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Sex ratios and life tables: Historical demography of the age at which women outnumber men in seven countries, 1850–2016

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ABSTRACT

The male/female sex ratio (SR) and its age-specific patterns vary considerably across time and place. The SR generally begins male-biased at birth and becomes female-biased later in life, but this relationship should respond to historical trends and events. Temporal trends in SRs remain largely unstudied and formal demographic relationships are not well defined. We (1) define SRs in a life table framework, (2) estimate the age at which the number of males and females achieves parity—the sex ratio crossover (SRX)—using basic life table methods, and (3) explore historical and international patterns in these trends. Using publicly-available data from the Human Mortality Database, we construct SR and SRX measures from period and cohort life tables. Analyses explore temporal patterns for seven countries in different global regions since 1850. Overall temporal trends show the SRX advancing to older ages. The SRX also appears to respond to historical events such as wars and epidemics. The measure is simple to construct from life table data, and provides additional insight into the historical context of gender dynamics.

INTRODUCTION

The sex ratio (SR; the ratio of males to females) has long been recognized as an important population-level variable. While influenced by a number of demographic processes, the SR is strongly correlated with the age structure of a population. Accordingly, the SR is central to understanding key social dynamics related to health, gender, and economy, including widowhood and family caregiving (Goldman and Lord 1983; Smith, Zick, and Duncan 1991), pensions (Belloni and Maccheroni 2006), labor force dynamics (Angrist 2002), and crime (Schacht, Tharp, and Smith 2016). Yet, surprisingly, little research exists on how age-specific SRs vary both temporally and spatially (Spoorenberg 2016).

More boys are born than girls. The ratio of live male to female births, called the sex ratio at birth (SRB), averages 1.05 cross-culturally, although sex selection and environmental stressors induce variations across time and space (Catalano et al. 2013). Across the life course, males generally have higher age-specific mortality rates (ASMRs) than do females (Wisser and Vaupel 2014). In late life, the SR of ASMRs declines, primarily due to survival selection but also due to increases in absolute levels of ASMRs for females. With respect to survival selection, frailer males experience higher rates of mortality earlier in life, concentrating more robust males in the aged population (Vaupel, Manton, and Stallard 1979).

A key demographic implication of these patterns is that in a population closed to migration, such as those used for calculating traditional stationary period or cohort life tables, males tend to outnumber females in the earlier ages, but this trend then reverses as females begin to increasingly outnumber males at later ages. While this pattern tends to hold across actual populations, migration patterns further complicate the relationship. For example, male-dominated occupations might yield transitory male-biased populations in labor migrants’ destinations, but female-biased populations in their origins (Ruddell 2017).

With these complications in mind, it remains the case that there is a distinctive pattern where the SR is male-biased in early life, and then increasingly female-biased later in life. Importantly, and surprisingly
underappreciated, is that at some age, the ratio equals 1 (i.e., the number of males in the population is equal to that of females). We call this age the sex ratio crossover (SRX). We suggest that this age has important social- and health-related policy implications.

Because of lower ASMRs among females, they have relatively higher life expectancies at birth than males across most populations; however, recent work suggests that this gap is shrinking (Kontis et al. 2017). Accordingly, as male life expectancy increases, we expect the SRX to occur at increasingly later ages as well. Previous research shows this phenomenon in select Scandinavian populations, a consequence primarily due to changing mortality dynamics (Spoorenberg 2016), and the U.S. Census Bureau explicitly noted this pattern in their recent population projections (Vespa, Armstrong, and Medina 2018).

We build upon this research by addressing the dynamics of secular shifts in ASMR patterns. We do so by first formulating SRs within a life table context using formal demographic definitions. Traditionally, age-specific SR patterns have been measured using census enumerations or population estimates (Fossett and Kiecolt 1991) and are straightforward to construct. Our life table approach is also easy to calculate from widely-available data, providing opportunity for regular surveillance and comparative research.

Our approach offers several additional advantages. It focuses attention on the relationship between mortality patterns and age-specific SRs, controlling for migration effects. We argue that the effects of these mortality patterns on population SRs are of considerable interest (Spoorenberg 2016; Vespa, Armstrong, and Medina 2018). The new measures also alert historians and demographers studying SRs to the opportunities of a trove of existing data and methods. High-quality life tables are widely available, and can be utilized to answer multiple questions of historical and current interest (Hacker 2010). For example, the Human Mortality Database (HMD), which we use in this article, presently houses highly-vetted, publicly-available historical and contemporary period and cohort life tables for 40 countries and regions (HMD 2018). Our method could also capitalize upon the extensive literature on indirect population estimation using model life tables (United Nations 1983).

After defining and interpreting the SRX measure, we use data from the HMD (2018) for selected nations to illustrate patterns in SRXs across time (1850–1950), with an emphasis upon recent decades (1950 to present). These demographic definitions and patterns should help researchers and planners anticipate future compositional shifts in population structure and aging, and provide historical researchers with additional tools to examine gender-related social dynamics such as living arrangements and poverty.

**Demographic definitions**

In this article, we define the sex ratio curve (SRC) as the ratio of males to females for a given stationary population at each age \( x \) in the life table. We expect the curve to be male-biased at birth, and become female-biased at a later age. Assuming the curve is monotonically decreasing, there is a single age at which the SR equals 1—the SRX.

**Sex ratio curve**

Within a life table framework, we assume a stationary population closed to migration. Let \( l(x,t) \) be the proportion of a population surviving to exact age \( x \) at time \( t \) (technically between time \( t \) and \( t+dt \)), which maps the survival curve. Let \( d(x,t) \) be the number of deaths during the comparable interval. Accordingly, the force of mortality is the instantaneous rate of death denoted by \( \mu(x,t) = d(x,t)/l(x,t) \).

The identity linking the force of mortality to the survival curve is

\[
\begin{align*}
  l(x,t) &= \exp \left[ - \int_0^x \mu(a,t)da \right].
\end{align*}
\]

The period SRC at age \( x \) is defined as the ratio of males to females in the population at time \( t \):

\[
\begin{align*}
  \text{SRC}(x,t) &= \frac{l_m(x,t)}{l_f(x,t)}.
\end{align*}
\]

The subscripts \( m \) and \( f \) refer to male and female, and \( \text{SRB}(t) \) is the SR at birth. By definition, \( \text{SRB}(t) = \text{SRC}(0,t) \), which is usually male-biased (1.05 on average). This formulation is similar to the one presented by Keyfitz and Caswell (2005, 223–225). As an example, Figure 1 shows the SR curve for the United States using 2010 period life tables from the HMD.

For cohort life tables, the notation can be adapted for birth cohort \( c \) as

\[
\begin{align*}
  \text{SRC}(x,c) &= \frac{l_m(x,c+x)}{l_f(x,c+x)}.
\end{align*}
\]

To enable a more succinct presentation, we drop the \( t \) and \( c \) notation moving forward. We also occasionally omit any identifying parameters when referring to the SRC across all ages. The following relations apply to both period and cohort life tables.
Absolute and cumulative difference in mortality rates

We can reformulate Eq. (2) in terms of differing forces of mortality:

$$\text{SRC}(x) = \text{SRB} \times \frac{\exp \left[ - \int_0^x \mu_m(a) da \right]}{\exp \left[ - \int_0^x \mu_f(a) da \right]} =$$

$$\text{SRB} \times \exp \left\{ - \int_0^x [\mu_m(a) - \mu_f(a)] da \right\} \text{ or}$$

$$\text{SRC}(x) = \text{SRB} \times \exp \left[ - \int_0^x \text{DMR}(a) da \right], \quad (4)$$

where $\mu_m(a)$ and $\mu_f(a)$ represent the male and female force of mortality, respectively, and $\text{DMR}(a)$ is the absolute difference of mortality rates between males and females at age $a$, in the notation employed by Wisser and Vaupel (2014). We can also refer to it as the excess male age-specific mortality.

Figure 2 diagrams the 2010 period life table $m(x)$ mortality rates for males and females in the US up through age 60 (we omit later ages, which are not directly used for calculating SRX, to improve readability). The vertical distance between the male and female curves in this chart is an approximation, based on...
Due to mortality selection (Wisser and Vaupel 2014), the female rates outpace those of males, the SRC will equal, then the SRC will be flat. In scenarios where female ASMRs could in practice outpace the male at a given age, this would violate the life table requirement that the force of mortality is always greater than 0 within our formulation. Accordingly, the resulting survival function would not be monotonically decreasing, and therefore not be a true survival function.

If there is an age where the respective ASMRs are equal, then the SRC will be flat. In scenarios where female rates outpace those of males, the SRC will increase. This situation may occur in advanced ages due to mortality selection (Wisser and Vaupel 2014), or in certain historical periods when maternal mortality outpaced male mortality during peak childbearing years (Lindahl-Jacobsen et al. 2013).

The area under the curve between 0 and age \(x\) in Eq. (4) can also be termed the cumulative absolute difference of mortality rates at age \(x\):

\[
CDMR(x) = \int_0^x DMR(a)da.
\] (6)

This CDMR quantity is easily calculated from life tables, and allows for clear interpretations of demographic phenomena by relating the cumulative mortality differentials for two groups. For example, the CDMR for low versus high socioeconomic groups would approximate the mortality that might be avoided if the poverty penalty were eliminated. In terms of the SRC, the measure further facilitates integration with previous research on DMRs, and a critical link to our understanding of the SRX.

**Sex ratio crossover**

The SRB will be greater than 1 except under the most extreme scenarios. Assuming a monotonic decrease, at least over the first several decades of life, there should be some age \(x\) at which SRC\((x)\) equals 1, and we define that age to be the SRX. In other words, SRC(SRX) = 1. It can be derived from Eq. (4) by setting SRC\((x)\) to 1:

\[
1 = SRB \times \exp \left[ -\int_0^x DMR(a)da \right].
\] (7)

SRX is the age \(x\) that satisfies Eq. (7). It is the age at which the number of men and women are modeled to be equal in number. The point of equal numbers is in many respects arbitrary—a researcher could easily adapt Eq. (7) to examine the point at which the number of women is double that of men, or some other metric. However, the narratives surrounding age-specific SRs often utilize the point of equality for expository purposes (see, for example, Vespa, Armstrong, and Medina 2018). This suggests our SRX statistic might address a range of applications.

There is no analytic solution for SRX, unless possibly a parametric “law of excess male mortality,” similar to more traditional “laws of mortality” (Gage and Mode 1993) identified DMR\((a)\) and permitted a closed-form solution. We are aware of no such formula.

We can substitute Eq. (6) into Eq. (7), take the natural logarithm, and rearrange terms to obtain:

\[
\ln (SRB) = CDMR(x).
\] (8)

This shows the SRX is the exact age \(x\) at which the cumulative excess male mortality equals the natural log of the SRB. Since the average SRB is 1.05, and its natural log is approximately 0.05, then a heuristic for estimating the SRX is to estimate the age at which the cumulative male mortality reaches 0.05. However, since SRBs vary across time and geography, the actual measure is preferred.

The DMR\((x)\) and CDMR\((x)\) for the United States in 2010 using period life tables are plotted in Figure 3, along with the natural log of the U.S. 2010 SRB, which is 0.047.

This DMR\((x)\) is the vertical distance between the \(m(x)\) curves previously shown in Figure 2. The age at which the CDMR\((x)\) crosses the natural log of the SRB is shown in Figure 3 and occurs during age 55. In Figure 1, the SRX occurred about age 56. The difference occurs because the metrics in Figure 1 were calculated following Eq. (2) and the \(l(x)\) column, whereas the metrics in Figure 3 were calculated following Eq. (8) and the \(m(x)\) column. The SRB is 1.048, with \(l(56) = 89,307\) for males, 93,594 for females. Using Eq. (2), this yields SRC(56) = 1.
There are two methods, then, for calculating the SRX. The first involves ratios of survival curves, as defined in Eq. (2). The second involves absolute sex differences in mortality as shown in Eq. (8). Both involve the identity $SRC(SRX) = 1$. Like any demographic analysis, the method used will depend on the context and data. In either case, the realities of discrete data often require approximation with familiar actuarial life table methods. We illustrate such a method below. R code (R Core Team 2017) and also an Excel wordbook to calculate SRXs are available for interested researchers.

**Temporal patterns in SRX for seven countries**

This study reviews, constructs, and presents SRXs for seven countries since 1850. Data were taken from the HMD for Australia, Chile, Italy, Japan, Russia, Sweden and the United States. These countries were selected because they provided useful geographic coverage throughout the world, for which data were available in the HMD. While data for Sweden are available as far back as 1749, we limit our examination to 1850 and later in order to maintain comparability with the other countries.

We adopt HMD data not only for wide geographic and historical coverage, but because of their high quality. Candidate HMD data are thoroughly vetted prior to inclusion, the life table construction process is rigorous, and a common protocol enables reliable cross-population comparisons (Barbieri et al. 2015). Analyses were performed using R Statistical Software (R Core Team 2017). Scripts were adapted from the R “demography” package (Hyndman et al. 2018) to interface directly with the HMD.

**Period life table analyses**

For period life table analyses, variables were calculated directly from the single-year-of-age $l(x)$ values published by HMD and the SRBs calculated from HMD births. As mentioned above, we utilize algorithm (2). These are discrete data, so we first find the minimum age at which the SRC is less than one. This indicates
parity must have just been achieved, and so the SRX is the age immediately prior.

The mean SRB for all data points was 1.052 with a standard deviation of 0.009. **Table 1** shows descriptive statistics for the SRXs using period life table methods. The estimated SRXs range from 3 through 101, with a mean of 51.9 over the period. The low and high values occur in Sweden and Italy, respectively. These two countries have data series extending prior to 1900, and also have large standard deviations. This is likely due to relatively poor data quality in the early years. However, it may be due to extreme historical mortality patterns. The highest calculated SRX is for Italy, with an age of 101 in 1882. Interestingly, calculations for Italy show SRX not even being realized for certain years, which can be inferred from **Table 1**. Many of these anomalies disappear in the cohort analyses below, which track actual experiences more closely than the synthetic cohorts used for period measures.

**Figure 4** plots the period-derived SRX for each country. Historically, Sweden had very low crossovers, and Italy very high (possibly never attained). In the most recent decades, Sweden generally has the highest SRX values. It is followed in varying order by Australia, Italy, and Japan, which often trade rank over time. The United States generally ranks fourth, followed by Chile. Russia’s SRX values are by far the lowest in the modern era.

In general, these trends show a steady increase in the SRXs in recent decades. A notable exception is Russia, where rates experienced a steep decline around the late 1980s and early 1990s, and have only recently begun to rise again. This likely reflects increasing mortality rates, particularly for males, related to circumstances incident to the Soviet Union’s dissolution (Zaridze et al. 2014). There is also a decline for the United States beginning in about the mid-1980s, with a rebound to increasing SRX values in the mid-1990s. This could be associated with the U.S. AIDS epidemic that drastically elevated male mortality during those years (Armstrong, Conn, and Pinner 1999). Interesting patterns also appear around the World Wars, but these are more clearly discussed in comparison with the cohort findings.

**Cohort life table analyses**

Long series of cohort life tables are not available for most of these countries in HMD, because HMD requires nearly extinct cohorts to calculate the life tables, and data often do not extend that far back. However, since the SRC often occurs long before a cohort is extinct, we generated cohort life tables by requiring only enough data for a cohort to extend beyond a reasonable SRX threshold. To balance data availabilities, we required each cohort to have at least 50 years of data. Even then, Chile had no crossover points and was excluded from the analysis. We took $q(x)$ values directly from HMD and converted them to $l(x)$ values using usual discrete life table methods. We did this for all countries to permit reliable international comparisons. We then calculated the cohort SRC using Eq. (3).

**Table 2** shows outcomes for SRXs using the cohort life table method. **Figure 5** plots these SRXs. Note that Japan and Russia each only have a few data points available for analysis. In general, these crossovers are
less dispersed than for the period crossovers, likely because we are not mixing cohorts, and clearer patterns emerge. The extraordinarily high crossovers for Italy in the late 1800s have disappeared, though they are still rather high compared to the other countries. The relative rankings of the countries are similar to those obtained with the period method.

A more discernable picture is painted by plotting a country’s period and cohort SRXs side-by-side. This is done in Figure 6 for the four countries with sufficient data to permit worthwhile comparisons. A delay, or shadow, becomes apparent, where the period crossovers reflect the cohort crossovers. The most noticeable case is Italy, where the period crossovers drop drastically during World Wars I and II. The cohort crossovers drop several decades earlier; these decrease by about one year each year, synchronized in striking harmony with the period movements. Clear in Figure 6, Sweden has a wave of decreasing SRXs in the late 20th century for cohorts born in the early 20th century; yet, no explanation for this trend readily presents itself. The dip in U.S. period crossovers (mentioned previously) also has a cohort counterpart, possibly in conjunction with the AIDS epidemic. In both the period and cohort cases, the recent trend for all these countries has been toward a delayed SRX.

### Discussion

Identifying and plotting the SRX over time reveals trends in the age at which women do or will begin to outnumber men. The recent trend in the crossover appears to be toward a postponed age at which women begin to outnumber men across populations, a pattern consistent with previous research among Scandinavian countries (Spoorenberg 2016). This finding might reasonably be hypothesized from the formal demographic relationships, which show the life table SRX to be a function of two key metrics: the male–female difference in mortality and the SR at birth.

If the difference between male and female mortality rates is held constant, lowering the ratio of males to females at birth will also lower the age at which males and females achieve parity in numbers. Research suggests adverse conditions decrease a population’s SR at birth. Events such as widespread natural disasters and economic hardship have been linked to higher rates of spontaneous abortions of male fetuses and possibly even lower likelihoods of conceiving males, resulting in lower SRBs (Bruckner, Catalano, and Ahern 2010; James 2015). Given improved prenatal care in developed countries and diminishing ecological hardship, it follows that the SRB should probably increase over time. However, the ratio tends to decrease for older parents (Nicolich, Huebner, and Schnatter 2000), so

<table>
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<tr>
<th>Table 2. Descriptive statistics for cohort life table sex ratio crossovers.</th>
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<tr>
<td>Sex ratio crossovers</td>
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<tr>
<td>Country</td>
</tr>
<tr>
<td>All</td>
</tr>
<tr>
<td>Australia</td>
</tr>
<tr>
<td>Italy</td>
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<td>Japan</td>
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<td>Russia</td>
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<td>Sweden</td>
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<td>United States</td>
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Source: Human Mortality Database, Calculations by Researchers.

![Figure 5. SRXs for seven countries using cohort life table methods.](source: Data from Human Mortality Database. Calculations by researchers.)
the shift toward delayed fertility (Morgan 2003) could then lower the SRB. Additionally, individual fertility choices might be affected by societal norms related to sex preferences of children (Bongaarts 2013). In the absence of further detailed research, it would be difficult to hypothesize a future trajectory for SRBs and associated implications for trends in the SRX.

However, shifting mortality patterns suggest the SRX will be increasingly delayed to later ages. If SRB is held constant, the SRX correlates negatively with the CDMR. In other words, when the age-specific difference between male and female mortality rates shrinks, then the cumulative difference will increase more slowly, and the age at which women begin to outnumber men will occur at a later age. Hypotheses about the future direction of the crossover can therefore be pictured in terms of the absolute difference in male–female mortality. Due to substantial health improvements, life expectancy is linearly increasing for the developed world, with no signs of slowing (Medford 2017; Oeppen and Vaupel 2002). While the age-specific male/female relative mortality risk has recently tended to increase at younger ages, the absolute difference in risks (i.e., the DMR) has narrowed (Wisser and Vaupel 2014). This likely occurs because relative rate reductions yield smaller absolute reductions over time (Tuljapurkar et al. 2000); and the dynamic results in a male-biased population for more of the life course.

The trend shown here, using two different estimation techniques, suggests a delay of the SRX. In other words, men will outnumber women for a longer period of the life course. The pattern is consistent with research documenting diminishing absolute sex-specific mortality differences (Wisser and Vaupel 2014). It is most prominent in recent decades and appears to be shared by a diverse set of developed nations around the world.

From a contemporary demographic perspective, these dynamics alter the age–sex structure of the old age population. The upward trend in the SRX suggests that we are seeing more males surviving to older ages. Recent trends in life expectancy have shown that the gender gap in life expectancy has shrunk, with gains in life expectancy being greater for men than women (Kontis et al. 2017). This rebalancing of the age–sex structure could be termed a “masculinization” of old age, yet even with these trends there remains an imbalanced SR in older ages, especially the oldest ages, where the number of older women outnumber men. Nevertheless, the delayed SRX trend we are seeing across multiple developed populations in recent decades may have implications on how we address the needs of the aging population.
From a historical demographic perspective, the SRX is a useful measure in that it can be constructed from historical life tables. In other words, it is an additional metric easily harvested from datasets that already exist. Identified patterns can provide additional context for studies of family relationships, gender dynamics, and the effects of historical events such as wars and epidemics. We have offered mostly descriptive results and offered possible interpretations. A more thorough analysis would incorporate extensive data in a statistical model that utilizes SRX as an independent or dependent variable with population covariates. Our method can be extended to incorporate causes of death, which could further refine analyses—although the data requirements would be greater.

The SRX is a single measure that compares two groups (male and female) and provides a summary of mortality-related dynamics for the population. Single-number statistics that try to summarize death rates have proven useful due to their tractability for interpretation and modeling. Life expectancy has proven to be an invaluable public health metric. Life expectancy is the weighted mean age at death in the life table; the median and modal ages at death have also proved informative (Canudas-Romo 2010). This feature of the SRX suggests its general usage as a mortality-relevant measure of public or population health, perhaps to be used as a predictor or outcome in statistical epidemiological models. The additional link with sex differences also suggests its use for examining gender-related patterns of living and adaptation.

Additional research should also include further integration with demographic relationships. In particular, the SRX presented here does not account for patterns of migration, which are often sex- and age-specific (Rogers, Little, and Raymer 2010). A SRC using actual stocks from a census might yield different patterns, especially in those contexts where significant sex-specific migration patterns are present. In a statistical model, migration might be included as a covariate along with SRX. The difficulty of incorporating migration into formal demographic frameworks is a problem endemic to life table analyses that rely on assumptions of closed populations, but considering such patterns would be important in applied fields such as population estimation, projection, and policy planning (Rogers 1995).

Looking to the future, the shifting SRX is altering the sex composition of the older population, affecting a number of social and economic conditions related to the patterning of relationship formation, possibly crime and violence, as well as for pension systems and living arrangements of aging families. Age of (and indeed the likelihood of) widowhood may be delayed for women, which could attenuate the feminization of poverty. However, since men tend to be less healthy than women, particularly as they age, the prolonged nature of men in poor health could place increased financial and caretaking obligations upon spouses and children. Accordingly, this population trend where the sex composition of the old age population is shifting in response to a delayed SRX has the potential to mediate some age-related socioeconomic inequalities, while, unfortunately, exacerbating others.

Acknowledgments

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