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Research Material

Visualizing fertility trends for 45 countries using composite lattice plots

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Research Material

Visualizing fertility trends for 45 countries using composite lattice plots

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Abstract

BACKGROUND
The Human Fertility Database (HFD) and Human Fertility Collection (HFC) provide disaggregated data on age-specific fertility rates for 45 countries. These sources offer the opportunity to learn about the development of different pathways of transition to low fertility both within and between countries.

OBJECTIVE
The aim of this paper is to use composite fertility lattice plots, which combine information from different visualization techniques of the Lexis surface, namely level plots and contour plots, to explore changes in age-specific fertility rates (ASFRs) and the implied (period-based) cumulative cohort fertility rates (cumulative pseudo cohort fertility rates, CPCFRs) across countries and geographic regions.

METHODS
Through key examples we introduce a new refinement of the Lexis surface, combining level plots, which use colour/shade to indicate ASFRs, and contour lines to indicate fertility milestones for given cohorts (CPCFRs). We have also developed a web-based app to allow researchers to produce their own fertility Lexis surfaces.

RESULTS
Results show that once countries have fallen below a replacement fertility level, they tend to not return to it. Exceptions are Norway and the United States, which saw rising fertility rates for cohorts born after the 1950s and late 1960s respectively. The age-specific fertility trends, as well as broader political and socioeconomic conditions, are very different in these countries, suggesting different paths by which replacement fertility rates might be achieved.

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CONTRIBUTION

Complex data visualizations show, in an intuitive way, how ASFRs are related to successive cohorts' fertility milestones (CPCFRs). Combining this information enables us to explore differences between countries and can make an important contribution to comparative fertility research.

1. Introduction

Data visualization techniques such as Lexis surfaces have become an increasingly popular tool to investigate trends in fertility and other population characteristics in recent years (Burkimsher 2017; Calot et al. 1998; Campbell and Robards 2014; Rau et al. 2018; Vaupel, Gambill, and Yashin 1987). They provide convenient visual arrangements of birth rates and related indicators by calendar time, age, and/or cohort, and are thus an effective tool for both the exploration and the identification of dynamic patterns and relationships arising from fertility data.

The transition to low fertility, below replacement levels, is a cornerstone of both demographic transitions (Davis 1945; Lesthaeghe 1995; Lesthaeghe 2010; Lesthaeghe and van de Kaa 1986; Notestein 1945) and one of the key drivers underpinning population change. A crucial question is whether fertility rates will fall and stabilize at below replacement levels for all developed countries. With reversals in period fertility trends for some European countries (Goldstein, Sobotka, and Jasilioniene 2009; Myrskylä, Goldstein, and Cheng 2013), the persistence of low fertility is increasingly debated. Recent analyses emphasise increasing instability and divergence between populations, characterising distinct fertility transition pathways (Billari 2018; Sobotka 2017). Key drivers include the diffusion of modern contraceptive methods, the expansion of higher education, the increase in economic uncertainty, the large-scale entry of women into the labour force, and gender role changes (Balbo, Billari, and Mills 2013; Basten, Sobotka, and Zeman 2014).

The aim of this paper is to show how differences in fertility trends and pathways can be identified using composite fertility lattice plots (CFLPs), a variant of the Lexis surface visualization in which both the colour/shade and contours represent different but related variables: age-specific fertility rates (hereafter ASFRs) and cumulative fertility by cohort implied by them (cumulative pseudo[4] cohort fertility rates, hereafter CPCFRs) respectively.

[4] We use the term 'pseudo' to indicate that the cumulative fertility rates are based on period-based fertility rates by age (Lexis squares) rather than true cohort-based rates (Lexis parallelograms). We use these period-based measures because they provide greater coverage by geography and period.

This novel combination offers a more efficient comparison of multiple pieces of information that provide insights into how the fertility transition varies across countries and geographic regions. We present a useful tool to analyse different interrelated aspects of fertility decline, giving hints into its causes and long-term sustainability.

To illustrate the benefits of this approach, we offer step-by-step descriptions of the process involved in producing a composite fertility lattice plot through key examples. We provide a comparison of West and East Germany, followed by a comparison of Norway and the United States. In these examples we offer practical suggestions on how to interpret and decode the information contained in CFLPs before concluding with a plot comparing 45 countries. Within this paper the final figure is split into three subfigures, but we also include a version of it as a single figure, which we suggest is best printed out as a large-scale (e.g., A-2-sized) colour poster. We include the R code used to produce the final plot, along with additional figures for selected clusters of countries by geographical region[5] and an interactive online app[6] that can be used to explore additional features of the data.

2. Methods

2.1 Data

Data from the Human Fertility Database (HFD) and Human Fertility Collection (HFC) were combined (Max Planck Institute for Demographic Research and Vienna Institute of Demography 2015, 2016; Grigorieva et al. 2015). The HFD includes ASFRs for 28 countries over different periods, drawn from national official vital statistics. The HFC supplements the HFD, providing data for sufficient observation periods from additional sources (Grigorieva et al. 2015) to add a further 17 countries. Where data is overlapping the value from the HFD was used first; otherwise, records from the HFC were used in the following order of preference according to the 'collection' field of the HFC dataset: (1) STAT (Official Statistical Data), (2) ODE (Data from the European Demographic Observatory, L'Observatoire Démographique Européen), and (3) RE (Research estimates). For most countries, this approach produced a dataset comprising ASFRs for contiguous years; linear interpolations of ASFRs were used for the few countries and years where this was not the case. The code for both combining data across sources and

5 See https://github.com/JonMinton/comparative_fertility.

6 See https://datascapes.shinyapps.io/cumulative_fertility_app/. This app has been developed in order to allow users to rapidly create and use these visualizations. It also includes three-dimensional and interactive Lexis surfaces using the Plotly graphics engine within R Shiny. The GitHub repository mentioned in the previous footnote contains the current state of the app and includes an 'issues' section to log issues, feature requests, and bugs.

interpolating values is available in the online appendix. Because of the stricter data quality standards for data within the HFD, users may wish to choose to restrict their analysis to only those countries, years and ages for which data is available from the HFD only, or to exclude from the analyses any entries within the HFD where the user has sufficient concerns about the data quality. However, our aim was to demonstrate the large amounts of data that can be visualized and interpreted within a single figure, hence the very large number of populations, years, and data sources used.

Data disaggregated by age in single year was derived from both the HFD and HFC, and Lexis squares (one year by one year) rather than Lexis triangles or Lexis parallelograms were used, as in practice the use of squares only has limited effect on the precision of cohort estimates (Caselli and Vallin 2005).

2.2 Lexis surface mappings

For each country, ASFRs were arranged onto Lexis surfaces with birth year on the horizontal axis and age in years on the vertical axis. As Lexis squares rather than triangles or parallelograms were used, these are not true cohort estimates, but they are sufficient to illustrate the visualization principles (the R code is available to iterate the approach further); we derive the cumulative 'cohort' fertility rates using ASFRs by period and refer to these quantities as cumulative pseudo cohort fertility rates (CPCFRs) for this reason. ASFRs for each country and year were mapped to colours and shades using the *Viridis* colour scheme (Garnier 2018). The visualizations were produced with the R packages *Lattice* and *LatticeExtra* (Sarkar 2008).

For cohorts where ASFRs were available from at least age 15 years, CPCFRs (implied cumulative cohort 'milestones') were produced for each age and birth year. If $A(x, y, p)$ refers to the ASFR in year x, at age y and for country p, then the CPCFR for age y can be defined as $C(z, y, p) = \sum_{i=\min(i)}^{y} A(z + i, i, p)$, where z is the simple index of cohort $(x - y)$, and *min(i)* is the youngest age group for which fertility data by single age was available for the given population of interest (at least 15 years of age). Within the Lexis surfaces, contours were added across the cohort-age surface where $C(z, y, p)$ reached specific values. A thin solid contour indicates $C(z, y, p)$ of 1.50 children per woman and a thick solid contour indicates $C(z, y, p)$ of 2.05 (replacement fertility level). These values were selected for their relevance in the comparative cohort fertility literature (Myrskylä, Goldstein, and Chen 2013; Zeman et al. 2018) but may not be identical to cumulative cohort fertility rates produced using alternative approaches, especially for countries with relatively high rates of immigration and emigration. However, it is important to emphasize that a wider range of monotonically-ordered cumulative values can be identified and analysed; the interactive app allows different numbers and values of threshold values to be selected.

3. Results

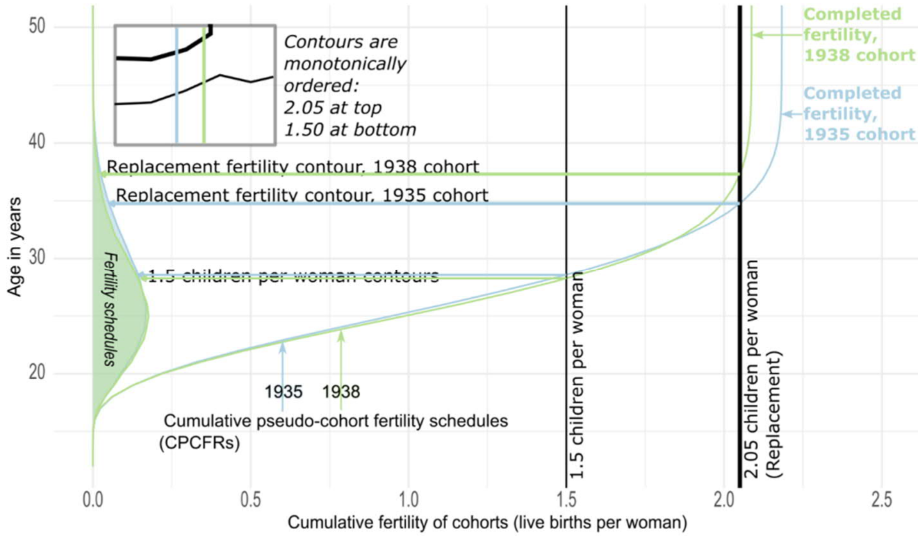
3.1 Unpacking composite fertility lattice plots: the case of West and East Germany

Figure 1a provides an illustration of how the CPCFRs are constructed from the ASFRs for any specific cohort. West German cohorts born in 1935 and 1938 are used in the example.

For both cohorts, pseudo cumulative fertility schedules are constructed indicating the ages at which different levels of cumulative fertility are reached. Two vertical ‘milestones’ are placed at 1.50 (thin solid line) and 2.05 (‘replacement’; thick solid line) children per woman. As the figure shows, the contours for any given cohort are the ages at which that cohort’s cumulative fertility schedule intersects with the corresponding fertility milestone. In the example used, there is little difference between cohorts in the ages at which the 1.50 children per woman milestone is reached, but the replacement fertility contour has moved upwards by around five years between the 1935 and 1938 cohorts.

By looking at the furthest right of the cumulative schedule, we can see that each schedule becomes vertical after a particular age: for later cohorts, this tends to be around the age of 44, and for earlier cohorts, a slightly earlier age. This is the maximum cumulative fertility reached by each cohort, and we can see that this has shifted to the left (become lower) for the 1938 cohort compared with the 1935 cohort. Although the age-specific fertility schedules (on the left of the figure) look similar for both cohorts, the effect of the slight differences in terms of the position of the replacement fertility contour is thus sizeable.

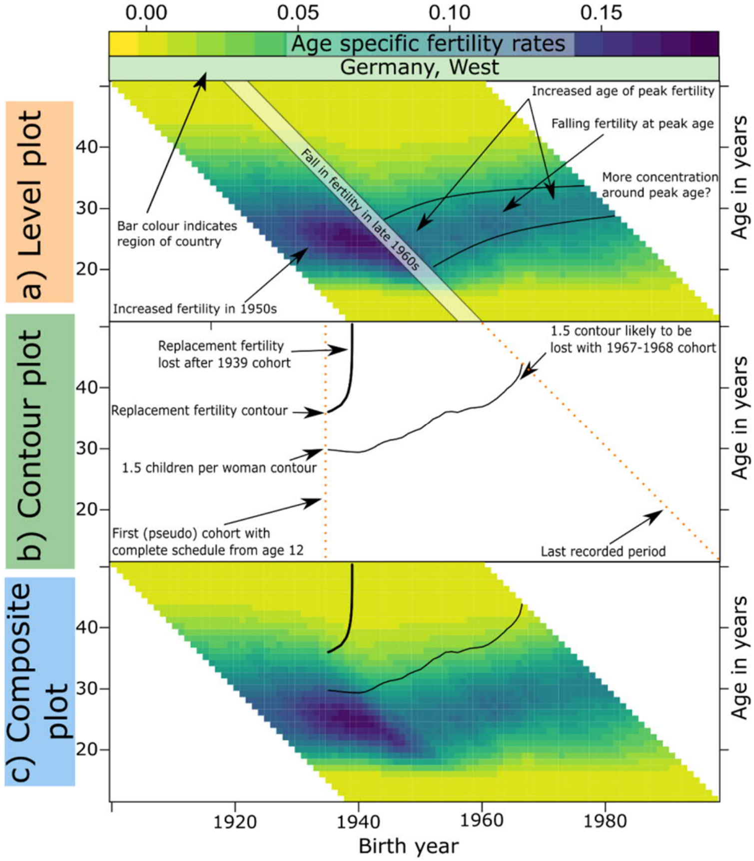
Figure 1a: Illustration of construction of cumulative pseudo cohort fertility contours



Notes: Illustration of how the cumulative pseudo cohort fertility contours are constructed, using fertility schedules from West Germany for cohorts born in 1935 and 1938; lines in the box on the top left are fictitious, for illustration only.
Source: Human Fertility Database (HFD) and Human Fertility Collection (HFC), own calculations.

This case study highlights two important features for interpreting the contours. First, and as shown in Figure 1b (mid subpanel), the ordering of the two contours will always be consistent: the thin solid line, implying cumulative fertility of 1.50 children, will always be lower than, and so not intersect with, the thick solid replacement fertility line (2.05 children per woman). Second, we can see how, as the total cumulative fertility of a cohort falls below any of the two fertility milestones, the corresponding contour will swiftly become vertical. In the case of West Germany, the total cumulative fertility first falls below replacement for the 1939 cohort, and it has never exceeded this level since.

Figure 1b: Production of composite fertility lattice plot for West Germany



Notes: (a) Cohort and not period is indicated on x-axis. (b) The shades in both the level and composite plots correspond to different age-specific fertility rates (ASFRs), as indicated in the shaded scale bar on the top of the figure. (c) The thick solid contour line indicates cumulative pseudo cohort fertility rate (CPCFR) = 2.05 children per woman (replacement fertility), and the thin solid contour line indicates CPCFR = 1.50 children per woman; both of these are based on ASFRs for the earliest cohorts that are not shown as coloured tiles for all years and ages. (d) The green colour of the tile containing the name of the country (Germany, West) indicates the macro-region of Western Europe (see also note (d) in Figure 3).
Source: Human Fertility Database (HFD) and Human Fertility Collection (HFC), own calculations.

Figure 1b continues the focus on West Germany by showing the two components of the composite plot separately and emphasizing some key features arising from the data. Panel (a) shows the level plot component of the composite plot, in which different ASFRs are mapped onto different colours, as per the key shown at the top of the figure. The colour of the tile containing the name of the country indicates the macro-region in which the country is grouped.[7] Annotation features have been added to highlight substantive patterns in the data. These include the fall in fertility rates at all ages seen in the late 1960s, coinciding with the diffusion of more effective contraceptive methods among other factors (as each vertical section through the figure is a cohort, a period effect will appear as a diagonal band moving bottom right to top left). After the 1960s, the age of peak fertility increased, whereas the level of fertility at the peak fertility age tended to fall.

Panel (b) shows the contours for different CPCFR milestones only. A vertical dotted orange line on the left of the figure shows the first cohort for which the contours were shown; earlier cohorts have incomplete age-specific fertility data at some younger ages, and so the CPCFRs for such cohorts would be incomplete and misleading if plotted. The diagonal dotted orange line shows the last period for which data are available, and so the highest ages at which CPCFRs can be calculated for more recent cohorts.

Starting with the 2.05 contour, we can see that this line quickly becomes vertical for the 1939 cohort; this was the last cohort that reached replacement fertility levels. The 1.50 children per woman contour is observed to move upwards and is likely to be lost for cohorts born after around 1967–1968. Panel (c) shows the composite plot, which brings together both level plot and contour elements.

Figure 1c presents the composite plots for both West and East Germany, with the plot for the latter presented in both annotated and non-annotated forms. As many features regarding West Germany have been previously discussed (when referring to Figure 1b), the focus is now on the corresponding features for East Germany, relating both to the level and contour plot aspects of the composite plot visualization.

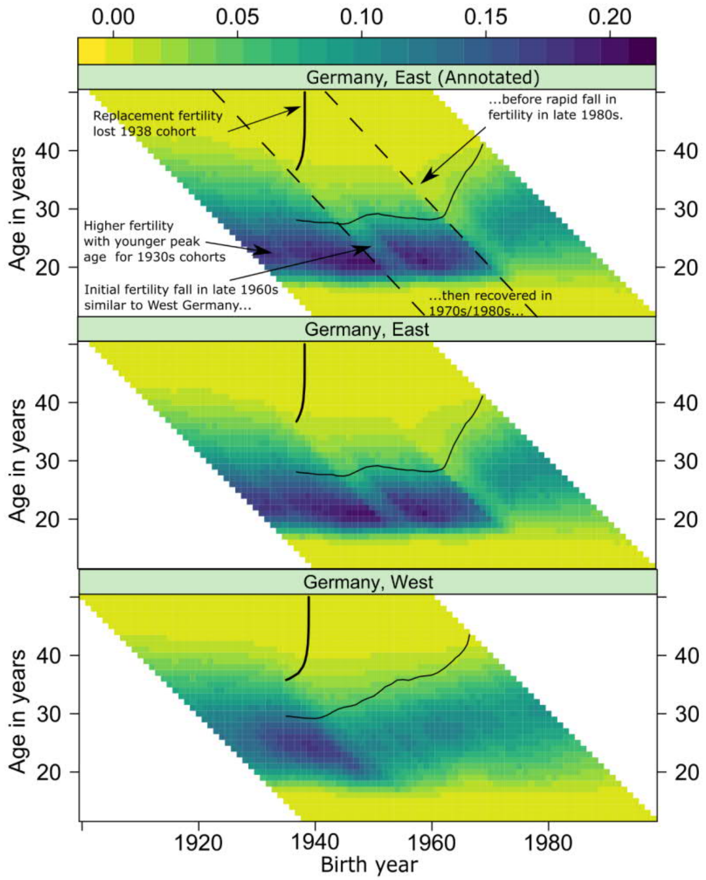
Unlike West Germany and most Western European and other developed countries, East Germany experienced two period effects/shocks (diagonal dashed lines) rather than just one. Though, like in most Western European nations, there was a sharp fall in fertility in the late 1960s, there was then a recovery in age-specific rates for most of the 1970s and 1980s. However, in the late 1980s, with the collapse of the Berlin Wall, fertility rates fell rapidly again, with fertility rates at many ages falling below corresponding rates in West Germany. Afterwards, there was a rapid convergence of East German fertility schedules to those seen in West Germany, with a rapid rise in the age of peak fertility.

By looking at the contours, we can see the effects that these changes in age-specific fertility, visualized over the whole period, had on completed cohort fertility rates. Replacement fertility rates were last reached for almost the same cohort for both East Germany (1938) and West Germany (1939). In contrast to West Germany, in East Germany for cohorts who were of childbearing age in the 1970s and 1980s, cumulative fertility levels of 1.50 were reached before the age of 30. However, after the late 1980s,

[7] The full list of macro-regions and corresponding tile colours together with the list of countries included in each macro-region are provided in note to Figure 3.

the 1.50 fertility milestone was reached by cohorts at ever older ages and in the last observed period after the age of 40 years. Because of this, it appears likely that East Germany will not sustain fertility rates above 1.50 children per woman in the years to come.

Figure 1c: Comparison of fertility trends in West and East Germany



Notes: (a) Cohort and not period is indicated on x-axis. (b) The shades in the plots correspond to ASFRs, as indicated in the shaded scale bar on the top of the figure. (c) The thick solid contour line indicates CPCFR = 2.05 children per woman (replacement fertility), and the thin solid contour line indicates CPCFR = 1.50 children per woman; both of these are based on ASFRs for the earliest cohorts that are not shown as coloured tiles for all years and ages. (d) Diagonal dashed lines indicate period effects. (e) The green colour of the tiles containing the name of the countries indicates the macro-region of Western Europe (see also note (d) in Figure 3).
Source: Human Fertility Database (HFD) and Human Fertility Collection (HFC), own calculations.

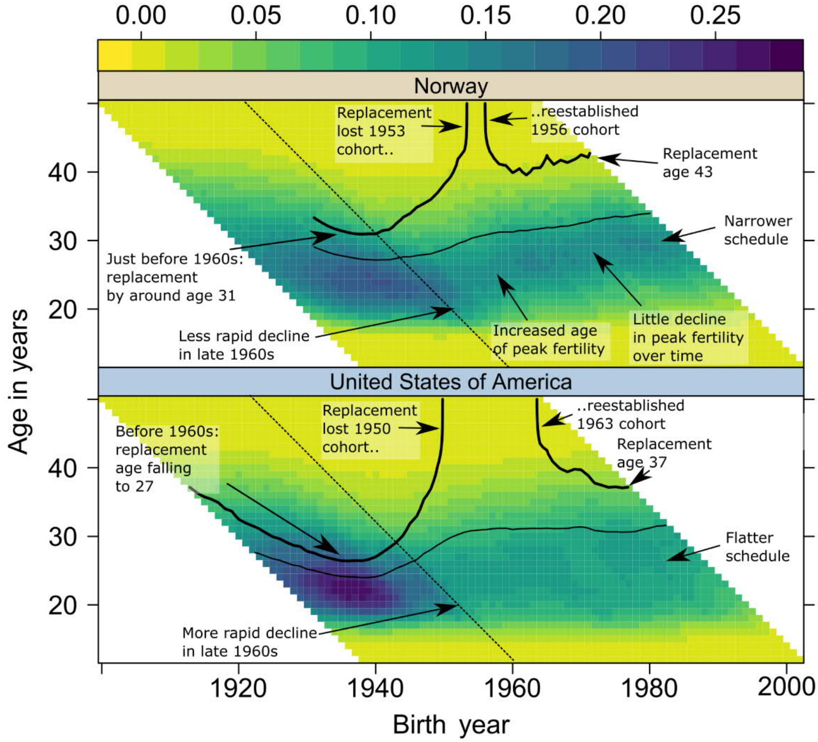
3.2 Comparing the fertility trends in Norway and the USA

Figure 2 compares the fertility trends for Norway with those in the United States. In the comparative welfare state literature, when these and other high-income countries are juxtaposed using a range of internationally comparable indicators, they tend to occupy different positions (Esping-Andersen 1999; Esping-Andersen and Billari 2015). However, the contours in the composite plots show that they have in common a feature shared with almost no other country covered by this study: Norway and the United States both 'regained' replacement cohort fertility levels after first losing them for several successive cohorts. We can see this visually by noting the arcing of the thick black contours: for both countries these arc vertically upwards for cohorts born in the early 1950s, arc vertically downwards from some cohort onwards, then remain plotted for later cohorts. Norway 'regained' replacement fertility levels after having lost these levels for three cohorts (1953–1956). The United States 'regained' replacement fertility levels after a much longer period: cohorts born between 1950 and 1962 did not reach replacement fertility, but cohorts from 1963 onwards did.

Although Norway and the United States both re-established replacement fertility levels, whereas almost all other countries have not, more careful exploration of the composite plots shows that they did so in different ways. Firstly, if we compare the late 1960s period effects (diagonal dashed lines) for both countries, the fall in fertility appears to be larger for the United States and more gradual in Norway. Secondly, if we compare the changing age schedules after the late 1960s, we can see that in Norway (as in West Germany), the age of peak fertility has moved upwards, from around 25 to 30 years of age.

Unlike in West Germany, in Norway there was not a pronounced fall in peak birth rates along with the increase in the age of peak birth rate; it has remained at or close to 0.15. In the United States, the post-1960s fertility schedules have not so much shifted as spread, producing a flatter age schedule than in Norway: there is a comparatively wide range of ages, from around 20 to 30 years of age, at which women in the United States have moderate birth rates (around 0.10–0.12 children per woman per year). In Norway, the peak birth rates have tended to be higher (around 0.14–0.15), but the drop off in birth rates the further a woman's age moves from this peak age is greater. So, replacement fertility levels were reached in Norway through high fertility at a narrow range of ages and in the United States by moderate fertility at a broader range of ages.

Figure 2: Comparison of fertility trends in Norway and the United States



Notes: (a) Cohort and not period is indicated on x-axis. (b) The shades in the plots correspond to age-specific fertility rates (ASFRs), as indicated by the shaded scale bar on the top of the figure. (c) The thick solid contour line indicates CPCFR = 2.05 children per woman (replacement fertility), and the thin solid contour line indicates CPCFR = 1.50 children per woman; both of these CPCFRs are based on ASFRs for the earliest cohorts that are not shown as coloured tiles for all years and ages. (d) Diagonal dashed lines indicate period effects. (e) The colours of the tiles containing the names of the countries indicate different geographical macro-regions, as per note (d) in Figure 3.
Source: Human Fertility Database (HFD) and Human Fertility Collection (HFC), own calculations.

If we consider the trajectories of the replacement contours for the United States and Norway after they were re-established, we can see that the line has been trending upwards for Norway but falling for the United States. By the end of the series, the age of replacement fertility was around 43 in Norway but 37 in the United States; if we apply the rule of thumb that cumulative fertility of a cohort by age 43 is likely to be close to that cohort's total completed fertility, we might assume that Norway looks likely to lose replacement fertility levels over the next few years. However, if we were observing missive trend changes for more recent cohorts, we might expect the contour line to go down again, even though it has recently gone upwards. By contrast, we might assume that replacement levels will be sustained for longer in the United States.

3.3 Fertility trends in 45 countries

Figure 3 shows the composite fertility lattice plots for 45 countries, representing a visual summary of hundreds of thousands of separate ASFRs. Country labels are coloured according to their geographic region. Countries are ranked in descending order by CPCFRs computed for women from the 1957–1958 birth cohort (who were 49 years old in 2007, the last year for which data are available for all countries[8]). A higher-resolution version of the figure, including subfigures and related annotations for smaller clusters of countries by geographic region, are included in the online appendix. Some interpretations of the many results presented in this section are discussed in section 4.1.

For most countries we observe a general shift of fertility schedules to increasingly higher ages. There are also clear differences across geographic regions in terms of cohort fertility pathways. For example, on one end of the fertility spectrum, we have Southeastern European countries such as Albania and Macedonia, which display relatively stable cohort fertility at both levels of 1.50 and 2.05 children per woman. These are followed by Western European countries, which show a higher degree of heterogeneity. In line with the study by Campbell and Robards (2014), Ireland and Northern Ireland present more pronounced patterns of cohort fertility trajectories, with both levels of CPCFR (1.50 and 2.05 children per woman) increasingly being reached at higher ages for women born approximately after 1955. On the other hand, both England and Wales and Scotland show lower cohort fertility with replacement fertility being lost for women born around 1955. For the remaining Western European countries, replacement fertility appeared lost even for earlier cohorts, with German-speaking countries, displaying more pronounced patterns in fertility measured at 1.50 children per woman (see earlier discussion for West and East Germany in section 3.1 and for the latter, Rau et al. 2018; for Switzerland, see Burkimsher 2017 and Calot et al. 1998). A high level of heterogeneity is also observed among Eastern and Central European countries, which either show lost fertility replacement or pronounced levels of 1.50 children per woman for cohorts born approximately after 1960, who have been affected by the collapse of the Socialist regime. Amongst the complex patterns and features shown for Eastern European countries is an apparent cohort effect for Russian women born in the late 1940s, apparent as a brief ‘uptick’ in the CPCFR line.

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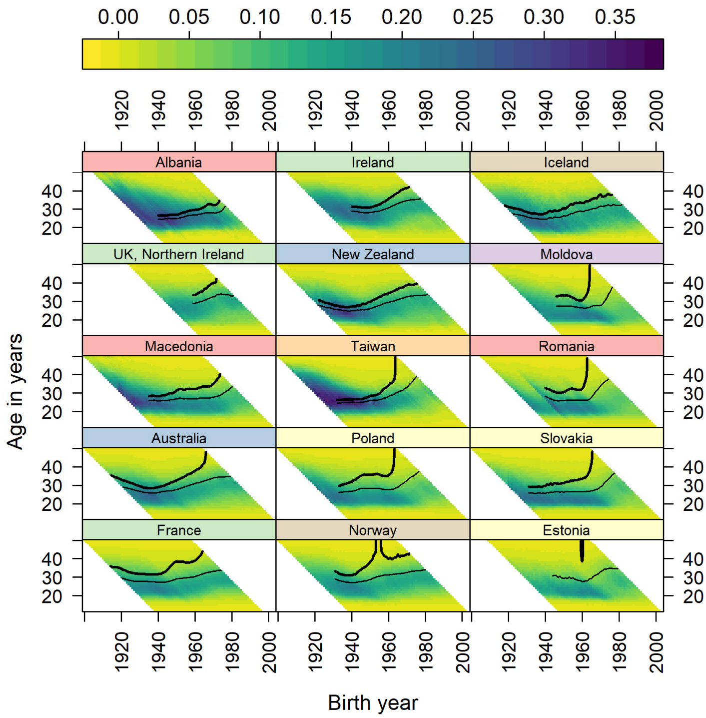
[8] An excel file containing the CPCFRs computed for the 1957–1958 birth cohort for each country is provided in the online appendix (see https://github.com/JonMinton/comparative_fertility).

Figure 3: Composite fertility lattice plot for 45 countries by geographic region



Notes: (a) Cohort and not period is indicated on x-axis. (b) The shades in the plots correspond to age-specific fertility rates (ASFRs), as indicated by the shaded scale bar on the top of the figure. (c) The thick solid contour line indicates cumulative pseudo cohort fertility rate (CPCFR) = 2.05 children per woman (replacement fertility), and the thin solid contour line indicates CPCFR = 1.50 children per woman; both of these CPCFRs are based on ASFRs for the earliest cohorts that are not shown as coloured tiles for all years and ages. (d) Countries are ranked in descending order by CPCFR computed for women from the 1957–1958 birth cohort (who were 49 years old in 2007, the last year for which data is available for all countries). (e) Countries are grouped into eight geographic macro-regions, as indicated by different colour-shaded tiles as follows:

(1) Southeastern Europe: Albania, Romania, Macedonia, Bosnia and Herzegovina, and Bulgaria;

(2) Western Europe: Ireland, UK-Northern Ireland, France, UK-England and Wales, UK-Scotland, Netherlands, Belgium, East Germany, Austria, Switzerland, and West Germany;

(3) Northern Europe: Iceland, Norway, Sweden, Finland, and Denmark;

(4) East and Southeast Asian countries: Taiwan, Republic of Korea, and Japan;

(5) Non-European English-speaking countries: New Zealand, Australia, United States, and Canada;

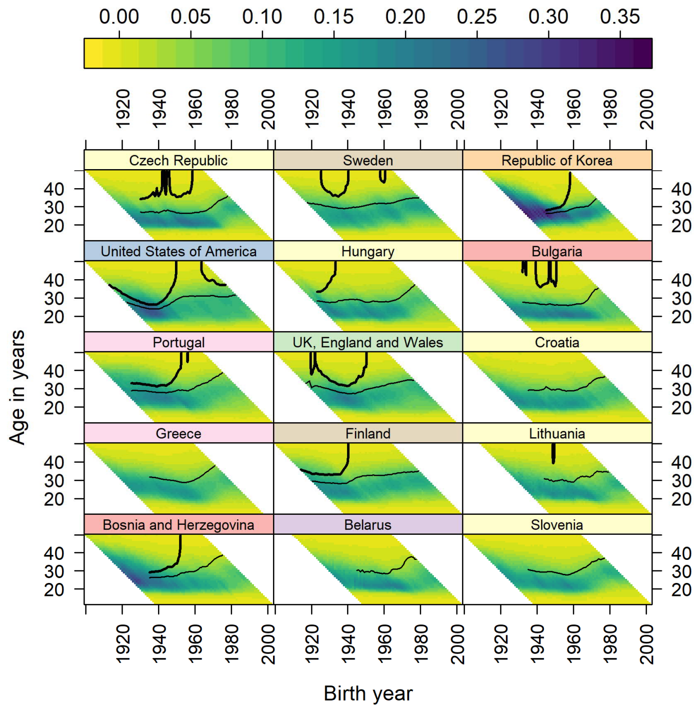
(6) Eastern Europe: Moldova, Belarus, Ukraine, and Russia;

(7) Central Europe: Slovakia, Poland, Czech Republic, Estonia, Hungary, Lithuania, Croatia, Slovenia, and Latvia;

(8) Southern Europe: Spain, Portugal, Greece, and Italy.

Source: Human Fertility Database (HFD) and Human Fertility Collection (HFC), own calculations.

Figure 3: (Continued)



Notes: (a) Cohort and not period is indicated on x-axis. (b) The shades in the plots correspond to age-specific fertility rates (ASFRs), as indicated by the shaded scale bar on the top of the figure. (c) The thick solid contour line indicates cumulative pseudo cohort fertility rate (CPCFR) = 2.05 children per woman (replacement fertility), and the thin solid contour line indicates CPCFR = 1.50 children per woman; both of these CPCFRs are based on ASFRs for the earliest cohorts that are not shown as coloured tiles for all years and ages. (d) Countries are ranked in descending order by CPCFR computed for women from the 1957–1958 birth cohort (who were 49 years old in 2007, the last year for which data is available for all countries). (e) Countries are grouped into eight geographic macro-regions, as indicated by different colour-shaded tiles as follows:

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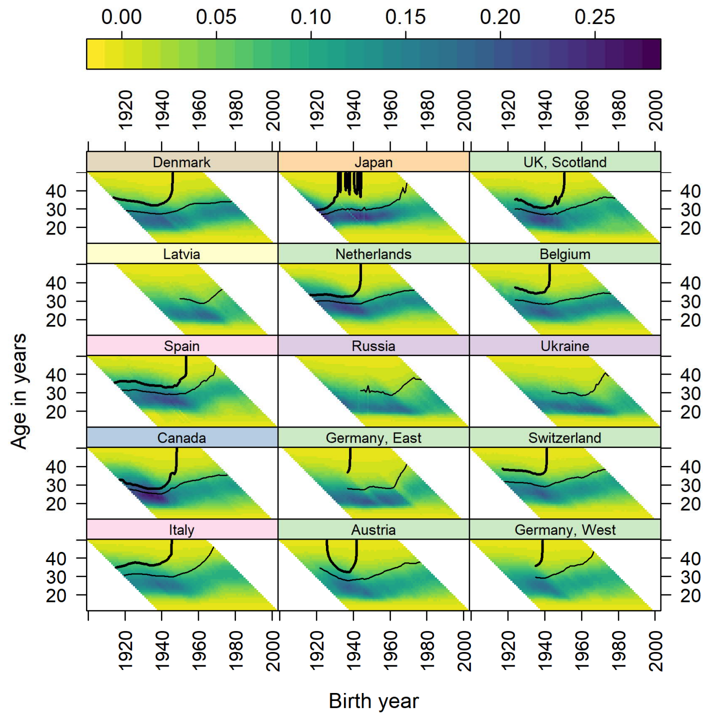
(6) Eastern Europe: Moldova, Belarus, Ukraine, and Russia;

(7) Central Europe: Slovakia, Poland, Czech Republic, Estonia, Hungary, Lithuania, Croatia, Slovenia, and Latvia;

(8) Southern Europe: Spain, Portugal, Greece, and Italy.

Source: Human Fertility Database (HFD) and Human Fertility Collection (HFC), own calculations.

Figure 3: (Continued)



Notes: (a) Cohort and not period is indicated on x-axis. (b) The shades in the plots correspond to age-specific fertility rates (ASFRs), as indicated by the shaded scale bar on the top of the figure. (c) The thick solid contour line indicates cumulative pseudo cohort fertility rate (CPCFR) = 2.05 children per woman (replacement fertility), and the thin solid contour line indicates CPCFR = 1.50 children per woman; both of these CPCFRs are based on ASFRs for the earliest cohorts that are not shown as coloured tiles for all years and ages. (d) Countries are ranked in descending order by CPCFR computed for women from the 1957–1958 birth cohort (who were 49 years old in 2007, the last year for which data is available for all countries). (e) Countries are grouped into eight geographic macro-regions, as indicated by different colour-shaded tiles as follows:

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(5) Non-European English-speaking countries: New Zealand, Australia, United States, and Canada;

(6) Eastern Europe: Moldova, Belarus, Ukraine, and Russia;

(7) Central Europe: Slovakia, Poland, Czech Republic, Estonia, Hungary, Lithuania, Croatia, Slovenia, and Latvia;

(8) Southern Europe: Spain, Portugal, Greece, and Italy.

Source: Human Fertility Database (HFD) and Human Fertility Collection (HFC), own calculations.

As this paper is largely methodologically focused, we have not explored the possible causes of this feature further but suggest it may be useful to investigate in more detail whether this is a genuine cohort effect or a data artefact.

By contrast, the cohort fertility level of 1.50 children per woman does not appear to decline further in Northern European countries, with Sweden gaining and losing replacement fertility levels for women born before 1940 and again around 1960 (resembling the cyclical pattern of total fertility rates described as ‘roller-coaster movement’ by Hoem and Hoem (1996)), with Norway standing out for losing but subsequently regaining replacement cohort fertility for women born after 1956 (see earlier discussion in section 3.2). Among non-European English-speaking countries, New Zealand stands out for presenting relatively stable cohort fertility levels.

At the lower end of the spectrum, we find Southern European countries, such as Spain and Italy, where replacement fertility levels where lost for women born around 1945 in Italy and 1954 in Spain. Both countries appear at increased risk of future cohorts not reaching 1.50 children per woman. East and Southeast Asian countries experienced a rapid industrialization that led to a sharp decline in total fertility rates during the second half of the 20th century, reaching levels close to one child per woman in recent years. Compared to Taiwan and the Republic of Korea (South Korea, hereafter), Japan witnessed an earlier onset of cohort fertility decline: for cohorts born between 1933 and 1944, we observe a series of vertical lines after around the age of 36, denoting that some cohorts lost and regained replacement fertility in rapid succession. By contrast, in South Korea and Taiwan replacement fertility was lost for women born in later years, around 1958 and 1964 respectively. Of the three populations, South Korea appears more likely to sustain fertility of at least 1.50 children per woman.

4. Conclusions

4.1 Summary and discussion of the main results

In this paper we describe a new refinement and adaptation of the Lexis surface optimised to fertility data. By using both colour/shade and contours to mark age-specific fertility rates, and the cumulative fertility milestones for different birth years they imply, respectively, we show how these two types of data are related and can be concisely represented in a single visualization. We present examples that introduce and comment on different features within specific countries to provide conceptual ‘stepping stones’ for developing familiarization with this novel visualization approach. We conclude with a visualization of fertility trends for 45 countries, based on hundreds of thousands of specific data points.

Previous studies using visualization techniques of the Lexis surface either focused on data from a single country (Calot et al. 1998), sub-national regions (Campbell and Robards 2014; Rau et al. 2018), or a more limited number of countries (Burkimsher 2017). Compared to previous research, our paper combines different tools of the Lexis surface in a novel way and explores a large number of countries, supporting a more fine-grained comparison of multiple pieces of information for the exploration of fertility trends over time and across geographic regions.

Our study shows that in many countries fertility rates have dramatically fallen over time to levels that are substantially below fertility replacement. For most countries, much of this shift has occurred starting from the 1960s. Once countries have fallen below a replacement fertility level, they tend to not return to it. These trends have been documented elsewhere (Burkimsher 2017; Calot et al. 1998; Rau et al. 2018). Contributing factors are changes in the socioeconomic and normative contexts, led for example by the introduction of modern contraception and the increase in both women's educational attainment and their labour force participation, along with changes in the political and institutional contexts, such as the collapse of the Socialist regime, the shifts in the labour market structures at both national and regional levels, and the availability of policies supporting work–family reconciliation (Balbo, Billari, and Mills 2013; Morgan and Taylor 2006; Rindfuss and Choe 2016).

Our study also shows that there is considerable variation around the general trend, both across and within geographic regions. For example, prior to the 1970s East and West Germany shared common trends in fertility decline and loss of replacement fertility for cohorts born before 1940. During the 1970s and 1980s, East Germany had a recovery in fertility while fertility continued to decline in West Germany, with a rapid convergence of fertility schedules after the collapse of the Berlin Wall. As reported in other studies (Frejka 2017; Sobotka, Skirbekk, and Philipov 2011), cohort fertility rates kept decreasing in East and West Germany and now appear to have stabilized below replacement level. Differences in fertility pathways between East and West Germany are largely attributed to disparities in socioeconomic conditions following the German reunification (Konietzka and Kreyenfeld 2002).

Another example is provided by East and Southeast Asian countries, which have witnessed exceptional falls in fertility following the rapid socioeconomic changes and expansion of education opportunities for women (Frejka, Jones, and Sardon 2010; Raymo et al. 2015). For these countries we observe diverging cohort fertility patterns, with Japan showing an earlier onset of cohort fertility decline compared to other countries in the region, and South Korea being the only country in the region to display sustained cohort fertility levels of at least 1.50 children per woman. Such intra-regional discrepancies may be attributed to different government interventions (Estévez-Abe and Naldini 2016;

Gauthier 2016), persisting inequalities in the gender division of labour and slow-changing normative contexts (Hertog and Kan 2019; McDonald 2009).

Our study also shows that only few countries that 'lose' replacement fertility end up to regain it. Clear exceptions are the United States and Norway, which display a certain degree of heterogeneity in their fertility pathways, reflecting contextual differences between geographic regions. Recovery patterns may be due to the influence of immigrant fertility in the United States (Choi 2014; Coleman 2006). In the case of Norway, sustained replacement fertility may also be explained by generous welfare provisions and widespread gender equality at the societal level (Kravdal 2016).

4.2 Main contributions and further research directions

The contributions of this paper are both substantive and methodological. The case studies have focused on two paired comparisons at the low and higher end of the fertility spectrum among developed countries. But perhaps the greatest potential value in this paper is in demonstrating how the visualization can be decoded and applied to understanding and comparing many other populations. Further methodological developments based on this approach are possible using an interactive app, which we have produced and hope to develop further.[9] The contour lines in our visualizations were based on CPCFRs calculated from period ASFRs (using data aggregated by Lexis square) rather than CCFRs calculated from cohorts directly (using data aggregated by Lexis parallelogram), and it would be useful to compare these period-based CPCFR estimates with real CCFRs. Because we use contour lines to represent one attribute over age and time and colour/shade to represent other attributes, our visualizations are effectively representations of four-dimensional data (age, time, and the two attributes ASFR and CPCFR); we consider this a powerful form of visualization but recognise that the complexity of such images can pose a limitation/challenge as well as opportunity, and it is possibly at the limits of the level of complexity of the information that can be effectively conveyed on screen or page. Further research to understand how easy or challenging users find information conveyed in this way is welcomed.

The associated online app facilitates the selection of specific countries and the comparison of associated attributes within the visualization, allowing interactive three-dimensional representations of the data surfaces to be created. The app also includes options to select different colour palettes, as well as to add, remove, and shift the fertility milestones represented with the contours. We hope that the enhancement of the Lexis surface we present in this paper and the associated app will facilitate the understanding

[9] See https://datascapes.shinyapps.io/cumulative_fertility_app/.

of fertility patterns within and across populations, as well as other forms of complex demographic data.

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