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Child mortality and cohort lifespan: a test of diminished entelechy

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Background The literature implies a 'diminished entelechy' hypothesis in which birth cohorts subjected to relatively many or relatively virulent environmental insults early in life do not realize their otherwise expected lifespan. No direct test of this hypothesis appears in literature.

Methods We test the hypothesis directly by measuring the association between mortality in the first 5 years and life expectancy at age 5 for male and female cohorts born in Sweden (1751–1912), Denmark (1835–1913), and England and Wales (1841–1912). The methods control for trends, seasonal cycles, and other forms of autocorrelation that could induce spurious associations.

Results Our results support the hypothesis in that life expectancy at age 5 fell below the values expected from history in cohorts in which child mortality before age 5 increased over its expected value. We find no evidence for culling effects in which a cohort remaining after suffering relatively many environmental insults may be smaller but hardier than expected.

Conclusions These findings converge with individual-level studies and suggest that suffering relatively virulent or many environmental insults during childhood reduces the subsequent lifespan of birth cohorts.

Keywords Cohort effect, child mortality, life expectancy, longevity, life course

Individual-level studies report that somatic insults predispose children to increased morbidity and mortality in adulthood.[1–3] This literature implies that birth cohorts subjected to relatively many or relatively virulent environmental insults early in life do not realize their otherwise expected lifespan. In the interest of parsimony, and consistent with the definition of 'entelechy' (i.e. 'the realization or complete expression of some function'[4]), we refer to this implication as the 'diminished entelechy hypothesis'.

We know of five empirical tests related to the diminished entelechy hypothesis.[3,5–8] None have objective measures of the early life insults experienced by birth cohorts and all use early life mortality as a surrogate. The tests assume that a relatively high fraction of a cohort born in stressful times will die either before age 1 or before age 5. Bengtsson and Lindstrom[3] performed a multivariate analysis on 128 years of data from parishes in a rural Swedish region and discovered increased adult (55–80 years) mortality among birth cohorts with high infant mortality rates. In addition, Crimmins and Finch[6] describe mortality curves in four European countries and infer an intra-cohort association between infant mortality and older age mortality. In their landmark paper in 1934, Kermack *et al.*[7] reported that childhood mortality up to age 15 correlated with subsequent cohort mortality in Great Britain and Sweden. Pearson, however, examines the Registrar General's Life Tables in 19th century England and Wales and reports discovering an inverse association between infant mortality in birth cohorts and death rates from age 1 to 5.[8] He infers a culling effect in which a cohort remaining after suffering high infant mortality may be smaller but hardier than expected.

Taken together, these studies do not offer compelling evidence for or against the diminished entelechy hypothesis even if their internal and external validity were high. They use differing periods of exposure and measure the presumed effect (i.e. age specific mortality) at differing points in cohort lifespan.[6] The work, therefore, says nothing about the effect of early insults on the entelechy, or realized fraction, of cohort lifespan. The 'net effect' of early insults on later life mortality, if any, remains unknown. Bengtsson and Lindstrom's findings have questionable external validity given the small, rural sample they describe. Researchers, moreover, have no way to judge the quality or comparability of Pearson's and Kermack *et al.*'s data.

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We report three tests, based on data of known provenance and quality, of the diminished entelechy hypothesis. More specifically, we measure the association between the odds of dying before age 5 and lifespan of those surviving to age 5 in Sweden, Denmark, and England and Wales. We analyse males and females separately because temporal variation in life expectancy differs by gender.

Methods

We acquired annual cohort life table data for males and females born in Sweden, Denmark, and England and Wales from the Human Mortality Database website.[9] The Swedish data allow a test for cohorts born between 1751 and 1912 (most recent cohort for which cohort life expectancy at five is currently available). The Danish data allow a test for cohorts between 1835 and 1913, while the England and Wales data allow a test from 1841 to 1912. The methodology for calculating cohort mortality rates and life expectancy can be found in the Human Mortality Database Methods Protocol.[9]

Based on earlier research, we defined 'early life' as before age 5.[10] Using life table data, we calculated the odds of dying before age 5 for each annual birth cohort. We began our analyses with data from Sweden because few, if any, societies have kept vital statistics for as long a time.

Because mortality rates in the 19th century decline earlier in Sweden than in other European countries,[7] epidemiologists have questioned the external validity of Swedish life table analysis.[11] To address this issue, we repeated our test on populations residing in Denmark as well as in England and Wales. We chose these populations for three reasons. First, both have complete cohort vital statistics for over 50 consecutive years, which permits time-series analysis. Second, the data are publicly available at the Human Mortality Database website,[9] thereby facilitating replication. Third, these data, like the Swedish data, have been developed consistent with explicit, well-understood demographic conventions intended to insure comparability over time and across societies. Demographers have used, for example, the same reverse intercensal survival methods to attribute deaths within 5 year age intervals to annual birth cohorts in the first half of the test period in all three test societies.[9] Knowing that these conventions may affect our time-series allows us to structure our tests, described below, accordingly.

Analyses

We, of course, cannot randomly assign birth cohorts to manipulated levels of lethal stress and measure life expectancy among survivors. Tests such as ours, therefore, must be observational. In essence, our test turns on whether lifespan at age 5 falls below its statistically expected value in cohorts that exhibited odds of dying before age 5 higher than their statistically expected value. Researchers typically assume that the statistically expected value of any variable is its mean. Early life mortality and lifespan, however, exhibit trends and the tendency to remain elevated or depressed or to oscillate after high or low values. The intercensal survival methods alluded to above, moreover, could induce 'memory' in the time series. These patterns, typically referred to as 'autocorrelation,' complicate observational tests because the expected value of an autocorrelated series is not its mean.

Researchers dating at least to Fisher and his 1920 study of crop variation have solved the autocorrelation problem by 'decomposing' time series into temporally predictable and residual components.[12] This approach removes patterns from the dependent variable before testing the effect of the independent variable and has the added benefit of avoiding spurious associations due to shared trends and cycles.

We implemented the Fisher approach to our test through the following steps recommended in epidemiological literature.[13]

(i) We used the methods devised by Dickey and Fuller[14] and Ljung and Box[15] to detect autocorrelation in lifespan for male and female birth cohorts surviving to age 5 in Sweden, Denmark, and England and Wales. We then used the strategy developed by Box and Jenkins[16] to model the autocorrelation. The strategy, Autoregressive, Integrated, Moving Average (i.e. ARIMA) modelling, allows any of a large family of possible models to be empirically fit to serial measurements. ARIMA models mathematically express various filters through which series without patterns can pass. Each filter imposes a unique pattern. The Box–Jenkins approach uses a model-building process by which the researcher infers the filter that imposed the observed pattern. The differences between the values predicted by the inferred model and the observed series are assumed to be the unpatterned values that were filtered.

(ii) We applied the routines described above to the odds of dying before age 5 to separate the series into expected and unexpected components.

(iii) The unexpected component of the mortality series (i.e. the residuals of Step 2) was added to the equation resulting from Step 1. The test equation that emerges from Step 3 is as follows:

$$\nabla^d Y_t = C + \omega_0 X_{1t} + \frac{\left(1 - \theta_1 B - \theta_2 B^2 - \cdots - \theta_q B^q\right)}{\left(1 - \phi_1 B - \phi_2 B^2 - \cdots - \phi_p B^p\right)} a_t, \quad (1)$$

where, ∇^d is the difference operator that indicates a series was differenced at order d (i.e. values at t subtracted from values at $t - d$) to remove secular trends or cycles detected by the Dickey–Fuller test; Y_t is life expectancy at age 5 in the test country for the cohort born in year t; C is a constant; X_{1t} is the statistically unexpected component of the odds of dying before age 5 for the cohort born in year t; ω_0 is the estimated parameter for the mortality variable; B^n is the 'backshift operator' that yields the value of the life expectancy variable at year n; θ is the moving average parameter; ϕ is the autoregressive parameter; B^p and B^q are backshift operators that yield the value of a at year $t - p$ for autoregressive and $t - q$ for moving average patterns, respectively; and a_t is the error term for year t.

(iv) We estimated Equation (1) and inspected the error terms for temporal patterns. If any were found, we added ARIMA parameters to the equation and estimated the resulting equation.

(v) We measured the association between the error terms of the equation and the mortality variable to ensure they were not related.

Table 1 Estimated Box–Jenkins equations of autocorrelation in the independent and dependent variables for Sweden (n = 161 years beginning 1751)

	Male lifespan at age 5	Female lifespan at age 5	Odds of death before age 5 among males	Odds of death before age 5 among females
Differencing	First differences	First differences	First differences	First differences
Constant	0.1327* (0.0363)	0.1429* (0.0350)	−0.0025* (0.0012)	−0.0024* (0.0011)
Moving average parameters	B = 0.2414* (0.0794)	B^5 = −0.2193* (0.0829)	B^2 = 0.1980* (0.0803)	B^2 = 0.1659* (0.0805)
			B^4 = 0.1813* (0.0813)	
Autoregressive parameters	B^5 = 0.2364* (0.0758)	B^3 = −0.1885* (0.0800)	B^5 = −0.1820* (0.0790)	B^4 = −0.2283* (0.0762)
	B^6 = −0.1873* (0.0749)	B^6 = −0.2321* (0.0797)		B^5 = −0.1975 * (0.0761)

* $P < 0.05$, two-sided test.

Table 2 Estimated equations for Swedish male and female birth cohort life expectancy at age 5 as a function of autocorrelation and the odds of dying before age 5 (n = 161 years beginning 1751)

	Male lifespan at age 5	Female lifespan at age 5
Differencing	First differences	First differences
Constant	0.1369* (0.0232)	0.1534* (0.0285)
Residuals of Box–Jenkins models for odds of dying before age 5	−8.3149* (1.4919)	−8.2189* (1.5989)
Moving average parameters		B^5 = −0.2082* (0.0823)
Autoregressive parameters	B^3 = −0.3006* (0.0816)	B^3 = −0.2568* (0.0813)
	B^6 = −0.3717* (0.0790)	B^6 = −0.3496* (0.0772)

*$P < 0.01$, one-sided test.

Results

Sweden

Table 1 summarizes the results of Steps 1 and 2 in which we identified and modelled autocorrelation in the independent and dependent variables for Sweden. Indications of P-values < 0.05 are based on two-tailed tests because autoregressive and moving average parameters may be positively or negatively signed.

All the series exhibited trend and required differencing. The upward trend in lifespan and downward trend in the odds of dying before age 5 were so steep at times during the test period that the first differences of the former had a positive mean while those of the latter exhibited a negative mean. Constants, therefore, appear in all equations.

Both life expectancy series exhibited autocorrelation best modelled with parameters suggesting that high or low values in either series were typically 'echoed' 5 and 6 years later. Both early life (i.e. before age 5) mortality series exhibited autocorrelation suggesting patterns in which high or low values were followed 2, 4, and 5 years later by smaller outlying values.

Table 2 shows the results of Steps 3 through 5 for Sweden in which we added the statistically unexpected values of the odds of dying before age 5 to the best fitting Box–Jenkins models of life expectancy at age 5. We used single-tailed tests of significance because we hypothesized an inverse association. Results from Sweden support the diminished entelechy hypothesis for both males and females in that the 99% confidence intervals (CIs) of the coefficients for the early child mortality variables do not include 0.

Our independent variable for males (i.e. deviations of observed from expected odds of dying before age 5) ranged from −0.1588 to 0.0527. Multiplying these values by the coefficient shown in Table 2 (i.e. −8.3149) implies that Swedish men gained as much as 1.31, or lost as much as 0.44, years of life owing to the forces that affected mortality before age 5.

The estimated parameter among women for the association between the odds of dying before age 5 and life expectancy at age 5 was very similar to that for males (i.e. −8.2189 for the former and −8.3149 for the latter). The range of deviations between expected and observed odds of dying before age 5 among women (i.e. −0.1353 to 0.0543), however, was smaller than that for men. The diminished entelechy hypothesis, therefore, would attribute a range of 1.11 gained to 0.45 lost years of life to the forces that affected mortality before 5 years of age among women.

Our estimates may have been affected by outliers (induced, for example, by the ending of reverse intercensal survival methods in 1861) in the dependent variable or by non-constant variance of the independent and dependent variables. To address the first potential problem, we applied outlier detection and correction routines to our original analyses.[17] Results did not differ in that parameters for the infant mortality variables remained negative, and their 95% CIs did not include 0 after outliers in the life expectancy variables were controlled.

We addressed the possibility of non-constant variance over time by transforming all variables to their natural logarithms and repeating the tests. Results, other than the metric of the parameters, did not change from the original tests.

Intuition suggests that the association between early life mortality and life expectancy may weaken over time with societal efforts to reduce the frequency and virulence of stressors with which populations must cope. We tested this possibility in our findings by repeating our tests separately for the first and last 80 years of the period. Early life mortality predicted life expectancy at age 5 for men and women in both periods (first 80 years: −8.4848, SE = 2.1612 for males, −8.6421, SE = 2.2602 for females; last 80 years: −5.8381, SE = 2.1559 for males, −3.6087, SE = 2.1612 for females). The relationship, however, was weaker in the second period

Table 3 Estimated Box–Jenkins equations of autocorrelation in the independent and dependent variables for Denmark (n = 79 years beginning 1835)

	Male lifespan at age 5	Female lifespan at age 5	Odds of death before age 5 among males	Odds of death before age 5 among females
Differencing	First differences	First differences	First differences	First differences
Constant	0.1562* (0.0281)	0.1945* (0.0492)	None	None
Moving average parameters	None	B^6 = −0.2385* (0.1112)	B = −0.5967* (0.0917)	B = −0.5137* (0.0978)
Autoregressive parameters	B = −0.2390* (0.1105)	None	None	None

* $P < 0.05$, two-sided test.

especially for women (i.e. the coefficient for the odds of dying before age 5 changed from −8.6 to −3.6).

We also tested the possibility that our results would change had we controlled for the fact that, as noted above, data collection methods changed in 1861. We created a binary variable score 1 for year 1751 through 1860 and 0 otherwise. We added this variable to our test equations and estimated them again. The results for males and females remained essentially unchanged.

Denmark

Table 3 summarizes the results of Steps 1 and 2 in which we identified and modelled autocorrelation in the independent and dependent variables for Demark. As in Sweden, all the series exhibited trends and required differencing. Unlike Sweden, however, the decrease in the odds of dying before age 5 did not accelerate sufficiently over the test period to require a constant. We attribute this to the shorter length of the test period. Indeed, no constant would have been required had the Swedish data been restricted to the same time period (i.e. post-1834).

Unlike Sweden, the life expectancy series for males and females exhibited very different patterns of autocorrelation. High or low values in the former appeared to persist for a year while in the latter they tended be followed by 'echoes' 6 years later. Both early life (i.e. before age 5) mortality series exhibited patterns in which high or low values persisted for a year.

Table 4 shows the results of Steps 3 through 5 for Denmark in which we added the statistically unexpected values of the odds of dying before age 5 to the best fitting Box–Jenkins models of life expectancy at age 5. Results from Denmark supported the diminished entelechy hypothesis only for males. The sign and magnitude of the coefficient for female child mortality appeared similar to that of males but did not reach statistical significance.

We applied outlier detection and correction routines to our Danish analyses.[17] Results did not differ for either males or females. We addressed the possibility of non-constant variance over time by transforming all variables to their natural logarithms and repeating the tests. Results, other than the metric of the parameters, did not change from the original tests.

Inspection of the scatter plot of the unexpected components of the odds of dying before age 5 and life expectancy at age 5 for females suggested a relationship in which the extreme values of the former appeared associated with the opposite extremes of the latter. To test this possibility *post hoc*, we used outlier detection methods to identify values of the odds of dying before age 5 that fell outside the 99% CI of the values expected from the best fitting Box–Jenkins model. We created a variable in which we re-scored years with other than the outlying values to 0. We repeated Steps 3 through 5 and found that extreme values of the odds of dying before 5 years of age were significantly and inversely associated with lifespan at age 5 for females (i.e. −9.9480, SE = 5.4714).

Table 4 Estimated equations for Danish male and female birth cohort life expectancy at age 5 as a function of autocorrelation and the odds of dying before age 5 (n = 79 years beginning 1835)

	Male lifespan at age 5	Female lifespan at age 5
Differencing	First differences	First differences
Constant	0.1587** (0.0253)	0.1940** (0.0486)
Residuals of Box–Jenkins models for odds of dying before age 5	−3.8959* (2.0712)	−4.1490 (3.0610)
Moving average parameters	None	B^6 = −0.2302** (0.1129)
Autoregressive parameters	B^2 = −0.2560** (0.1021)	None

* $P < 0.05$, one-sided test.
** $P < 0.01$, one-sided test.

England and Wales

Table 5 shows the results of Steps 1 and 2 in which we identified and modelled autocorrelation in the series for England and Wales. All series exhibited trend and required differencing. For females (but not males), the decrease in the odds of dying before age 5 accelerated sufficiently over the test period to require a constant. Like Sweden, the downward trend in the odds of dying before age 5 for females (but not males) was so steep that the first difference exhibited a negative mean.

The life expectancy series for males and females exhibited different patterns of autocorrelation. While high or low values for males and females appeared to persist into the subsequent year, those for the latter continued to be different from expected into the second year. High or low values for females, moreover, had 'echoes' 3 and 10 years later. Both early life mortality series exhibited patterns in which high or low values were followed in the sixth year by smaller outlying values.

Table 6 shows the results of Steps 3 through 5 for England and Wales in which we added the statistically unexpected values of the odds of dying before age 5 to the best fitting

Table 5 Estimated Box–Jenkins equations of autocorrelation in the independent and dependent variables for England and Wales (n = 72 years beginning 1841)

	Male lifespan at age 5	Female lifespan at age 5	Odds of death before age 5 among males	Odds of death before age 5 among females
Differencing	First differences	First differences	First differences	First differences
Constant	None	0.2519** (0.0271)	None	−0.0031** (0.0015)
Moving average parameters	None	None	None	None
Autoregressive parameters	B = 0.4174* (0.1150)	B = −0.3473* (0.1248)	B^6 = 0.3083* (0.1198)	B^6 = 0.2484* (0.1173)
	B^2 = 0.2914* (0.1152)	B^3 = −0.4007* (0.1202)		
		B^{10} = 0.4724* (0.0911)		

* $P < 0.05$, two-sided test.
** $P < 0.05$, two-sided test.

Table 6 Estimated equations for male and female birth cohort life expectancy at age 5 in England and Wales as a function of autocorrelation and the odds of dying before age 5 (n = 72 years beginning 1841)

	Male lifespan at age 5	Female lifespan at age 5
Differencing	First differences	First differences
Constant	None	0.2329** (.0201)
Residuals of Box–Jenkins models for odds of dying before age 5	−11.2504** (2.8833)	−4.3753* (2.3074)
Moving average parameters	B^8 = 0.3207** (0.1273)	None
Autoregressive parameters	B = 0.6968** (0.0911)	B = −0.3019** (0.1333)
		B^3 = −0.4602** (0.0986)
		B^{10} = 0.4269** (0.0847)

* $P < 0.05$, one-sided test.
** $P < 0.01$, one-sided test.

Box–Jenkins models of life expectancy at age 5. Results support the diminished entelechy hypothesis for both males (−11.2504, SE = 2.88) and females (−4.3753, SE = 2.88) although the association appears stronger, as in Denmark, for males.

Our independent variable for males ranged from −0.0313 to 0.0349. Multiplying these values by the coefficient shown in Table 6 (i.e. −11.2504) implies that males in England and Wales gained as much as 0.35, or lost as much as 0.39, years of life owing to the forces that affected mortality before age 5. Applying the same logic to females (independent variable range: −0.0222 to 0.0274), the coefficient in Table 6 (i.e. −4.3753) indicates that women in England and Wales gained as much as 0.10, or lost as much as 0.12, years of life owing to the forces that affected mortality before age 5.

As in the other test countries, we applied outlier detection and correction routines to our analyses.[17] Results did not differ for either males or females. We addressed the possibility of non-constant variance over time by transforming all variables to their natural logarithms and repeating the tests. Results, other than the metric of the parameters, did not change from the original tests.

Discussion

Time series analyses of three European countries with data of known provenance and quality support the diminished entelechy hypothesis in males and, to a lesser extent, females. Lifespan among children surviving to age 5 fell below the values expected from history in cohorts in which the odds of mortality before age 5 increased over its expected value. These findings suggest that suffering relatively virulent or many environmental insults during early childhood may reduce the subsequent lifespan of birth cohorts. This result converges with individual-level studies that report associations between early life conditions, and adult morbidity and mortality.

While analyses for females from two of the three test countries offered support for the diminished entelechy hypothesis, the data suggest a considerably weaker association. We speculate, *post hoc*, that the attenuated effect among females reflects their relative resiliency compared with males at all ages in the life course.[18]

Strengths of our study include testing the hypothesis with data of known provenance and quality for three countries with long series of consecutive birth cohorts. The time-series design also has the advantage of protecting against a Type I error due to shared autocorrelation of early life mortality and life expectancy at age 5. Trends, seasonality, or the tendency to remain elevated or depressed after high or low values could not have spuriously induced the estimated association because we removed autocorrelation, including any induced by reverse intercensal survival methods, from both the dependent and independent variables. Using cohort life expectancy at age 5 as the dependent variable, moreover, allowed us to test, unlike earlier work, the net effect of early insults on mortality.

This study has several limitations including that the results may not generalize beyond Sweden, Denmark, and England and Wales or to the contemporary experience there or elsewhere. Only replication can determine the external validity of these findings. We cannot, moreover, discriminate among the environmental insults (e.g. infectious or non-infectious toxins, extreme weather, food quantity or quality) that might affect cohort mortality. Nor can we determine when in the first 5 years of life such exposures have their greatest effect on subsequent mortality.

While our analyses support the argument for 'cohort effects' (i.e. that the early life experiences of birth cohorts predict their

lifespan), they do not necessarily detract from the related 'period effects' argument (i.e. that societal stressors later in life also affect cohort mortality).[19] Further research should, in fact, estimate the relative contribution of cohort and period effects to age-specific mortality.[20]

As noted at the outset, results from contemporary individual-level studies of morbidity over the life course have been consistent with, but do not directly support, the theory of diminished entelechy. Our findings add greater support to the theory and should make it more compelling to epidemiologists, demographers, and others interested in the sequelae of early life insults.

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KEY MESSAGES

- Time-series analyses of Sweden, Denmark, and England and Wales support the diminished entelechy hypothesis in that lifespan among children surviving to age 5 fell below the values expected from history in cohorts in which the odds of mortality before age 5 increased over its expected value. These findings suggest that suffering relatively virulent or many environmental insults during early childhood may reduce the subsequent lifespan of birth cohorts.
- While analyses for females from two of the three test countries offered support for our hypothesis, the data suggest a considerably weaker cohort effect in females.
- Our population findings converge with individual-level studies that report associations between early life conditions and adult morbidity and mortality.

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