, 5], and the 2009 H1N1 pandemic, resulting in 18 500 laboratory-confirmed deaths but $\leq$600 000 through modeled estimates [6]. Though the overall deaths in 2009 resembled seasonal influenza, mortality was again skewed toward younger people [3, 7], with a mean age of death of 37 years [3, 8]. In contrast, the mortality in young adults during the 1957 and 1968 events remains less well documented, leaving the universality of young-skewed pandemic influenza mortality as an open question.

Excess mortality in school-aged children and young adults was noted in both 1957 and 1968, primarily in North America [4, 9–11]. The WHO Weekly Epidemiological Records suggest that the outbreaks of influenza during 1957 and 1968 were generally mild, but highlight several instances of severity in younger individuals: "Although the death rate remains low, the number of fatal cases in children and young adults has increased this week" [12]; "[…] isolated reports of death primarily due to influenza in young, apparently healthy individuals, have been received" [13]. These reports, based on limited data on an international scale and occurring against the backdrop of high young-adult excess mortality in 1918, have created an impression that pandemic influenza disproportionately harms younger adults [4].

The estimated impact on older adults is less consistent. Some studies report negative excess mortality (lower-than-expected mortality) in the elderly in 1918 [14], while others experienced positive excess mortality (higher-than-expected mortality) [15–18]. By contrast, excess mortality in older adults was consistently positive among examined countries in 1957 and 1968 [10, 11, 14, 19, 20], but negative in 2009 in several countries [21–23].

Whether these patterns represent generalizable features or, instead, artifacts of US-heavy data remains uncertain. Clarifying age-specific mortality across pandemics is essential for understanding underlying mechanisms and informing preparedness. Specifically, avian influenza has been identified as a potential pandemic threat. While studies of age-specific risk are scarce, reports suggest that, in some regions, individuals aged 5–15 years have the greatest H5N1 exposure risk and risk of death when controlling for confounding factors [24], although this is likely subtype-specific [25].

The age patterning of influenza pandemic mortality, if accurately understood, can adjudicate hypotheses about its mechanisms. One notable hypothesis holds that increased morbidity and mortality in naive populations stems from antigenic shift resulting in novel influenza subtypes of pandemic potential [26]. Antigen recycling may have resulted in older adults retaining immune protection against new pandemic strains. It has been proposed that older adults were spared during the 1918 influenza pandemic due to exposures to H1-like viruses earlier in life [27]. Furthermore, sero-archeology studies have found antibodies against H3-like viruses in the elderly prior to the 1968 pandemic [28] and cross-reactive antibodies against the 2009 pandemic strain in serum samples taken from older adults prior to that pandemic [29]. Other potential mechanisms for age-specific risk during influenza pandemics include a dysregulated immune response in otherwise young, healthy individuals, leading to cytokine storm [30], and immune imprinting, whereby the first influenza strain encountered reshapes the immune response to subsequent infections [31]. These mechanisms implicate risks that are age-specific (cytokine storm) or cohort-specific (prior exposure or imprinting with antigenically distinct influenza viruses) [30, 31]. Understanding both the main age patterning of influenza mortality risk in each pandemic and its variability across national populations thus provides crucial population-level evidence about the plausibility of these mechanisms.

We use Human Mortality Database (HMD) data from 48 populations to examine age-specific all-cause excess mortality rates, in absolute and percentage metrics, across all four pandemics [32]. We show that, although a peak in absolute excess mortality among young adults was a consistent feature in 1918, age-specific mortality patterns within 1918 itself varied markedly across the populations, while later pandemics lacked a young-adult peak and displayed highly variable patterns, especially among older adults.

Methods

Data source

We used all-cause death and population-size data from the HMD, freely accessible from https://www.mortality.org/ [32]. The HMD observes uniform procedures to estimate death rates and population to harmonize data across populations. A complete list of citations for country-specific data is provided in Supplementary Table S1. Data were current as of 30 June 2025. To minimize confounding from conflict-related mortality during World War 1, civilian-only population data were used in place of total population for England and Wales and for France. In addition, female-only data were used for France, Italy, Finland, and the New Zealand non-Māori population, as the male mortality in these regions was affected by war-related artifacts, likely reflecting the impacts of conscription and other conflict-associated data-quality issues. The New Zealand non-Māori population was used for analyses of the 1918 pandemic, as Māori and total-population data were not available for years prior to 1948. Due to data-quality limitations, Belarus, Bulgaria, Hungary, Latvia, Lithuania, Russia, Slovakia, and Ukraine were similarly excluded from analyses of the 1957 and 1968 pandemics. Pandemics are named as the first year of the disease outbreak, regardless of whether a country recorded cases in that first year; however, death rates for the first year in which a country recorded cases were used for analysis. The initial month in which countries recorded cases of pandemic influenza are shown in Supplementary Figure S1, with citations listed in Supplementary Table S2. Where there is limited information available to determine when pandemics began in a country, the first year of the pandemic was determined to be the same as in surrounding countries with available information.

Since the 1950s, distinct age peaks in the occurrence of heart disease, cerebrovascular disease, and cancers have been noted [33]. Reported pneumonia and influenza (P&I) deaths are conventionally used in the literature for examining age-specific mortality patterns during influenza pandemics. However, deaths as a result of a pandemic are not always directly attributable to the causative agent of a pandemic; historically, indirect causes of death resulting from influenza pandemics—which may not be included in mortality totals for P&I causes—include coinfections [34, 35], heart disease [34, 36], cancer [34], stroke [36], and malnutrition [35]. Here, we use all-cause death data to capture a broader picture of mortality consequences during influenza pandemics.

The fundamental units of our analysis are the age-specific mortality rates for age group (a) in a given country (c) and year (i), defined as:

$$\frac{Number\ \ of\ \ deaths\ \ in\ \ age\ \ group\ \ (a,\ \ c,\ \ i)}{Total\ \ population\ \ in\ \ age\ \ group\ \ (a,\ \ c,\ \ i)} \times 100000$$

The age-specific absolute excess mortality rates for each age group were then defined as:

$$Observed\ \ mortality\ \ rate - Expected\ \ mortality\ \ rate$$

In estimating these absolute excess mortality rates, we defined the expected death rate as the age-specific death rate predicted by a linear regression using data from the 10 years prior to each respective pandemic year for each age group. This approach is discussed further in Supplementary Figures S2–S4. In the event that the estimated expected death rate was negative due to a declining trend, we replaced its value with the lowest rate observed in the 10-year baseline. We additionally calculated 95% prediction intervals (PIs) around the expected mortality rates by using the standard errors from the linear regression model.

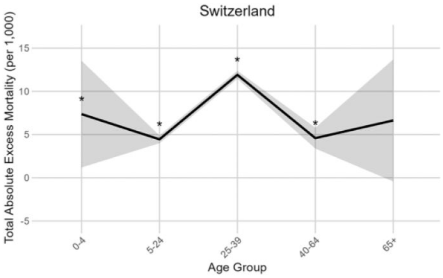
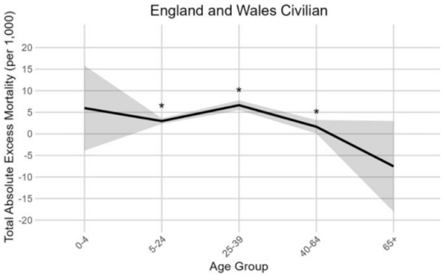
Populations were then classified based on the criteria outlined in Table 1, through the general shape of the age-specific absolute excess mortality rate curve (see further details in the Supplementary material). These classifications are not intended to imply uniformity within each shape category; rather, they are a starting point for identifying and discussing deviations.

To analyse the relative impact of excess mortality, we measured the percentage excess mortality rates for each age group in each country and pandemic as:

$$\frac{(Observed\ \ mortality\ \ rate - Expected\ \ mortality\ \ rate)}{Expected\ \ mortality\ \ rate} \times 100$$

where the expected mortality rate was estimated from a 10-year linear regression, as described above. We analysed both the absolute and percentage excess mortality rates because both have been important in prior pandemic research and to highlight similarities and differences across these metrics.

Table 1 Comparison of different age-specific all-cause absolute excess mortality (AEM) curve shapes for total population. Shape is specific to the first year of each pandemic that a country experienced. Individual plots are shown in Supplementary Tables 3–6. Female symbols (♀) indicate a divergence between the AEM shape of the total population and the female population. Male symbols (♂) indicate a divergence between the AEM shape of the total population and the male population. Male and female underlying shape classifications are shown in the Open Science Framework (OSF) repository.

Shape description	Age patterns	Sample visual
W-shaped	Peak in AEM at 0–4, 25–39, 65+ years; dip at 5–24, 40–64 years. Sample: Switzerland, 1918	
Inverted-μ-shaped	Peak in AEM at 0–4, 25–39 years; dip at 5–24, 40–65+ years Sample: England and Wales Civilian, 1918	

(continued)

Table 1 (continued)

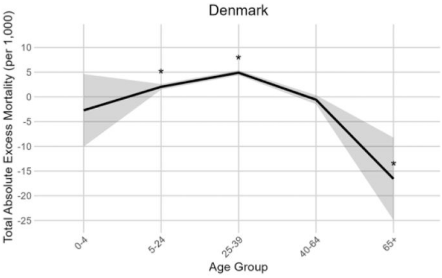
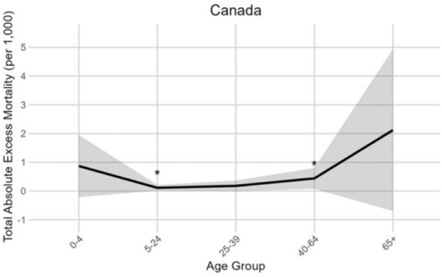
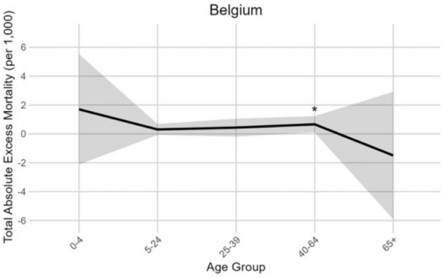
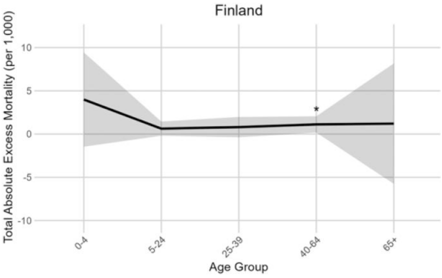
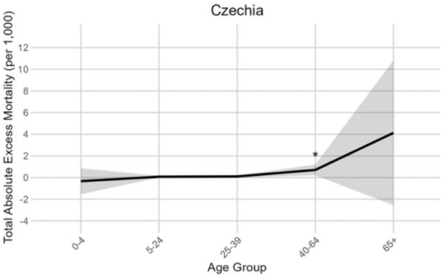
Shape description		
	Age patterns	**Sample visual**
Inverted-U-shaped	Peak in AEM at 25–39 years; dip at 0–4, 65+ years Sample: Denmark, 1918	
U-shaped	Peak in AEM at 0–4, 65+ years; dip at 5–64 years Sample: Canada, 1957	
Stair-down	Peak in AEM at 0–4 years; decrease to flat at 5–64 years; decrease at 65+ years Sample: Belgium, 1957	
Hook-up	Peak in AEM at 0–4, decrease to flat at 5–65+ years Sample: Finland, 1957	
Stair-up	Dip in AEM at 0–4 years; increase to flat at 5–64 years; increase at 65+ years Sample: Czechia, 1968	

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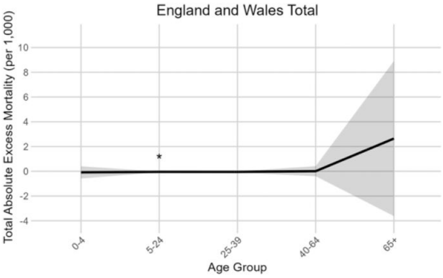
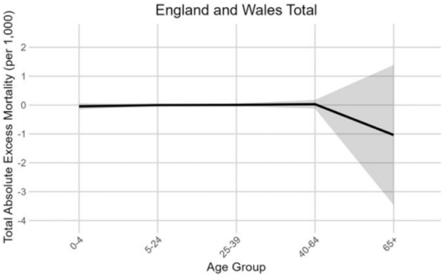
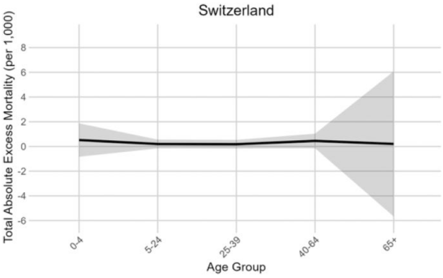
Table 1 (continued)

Shape description

	Age patterns	Sample visual
J-shaped	Flat AEM at 0–64 years; peak at 65+ years Sample: England and Wales, 1968	
Hook-down	Flat AEM at 0–64 years; decrease at 65 + years Sample: England and Wales, 2009	
Flat	All age groups are within range of 1 per 1000 AEM Sample: Switzerland, 1957	

Shapes by pandemic country

	1918	1957	1968	2009
W-shaped	Italy Spain Switzerland			
Inverted-μ-shaped	England and Wales civilian Finland France civilian Netherlands			
Inverted-U-shaped	Denmark Iceland♀ New Zealand Non-Māori♀ Norway Scotland Sweden			
U-shaped		Canada Czechia Denmark Japan New Zealand Total♀ Norway♂	Australia Austria Estonia♀ Germany East Germany West Netherlands♀	Belarus♀ Croatia♂ Lithuania♀ Russia Ukraine

(continued)

Table 1 (continued)

Shapes by pandemic country				
	1918	**1957**	**1968**	**2009**
		Spain Sweden USA	Poland Portugal Spain♂	
Stair-down		Australia Belgium England and Wales Total France Total Italy Netherlands Northern Ireland♂ Portugal Scotland	Finland♀ Japan New Zealand Total♀	Bulgaria♀ Luxembourg♂
Hook-up		Austria♂ Finland		
Stair-up		Iceland♂	Czechia Northern Ireland♂ Sweden♂ USA	
J-shaped			England and Wales Total♀ France Total Norway♀ Scotland♀♂	Austria♂ Belgium♀ Finland♂ France Total Germany Total Ireland♀♂ Italy Poland♂ Slovenia
Hook-down			Denmark	England and Wales Total♂ Latvia♀ Scotland♂ Slovakia Sweden USA♂
Flat		Ireland♀♂ Switzerland	Belgium Canada Iceland♀♂ Ireland Italy Luxembourg♂ Switzerland	Australia♀ Canada♀ Chile Czechia Denmark Estonia♂ Greece Hong Kong♂ Hungary Israel♀ Japan Netherlands New Zealand Total♀ Northern Ireland Norway Portugal♀ Republic of Korea Spain Switzerland♀ Taiwan♂

Results

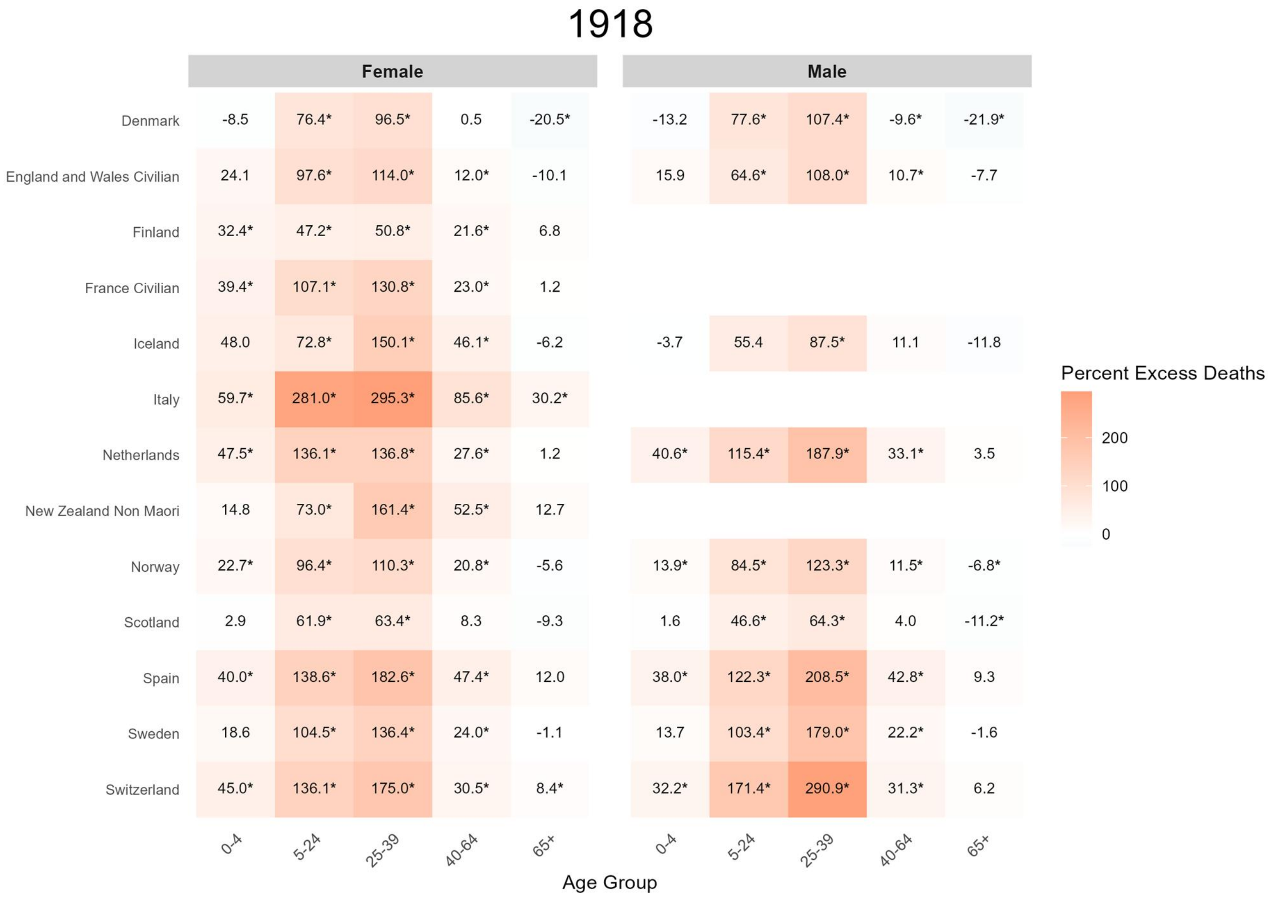
To determine whether the age-specific all-cause absolute excess mortality was consistent between populations in each pandemic, we compared the shape of the all-cause age-specific absolute excess mortality rate curves (Table 1). In contrast to previous literature [4], there is no universal age-specific pattern showing positive absolute excess mortality in younger age groups during influenza pandemics (Table 1). We instead defined 10 different "shapes" of age-specific absolute excess mortality rates to differentiate the patterns seen (Table 1).

The age patterns of absolute excess mortality rates during the 1918 pandemic are distributed across three shapes, each of which features a peak in absolute excess mortality in younger adult ages (25–39 years). In the 1918 pandemic, this young-adult excess mortality peak occurred in all populations; however, the sign and magnitude of the absolute excess mortality in the youngest children and the elderly varied across the populations (Table 1).

No observations from the 1957, 1968, and 2009 pandemics have any of the three shapes of the 1918 pandemic, highlighting the unique age-specific mortality distribution of that pandemic. Instead, the three later pandemics typically show all-cause absolute excess mortality close to zero for ages >4 and <65 years (Table 1). As in 1918, there is no immediately discernible relationship between populations showing any particular shape and many populations show some variation by sex.

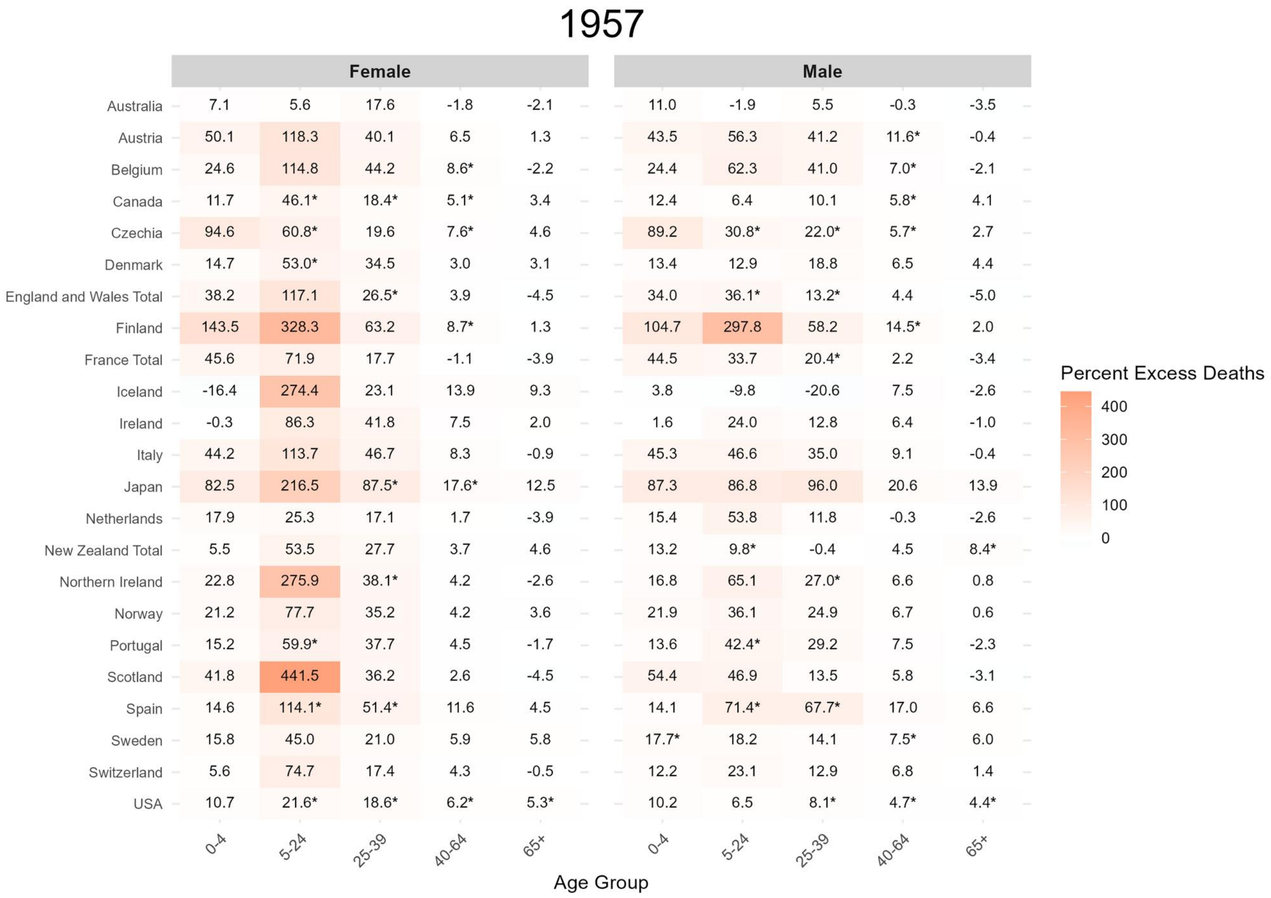
Similarly to the age-specific absolute excess mortality rates, the age-specific percentage excess mortality also varied substantially by pandemic and population, for both women and men (Figs 1–4). Analogous to the absolute excess mortality shown in Table 1, during the 1918 pandemic in all populations and for both women and men, there was a peak in the percentage excess mortality in younger adults (25–39 years) and to a lesser extent in adolescents (5–24 years) (Fig. 1). There is some variability in the scale of the excess mortality between different populations, consistently with previous reports of fluctuating mortality rates based on geography [1].

The all-cause percentage excess mortality in the 1957 pandemic broadly resembled that of the 1918 pandemic in that peaks occurred in individuals aged 5–24 years, particularly for female rates, but it did show less pronounced increases among those aged 25–39 years (Fig. 2). However, the all-cause percentage excess mortality rates in the 1968 and 2009 pandemics show a much smaller scale, with no consistent age or sex patterns (Figs 3 and 4). The percentage excess mortality among



	Female 0-4	Female 5-24	Female 25-39	Female 40-64	Female 65+	Male 0-4	Male 5-24	Male 25-39	Male 40-64	Male 65+
Denmark	-8.5	76.4*	96.5*	0.5	-20.5*	-13.2	77.6*	107.4*	-9.6*	-21.9*
England and Wales Civilian	24.1	97.6*	114.0*	12.0*	-10.1	15.9	64.6*	108.0*	10.7*	-7.7
Finland	32.4*	47.2*	50.8*	21.6*	6.8					
France Civilian	39.4*	107.1*	130.8*	23.0*	1.2					
Iceland	48.0	72.8*	150.1*	46.1*	-6.2	-3.7	55.4	87.5*	11.1	-11.8
Italy	59.7*	281.0*	295.3*	85.6*	30.2*					
Netherlands	47.5*	136.1*	136.8*	27.6*	1.2	40.6*	115.4*	187.9*	33.1*	3.5
New Zealand Non Maori	14.8	73.0*	161.4*	52.5*	12.7					
Norway	22.7*	96.4*	110.3*	20.8*	-5.6	13.9*	84.5*	123.3*	11.5*	-6.8*
Scotland	2.9	61.9*	63.4*	8.3	-9.3	1.6	46.6*	64.3*	4.0	-11.2*
Spain	40.0*	138.6*	182.6*	47.4*	12.0	38.0*	122.3*	208.5*	42.8*	9.3
Sweden	18.6	104.5*	136.4*	24.0*	-1.1	13.7	103.4*	179.0*	22.2*	-1.6
Switzerland	45.0*	136.1*	175.0*	30.5*	8.4*	32.2*	171.4*	290.9*	31.3*	6.2

Figure 1 All-cause percentage excess mortality for all countries in 1918, where expected mortality was calculated using the linear trend of the preceding 10 years. Numbers indicate the percentage change from the expected mortality for each age group. * indicates values outside PIs for expected mortality in the pandemic year [refer to the Open Science Framework (OSF) repository for underlying data].



	Female					Male				
	0-4	5-24	25-39	40-64	65+	0-4	5-24	25-39	40-64	65+
Australia	7.1	5.6	17.6	-1.8	-2.1	11.0	-1.9	5.5	-0.3	-3.5
Austria	50.1	118.3	40.1	6.5	1.3	43.5	56.3	41.2	11.6*	-0.4
Belgium	24.6	114.8	44.2	8.6*	-2.2	24.4	62.3	41.0	7.0*	-2.1
Canada	11.7	46.1*	18.4*	5.1*	3.4	12.4	6.4	10.1	5.8*	4.1
Czechia	94.6	60.8*	19.6	7.6*	4.6	89.2	30.8*	22.0*	5.7*	2.7
Denmark	14.7	53.0*	34.5	3.0	3.1	13.4	12.9	18.8	6.5	4.4
England and Wales Total	38.2	117.1	26.5*	3.9	-4.5	34.0	36.1*	13.2*	4.4	-5.0
Finland	143.5	328.3	63.2	8.7*	1.3	104.7	297.8	58.2	14.5*	2.0
France Total	45.6	71.9	17.7	-1.1	-3.9	44.5	33.7	20.4*	2.2	-3.4
Iceland	-16.4	274.4	23.1	13.9	9.3	3.8	-9.8	-20.6	7.5	-2.6
Ireland	-0.3	86.3	41.8	7.5	2.0	1.6	24.0	12.8	6.4	-1.0
Italy	44.2	113.7	46.7	8.3	-0.9	45.3	46.6	35.0	9.1	-0.4
Japan	82.5	216.5	87.5*	17.6*	12.5	87.3	86.8	96.0	20.6	13.9
Netherlands	17.9	25.3	17.1	1.7	-3.9	15.4	53.8	11.8	-0.3	-2.6
New Zealand Total	5.5	53.5	27.7	3.7	4.6	13.2	9.8*	-0.4	4.5	8.4*
Northern Ireland	22.8	275.9	38.1*	4.2	-2.6	16.8	65.1	27.0*	6.6	0.8
Norway	21.2	77.7	35.2	4.2	3.6	21.9	36.1	24.9	6.7	0.6
Portugal	15.2	59.9*	37.7	4.5	-1.7	13.6	42.4*	29.2	7.5	-2.3
Scotland	41.8	441.5	36.2	2.6	-4.5	54.4	46.9	13.5	5.8	-3.1
Spain	14.6	114.1*	51.4*	11.6	4.5	14.1	71.4*	67.7*	17.0	6.6
Sweden	15.8	45.0	21.0	5.9	5.8	17.7*	18.2	14.1	7.5*	6.0
Switzerland	5.6	74.7	17.4	4.3	-0.5	12.2	23.1	12.9	6.8	1.4
USA	10.7	21.6*	18.6*	6.2*	5.3*	10.2	6.5	8.1*	4.7*	4.4*

Figure 2 All-cause percentage excess mortality for all countries in 1957, where expected mortality was calculated using the linear trend of the preceding 10 years. Numbers indicate the percentage change from the expected mortality for each age group. * indicates values outside PIs for expected mortality in the pandemic year [refer to the Open Science Framework (OSF) repository for underlying data].

individuals aged 40–64 and 65+ years also varies in magnitude and, especially in 2009, directionality during these later pandemics.

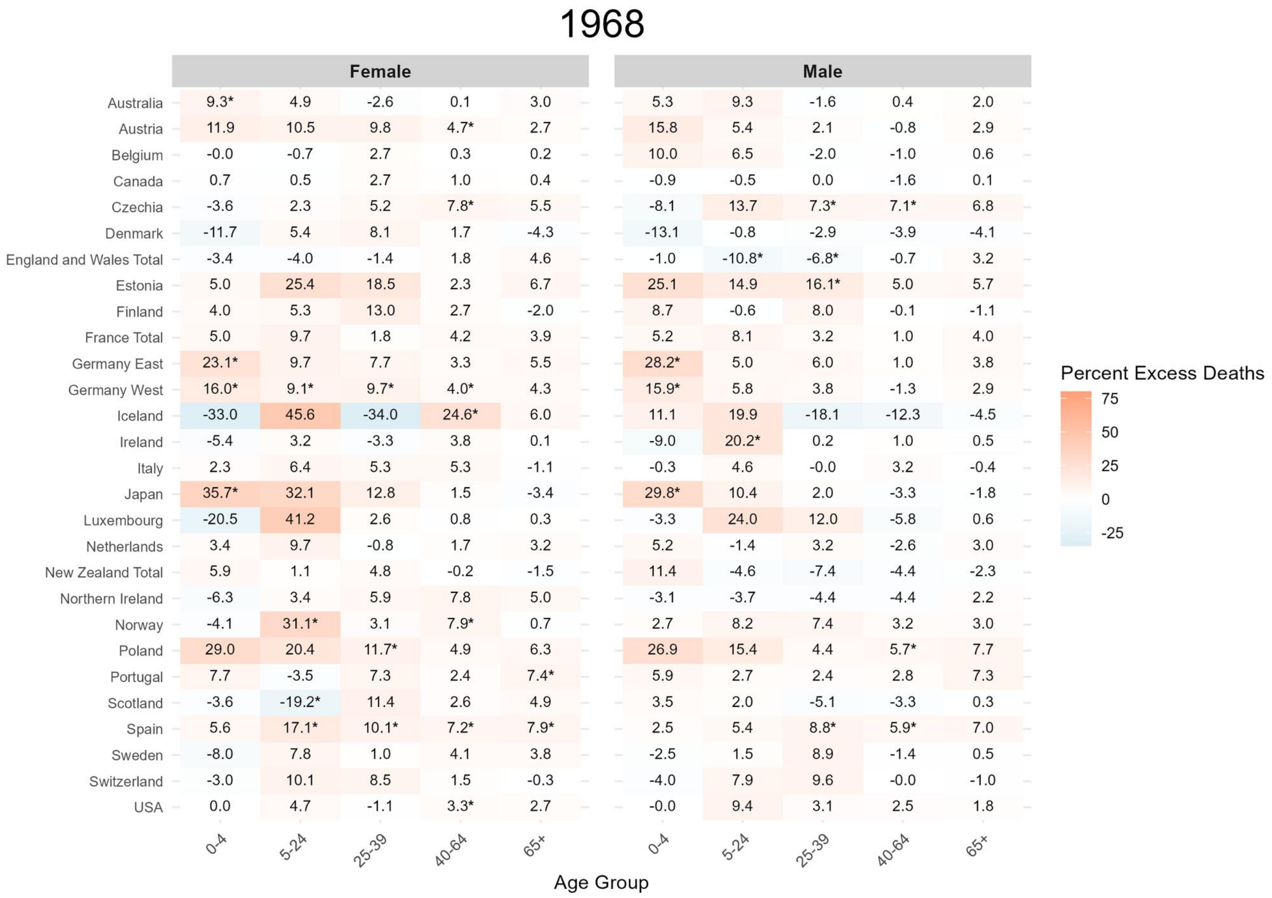
In total, both the absolute and percentage excess mortality rates reveal different age patterns of risk across pandemics and, often, within pandemics across populations.

Discussion

The results demonstrated that, contrary to the results of previous analyses [8], young adults do not uniformly experience the greatest excess mortality during influenza pandemics. Notably, the absolute excess mortality peaked at young-adult ages in every 1918 observation, but in no observation in any other pandemic. In a percentage metric, 5- to 24-year-olds showed large excess mortality in the 1957 pandemic, but the percentage excess mortality was smaller among those aged 25–39 years and was typically small among both of these age groups in 1968 and 2009. Even in 1957, the absolute excess mortality among those aged 25–39 years was consistently close to zero.

Thus, while the 1918 pandemic was notable for its impact on young-adult mortality, similar age patterns of absolute and percentage excess mortality were generally not observed in the 1957, 1968, and 2009 influenza pandemics. Furthermore, the 1918 age-specific excess mortality was far from uniform across the populations, particularly at older and early-childhood ages. This heterogeneity indicates that the influential age profiles derived from single-country studies do not capture the full range of 1918 mortality patterns. We suggest that the historical reports of increased severity in the young during the latter three influenza pandemics [37, 38] were overstated as an enduring reaction to the unprecedented young-adult mortality observed in 1918. The historically unusual peak in positive excess mortality among young adults in 1918 supports theories that mortality reflected both the virus's unusual virulence [39] and host immunological naivete [26, 35, 40].

However, the age patterning of pandemics likely reflects social as well as physiological risks, both of which are likely to vary across pandemics and even to interact [41]. After the 1918 pandemic, an expectation of high influenza-related mortality in younger age groups may have led to a disproportionate focus on deaths within these groups, even when the underlying absolute death rates were low relative to those of the other groups. We speculate that this lasting response to the unprecedented young-adult mortality in 1918 may have produced a protective feedback loop. Early perceptions about age-based risk may have encouraged interventions, such as non-pharmaceutical interventions and targeted vaccination (in the case of the 2009



	Female					Male				
	0-4	5-24	25-39	40-64	65+	0-4	5-24	25-39	40-64	65+
Australia	9.3*	4.9	-2.6	0.1	3.0	5.3	9.3	-1.6	0.4	2.0
Austria	11.9	10.5	9.8	4.7*	2.7	15.8	5.4	2.1	-0.8	2.9
Belgium	-0.0	-0.7	2.7	0.3	0.2	10.0	6.5	-2.0	-1.0	0.6
Canada	0.7	0.5	2.7	1.0	0.4	-0.9	-0.5	0.0	-1.6	0.1
Czechia	-3.6	2.3	5.2	7.8*	5.5	-8.1	13.7	7.3*	7.1*	6.8
Denmark	-11.7	5.4	8.1	1.7	-4.3	-13.1	-0.8	-2.9	-3.9	-4.1
England and Wales Total	-3.4	-4.0	-1.4	1.8	4.6	-1.0	-10.8*	-6.8*	-0.7	3.2
Estonia	5.0	25.4	18.5	2.3	6.7	25.1	14.9	16.1*	5.0	5.7
Finland	4.0	5.3	13.0	2.7	-2.0	8.7	-0.6	8.0	-0.1	-1.1
France Total	5.0	9.7	1.8	4.2	3.9	5.2	8.1	3.2	1.0	4.0
Germany East	23.1*	9.7	7.7	3.3	5.5	28.2*	5.0	6.0	1.0	3.8
Germany West	16.0*	9.1*	9.7*	4.0*	4.3	15.9*	5.8	3.8	-1.3	2.9
Iceland	-33.0	45.6	-34.0	24.6*	6.0	11.1	19.9	-18.1	-12.3	-4.5
Ireland	-5.4	3.2	-3.3	3.8	0.1	-9.0	20.2*	0.2	1.0	0.5
Italy	2.3	6.4	5.3	5.3	-1.1	-0.3	4.6	-0.0	3.2	-0.4
Japan	35.7*	32.1	12.8	1.5	-3.4	29.8*	10.4	2.0	-3.3	-1.8
Luxembourg	-20.5	41.2	2.6	0.8	0.3	-3.3	24.0	12.0	-5.8	0.6
Netherlands	3.4	9.7	-0.8	1.7	3.2	5.2	-1.4	3.2	-2.6	3.0
New Zealand Total	5.9	1.1	4.8	-0.2	-1.5	11.4	-4.6	-7.4	-4.4	-2.3
Northern Ireland	-6.3	3.4	5.9	7.8	5.0	-3.1	-3.7	-4.4	-4.4	2.2
Norway	-4.1	31.1*	3.1	7.9*	0.7	2.7	8.2	7.4	3.2	3.0
Poland	29.0	20.4	11.7*	4.9	6.3	26.9	15.4	4.4	5.7*	7.7
Portugal	7.7	-3.5	7.3	2.4	7.4*	5.9	2.7	2.4	2.8	7.3
Scotland	-3.6	-19.2*	11.4	2.6	4.9	3.5	2.0	-5.1	-3.3	0.3
Spain	5.6	17.1*	10.1*	7.2*	7.9*	2.5	5.4	8.8*	5.9*	7.0
Sweden	-8.0	7.8	1.0	4.1	3.8	-2.5	1.5	8.9	-1.4	0.5
Switzerland	-3.0	10.1	8.5	1.5	-0.3	-4.0	7.9	9.6	-0.0	-1.0
USA	0.0	4.7	-1.1	3.3*	2.7	-0.0	9.4	3.1	2.5	1.8

Figure 3 All-cause percentage excess mortality for all countries in 1968 or 1969 (see Supplementary Figure S1), where expected mortality was calculated using the linear trend of the preceding 10 years. Numbers indicate the percentage change from the expected mortality for each age group. * indicates values outside PIs for expected mortality in the pandemic year [refer to the Open Science Framework (OSF) repository for underlying data].

pandemic [42]), providing disproportionate protection and subsequent negative excess mortality in younger age groups.

Across the later pandemics, the percentage excess mortality varies substantially among individuals aged 25–39 years, while the absolute excess mortality remains close to zero. This divergence reflects the very low expected mortality rate in this age group, such that even small increases in observed deaths can produce a high percentage excess mortality. More generally, some mortality patterns depended on whether excess mortality was measured in absolute or percentage metrics. For example, in the 1918 pandemic, the absolute excess mortality in the elderly (65+ years) is variable—either positive and comparable to that in young adults or greatly negative; however, the percentage excess mortality was consistently lower in the elderly than in younger adults (with the exception of those in New Zealand and Scotland). Absolute and percentage metrics have both been important in the literature on pandemic excess mortality and may be relevant for different public health purposes. Absolute excess mortality is arguably most relevant for targeting vaccination or non-pharmaceutical interventions, while percentage excess mortality is more informative for elucidating the mechanisms underlying age-specific risks [43].

Studies detailing age patterns of mortality during influenza pandemics have primarily focused on geographically restricted areas, using country-specific data from national sources [2, 3, 8, 11, 14, 19, 20, 34, 44]. This geographical constraint in prior literature makes it difficult to accurately compare outcomes between different populations due to inconsistencies in data collection and record keeping. We show that assumptions and extrapolations made from studies using US-centric data [2, 3, 8, 11, 14, 19, 20, 34, 44] are misleading, especially as country-specific responses may have influenced which ages were the most susceptible to severe disease. Medical advances and access to state-of-the-art medical care are also not homogenous across populations. Relying only on data from the USA, or indeed any other single developed country, risks misrepresenting the at-risk age groups during influenza pandemics.

This study limits complications associated with heterogeneous data processing and limited geographical representation by using the HMD, which provides unified, in-depth death and population statistics for numerous populations. While the internal consistency of the HMD supports robust comparisons across populations and time, most included populations are high-income and located in Europe, North America, or Oceania, limiting the generalizability of these findings to other global regions. Nonetheless, this study provides a comprehensive investigation into the age-specific excess mortality patterns across all four influenza pandemics in ≤48 populations and makes it clear that no single age group was most at risk of mortality in every region for all pandemics.

	Female					Male				
	0-4	5-24	25-39	40-64	65+	0-4	5-24	25-39	40-64	65+
Australia	-4.6	7.7	6.6	4.3	-2.8	0.6	11.9	10.4	2.8	-0.7
Austria	14.7	-1.0	13.3	4.1	2.5	-0.2	-2.1	3.2	7.0*	4.6
Belarus	13.0	4.2	1.9	3.5	5.7*	18.2	0.8	-6.7	2.0	1.6
Belgium	-1.9	22.1	1.0	3.7	2.3	2.4	-1.3	2.4	3.4	2.8
Bulgaria	7.8	-12.7	5.4	-0.3	-2.6	18.1*	-0.4	-0.3	-2.4	-5.3*
Canada	-2.3	-0.5	6.9	1.8	-2.6*	-7.8*	-4.6	-0.4	0.9	-0.1
Chile	7.8	2.5	0.5	1.5	-1.1	7.3	5.1	0.4	4.4	-0.5
Croatia	19.7	7.4	-5.6	-1.2	3.0	14.1	0.1	-11.0*	1.3	0.7
Czechia	12.9	27.6*	6.4	-2.8	1.4	-11.5	-5.0	1.6	-1.2	0.6
Denmark	-4.3	15.6	7.4	-0.2	-0.9	-29.2*	-13.6	7.2	-1.6	0.1
England and Wales Total	-2.9	-0.4	-0.8	0.1	-3.8	-4.7	-1.5	1.1	1.1	-0.2
Estonia	-10.6	-8.6	14.7	-6.3	1.4	-8.7	-33.3*	6.4	-8.4	-3.8*
Finland	14.3	-2.5	4.7	-0.5	4.3	-22.4	-4.4	6.3	-3.2	6.9*
France Total	9.8	13.7*	5.4	2.9	5.7	7.9	9.2	8.0*	2.9	2.9
Germany Total	-1.6	15.2*	5.7	3.1	5.2	5.1	4.9	5.9*	4.1*	8.1*
Greece	13.1	13.3	13.5	-0.2	0.5	27.4	5.2	2.7	3.4	0.8
Hong Kong	1.8	9.9	-1.3	9.9	-0.9	0.4	11.5	-2.6	7.2	-2.3
Hungary	2.8	5.3	8.1	-0.1	0.5	-8.4	1.6	6.3	-2.3	-0.7
Iceland	-41.2*	48.9	35.0	-12.6	2.4	-16.9	-35.5	91.6	15.4	1.8
Ireland	8.8	-11.7	16.9	3.8	1.6	18.7	-4.2	27.7*	9.0	6.4
Israel	12.9	-0.6	2.7	5.5	-2.2	3.2	-10.2	4.0	-0.7	-0.3
Italy	17.0*	18.7	7.3	4.8	4.0	15.2	8.6	2.7	5.0*	4.0
Japan	-2.0	0.1	0.8	-2.4	-0.6	6.2	4.8	0.1	-1.9	0.0
Latvia	15.1	7.7	-6.6	-8.4	-3.5	2.1	-8.1	-9.3	-14.2*	-4.6*
Lithuania	-11.8	-5.7	-19.3	-14.8*	-1.3	6.2	-0.0	-23.6*	-18.3*	-1.2
Luxembourg	39.3	-77.7*	-12.6	12.6	-4.1	52.1	4.2	4.5	-2.9	-0.8
Netherlands	9.4	4.3	2.9	0.3	-1.6	3.6	10.1	-2.7	3.8	0.5
New Zealand Total	5.3	0.1	-1.1	4.3	-2.5	-2.1	3.6	6.4	3.8	1.8
Northern Ireland	13.7	8.7	-9.3	5.7	0.9	-6.9	-6.7	-1.6	-4.1	-2.1
Norway	5.8	13.2	-0.8	-0.9	0.4	24.9	6.9	11.5	3.4	-1.3
Poland	6.3	6.0	12.2	5.2	7.5	2.7	5.8	4.5	2.6	5.2
Portugal	35.7	5.8	9.0*	8.4*	2.9	58.6*	15.0	5.9	1.1	0.7
Republic of Korea	3.6	3.5	10.5	4.2	-0.5	-1.3	14.6	19.1	6.2*	-1.2
Russia	5.6	-6.6	-13.4	-5.3	2.3	4.6	-11.9	-16.0	-8.9	0.3
Scotland	-19.1	4.2	-0.8	1.3	-2.9	-7.7	-12.2	-7.1	-1.6	-0.9
Slovakia	-4.4	-1.5	5.1	3.8	-1.9	5.7	-5.2	-5.5	1.0	-4.8*
Slovenia	-3.9	-24.2	-5.0	2.6	4.2	-15.6	-12.3	-3.3	-2.2	2.9
Spain	1.1	1.6	-0.2	1.5	-0.8	-2.8	-16.3*	-0.1	-1.2	-0.9
Sweden	-5.6	0.0	-6.5	-0.4	-3.9	13.7	-0.5	7.9	-3.0*	-2.4
Switzerland	4.2	0.3	-9.3	-0.3	2.7	17.2	9.2	6.3	1.6	1.5
Taiwan	5.1	16.3	-1.3	4.3	0.8	-2.5	7.7	-5.5	-0.5	-2.2
Ukraine	-6.4	-10.6*	-20.7*	-9.8*	2.3	-9.0	-12.5	-22.4*	-16.4*	-0.8
USA	-5.9*	-4.8	1.4	0.8	-3.7	-5.8*	-11.8*	-3.3	0.2	-1.4

Figure 4 All-cause percentage excess mortality for all countries in 2009, where expected mortality was calculated using the linear trend of the preceding 10 years. Numbers indicate the percentage change from the expected mortality for each age group. * indicates values outside PIs for expected mortality in the pandemic year [refer to Open Science Framework (OSF) repository for underlying data].

The mortality patterns in the elderly during influenza pandemics were contradictory, varying by country and pandemic. This was unexpected, and likely reflects the overrepresentation of US-focused studies in the current literature. Inconsistencies in elderly mortality have been observed before in the 1918 pandemic, with some studies identifying decreased mortality [14] and others increased mortality [15–18]; however, earlier studies consistently identify increased mortality in the elderly during the 1957 and 1968 pandemics [10, 11, 19, 20] and decreased mortality during the 2009 pandemic [21–23]. Prior exposure to antigenically similar viruses is often proposed as a protective mechanism, reducing excess mortality in older individuals [45]; however, "senior sparing" was not previously thought to occur to the same extent in 1957 and 1968, potentially due to limited exposure to the H2 and H3 influenza viruses or the concurrent rise in comorbidities [10, 11, 20]. Future work analysing the historic infection, regional, socioeconomic, or demographic context of each country is necessary to determine whether older-age protection depends on cohort-specific exposure to previous pandemic strains.

The 2009 pandemic is noteworthy. The smaller scale of the all-cause excess mortality may provide insights into risk mitigation for future influenza pandemics. It was the first to occur in the twenty-first century, when modern genetic, molecular, and epidemiological techniques were widespread. Moreover, the expansion of social media, the 24-hour news cycle, and general global connectedness between 1968 and 2009 allowed the essentially instantaneous transmission of scientific and health-related information across the world at the start of the 2009 pandemic. The presence of H1N1 antibodies in the population prior to 2009 [46], the rapid introduction of an effective vaccine, specifically targeted towards younger age groups in some countries [42], and greatly accelerated pandemic responses [47] meant that the 2009 influenza pandemic was relatively mild in comparison to the pandemics of the twentieth century [48]. The 2009 pandemic virus also replaced the previous seasonal H1N1 influenza strain [49], so we propose that these features together may have led to a greatly reduced scale of excess mortality in all age groups. Understanding the factors contributing to relatively low mortality of the 2009 pandemic is important given the recent politically motivated calls to dismantle the pandemic-preparedness infrastructure following the COVID-19 pandemic [50].

These data highlight the importance of analysing country-specific outcomes for each pandemic, rather than relying on inferences from restricted geographical areas. Pandemic preparedness is not a one-size-fits-all endeavor. The next influenza pandemic is not a question of if, but when, and understanding who is most vulnerable to severe disease and death is critical for guiding targeted interventions. Future work analysing the historical infection context of each country is necessary to reveal the complex interactions between immunologic, demographic, and geographic determinants of age-specific mortality risks—insights that will be essential for developing more effective preparedness strategies.

Ethics approval

Ethics approval is not required, as the database is publicly available, aggregated, and de-identified.

Author contributions

L.E.S. and K.R.S. conceptualized the research. All authors contributed to designing the research. L.E.S., A.M.T., and E.W.-F. collected, interpreted, and analysed data. L.E.S. wrote the manuscript. L.E.S., A.M.T., and E.W.-F. led critical revisions of the manuscript. All authors reviewed and edited the manuscript. L.E.S., A.M.T., and E.W.-F. acted as guarantors for the paper.

Supplementary material

Supplementary material is available at *IJE* online.

Conflicts of interest

None declared.

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Data availability

Data from the HMD are freely accessible from https://www.mortality.org/. All data presented here are fully reproducible and the link to our Open Science Framework (OSF) repository is available at https://osf.io/3jzxy/?view_only=a472559852c448739f6d53fa2419d6f8.

Use of artificial intelligence (AI) tools

None declared.

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