

Visualizing Compositional Data on the Lexis Surface*

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Background The Lexis surface plot is an established visualization tool in demography. Its present utility however is limited to the domain of 1-dimensional magnitudes like rates and counts. Visualizing multiple group proportions (shares of a whole / compositions) on a period-age grid is an unsolved problem.

Objective We seek to extend the Lexis surface plot to the domain of compositional data.

Methods We introduce, demonstrate, evaluate and compare four techniques for visualizing group compositions on a period-age grid. To demonstrate the techniques we use publicly available data on age-specific cause of death compositions in France from 1925 to 1999. We compare the visualizations for compliance with multiple desired criteria.

Results Compositional data can be visualized on the Lexis surface. The key feature of the classical Lexis surface plot – to show cohort-, period- and age patterns in the data – is retained in the domain of compositional data. The optimal choice of technique depends mainly on the number of groups in the compositional data.

Contribution We introduced techniques for visualizing compositional data on a period-age grid to the field of Demography. We demonstrated the novel techniques by performing an exploratory analysis of age-specific French cause of death patterns across the 20th century. We identified strength and weaknesses of the four proposed techniques.

*See <https://github.com/jschoeley/viscomplexis> for an online repository containing all the resources necessary to replicate this paper.

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1. Introduction

From the display of population numbers by shading map regions, the graphical representation of population dynamics on a grid of year-age-cohort parallels, and the widely recognized population pyramid to today's heatmaps of mortality surfaces: Demography has always had a close relationship with information visualization.¹ The visual display helps making sense of the data at hand which in demography, for the most part, are *counts, rates and proportions*. Visualisation methods that are currently used in demography present counts or rates. This paper is about *compositional data*, represented by proportions, i. e. shares of a whole. Examples for this data type are proportions within a population (e. g. age composition, distribution by occupation, region of residence or level of education), proportions of events (e. g. deaths by cause), proportions of durations (e. g. life expectancy by health status), and proportions within a total rate (e. g. death rate by cause of death).

While rates and counts provide a *single value* for each point on the Lexis surface a *vector of values* is needed in the case of compositional data. Classical solutions for the visualization of population dynamics, such as contour maps or a one-dimensional heatmap of continuous data on the Lexis surface, do not work for compositional data. On the other hand graphs specifically designed for compositional data like the ternary coordinates (Aitchison 1986:5 ff) or the biplot (Gabriel 1971; Aitchison 2002) do not address the basic demographic dimensions period, age and cohort and therefore are unsuited to show corresponding effects in a single display.

This paper aims to extend the visual repertoire of demography by introducing and discussing different techniques of graphing compositional data on the Lexis surface. Hereby we hope to facilitate the exploratory analysis of compositional data and the communication of research results in graphical form. To demonstrate the techniques we use publicly available data on age-specific death counts by cause of death in France from 1925 to 1999 (Vallin and Meslé 2014). Four visualizations are discussed in this paper. The first is the three-variable balance scheme or *ternary-balance-scheme*.² It is a technique to display three attributes in a single point. Each attribute is mapped to a primary colour and the mixture of three colours shows the composition of attributes in a population. The second visualization is the *qualitative-sequential-scheme*. In that scheme, a qualitative or categorical variable (e. g. cause of death) is represented by a colour and the quantitative variable (e. g. number of deaths due to that cause) is represented by sequences of lightness steps within each colour. The third visualization, the *agewise-area-graph*, is composed of stacked area charts drawn separately for every age group and assembled on a Lexis-like grid. The fourth is a collection of heatmaps portraying different subsets of the data. The resulting visualization is also known as trellis plot, lattice chart or panel chart. Tufte (1990) refers to it as *small-multiples*. This conventional techniques serves as a benchmark to compare our innovations against. Furthermore we propose a slight refinement to the small-multiple graph making it more suitable for the display of compositional data.

¹One of the first choropleth maps of population densities can be found in d'Angeville (1836). The year-age-cohort grid is commonly attributed to Lexis (1875) but for a full account of the inventors of the "Lexis"-diagram cp. Vandeschrick (2001). Population pyramids were first published in Walker (1874). In 1987 Vaupel, Gambill, and Yashin (1987) discussed the use of heatmaps in a demographic context.

²Ternary refers to a system with three states.

The four techniques showcased in this paper mark only a tiny spot in the space of possible visualizations concerning proportions structured by age and period. Typically the number of effective visualizations is much smaller than the number of possible visualizations (Munzner 2014) and therefore a strategy is needed in order to arrive at viable solutions. Our final picks are the result of multiple constraints on the design space: (1) We require the dimensions *time and age to constitute a grid*. This is to be in-line with the Lexis surface plot, an already established visualization tool in demography which highlights patterns along age-, period- and cohort time dimensions. Demographers have build expertise in the interpretation of Lexis surfaces and by extending these to the domain of compositional data we hope to transfer the expertise as well. (2) We require *techniques to be discussed in the literature and/or commonly used to display compositions*. Cartography, statistics and computer science are fields with a strong research agenda on visualization and we believe that demography should form ties with the existing body of knowledge in visualization research. Furthermore, visualizations are easier understood if the users are already familiar with the visual encoding. (3) The techniques have to *differ in their strengths and weaknesses*. While exploring the design space we did not come across a one-size-fits-all solution. Some visualizations work better with a small number of groups, some allow for larger numbers. Some will not work for users with impaired colour vision while some will work flawlessly in black and white print etc. We strive to select a collection of solutions which cover a wide range of use-cases. In order to do so we compare the different visualizations regarding the amount of displayed data, their geometrical preservation of the Lexis surface, their ability to communicate precise values as well as patterns along age, period and cohort, their space economy and their accessibility for users with impaired colour vision. Some evaluation criteria, like the amount of data encoded in the visualization, can be assessed precisely. Other questions, like the ability of the visualization to show patterns in the data, are ultimately a matter of subjective judgements. We back up our personal assessment of these subjective criteria by references to experiments done in graphical perception and by demonstration of the visualizations using real world data.

The paper consists of 9 sections. In section 2, we briefly present the Lexis surface, which represents the state-of-the-art of visualization of demographic data grouped by age, period (and cohort). The techniques presented in this paper are extensions of the Lexis surface to the domain of compositional data. Section 3 introduces colour terminology and the concepts of colour composition and colour spaces – matters which are referred to in the subsequent description of the visualizations, sections 4–7. Finally we compare the proposed visualization techniques with each other and assess the individual features according to our evaluation criteria.

2. The Lexis Surface

The *Lexis diagram* connects calendar time with age and cohort by the use of a two dimensional diagram with period on the ordinate (x) and age on the abscissa (y). By interconnecting the three essential time-scales of demography the Lexis diagram serves as an aid in working with population processes and is used to represent events (e. g. birth, death, migration) or occupied states (e. g. single, cohabiting, married, divorced) along the individual life course as well as on the population level. Ages are represented as horizontal parallels, single years as vertical parallels, and each birth cohort is represented by a 45° diagonal. Individuals or populations can be located and tracked on the Lexis diagram as they progresses through time and age (see figure ??). The tool is widely used by demographers and epidemiologists to study population and disease dynamics.³

The term *Lexis surface* has been introduced by Arthur and Vaupel (1984) to describe a collection of demographic rates given by discrete time and age. The term now extends to the visualization of population data (counts, rates) across time and age in the form of contour maps or heatmaps (for examples see e. g. Rau et al. 2008; Scherbov and Vianen 2002). *Contour-maps* indicate regions of equal value for a variable on the time-age plane by a contour line (isoline). Vaupel, Gambill, and Yashin (1987) trace the use of these graphs in Demography back to Kermack, McKendrick, and McKinlay (1934) and Delaporte (1941). *Heatmaps* express the value of a variable for every point on the time-age plane by the use of colour (e. g. light regions might indicate high values, dark regions in turn low values, see figure ??). Gambill and Vaupel facilitated the use of these graphs in demography by developing a plotting software running on personal computers: LEXIS (Gambill and Vaupel 1985) was able to produce *shaded contour maps*, a combination of heatmaps with contour lines, from demographic data. *Thousands of Data at a Glance: Shaded Contour Maps of Demographic Surfaces* showcases the software and the Lexis surface plots across a variety of demographic applications and datasets. Recent refinements to the Lexis surface plot were done by Riffe, who plotted fertility rates structured by period, age *and* cohort resulting in a surface made of triangles instead of rectangles. Riffe also proposed and demonstrated the use of equilateral coordinates to avoid visual distortion along the cohort lines. The programs are written in R and published on Riffes personal webpage (Riffe 2014).

This paper applies the term “Lexis surface” to the visual display of compositional population data given on an period-age-grid.

³Implementations are available for the statistical software R: The packages Epi (Carstensen et al. 2014) and Biograph (Willekens 2013) both include functions to display data on a time-age-cohort grid.

3. About Colour

This section introduces colour terminology and the concepts of colour composition, colour spaces and colour schemes. These concepts are used later on in the description of the visualization techniques.

Why use colour to display compositional data on the Lexis surface?

1. Colour can be used to visualize the value of a third variable on a plane. This is done in the classical Lexis surface plot (e. g. mortality rates across age and period).
2. Colour is a visual attribute that is both inherently *compositional* (a colour can be decomposed into shares of primary colours) as well as *multidimensional* (a colour can be light or dark, pale or strong...).










Two of the visualizations presented in this paper – the ternary-balance-scheme and the qualitative-sequential-scheme – make use of these features. The ternary-balance-scheme employs the compositional nature of mixed colours to display compositional data. The qualitative-sequential scheme maps different dimensions of colour to different data dimensions. In order to understand these techniques some understanding of colour terminology, colour mixing and colour spaces is needed. We will start off with a familiar setting...

Children learn how to produce a wide range of colours by mixing blue, red and yellow paints. The resulting colour depends on the ratio between these *primary colours*: Mix yellow with blue to get green, red with blue to get purple and three parts of yellow with one part of red to produce orange. If you want to change the *lightness* of the colour, add either black (darkens) or white (brightens) paints into the mix. Digital printers use the same principle but use a slightly different set of primary colours, namely cyan, yellow and magenta. A colour computer screen uses yet a different set of primaries: its pixels are composed of red, green and blue subpixels. The relative light-output of these subpixels (*luminance*) determines the colour of the pixel. Furthermore, when mixing red, blue and green light sources by equal parts the resulting colour will be white (*additive colour mixing*) whereas mixing yellow, blue and red paints on a canvas will result in a dark brown (*subtractive colour mixing*).

We can see that there is much more to colour mixing than the few rules taught in basic art classes. The choice of primary colours in the end is arbitrary (Ware 2013:100 f). There is nothing special about blue, red and yellow. Additionally, when working with coloured light sources you will observe different mixtures compared to working with coloured, reflective surfaces.

A *Colour space* is a model of colour. It provides a rigorous way to work with colour by parametrizing and quantifying it. Some colour spaces refer to our experiences of how colour is mixed in everyday situations (RGB for light sources, CYMK for printing), others are more abstract. The common ground is the prediction of a colour dependent on a set of input parameters. In case of the RGB colour space – used to display colours on a television or computer screen – the input parameters are the amounts of red, green and blue light emitted, commonly encoded with values from 0-255. Here the mixed colour is expressed as a composition of primary colours.

It is also possible to build a colour space on parameters relating to human colour perception. When asked to describe a colour it would be a remarkable feat for a person to express it in terms of the proportions of primary colours. Instead we tend to say that a colour is dark or

bright (*lightness*:   ), very pale or very pure (*chroma*:   ) and tending to green, blue, red... (*hue*:   , see Fairchild 2005 chapter 4 for colour terminology).

The *CIE-Lch* (Lightness, chroma, hue) colour space expresses a colour in terms of these three perceptual parameters. Geometrically it can be thought of as a cylinder filled with different colours. The hue of the colours changes around the circumference, the chroma changes along the radius, with neon colours far out and perfect grey at the centre. The lightness changes along the height of the cylinder with black at the bottom and white at the top. This colour space is not parametrized in terms of primary colours. Therefore colour mixtures are not to be seen from the parameters. However, choosing multiple points in the CIE-Lch colour space, colour mixtures can be constructed by simple geometric operations (see Appendix A).

Apart from an intuitive interpretation of the parameters CIE-Lch has other features making it feasible for use in visualization. Its parameters are not correlated with each other, e. g. changing the lightness will not change the hue or chroma of a colour. Furthermore the function that maps the parameters to the predicted colours is derived from experiments in colour perception. If we specify a range of colours with equal lightness the average observer will perceive the colours as very similar in lightness. On the other hand, the magnitude of perceived differences between two colours will roughly correspond to the magnitude of the quantitative differences in the colour parameters. The usage of such a *uniform* colour space is crucial when translating quantitative data into truthful visual representations (Ware 2013:105, Fairchild 2005:185).

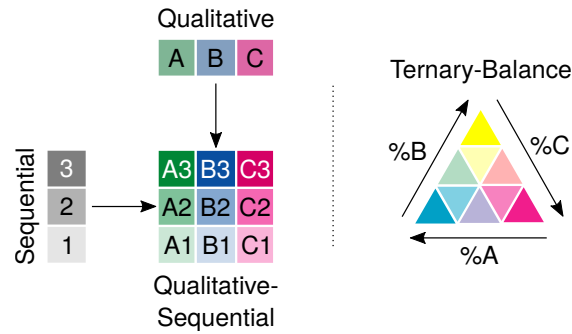


Figure 1: Colour schemes used in this paper (derived from an illustration in Brewer 1994b).

All these technical foundations ultimately translate into different colour schemes which map data to colour. Cartographers have a long tradition of using colour for data representation and it comes to no surprise that elaborated systematics of colour schemes emerged in this field. A field-agnostic systematic is proposed by Brewer (1994b) (see also Brewer 1994a). She differentiates four basic types of colour schemes: *Binary*, *qualitative*, *sequential* and *divergent*. These types relate to the scale level of the variables which are to be encoded by colour. Binary and qualitative schemes use different hues to encode a variable which is on a nominal scale level (such as sex or cause of death). A sequential scheme uses ordered shades of the same hue to encode a variable which is on an ordinal, interval or ratio scale level (such as personal well-being, mortality rate, weight). Divergent colour schemes are not part of this paper. Figure 1 illustrates the colour schemes used in this paper.

Brewer also proposes multidimensional colour schemes such as the *qualitative-sequential* and the *ternary-balance-scheme*. Both these schemes are used in this paper to display compositional data on the Lexis surface. Their usage is discussed in the respective sections (see 4 and 5).

4. Ternary-Balance-Scheme

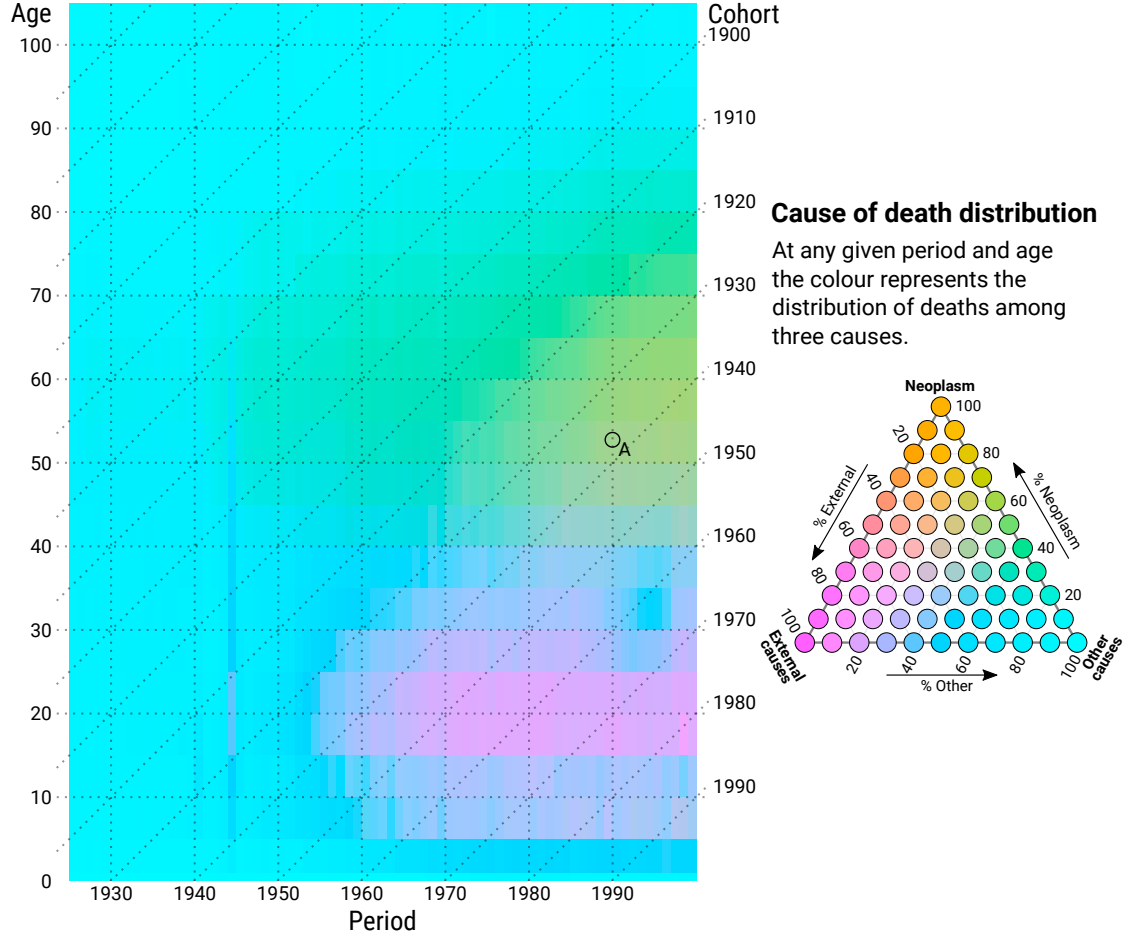


Figure 2: Ternary-balance-scheme: Proportion of people dying from a given cause by time and age (France, total population; Data: Vallin and Meslé 2014).

The idea behind the *ternary-balance-scheme* is to represent the proportions among three groups with a mixture of three basic colours. The basic colours have different hues, each corresponding to a category of a ternary variable. They are mixed in proportions equal to the proportions between the three groups in the data. The resulting colour mixture is unique for every possible combination of proportions among three groups. The colour-coded ternary diagram can be used as a legend for this type of graph.

While using colour mixtures to encode multiple data dimensions in a single point has been proposed several times (cp. Trumbo 1981 and Eyton 1984 for bivariate data on geographical maps; Ware 1988 for cluster identification in high-dimensional spaces) such techniques are not in widespread use. A possible reason is a difficulty in interpretation and the usage of legends which are not easily memorized, criticisms which have been put forward by Wainer and Francolini 1980. We seek to alleviate these issues by providing straightforward interpretation

guidelines along with a legend that builds upon an already established tool in compositional data analysis – the ternary diagram.

The dominant group at any point in time as well as the overall distribution of the group proportions can be understood keeping two principles in mind:

1. The higher the proportion of a group the more the mixed colour resembles the base colour for that group, and
2. the more equal the proportions among the groups are the more the mixed colour tends to grey.

The ternary diagram serves as a legend colour coding all possible proportions among three groups in a structured way so that each point on the Lexis surface can be decoded into its precise shares if needed.

Figure 2 shows the ternary-balance-scheme applied to agewise French cause-of-death data across the 20th century. All deaths are divided by cause into the categories *Neoplasms* (ICD-9 codes 140–239), *External* (injury, suicide, accident; ICD-9 codes 800–999 and E–V) and *Other* (all remaining causes of death). Magenta was chosen as a primary colour for external causes of death, orange means death by neoplasm and cyan encodes all remaining deaths.

EXAMPLE: Consider point *A* in figure 2. The proportion of deaths caused by neoplasm is given in the legend by the position on a horizontal line through the point with the colour of *A*; likewise the proportion of deaths caused by external causes is indicated by the position on a / line and the share of all other causes is indicated by the position on a \ line. The mixture of magenta, orange and cyan at point *A* indicates that more than half of the deaths (about 60 %) are caused by neoplasms, 10 % by external causes and the remainder (30 %) by all other causes of death.

The mid-century marks a turning point. Before 1950 external causes of death and cancer were only sporadically found on the death certificates the prominent exception being World War II. Period effects are visible in 1940 (German occupation of France) and – much stronger – in 1944 (Allied landing in Normandy). In both years the war contributed to external causes of deaths, visible in the age range 5–60. After 1950 two major trends in the distribution of death causes emerge: 1. Adolescent deaths rapidly become dominated by external mortality. The “accident hump” (Heligman and Pollard 1980) as a juvenile pattern of mortality comes into existence. 2. Deaths due to cancer gradually become more common in the age range 40–80, dominating the ages 50–70 since the 1980. The onset-age of “other” causes of death as most prominent increases in a linear fashion.

The ternary-balance-scheme allows us to identify major patterns in the change of group-composition over time and age. We are able to identify group-mixtures and group-monopoles. Period-, age- and cohort-effects look much like they would on a 1-dimensional heatmap of all-cause mortality rates on a Lexis surface: Local outliers are visible by a sharp shift in hue – vertical for period effects, horizontal for age effects and on a 45° slope for cohort effects. Slower transitions are visible through smooth colour gradients. The obvious drawback of the ternary-balance-scheme is the limitation to three distinct groups. Also, using colour as a quantifier, small changes in the values are hard to detect and the very nature of the graph makes it unsuitable to use for people with impaired colour-vision (though this limitation could be somewhat relaxed by changing the lightness between the hues).

5. Qualitative-Sequential-Scheme

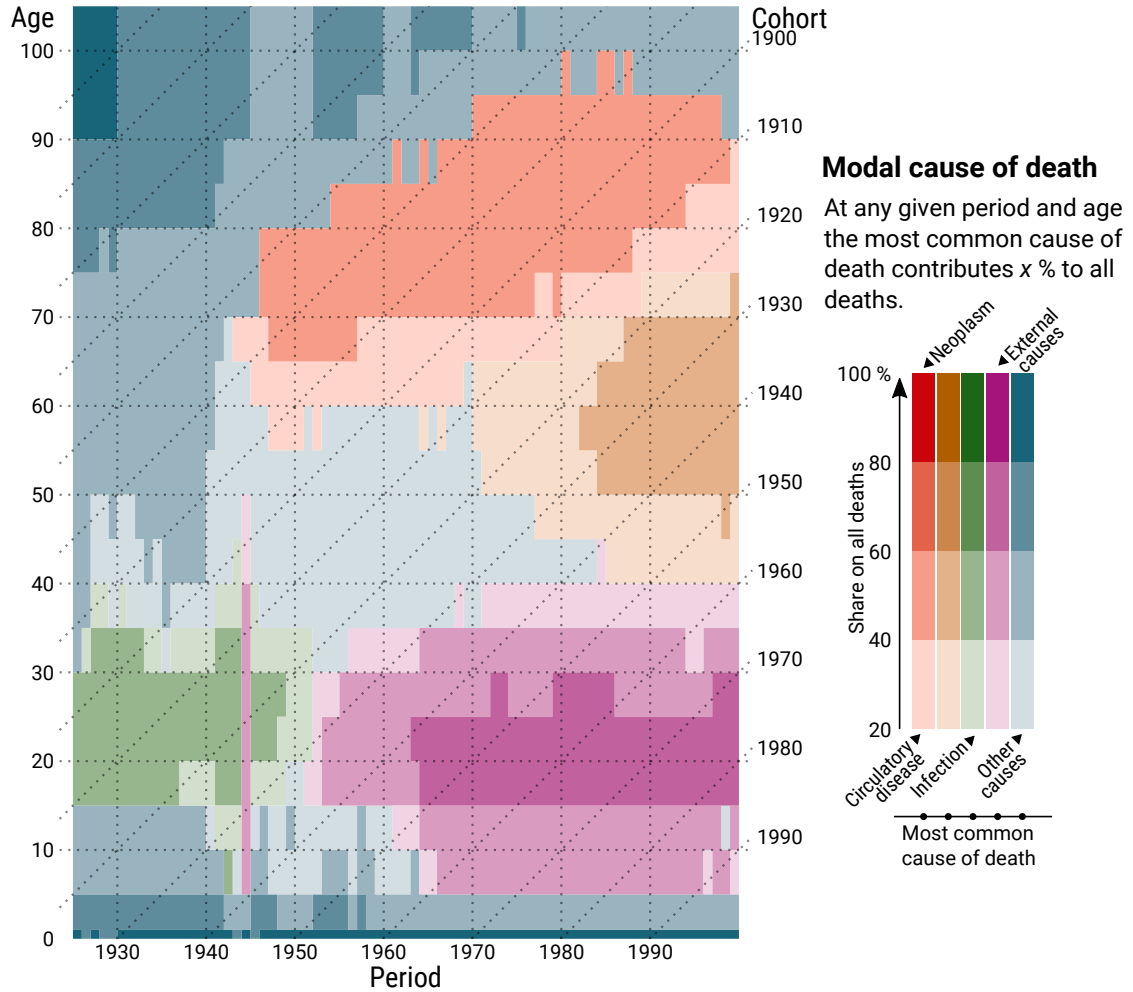


Figure 3: Qualitative-sequential-scheme: The most common cause of death and its share on all deaths by time and age (France, total population; Data: Vallin and Meslé 2014).

Another form of multivariate colour scheme is the qualitative-sequential-scheme (Brewer 1994b). The idea is to use a qualitative palette of different hues to signify group-membership and to construct a sequential palette for every group by varying the lightness of the group-colour and thereby encoding group-specific quantities.

See figure 3 for an example using the same dataset as in figure 2 but with two additional categories, namely death due to infectious diseases (ICD-9 codes 001–139) and diseases of the circulatory systems (ICD-9 codes 390–459). Each group is given its own sequential colour scheme. The values given by the colours on the Lexis surface represent the *share of deaths from the most prominent cause of death at year t and age x* .

This approach allows to account for more than three groups in the graphic. The downside is an incomplete picture for every point on the Lexis surface. Only information on the group with the highest share is given. However, in a dataset with a lot of change between the group proportions interesting patterns emerge.

EXAMPLE: Consider the horizontal line at age group 60–64 in figure 3. Before 1945, we see a grey colour: “other” causes of death are dominant. This dominance declines about 1940 (a lighter grey) until, in 1945, circulatory diseases become the main cause of death with a share on all deaths of 20–40 %. Around 1970, the main cause of death shifts from circulatory diseases to neoplasms (the hue shifts from red to yellow). The dominance of neoplasms over other causes of death for 60–64 old males and females increases with time (the yellow hue gets darker and more saturated).

One new insight this visualization yields is the importance of infectious diseases as a cause of death for people aged 15–40 prior to 1950. In these years and ages 20–60 % of the deceased die from infection making this the most likely cause of death in adolescence and middle-age. This pattern abruptly changes after 1950 with external causes of death taking the top spot. Similar to figure 2 we see the accident hump peaking around ages 15–30. Looking at data for five groups we get a more differentiated picture at the death causes in higher ages. Old age mortality is dominated by failures of the circulatory system. The onset of circulatory conditions as the main cause of death moves into higher ages in a linear fashion starting at around age 60 in the 1940s to age 75 in the 1990. For people with an extraordinarily long lifespan the death causes are more diverse with “other” causes of death in the lead.

While confined to visualize shares only for the most prominent group at any given point on the Lexis surface the qualitative-sequential scheme still reproduces a lot of the information gained from figure 2 while adding new insights. In cases where the changes of the group composition in the data are more subtle (no shift in order of group shares) this visualization would lose most of its explanatory power.

6. Agewise-Area-Graph

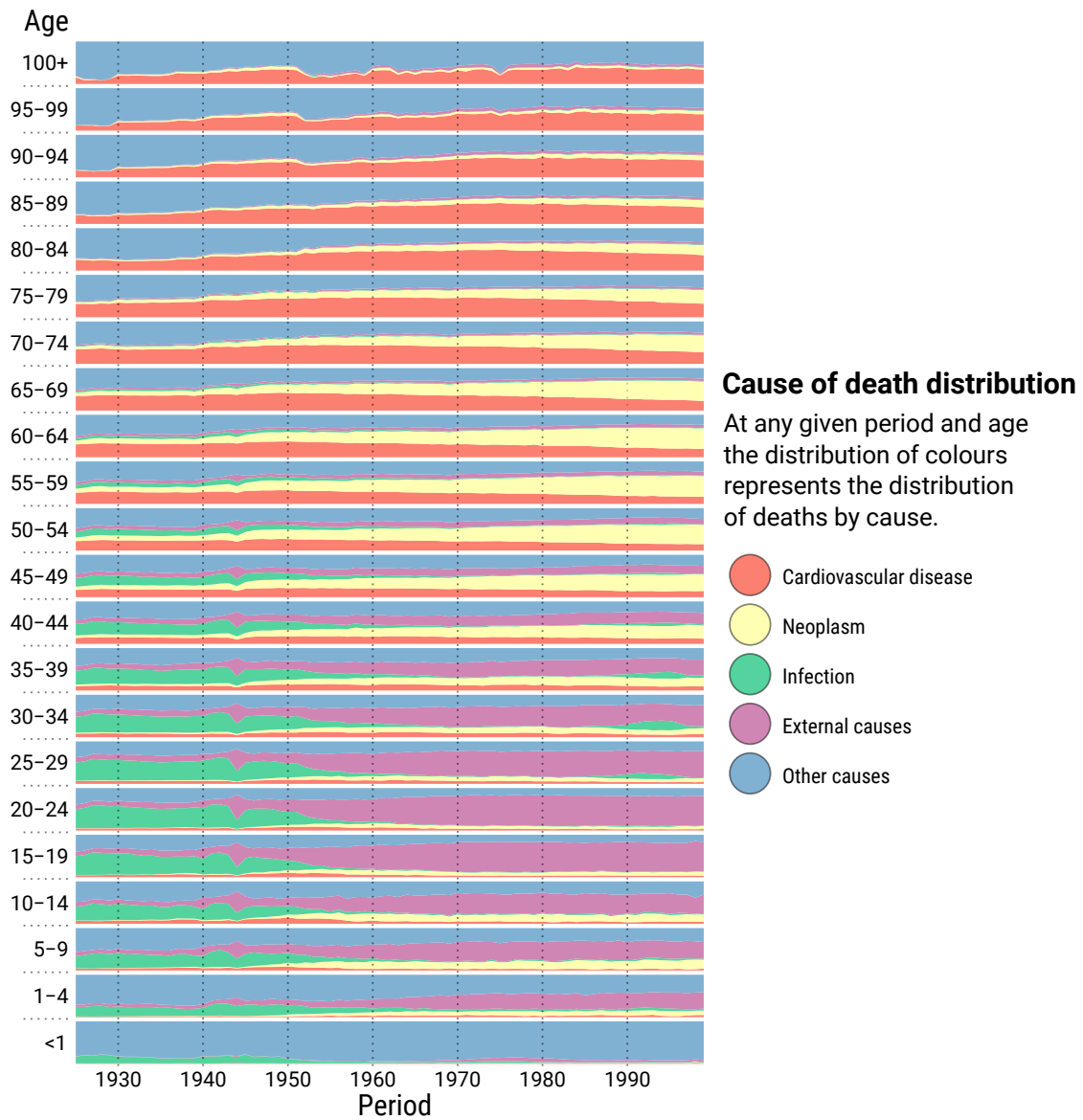


Figure 4: Agewise-area-graph: Proportion of people dying from a given cause by time and age (France, total population; Data: Vallin and Meslé 2014).

The *stacked-area-chart* can be thought of as the continuous version of the stacked-bar-chart. Coloured areas indicate group shares which change along the x-axis. As the value of each individual group share is indicated by *length* as opposed to colour this technique is better suited to detect slight changes in group composition over time than the previous approaches. Cleveland

and McGill (1984) show that people are able to decode visual information more precise into their numerical equivalents when it is represented by length and not by colour.

For the *agewise*-area-graph we produce the stacked area chart separately for every age-group and assemble all of them on a Lexis-like grid. See figure 4 for the resulting plot. Unlike the ternary-balance-scheme we are able to distinguish more than three groups and unlike the qualitative-sequential-scheme the full information about the group distribution is retained.

EXAMPLE: One feature of the data which was hidden by the former graphical representations is the unusual surge of fatal infectious diseases in ages 25–40 around the mid 1990s. Looking at the exact cause of death data we see that HIV related deaths are a cause for this local phenomena. Other new insights from this graph are the relative importance of cancer as a cause for childhood mortality and the high share of “other”-cause-mortality for people aged 90+.

The graph does not exhibit a true Lexis surface. The period-age grid is *non-continuous* as it is composed of multiple stacked-area-charts each having a separate y-axis ranging from 0 (0 %) to 1 (100 %). This breaks the plot area into separate sections making the perception of global patterns harder because the global graphical patterns (the shape of the equal-colour areas across period and age) are interrupted along the age-scale. Also, while area charts (or continuous divided bar charts to stay within the vocabulary of Cleveland) are better than colour encodings for exact table-look up operations they are far from optimal for exact judgements about singular data values (Cleveland 1994).

The focus of the *agewise*-area-graph lies on the detection of small local phenomena and developments within single age groups while still giving an overview of the global patterns for multiple groups on a single period-age-grid.

7. Small-Multiples

*Small-multiples*⁴ are tables of graphs (Wilkinson 2005:319). Each graph represents a category of a categorical variable or an intersection of categories of multiple categorical variables. Small-multiples are a fairly common technique and have already been discussed by Vaupel, Gambill, and Yashin (1987) as a way of plotting mortality/fertility-surfaces for multiple sub-populations. We discuss this technique in the context of compositional data and propose a small adjustment facilitating cross-panel comparisons.

In figure 5 we see multiple heatmaps of cause-specific shares of deaths in France across period and age. The graphs are augmented by border lines at calendar years and ages for which a given cause of death is dominant.

EXAMPLE: Consider the lower left panel. It shows the proportion of deaths caused by infectious diseases by age and calendar time. Point A indicates that in 1930 infectious diseases are the dominant cause of death for persons aged 30-34. Between 40–50 % of all deaths are caused by infection. Infectious diseases stop being the dominant cause of death around 1950. Injuries start to become dominant for persons between 1 and 40 in 1950. This leading position strengthens over time.

Unlike the other visualization techniques described in this paper the small-multiples allow us to display the death-shares for each of the 10 most prominent categories of ICD-9. This power of course comes with a price: The data is not contained in a single graphic. This means that the eye (and the mind) not only have to move between and compare different regions of a graph but make connections between different graphics in order to *see the whole picture*. To make these comparisons easier we mark every period-age combination in which the corresponding cause of death has the highest share among all deaths with a black outline. This way it immediately becomes obvious where specific causes of death dominate over all other causes.

Yet again the new visualization technique shines a different light on our data and allows for additional insights. We can see that ill-defined causes of death are common in the old ages. Prior to World War II an ill-defined cause of death is the norm for people dying at ages 80 or higher. Perinatal conditions followed by congenital anomalies are the main causes of death for infants through most of the 20th century in France. Prior to 1950 deaths of infants and young children are, for the most part, attributed to respiratory diseases. For adults fatal respiratory diseases move into higher and higher ages, reaching a plateau around 1970 and being nearly exclusively an old-age phenomena from there on. A period-age effect can be identified in the realm of digestive diseases. The latter half of the 20th century sees a rise in the share of people aged 35-65 dying from conditions of the digestive system. However, note that the data is binned into 10 % categories simplifying a correct look-up of the colour values but forbidding the exact judgement of small differences.

⁴We use the terminology of Tufte (1990). Closely related concepts are *facets* (Wilkinson 2005) or *trellis-plots* (Becker, Cleveland, and Shyu 1996).

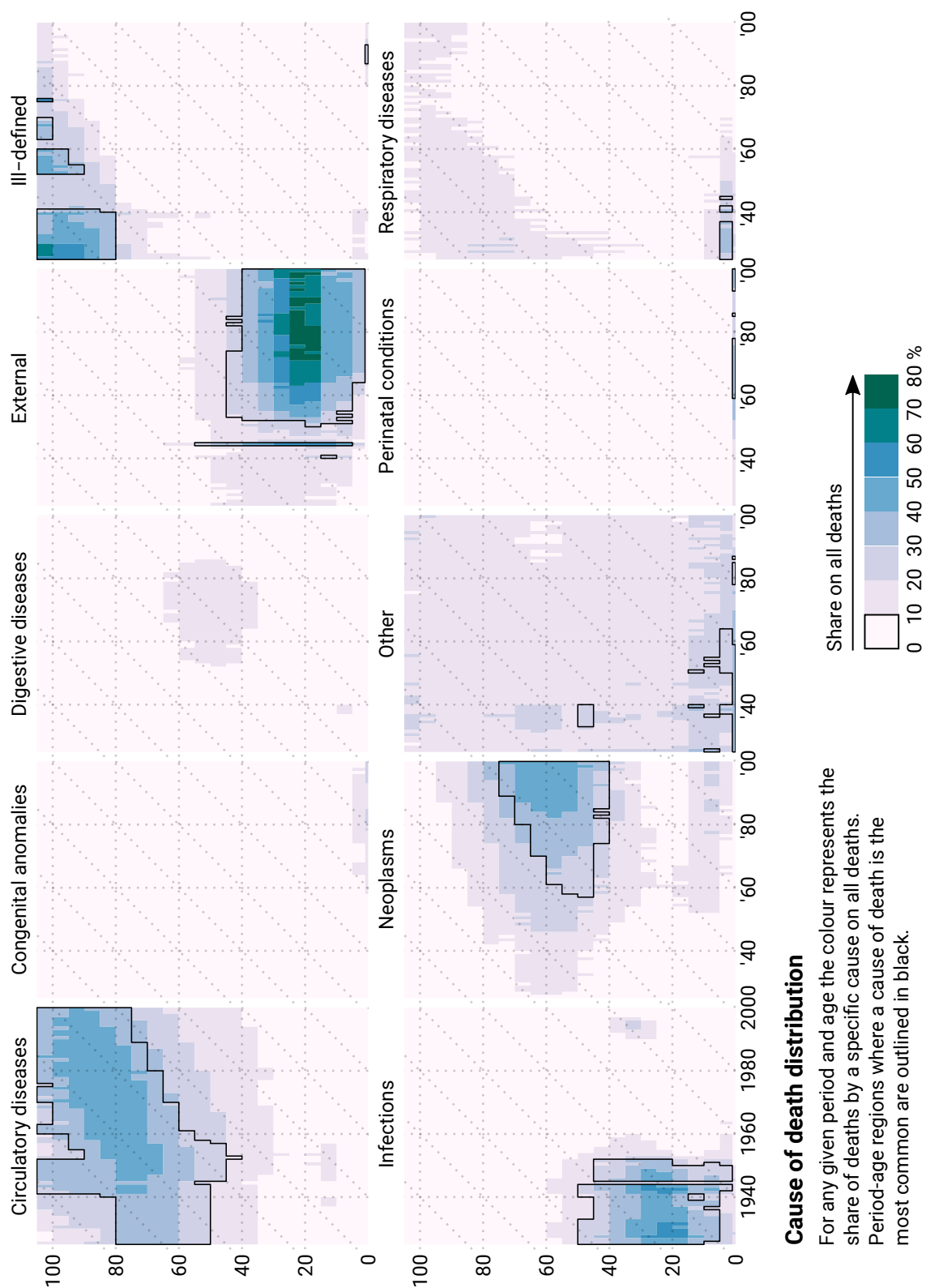


Figure 5: Small-multiples: Proportion of people dying from a given cause by time and age (France, total population; Data: Vallin and Meslé 2014).

8. Comparative Evaluation

Completeness is the question whether or not all values of the compositional data (e. g. all individual group shares for each period-age) are displayed in the visualization or if only a subset of the group data (e. g. the share of the largest group for each period-age) is visualized. Visualising the complete dataset is desirable during exploratory data analysis.

If the visualization must contain complete information about every group in the composition the qualitative-sequential-scheme is not an option as only the group with the highest share at a given period-age is considered. The remaining three techniques always are sufficient in showing the complete distribution of group shares.

Continuity requires that the continuous Lexis grid is preserved in the visualization, e. g. the period and age axes constitute a rectangular grid unbroken by whitespace or period-wise/age-wise scales.

The Lexis surface approximates a continuous grid of age by time. The age-wise-area-graph breaks this essential feature by fracturing the surface into separate graphs by age. As each age group uses its own y-axis the surface becomes discontinuous along the age dimension. From a perceptual standpoint this hinders the identification of period- and cohort-effects as these would form continuous patterns along the age-(time)-axes but cannot do so in the age-wise-area-graph. The remaining visualization techniques use a continuous Lexis surface.

The Category limit is the maximum number of categories/groups in the compositional data that can be displayed at once. It is precise if limited by technical reasons or approximate if limited by perceptual reasons.

The ternary-balance-scheme – as the name suggests – only allows for the display of proportions between three groups. If a visualization of ratios between a large number of categories is required the small-multiples approach is best suited as a virtually unlimited number of group shares can be displayed at once.

The maximum number of groups allowed for in the qualitative-sequential-scheme and the age-wise-area-graphs is not restricted by technical- but by perceptual limits. The qualitative-sequential scheme uses lightness steps within different hues to show different group shares. Therefore the number of groups which can sensibly be displayed at once is limited by the number of distinct hues one can perceive. Different lightness steps based on these hues should not be confused across hues. Ware (2013):123 lists four unique hues: red, green, blue and yellow. These hues are generally perceived as pure/unmixed colours which do not resemble each other. Yellow is problematic as a base hue for a lightness sequence as it is already a very light colour (ibid.:127). Orange, still being perceived distinct from red and yellow, is the better choice here. Adding black one can construct five sufficiently different lightness sequences. Some few additional hues, like purple, might also work.

The age-wise-area-graphs contain a lot of information in a small vertical space. The more groups one adds the more crowded this vertical space gets and information retrieval will be more difficult.

Pattern perception describes the “visual decoding of physical information” (Cleveland 1994:223 f).

Within the context of our paper this translates into the degree at which period-, age-, and cohort-effects in the composition of the data are revealed by the visualisation.

The ternary-balance-scheme, the qualitative-sequential-scheme and the small-multiples are all heatmaps and differ only in the applied colour scheme. As such they are particularly suited to show patterns in the data such as period-, age- and cohort-effects or local outliers (as demonstrated for 1-dimensional data in Vaupel, Gambill, and Yashin 1987). For the small-multiples approach this merit only applies to each group on its own as the visualization is spread out across multiple panels – the inter-group patterns are not directly visually encoded and have to be inferred from a comparison between multiple panels. The marking of modal values eases this task.

The case for agewise-area-graphs is more complicated. Due to the discontinuities across the age dimension the global pattern-perception from these graphs is comparatively worse. However, changes over time within single age groups, even small ones, can be seen very well using this approach.⁵

Table look-up “[is the] visual decoding of scale information [...]” (Cleveland 1994:223 f). It takes place when attempting to extract the exact numbers from a displayed data point. Some visual primitives (such as xy-position, height, size etc.) – and therefore some visualizations – make this task easier than others. Being able to easily decode the data values from a visualization is desirable as it allows for numerical judgements (e. g. “A is 2.5 times higher than B”).

None of the discussed techniques allows for a very efficient table look-up operation (the quick and accurate retrieval of the underlying data values). Colour, as used by three out of the four techniques as encoding for the group shares, is generally regarded as the weakest graphical element in terms of table look-up (Cleveland and McGill 1984:536). The judgement of areas and lengths as used in the agewise-area-graphs fares better, but the matter is complicated by the use of *stacked-relative-area-graphs*. Here the value can only be directly read from the y-axis for the bottom group/area. For all other areas differences between two points on the y-axis equal the data value.

The Footprint is often of concern when publishing results. Some visualizations gain their descriptive power by occupying a large area.

The footprint of all techniques but the small-multiples is equal to a conventional heatmap across the same period-age-range. The small-multiples technique, depending on the number of groups, might be much larger up to the point of filling the whole page.

⁵Given that no steep slopes occur or else there will be problems correctly judging the difference between the upper and lower boundary of an area – the value (Cleveland 1994:227 ff).

	Ternary- balance- scheme	Qualitative- sequential- scheme	Agewise- area- graph	Small- multiples
Completeness	yes	no	yes	yes
Continuity	yes	yes	no	yes
Category limit	3	$\approx 5-6$	≈ 8	unlimited
Pattern perception	good	good	limited	good
Table look-up	limited	limited	limited	limited
Footprint	small	small	small	large

Table 1: Evaluation of different visualization techniques for compositional data on the Lexis surface.

9. Conclusion

We demonstrated four different visualization techniques for showing cause of death distributions across period and age, extending the conventional period-age heatmap of 1-dimensional continuous data (e.g. surfaces of mortality rates) to multidimensional compositional data. We applied multivariate colour schemes originating from cartography to the Lexis surface (ternary-balance-scheme, qualitative-sequential-scheme), introduced agewise area graphs as a means of visualizing compositional change over time within ages and improved upon the well known small-multiple technique in the context of compositional data. Each of these techniques serves the cause of making sense of compositional data across time and age, while at the same time these techniques complement each other by having different strong points.

The ternary-balance-scheme is the best candidate for visualizing the *shares of three groups*. Using principles of colour composition it produces smooth rainbow-like surfaces immediately indicating time-, age-, and cohort patterns in the data. The qualitative-sequential-scheme *extends beyond three groups* and shows the shares of the most dominant groups on a surface. The agewise-area-graphs use the power of the line to point out *slight, age-specific changes* in group composition over time. Plotting a separate heatmap for each group is a well-tried technique and still the most practical way to plot compositions for a *large number of groups*. Adding a contour line to each panel, indicating the regions of dominance of one group over the others, reduces the need for cross-panel comparisons and therefore adapts this proven technique further to the display of compositional data.

What share of a population features attribute i at period t and age x ? The proposed visualizations are tools helping to answer this question. We demonstrated the techniques using data on causes of death. Other possible applications include time-age surfaces of population shares by labour-market status (unemployed and seeking job, unemployed and not seeking job, employed), distributions of labour force over industries (agricultural, industry, service) or partnership status (single, in relationship and living alone, in relationship and cohabiting, married). The visualizations can also help interpreting the output from estimated models. The Heligman and Pollard model of overall mortality by age (Heligman and Pollard 1980) for example is written as the sum of childhood-, accident- and senescent mortality by age. The relative magnitudes of these components can be clearly visualized using the ternary-balance-scheme, producing graphics of quasi cause-specific-mortality from all cause mortality data.

Good visualizations can be thought of as a visual model of the data at hand, able to identify relationships between variables. They go hand in hand with mathematical models of the data as both can be checked against the other. We hope to have contributed useful techniques for revealing information about compositions across time and age.

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A. Construction of the Ternary-Balance-Scheme

There are multiple ways to construct the *Ternary-balance-scheme*. Deriving the scheme from a perceptual colour-space ensures that differences in the numeric data are mapped to perceptually equivalent differences in the colour representation. The perceived difference between any two hues should correspond to the difference between the underlying data values. Additionally a constant lightness of the colour-mixes is desirable as colour-lightness usually is assigned to the magnitude of a continuous variable (Brewer 1994a), but we are dealing with compositional data which always sums up to unity. The *CIE-Lch* colour-space suits these needs as it is perceptually balanced and allows for the truly⁶ independent specification of lightness (L), hue (h) and chroma (c) of a colour.

The geometry of *CIE-Lch* can be thought of as a cylinder with different hues along the circumference, decreasing chroma along the radius towards the centre and increasing lightness along the vertical axis. Figure A.1a shows a “slice” of this cylinder with a fixed lightness level. We will use this slice to construct the ternary-balance scheme for our graphic: In a first step the three groups in the data are assigned to *equidistant* hues along the circumference of the circle. These are the base colours for each category. Next, vectors originating from the centre and pointing towards the base colours are constructed. The length of each vector is given by the share of the corresponding group on the total. This share is then mapped to the available chroma value range (in our example $[0, 140]$, other upper limits are possible) with $c = 0$ corresponding to a share of 0 % and the upper limit of c corresponding to 100 %. Finally the group specific vectors are added and the resulting vector returns the hue and chroma of the colour-mixture used to represent the distribution of the three groups. The possible colour-mixes form a triangular subset of the original *CIE-Lch* slice and therefore can be conveniently labelled with a ternary scale which allows for numerical interpretation of each mixed-colour (see figure A.1).

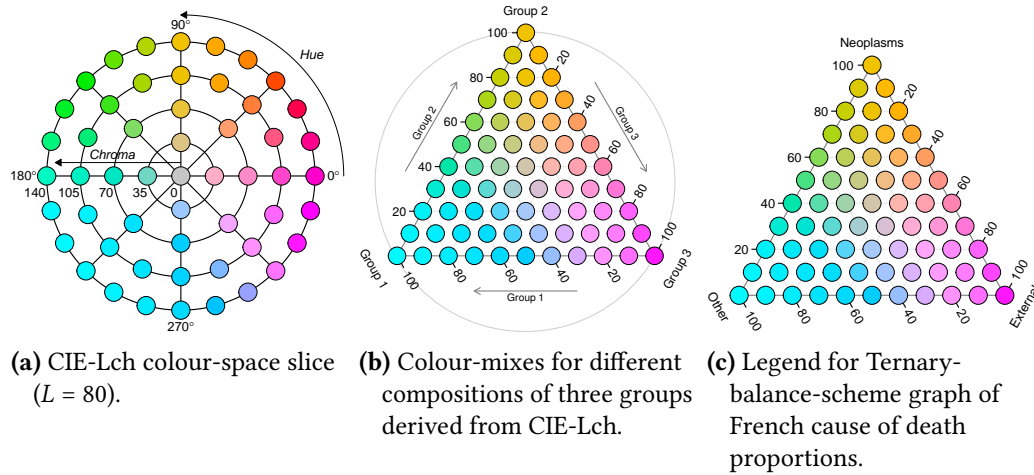


Figure A.1: Construction of the Ternary-balance-scheme.

⁶Unlike the widely used HSV/HLS colour-spaces which confound the perceptual dimensions. Using these colour-spaces an increase in saturation also changes the perceived lightning of the colour (Brewer 1999).