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Situating Mortality: Quantifying Crisis Points and Periods of Stability

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ABSTRACT A wide range of stressors can cause a dramatic and sudden rise in the death rate in populations, typically resulting in what is referred to as crisis mortality. Here we present a method to standardize the assessment of identifying moments of crises. A modification of the mortality *Z*-score methodology which is combined with time series analysis was used to investigate mortality events over the course of nearly two centuries for two populations: Gibraltar and Malta. A benefit of this method is that it situates the yearly death rate within the prevailing mortality pattern, and by doing so allows the researcher to assess the relative impact of that event against the norm for the period under investigation. A series of threshold values were established to develop levels of mortality to distinguish moments of lower mortality than expected, background mortality, a crisis, and a catastrophe. Our findings suggested that within defined periods, a limited number of events constituted moments of excessive mortality in the range of a crisis or higher. These included epidemics (yellow fever and influenza in Gibraltar only, and cholera) and casualties associated with World War II. Episodes of lower than expected mortality were only detected (although not significant) in the 20th century in Malta, and at the micro level, the harvesting effect appears to have occurred following cholera epidemics in both locations and influenza in Gibraltar. The analysis demonstrates clearly that the impact of epidemics can be highly variable across time and populations. Am J Phys Anthropol 152:459–470, 2013. © 2013 Wiley Periodicals, Inc.

Historically, investigations into periods of elevated mortality that may constitute a state of crisis have received the attention of investigators from a host of different disciplines including geography, demography, history, and anthropology (Pelling, 1978; Charbonneau and Larose, 1979; Coleman, 1987; Fox, 1989; Dobson, 1997; and Swedlund, 2010; Bengtsson and Gagnon, 2011). We follow the definition of crisis mortality by Bouckaert (1989), as a sudden and dramatic increase in the mortality rate arising from a common, extraordinary causal factor operating for a limited period of time. A host of stressors such as droughts, famines, floods, tsunamis, epidemics, volcanic eruptions, and wars can lead to a moment of crisis (see for example, Hollingsworth, 1979; Palloni, 1990; Sawchuk, 1996; Howe and Devereux, 2004; and Witham and Oppenheimer, 2005). Inquiries into crisis mortality are beset by the lack of a standardized methodology to identify and evaluate the severity of a usual mortality event. The net result is an inconsistency of what precisely constitutes an unusual event that can be characterized as a crisis moment. For details on merits and drawbacks of various methods proposed by Hollingsworth, Dupaquier, Imhof, Schofield, and others, see Appleby (1979).

In the case of assessing the impact of epidemics, for example, Green et al. (2002) have noted that the term epidemic itself is typically fraught with ambiguity, along with the use of interchangeable terms, which are often emotionally charged and mutable over time and space. Accordingly, we offer a straightforward approach for the identification of a period of unusually high (and low) death rates, by means of contextualizing within the normative background mortality pattern, as well as employing a range of thresholds that captures the magnitude of the extraordinary event. Despite the attention given to identifying crisis events, to date there has been little work on empirically defining the state of background mortality in relative terms, and more precisely, the degree of variation present in the death rates. The detection of significant differences in intrinsic variation across time and space may prove useful as a comparative population-based tool as well as an indicator of broad changes that result from sanitary reform, medical intervention, rise in the standard of living, and/or major behavioral changes that enhance or limit the mortality experience of a population.

THE STUDY SITES

To illustrate our approach we examine the mortality experience of two British colonies, Gibraltar and Malta, both of which from a research perspective share a number of desirable attributes. These include 1) a long-

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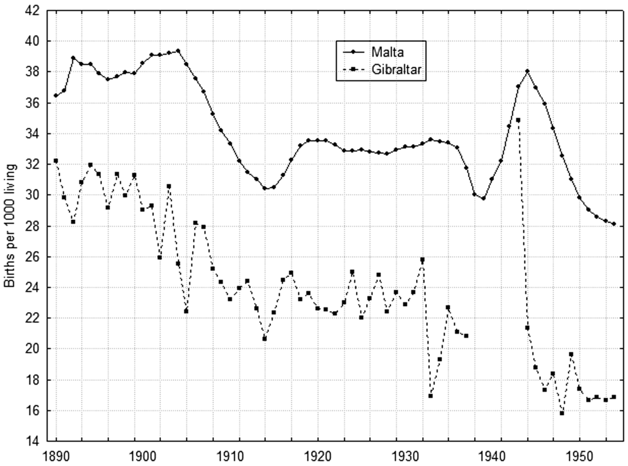

Fig. 1. Crude birth rates: Malta and Gibraltar—5 year moving averages.

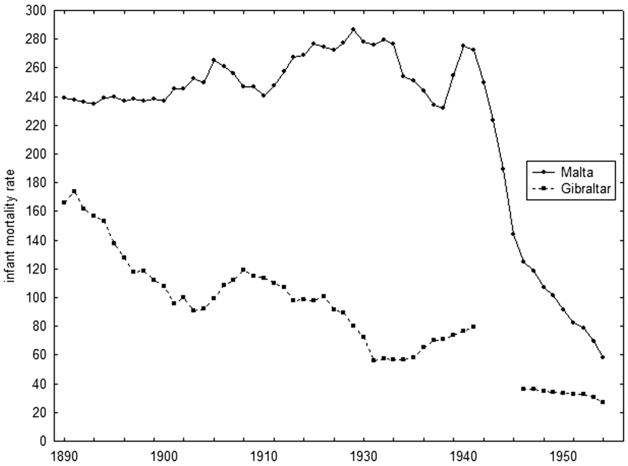

Fig. 2. Infant mortality rates: Malta and Gibraltar—5 year moving averages.

standing tradition of reliable record keeping; 2) a dataset collected from the same source over time; 3) a temporal depth that is sufficient to minimize short-term aberrations, and finally; 4) an extensive narrative of information covering the study period.

In addition to these essential research attributes, these two populations share a number of commonalities that superficially would put them on an even footing in terms of health during the 19th and early 20th centuries. These include a Mediterranean climate with protracted hot and dry summers acting as a powerful ecological stressor; an overcrowded population; a deficiency in even the most rudimentary sanitary infrastructure, and public and domestic hygiene, particularly in the urban centers; and a port city (urban center) that increased risk of exposure to pathogens (e.g., cholera and yellow fever) for the natives from transient individuals or migrants disembarking from sea vessels. Furthermore, as British colonies the civilian community coexisted with a garrison presence where civilian needs were subordinate to colonial and military needs (Anderson, 1998).

However, the ostensibly similar geographic and living conditions do not extend to the demographics and health of the two populations. As shown in Figures 1 and 2, the two proxy measures of population health—the birth rate and infant mortality rates (IMRs)—differ drastically between the two locales. Over the last 60 years the crude birth rates were consistently higher in Malta. However, both populations showed a secular decrease in fertility rates over time; the only exception was a precipitated increase following World War II (see Fig. 1). Of note here, and for the dataset used in this study, the population of Gibraltar was evacuated during World War II, and as such, there are no vital statistics to report from 1940 to 1945 (Finlayson, 1991). The population was not completely repatriated until 1950. The risk of nutritional deficiency was a common consequence of the high birth rate in Malta, especially among mothers who bore infants with short birth intervals. Even more telling of the dire state of health in Malta over the 60-year period were the elevated IMR compared to its sister colony, Gibraltar (see Fig. 2). While IMR in Gibraltar can be described as a gradual and progressive decline between 1890 and 1940, Malta's IMR remained persistently high until the early 1940s, after which time it finally declined at a notably fast pace.

The differences in overall health of the two populations can be attributed in part to scale differences in territory and population size. For more details on scale differences between Gibraltar and Malta, see Tripp and Sawchuk (in press). Gibraltar is located at the western end of the Mediterranean, a "continental enclave," situated at the southern tip of Andalusian Spain by a flat sandy strip of land that runs nearly due north and south. The relatively small territory with a single fortress covers approximately just 1,266 acres or about 4.22 square miles.

The Maltese islands (Malta, Gozo, and Comino), a former British colony, are located in the middle of the Mediterranean Sea. Although Malta is one of the smallest countries in the world, the archipelago's combined area of ~240 square miles is large compared to Gibraltar. Unlike Gibraltar, the civilian population and the military bases in Malta are dispersed across various towns in Malta and Gozo, and Comino is largely uninhabitable (for this reason we have used only demographic information from Malta and Gozo). Confounding the problem of providing for a dispersed population is the sheer population size of Malta, which numbered several hundred thousand people during our study period (see Fig. 3), whereas the population of Gibraltar peaked at just under 30,700. Thus as aptly put by the Governor of Gibraltar, Duddurk, in 1896, Gibraltar's, "requirements are thus more easily dealt with than those of the larger Colonies with scattered populations" (Governor letter to J. Chamberlain). Thus, these "requirements," which can include health needs, appear to have been easier to provide for in Gibraltar, and we can extend this logic to prevention and control of disease as well. However, the concentration of individuals within the fortress walls of Gibraltar may have increased susceptibility to crises of infectious diseases, whereas the dispersed population of Malta may have acted as a protective factor in preventing infectious diseases from entering urban center ports and running rampant outside the city walls (Grob, 2002).

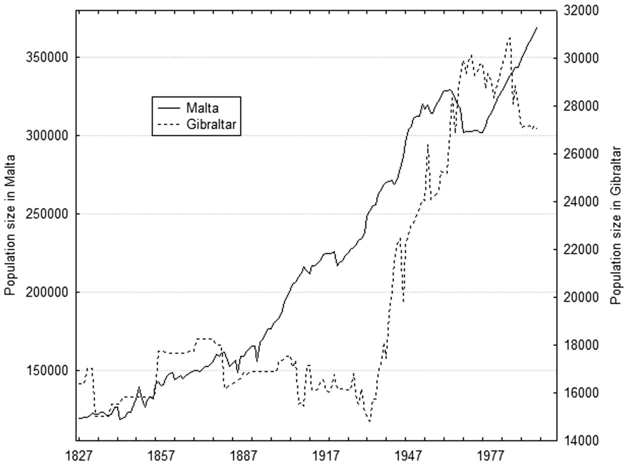

Fig. 3. Population size for Gibraltar and Malta from 1827 to 1994.

MATERIALS AND METHODS

Data

Our comparison of Gibraltar and Malta is based on 1823–1899 government vital statistics published in a common resource known colloquially as the *Blue Books*. Each colony in the British Empire was responsible for sending information back to the Colonial Secretary on a variety of subjects, including commercial, wages, expenditures, imports, exports, and general information (Martin, 1843). One important category was demographic information that dealt specifically with population size, births, marriages, and deaths. This information was considered consistent, and deemed reliable as it was used by the colonial authorities locally and abroad for purposes of management and administrative oversight. However, the information provided in these records did not contain individual specifics, such as age and sex. While it is a highly desirable feature of mortality studies, it is very unusual to see detailed age and sex information available for most historical populations over a consistent and prolonged period of time. The opportunity of addressing elevated mortality over vast periods of time for most populations is simply not possible given the late development of registration systems (see Willigan and Lynch, 1982). In this paper, we will periodically address age- and sex-specific mortality when focusing on a period of heightened morality. Additional limitations with our dataset include the inability to tease apart co-mortality; the possibility of underestimation of the population at risk, since many flee epidemics; and the overestimation of exposed individuals when acquired immunity is present in the population.

After 1899, data was drawn from another government source, the *Annual Reports of Public Health*. Published under the auspices of the Medical Officer of Health, the reports provided information on basic vital statistics as well as health-related matters on infants, maternity sanitation, housing, food quality, water, and detailed accounts of morbidity and mortality by notifiable diseases. Using the aforementioned data sources we compiled annual mortality rates covering the years 1825–2011 for Gibraltar and 1827–1993 for Malta.

Description of methodology

To identify years of abnormally high or low mortality our proposed method proceeds in two stages: first, we identify subperiods (phases) in the original series that exhibit consistent mortality behavior using a sequence segmentation algorithm; and second, we calculate Z-scores in relation to mortality rates within each phase, taking into account potential time-series characteristics of the data. Our entire analysis is performed on the logit transformation of the original mortality data, which maps rates in (0, 1) to the real numbers. The logit transformation is commonly applied to rates or proportions to make them amenable to methods of analysis borrowed from measurement data, such as logistic regression (MacCullagh and Nelder, 1995). In situations where only the number of deaths is known, and assuming the total population size is relatively constant through time, we propose our method be applied to the logarithmic transformation of the count data, for similar reasons. Furthermore, inferences for the transformed data can be readily translated to the original data using the respective inverse transform. The two stages of our proposed method are described in detail below.

Mortality rates have been evolving over the last two centuries, typically exhibiting a diachronic decline at various rates or remaining stable. It is therefore important to place relative comparisons in the context of well-defined historical periods within which the overall behavior of mortality rates is stable. Available contextual or historical information—such as periods of epidemiological transitions that are demarcated by changes in trends of disease etiology and knowledge in medicine (Omran, 1971)—can help specify the number of periods and fine-tune each period's boundaries. Bearing in mind that each population has its unique trajectory through the three transitions, the development of our mortality phases loosely reflects Omran's concept of the epidemiological transition. As such our dataset appears to follow the trend as in most industrialized societies with an "Age of Receding Pandemics" that began around the middle of the 19th century, but does not capture the more recently proposed "fourth or hybristic stage" that began in the mid-1960s or 1970s with a rapid decline in cardiovascular diseases (Omran, 1977; Olshansky and Ault, 1986; Mackenbach, 1994; Omran, 1998; Vallin and Meslé, 2004). The establishment of these phases from a purely epidemiological standpoint can be problematic as the timing of changes in health care practices, knowledge, and shifts in mortality patterns and associated diseases are ambiguous. For instance, it has been argued that the European bacteriological revolution of the 1880s did not occur in Great Britain as is assumed by most historians. In fact the acquisition of germ knowledge occurred over a much longer period of time: the improvement in prevention and treatment of diseases (such as syphilis and leprosy) and the shift towards reductionist and/or contagionist trajectories occurred after the supposed revolution from 1870 to 1910 (Worboys, 2007).

The objective of the first stage of our method is to identify historical periods in an objective manner, for which we employ a linear segmentation procedure based on dynamic programming (Bellman, 1961; Guthery, 1974). For a fixed number of periods, the procedure identifies optimal period boundaries and corresponding linear segments, so as to minimize the total squared residuals between the data and the linear segments.

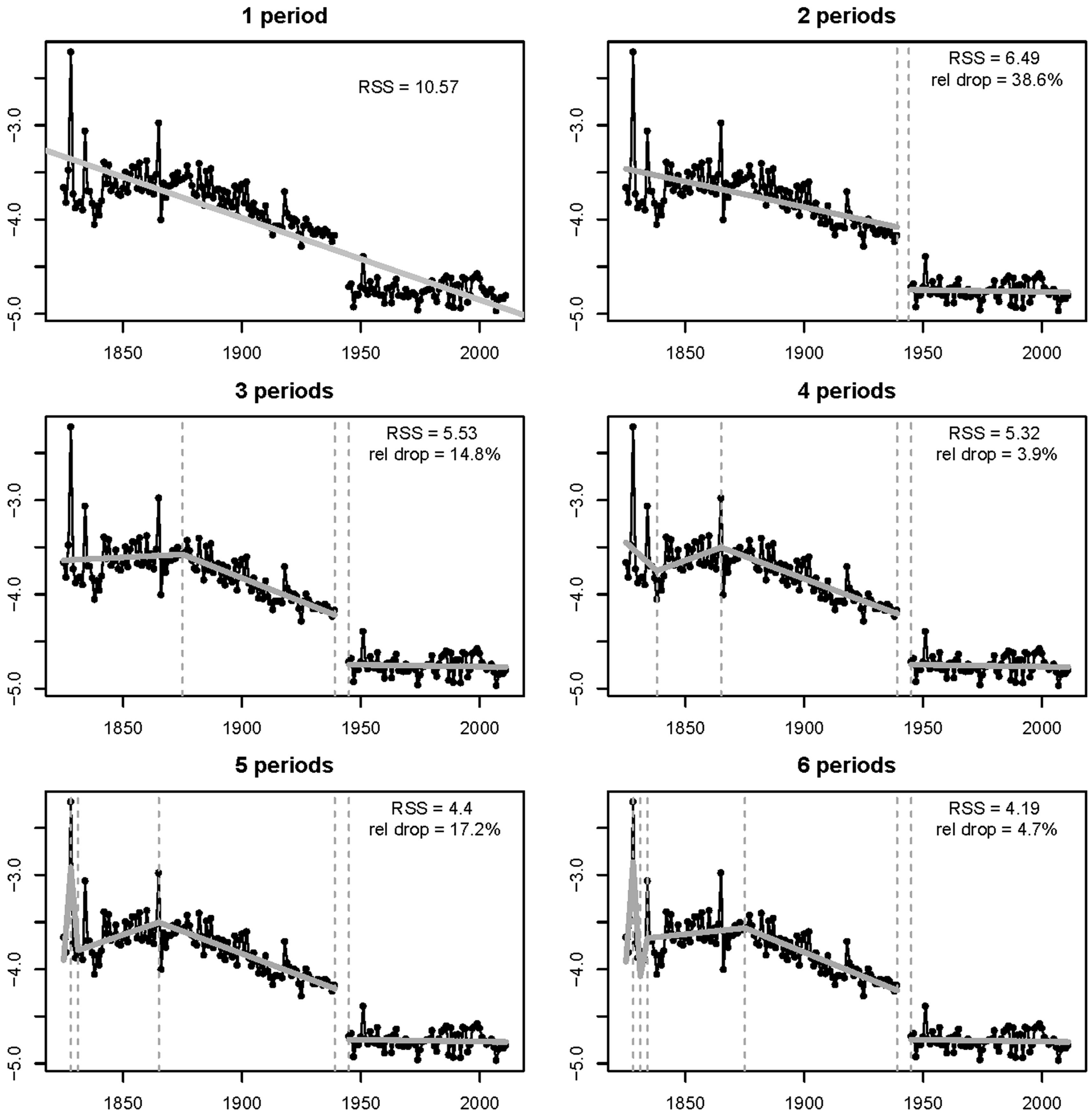

Fig. 4. Output of proposed segmentation procedure applied to the logit of Gibraltar's mortality rate series. Each plot shows the fitted linear segments (thick solid lines) and the breakpoints (vertical-dashed lines) defining them, for different numbers of periods. We also report the total residual sum of squares (RSS) and the relative decrease in RSS for each fit, as compared to its previous one. Note that due to the missing data from 1940 to 1945, we allowed the linear segments before and after this interval to be discontinuous; all other linear segments, however, are connected at their boundaries.

Our procedure is adapted to ensure linear segments are connected (Ertel and Fowlkes, 1976), resulting in a continuous piecewise-linear fitted trend in mortality. The procedure is adept at identifying linear trends in mortality, but it does not explicitly specify how many periods to use. Therefore, we suggest evaluating increasing numbers of periods and stopping at the smallest sufficient number, i.e., when the introduction of a new segment does not improve the interpretation of the data. We deem a new segment as being redundant in two cases: a) if it covers a very short time span, e.g., a period of a few years; or b) if its introduction does not substantially improve the most recent fit of the data, i.e., the drop in the sum of squared residuals is small (e.g., 5%). Figure 4 demonstrates the procedure applied to Gibraltar's data for different numbers of segments. We decided to adopt a three-period model for the data since the introduction of a fourth period did not considerably improve the fit. Considering a fifth period gives a substantial decrease in squared residuals (17%), but this is just an artifact of the procedure trying to track an extreme value using two very short consecutive periods. These brief fitted spikes commonly appear when there are big outliers in the data, but they do not represent any sustained trend and can be safely removed from the analysis.

The second stage of the analysis involves quantifying how abnormal a mortality rate is, relative to rates within its respective period. Previous investigators (see for example, Appleby 1979; Witham and Oppenheimer, 2005) have used the *Z*-score, defined as:

$$Z={}^{M-m}\!/_{\sigma}$$

where the mortality rate, the mean, and the standard deviation are M, m, and σ, respectively, for each year. Our methodology adopts refinements to the calculation of both of these quantities. We start with the mean level, which we have already partially described using the linear trends of the first stage. For some historical periods, the trend alone is enough, but other periods exhibit positive autocorrelation in mortality rates, manifested by random excursions around the trend. To deal with such time-series behavior, researchers have used simple moving averages with a typically ad hoc choice of window size; e.g., Dupaquier (1989) used a 10-year moving average on annual data. We propose using an exponentially weighted moving average (EWMA) instead, where the smoothing factor α is independently estimated for each distinct period (Makridakis et al., 1998). The EWMA is a simple but very effective model for tracking the mean level of a time-series (Newbold and Granger, 1974), and it has been successfully applied to a wide range of data. The model estimates the average of the series at time t, denoted by $s[t]$, as a weighted combination of the previous series' value $x[t-1]$ and the previous EWMA $s[t-1]$, with weights α and $(1-\alpha)$, respectively[1].

$$s[t]=\alpha * x[t-1]+(1-\alpha) * s[t-1]$$

The smoothing parameter $0 \leq \alpha \leq 1$ represents the "memory" of the process: when $\alpha = 1$, the most recent value is used as the average of the next one, whereas when $\alpha = 0$, the average remains constant in time. We select the value of α by minimizing the sum of squared errors between the series and its EWMA. Note that the EWMA is a special case of the Holt–Winters method of exponential smoothing, where the latter also addresses trend and seasonality (Chatfield, 1978). Since our approach models the trend explicitly at the first stage, we only need to apply a simple EWMA to the differences from the fitted linear trend. If there is seasonality in the series, as could be the case for monthly rates, we propose using seasonally adjusted Holt–Winters smoothing without trend. Once moving averages within a period have been calculated, we estimate the standard deviation of the residuals based on their median absolute deviation (MAD) as St. Dev. = MAD/0.6745 (Hoaglin, 1983). We use this robust measure of variability to prevent outliers, i.e., mortality crises, from artificially inflating the standard deviation.

Putting the pieces together, the Z-scores we use to quantify abnormal mortality are defined as:

$$Z-\text{score}=[\text{logit}(\text{mortality})-(\text{linear trend})-(\text{EWMA})/\text{St.Dev.}]$$

The linear trend is derived from the first stage of our analysis and the EWMA and standard deviation come from the second. The resulting Z-score values can be used directly for ranking mortality events within a period, yet their magnitude is not readily interpretable. To assess the severity of a mortality event we propose comparing its Z-score to a reference distribution using the concept of a P value, i.e., the probability of getting an equal or more extreme Z-score from the distribution. The standard Normal distribution can serve as a reference for periods with a large number of data, typically greater than 30. For shorter periods we propose using a Student's t distribution with n-2 degrees of freedom, with n being the number of data in the period, to account for the small-sample estimation of the mean based on the linear trend and the EWMA. Based on Dupaquier's concept of categorization of crisis (Appleby, 1979; Dupaquier, 1989), we also suggest thresholds for characterizing the severity of an event. The two qualitative descriptors used are a *crisis*, determined when the P value is less than 0.01; and a *catastrophe*, determined when the P value is less than 0.001. Note that, if the modeling assumptions hold true, we would expect to see one crisis event every 100 years and one catastrophe event every 1,000 years just by random variation, which roughly describes the calibration of our thresholds. Since our approach assumes symmetry around the mean it can be used for identifying unusually low mortality as well, although such situations appear less often in practice.

Illustration and comments

Our procedure is illustrated in Figure 5a,b, where it is applied to the mortality data from Gibraltar and Malta, respectively. The plots show the logit of the annual mortality rates annotated with results from our procedure. We identify three distinct periods for Gibraltar and four for Malta. Malta includes an additional brief post-war adjustment period, whereas for Gibraltar this adjustment is accommodated by the discontinuity of the trend over the missing war years. Overall, the mortality rates do not exhibit very persistent memory as defined by the smoothing parameter α, perhaps because the data are aggregated over a year. In fact, only the second and fourth periods in Malta had a nontrivial EWMA; for all other periods the selected smoothing parameter was zero. Note that when $\alpha = 0$, the EWMA coincides with the linear trend, whereas when $\alpha > 0$, the EWMA lies at the center of the 95% confidence band. Nevertheless, the general mortality patterns for both sites are roughly parallel. Mortality rates start off relatively stable and enter a period of decline before the turn of the 19th century; they then have a sudden drop at the end of WWII and roughly stabilize until the present. Interestingly the standard deviations for both sites also seem to decrease in parallel, with Gibraltar having slightly higher variation than Malta, perhaps due to the smaller population size. Any points outside the 95% confidence band merit consideration as potential mortality events. To keep the plots legible, however, we have only labeled the ones large enough to fall into our qualitative categories. Beyond serving as a descriptive tool, these standard deviations may provide insights into how variability in mortality fits with Omran's (1971) construct of "fluctuations" and heightened mortality observed during Stage 1 of the of the epidemiological transition: "The age of Pestilence and Famine." These standard deviations also show the movement from Stages 1 to 2 by assessing changes in variation in the death rate, since it is implicated that during this transition there was a reduction in fluctuations of mortality. In addition, it might be interesting to compare the range of variability seen in populations in the same transition stage.

We conclude this section with some comments on our procedure, highlighting its virtues and limitations. We used simple and general statistical techniques such as linear regression and EWMA, while keeping assumptions about the data at a minimum in an effort to make the procedure as widely applicable as possible. At the first stage, we defined distinct periods of analysis to account for temporal changes in the center and

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[1] We set the series' mean as the starting value [0].

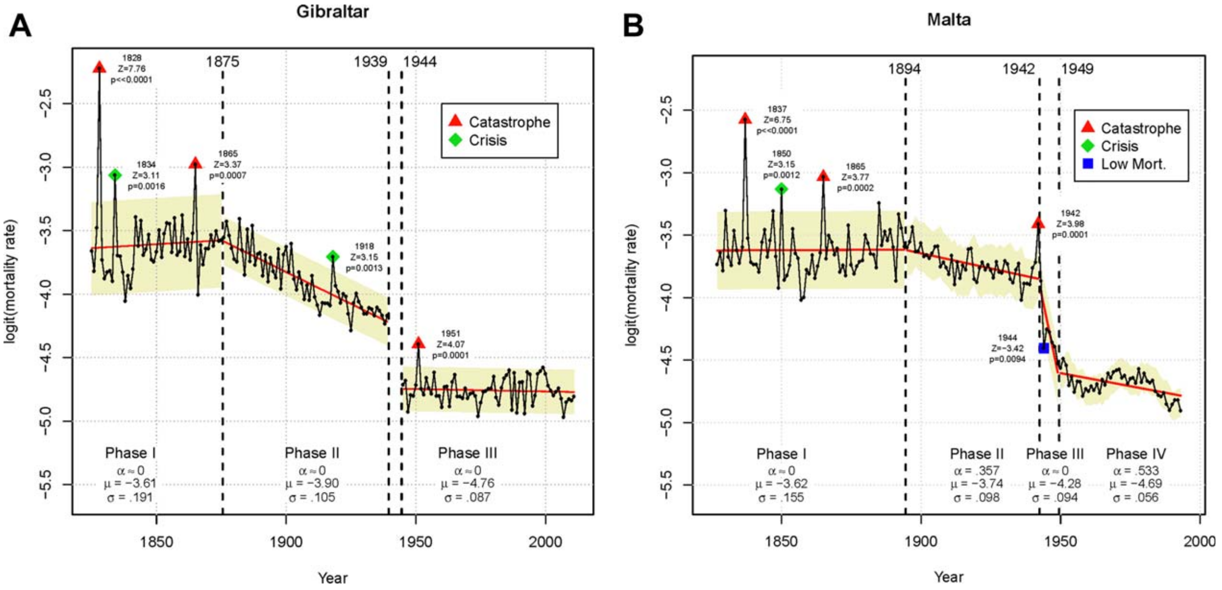

Fig. 5. (**a**) Results of proposed procedure applied to the annual logit-mortality rates of Gibraltar. (**b**) Results of proposed procedure applied to the annual logit-mortality rates of Malta. Vertical-dashed lines delineate the periods chosen by the segmentation algorithm. Solid dark gray lines represent the linear trend fitted for that period. Shaded light gray bands represent 95% confidence intervals for the series centered around the EWMA and extending by roughly ±2 standard deviations on either side. The years with exceptionally high mortality according to our categorization have been labeled, and their Z-scores and P values are reported next to them. At the bottom of the plot, we provide the following descriptive measures for each period: α is the selected EWMA smoothing parameter, μ is the center of the fitted trend, and σ is the estimated standard deviation of the series around its EWMA. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

TABLE 1. H-*indices for epidemics in Gibraltar and Malta from 1828 to 1951*

Year	Epidemic	Location	*H* value	Duration (weeks)
1828	Yellow fever	Gibraltar	176.47	19
1834	Cholera	Gibraltar	72.05	13
1837	Cholera	Malta	87.02	17
1850	Cholera	Malta	32.21	18
1860	Cholera	Gibraltar	5.11	16
		Gibraltar	73.90	12
1865	Cholera	Malta	26.54	23
1867	Cholera	Malta	3.93	22
1885	Cholera	Gibraltar	4.21	12
1887	Cholera	Malta	5.49	16
		Gibraltar—2nd wave	20.96	12
1918	Influenza	Malta—2nd wave	6.47	12
1919	Influenza	Malta—3rd wave	1.05	12
1951	Influenza	Gibraltar	2.58	4

dispersion of mortality rates. These periods were only determined by changes in the mean level of mortality, but variation seems to decrease along the same times. We tracked the mean mortality level with the help of piecewise linear trends to allow the flexibility to describe different rates of change. Using a single moving average throughout, it would not have been possible to adapt to abrupt changes or level shifts that quickly. The Z-scores from the second stage of the procedure were used to calculate P values based on reference distributions. These distributions were only rough approximations, so the resulting P values are mainly indicative rather than accurate probabilistic statements. For example, the logit-mortality rates in our data were not exactly symmetric because most outliers are above the mean. For this reason we suggest reporting both Z-score and P value for extreme observations, as well as examining a plot of the data. Also keep in mind that the interpretation of Z-scores should be relative to their period, in the sense that two outliers of different magnitude can have the same Z-score just because the standard deviations of their respective periods are different. As a result, the interpretation of Z-scores on or around period boundaries can be contentious, since there can be a change in both mean and standard deviation depending on where the boundary is drawn.

Another limitation of our procedure is that it only uses number of deaths aggregated over regular time intervals, typically a year, which is suppressing information on the temporal intensity of a mortality event. To rectify this we propose complementing our procedure with the use of the Hollingsworth index (H index), a very simple statistic, to address the intensity of an epidemic (see Table 1) as well as to make intrapopulation examinations of different epidemics (e.g., epidemics in Gibraltar over time) and interpopulation comparisons (e.g., between Gibraltar and Malta). In essence this method uses the information on cause-specific deaths of a particular epidemic (d); the population at risk (P); and the duration of the epidemic (t). Where $q = d/P$, the equation is as follows (Hollingsworth, 1979):

$$H=q/(1-q)*(1/\sqrt{t})$$

This assessment of intensity of the crisis moments not only takes into account population size and number of deaths but more importantly, it assesses the duration of the epidemic. The importance of the duration is especially apparent when the death rates are similar. For example, an epidemic with a shorter duration (e.g., 3 weeks) that has the same number of deaths as an epidemic with a longer duration (e.g., 8 weeks) would have a greater intensity. Thus, values of higher indices are considered to have been more intense experiences. As one would expect, moments of crisis or catastrophe would be associated with epidemic events of significance (i.e., high H values).

RESULTS AND DISCUSSION

Set within the prevailing or normative mortality, extraordinary death rates can be clearly delineated from the background. Crises or catastrophic events were most common during the earliest phase for both populations. During our study period, it is clear that the arrival of novel pathogens from abroad constituted the most serious threat to the wellbeing of its citizens. It was also a period of instability as death rates would fluctuate dramatically from 1 year to the next (phase I: SDGibraltar = 0.191 and SDMalta = 0.155). The transition to lower and less variability in mortality (phase II: SDGibraltar = 0.105 and SDMalta = 0.104) in Malta and Gibraltar shows that each population entered their new mortality phase at different times.

In the case of Gibraltar, three distinct mortality phases can be delineated over the study period: 1823–1875, 1876–1939, and 1945–2011. The first phase can be described as the period of "The Great Epidemics". The second or transitional phase (1876–1939) was characterized by a progressive decline in the death rate following a series of initiatives that targeted improvements to the sanitary infrastructure. While a number of reforms can be cited for this phase, the earliest changes targeted improvements to the water supply. The onset of the second phase began following the establishment of the Sanitary Order in Council (1874), which introduced a provision of the water supply for the inhabitants, overseen by the newly formed local Sanitary Commissioners. Reforms were gradually implemented to ensure the consistent supply of water during summer droughts (e.g., water condensers), stoppage of (contaminated) water brought in from Spain, supervision of water vendors, and reduction in cost of water. Gradually, by-laws directed at enforcing health reforms for civilians were introduced throughout the period. During WW II, the majority of the civilian population was evacuated. The final phase is characterized by the gradual repatriation of the civilian population that was largely complete by 1949 when 15,313 Gibraltarians had returned from living abroad for the duration of the war. By the 1950s, significant reductions in overcrowding as well as improvements in health care delivery and public sanitation began to take hold.

Malta's secular trend in mortality can be delineated into four phases with segmentation results, as follows: 1823–1894, 1895–1942, 1943–1949, and 1950–1993. The first phase, similar to Gibraltar's, can also be characterized as a period of "The Great Epidemics". Toward the close of the first phase, authorities began to focus more attention on the state of health in the Maltese Islands. One illustration of this trend began in the 1870s when the chief police physician wrote a series of reports on mortality in Malta and Gozo, detailing unhealthy conditions for the years 1874–1876. The rudimentary state of knowledge regarding the determinants of health at this time is telling when the primary causes of death were attributed to "sudden changes of temperature from heat to cold, especially in the summer, by which perspiration is checked" (Ghio, 1875: 6). The next phase (1895–1942) can be described as a period of declining mortality, although not as pronounced as Gibraltar's. Significant reforms coincided with the establishment of the Public Health Department in the 1890s. During this phase, annually published medical reports drew attention to high death rates and factors responsible for the poor health of Malta's citizens. It was also during this time that specific measures were initiated to improve the health of the civilian Maltese populations. One specific illustration was the Mediterranean Fever Commission, an inquiry into undulant fever, in 1904, which was instrumental in discovering the etiology of the disease (Naudi, 2005). Similar regard was given to diseases of higher case fatality rates, such as cholera and influenza, as reports of these diseases were recorded and detailed in the *Annual Health Reports*. However, by the end of the phase, there was a sharp rise in the death rate because of casualties related to the Siege of Malta during World War II from 1940 to 1942. The fourth period (1950–1993) represents yet another period of transition of a rapid decline, but with fluctuations in death rates around the mean. During this last phase from 1950 to 1993 the mortality rate averaged 9.0 per 1,000 living following marked improvements in the social determinants of health.

Events of heightened mortality

The first epidemic, the yellow fever outbreak of 1828, during Gibraltar's first phase can be classified as a catastrophe and notably, it overshadowed every event that has occurred during the last two centuries with Z and H values of 7.4 and 176.4, respectively (see Fig. 5a and Table 1). Catastrophic events are typically rare and of such an extreme nature that there is high potential for an irreversible change to a population. With the death of vast numbers of individuals in a very brief time, immigrants seized opportunities for settlement, employment, new business opportunities, and marriage to local widows and widowers. This rapid turnover in the societal fabric can occur in a single generation. Such was the case in Gibraltar as the yellow fever outbreaks swept off substantial numbers in the epidemics of 1804, 1813/14, and 1828. Encounters with the deadly virus were not unique to Gibraltar, as countless populations that scattered throughout the Iberian Peninsula from 1800 to 1830 underwent heightened mortality owing to their status as virgin soil populations (Augustin, 1909; Moreda, 1997). The impact of yellow fever in 1828 on a

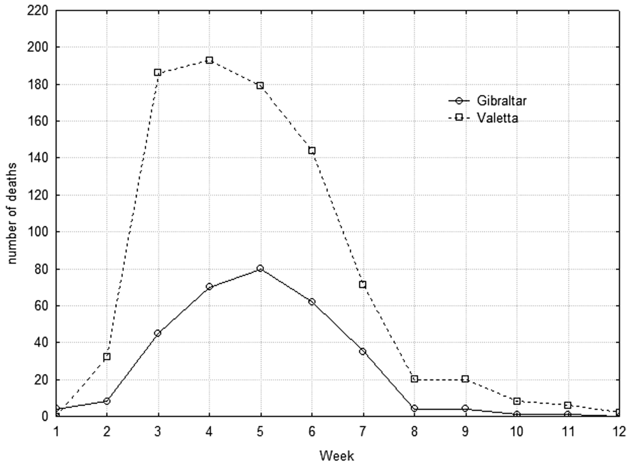

Fig. 6. Weekly distribution of first cholera epidemics in Gibraltar (1834) and Valetta (1837).

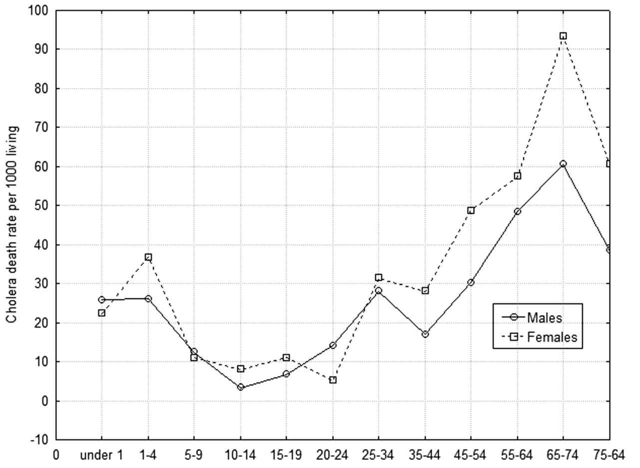

Fig. 7. Age- and sex-specific death rate for cholera in Gibraltar 1834.

population with partial herd immunity serves as a rough indication of the state of crisis that would have occurred when virtually all individuals were susceptible in 1804. Estimates suggest that during that epidemic one-half of the population died over a 4-month period (Sawchuk and Burke, 1998).

Unlike Gibraltar's experience with yellow fever, cholera was chameleon-like, at times attaining the status of a crisis or falling well within the prevailing normal pattern of mortality in both Gibraltar and Malta (see phase I in Fig. 5a,b). Cholera was an ideal agent for the genesis of a crisis event in most industrialized countries until the 20th century, as this disease exploited conditions of poor personal hygiene, inadequate public sanitary infrastructure, deficient sources of safe and pure drinking water, and high-density living. During the first phase of Gibraltar's mortality pattern, cholera appeared twice with sufficient force to attain crisis (1834) and catastrophe (1865) status (Sawchuk, 2001). Gibraltar's first encounter with cholera during the second global pandemic occurred on June 17, 1834 (H = 72.04) and the second major epidemic took place in 1865 (H = 73.8). It is important to add that the 1865 epidemic in Gibraltar was not homogenous in its impact, as there was considerable community variation for the military and convict communities with H values of 57.1 and 274.2, respectively. The severity of the cholera among the convicts was the byproduct of a cluster of vulnerabilities intrinsic to the convict way of life, where exposure to a host of risk factors played out during a compressed period of 9 weeks (Sawchuk et al., 2010). Other cholera outbreaks occurred (1860 and 1885), but these were slight visitations of little demographic consequence.

Cholera made numerous visitations to the Maltese Islands, breaking out in 1837, 1850, 1865, 1867, and 1887 (Pisani, 1888). The outbreak that occurred in 1837 proved to be catastrophic, with a total of 4,152 cholera deaths among civilians (Stilon et al., 1848). Its singularity was further accented by the fact that it formed one single epidemic throughout Malta's highly variegated urban rural landscape (Pisani, 1888). Cholera broke out in 1850 in the Maltese Islands affecting both the civilian and military communities, with the latter group being particularly hard-hit with 135 deaths out of a garrison of 3,475 (H = 108.02). As was the case in Gibraltar, cholera also broke out in 1865 in Malta, attaining catastrophe status with a total of 1,713 deaths over the course of 13 weeks (H = 26.54) (Sutherland, 1867; Ghio, 1867).

TABLE 2. Cholera cases admitted to the Gibraltar Colonial Hospital, 1834

	Admitted	Slight	Severe
Men	538	345	193
Women	483	267	216
Children	145	95	50
Total	1,166	707	459

While the first encounters of cholera in Gibraltar and Malta were very similar as indicated by the Z and H values, closer inspection of the distribution of deaths over time reveals that the experience in the two locales differed in tempo (see Fig. 6). The "typical pattern" of a common-source epidemic—an abrupt rise in the mortality rate, a peak, and finally a rapid decline in the number of deaths—was observed in the capital city of Valetta in Malta. The Gibraltar pattern did not resemble that of an explosive outbreak due to a common-source origin of contamination but operated primarily through person-to-person transmission owing to a highly decentralized water supply system.

Gibraltar's first encounter with cholera offers further insight into how differences can arise through the social production of disease. To illustrate, we draw from Gibraltar's Roman Catholic death registers that provide information on name, age, sex, residence, birthplace, and cause of death. The nominative census of 1834 yields individual-based information on age and sex as well as the ability to distinguish Catholics from other civilian groups. Here we see a divergence in the pattern in the post-34 age bracket as shown in Figure 7. Females showed a markedly higher death rate in the older age categories. Further evidence of a marked difference in mortality between the sexes can be seen from the examination of the Colonial Hospital returns taken from mid-June to August 9 (see Table 2). Women were significantly more likely to enter the hospital with "severe" cholera (Chi square for sexes = 8.296, 1 df, P = 0.004). Elevated mortality in older women may be attributed to their roles as primary caregivers coupled with the tradition of putting family first; only when a woman's state of health was severely compromised would she seek medical attention and/or utilize hospital facilities.

Influenza has the potential to cause heightened mortality not only during annual outbreaks, but more notably during the appearance of novel strains that appear in a pandemic manner on the global stage. The 1918 influenza pandemic was the most infamous, accounting for 20–40 million deaths and affecting 20–50% of the world's population (Reid et al., 2001). During Gibraltar's second phase, influenza attained the status of a crisis with a Z value of 2.88 and an H value of 20.96 (see Fig. 5a and Table 1). For more information on sex difference in influenza deaths during this epidemic, see Sawchuk (2009). Interestingly, while the flu made numerous visitations to the Maltese Islands, including the pandemic of 1918 (second wave $H = 6.47$, third wave $H = 1.05$), influenza never appeared to play a significant role in the pattern of mortality as indicated by low Z values throughout the study period (see Fig. 5b and Table 1). The 1951 epidemic of influenza was a catastrophic event that began "with almost dramatic suddenness toward the end of January, spread with lightning rapidity throughout the City, attained a peak within a fortnight of its onset and quickly subsided, the outbreak terminating by the end of the third week in February" (Durante, 1952:31). Estimates of the incidence of influenza ranged from 50 to 60% of the population. Only a small number of deaths were recorded from influenza ($n = 4$) and pneumonia ($n = 11$) among those 60 and over, and the overall H index attributed solely to the flu and pneumonia stood at a mere 2.58 (see Table 1).

While war has the potential of demographic displacement, heightened mortality, and a host of destabilizing issues similar to epidemics, the civilian population exposed to this particular stressor is not necessarily selective in terms of age, sex, or other vulnerability characteristics. During WWII, the civilian populations of Gibraltar and Malta experienced dramatically different stress during the war years. Unlike Gibraltar, Malta from 1940 to 1943 was directly involved in the military campaign in the Mediterranean theatre (Holland, 2004). As a significant military and naval base, Malta played a vital role in the British war campaign. While the civilian population suffered bombings and food shortages during this period, 1942 was most notable as a mortality event with close to 1,088 civilian deaths classified due to the operations of the war. Nearly half of these occurred in the months of March and April alone. The impact was a crisis event with a Z-score = 3.98.

Events of lower mortality

Harvesting effects. Periods of lower than expected mortality have in some cases been attributed to a drop in the death rate in the aftermath of the harvesting of the fragile segment of a population. The "harvesting effect", or "short-term mortality displacement," occurs when there is a heightened, albeit temporary, mortality rate in those with health complications because of underlying health problems, especially cardiorespiratory diseases and among the elderly (Dominici et al., 2003; Nobetti et al., 2000), or increased vulnerability associated with lower socioeconomic status. It is expected that even without a stressor, the vulnerable individuals would have died within a few days or weeks, much sooner than their peers of the same cohort (Kunst et al., 1993; Toulemon and Barbieri, 2008). Following such episodes of exceptionally high mortality is a period of temporary enhanced survivorship that can persist for a few weeks to months because the "weak and frail" have been removed. However, the limits of "healthy" periods have not been established (Toulemon and Barbieri, 2008). This "selective mortality" effect is most apparent in the third stage of the epidemiological transition, when infectious diseases and infant mortality are low, and in populations where hot temperatures are not the norm (Hajat et al., 2005).

Although traditionally applied to explaining the aftermath of mortality experiences following outbreaks of respiratory disease among older individuals when preceded by heat waves, or episodes of air pollution (Smith, 2003; Toulemon and Barbieri, 2008), more recent studies have examined the possibility of harvesting in younger individuals following influenza, cholera epidemics, and myocardial infarctions of spectators watching British football matches (Noymer and Garenne, 2000; Carroll et al., 2002; Dushoff et al., 2005; Sawchuk, 2010). It has been suggested by Carroll et al. (2002) that the culturally induced stressor, such as watching a favorite team lose a football match, can create a temporary vulnerable population by increasing morbidity of myocardial infarction for up to 2 days after the match, among male spectators of a wide age band (18–64 years). However, harvesting does not completely explain excess morbidity as the decrease in morbidity following the "harvest," is much less than the increase. Kirkup and Merrick (2003) have even found that males are also more vulnerable to increased mortality due to myocardial infarction and stroke on the day of their home team losing a football match. Regarding cholera and harvesting, the vulnerable group would be the fragile, i.e., those at lower socioeconomic and sanitation status. With respect to influenza and harvesting, Noymer and Garenne (2000) have provided evidence that young adults infected with tuberculosis were more susceptible to mortality during the 1918 influenza pandemic, and Murray et al. (2006) suggest that the "harvesting effect" will predict the pattern of mortality in future influenza epidemics. We posit that for diseases where survivors are granted immunity, the harvesting effect would rarely be observed, and only if the epidemic were followed by another episode of the same disease (such as yellow fever). It is possible then that the harvesting effect may be observed following epidemics of a wide range of infectious and noninfectious diseases and in individuals across all ages.

The results of our analysis suggest that in the year(s) following the cholera epidemics of 1834 and 1865 in Gibraltar, harvesting may have taken place. For the 1834 epidemic, although mortality following the epidemic declines, at the gross level it falls within the normal range of mortality for that period. It is not until 1838 that the mortality would be considered well below the prevailing mortality pattern. We do not have microlevel data to statistically support the harvesting effect after the crisis of 1834.

The case for 1865 can be supported by a substantial rise in childhood mortality during the cholera epidemic relative to the prevailing mortality pattern in the preceding 4 years (see Table 3). In the aftermath of the epidemic, childhood mortality fell by 70% and was 50% below the level of background mortality seen in children

TABLE 3. Child mortality prior to, during and following the 1865 cholera epidemic

Years	Event	Mortality per 1000 children aged 1–4.9 years
1861–1864	Background mortality	72.47
1865	Cholera epidemic	118.50
1866	Harvest effect	35.50

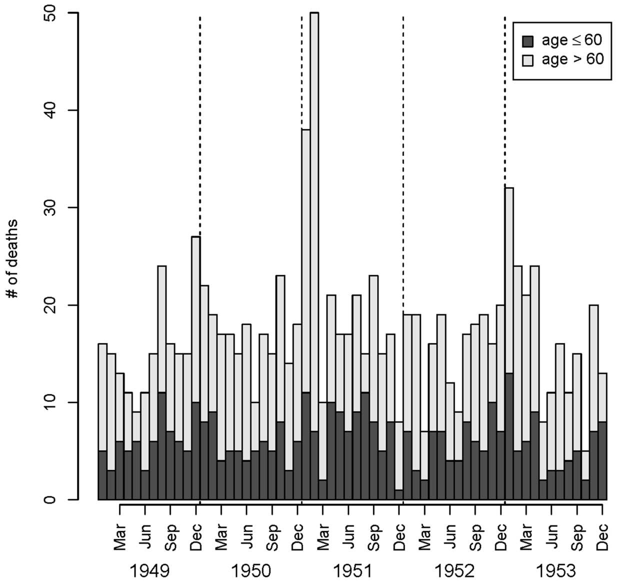

Fig. 8. Deaths for under and over 60 in Gibraltar from 1949 to 1953.

for 1861–1864. The significance of the event was not lost on Gibraltar's Medical Officer of Health, who remarked that cholera had "swept off a large number of the weak, the intemperate and those disposed to disease, there was therefore a more favorable condition of the population in the following year" (Stokes, 1867:47).

The influenza epidemic of 1951 provides another possible illustration of harvesting. During the epidemic, there was a marked increase in the death rate of the elderly during the relevant period as compared to previous years. According to the Medical Officer of Health, "I suspect that many [deaths] were certified as having been due to cardiovascular diseases, bronchitis and other respiratory infections, may have been precipitated by attacks of influenza" (Durante, 1952:32). Figure 8 illustrates the dramatic increase in the death rate among the aged in 1951, followed by an immediate decline in mortality in March. The occurrence of two later pandemics in 1957 (H2/N2) and in 1968 (H3/N2) did not show any direct or indirect mortality effects in Gibraltar (data not shown here).

Healthy years. One of the expectations of our research was that there would be occurrences of lower than expected mortality or "healthy years" that were not necessarily linked to harvesting. For example, unusually low mortality might occur because of exceptionally good weather observed during months free of excess heat or cold, or a bountiful year where food was abundant and cheap in a resource-poor population.

In defining a healthy year we used the criteria of an event attaining a negative Z-score with P equal to 0.01 or less. On the basis of these stringent criteria, we would conclude that no single event in our study fulfilled our definition of a healthy year. However, it is worth noting that Malta in 1944 came very close with a value of 0.0188, using the conservative two-tailed approach. Consequently, our ability to detect such an event during this third phase was hampered by the abbreviated length of time, with a t-distribution of only 5 degrees of freedom. With this caveat, the year 1944 warrants closer attention because of the extraordinary mortality observed in that year. As discussed earlier there was a crisis event in 1942 associated with a large number of war deaths. Starting in October of 1943, there was a dramatic decrease in the death rate in 1944. Commenting on the remarkable and sudden drop in mortality, the Chief Government Medical Officer described the trend as "paradoxical" as

> . . .in a very short space of a few months the health conditions of these islands from the depressed level of the period of siege came up to the standard definitely better even than that of the pre-war times...it is paradoxical that this spectacular reduction in mortality should have taken place when housing conditions and overcrowding are worse than they have ever been and environmental sanitation is far from perfect. (Bernard, 1945: i)

Further, the observed decline in mortality occurred under practically all of the principal causes of death, including the infectious and parasitic diseases. A number of possible explanations were offered, including an improvement in nutrition; an absence of outbreaks of infectious diseases; a change in the fertility pattern with a greater proportion of first or second infants in the population**;** an increased use of sulfonamide drugs; and a greater attention to the welfare of the young by the "Health Visitors." But in the end, Maltese health authorities reluctantly admitted that they were at a loss to explain the suddenness of the decline.

Long-term consequences of diseases and epidemics

Up to this point, we have concentrated on an event and its impact over a brief period of time. Long-term effects associated with scarring provide further evidence of the impact that a stressor can have on the future health of a population. As originally put forward by Preston et al. (1998), the scarring effect can be defined as the impact on health in later years when an individual at a very young age has been exposed to a disease (e.g., tuberculosis, hepatitis B, rheumatic fever) or to adverse environmental conditions (e.g., famine, see Painter et al., 2008). While current research in this area may hold promise for understanding how improvements *in utero* and for childhood living conditions can result in better health over the life cycle (see for example, O'Callaghan et al., 1991; Almond, 2006; Gagnon and Mazan, 2009; Cohen et al., 2010), our research strategy cannot address this issue directly. However, our methodology can be used to identify cohorts that have been through moments of great stress, and as such, that may experience heightened mortality later in life. A growing body of literature suggests that there may or may not have been long-term effects associated with exposure to the 1918 influenza virus.

CONCLUSIONS

We have offered a novel methodology that incorporates an algorithm into the time-series analysis of the data that differentiates distinctive phases of mortality. Fundamental to our research strategy is the recognition that one must contextualize prevailing mortality rates when undertaking inter- and intra-population comparisons over time. The underlying rationale is that each population is unique and enters periods of transition that are influenced not only by global events but also by local factors. Accordingly, our approach has broad applications in a variety of different populations in different settings where the data set is limited to crude data on population size and where the number of deaths is available.

Using a modified *Z*-score strategy, states of mortality were distinguished into discrete categories: unusually low mortality, background or prevailing mortality, a crisis event, and a catastrophic event. Our results show that the weight or importance of an epidemic is population specific and variable over time. Under specific circumstances, the impact of an epidemic can act as a stressor causing heightened mortality and in turn, result in a less fragile population with lower mortality after the event, or what has been referred to as harvesting. Like epidemics, the impacts of war are contingent on factors that extend well beyond the local level. In the case of Malta, World War II proved to be a crisis event. Interestingly, in the aftermath of this crisis event we have observed a period of unusually good health. Medical authorities at the time recognized the unusually sudden and dramatic decline in mortality but regarded the event as paradoxical given the unsanitary state of affairs and excessive overcrowding.

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