

Calendar-based graphics for visualizing people's daily schedules

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Abstract

Calendars are broadly used in society to display temporal information, and events. This paper describes a new R package with functionality to organize and display temporal data, collected on sub-daily resolution, into a calendar layout. The function `frame_calendar` uses linear algebra on the date variable to restructure data into a format lending itself to calendar layouts. The user can apply the grammar of graphics to create plots inside each calendar cell, and thus the displays synchronize neatly with `ggplot2` graphics. The motivating application is studying pedestrian behavior in Melbourne, Australia, based on counts which are captured at hourly intervals by sensors scattered around the city. Faceting by the usual features such as day and month, was insufficient to examine the behavior. Making displays on a monthly calendar format helps to understand pedestrian patterns relative to events such as work days, weekends, holidays, and special events. The layout algorithm has several format options and variations. It is implemented in the R package `sugrrants`.

Keywords: data visualization, statistical graphics, time series, grammar of graphics, R

1 Introduction

We develop a method for organizing and visualizing temporal data, collected at sub-daily intervals, into a calendar layout. The calendar format is created using linear algebra, giving a restructuring of the data, that can then be piped into grammar of graphics definitions of plots, as used in **ggplot2** (Wickham et al. 2018). The data restructuring approach is consistent with the tidy data principles available in the **tidyverse** (Wickham 2017) suite. The methods are implemented in a new package called **sugrrants** (Wang et al. 2018) .

The purpose of the calendar-based visualization is to provide insights into people’s daily schedules relative to events such as work days, weekends, holidays, and special events. This work was originally motivated by studying foot traffic in the city of Melbourne, Australia (City of Melbourne 2017). There have been 43 sensors installed that count pedestrians every hour across the downtown area (Figure 1). The dataset can shed light on people’s daily rhythms, and assist the city administration and local businesses with event planning and operational management. A routine examination of the data would involve constructing conventional time series plots to catch a glimpse of temporal patterns. The faceted plots in Figure 2, give an overall picture of the foot traffic at 3 different sensors over 2016. Further faceting by day of the week (Figure 3) provides a better glimpse of the daily and sub-daily pedestrian patterns.

However, the conventional displays of time series data obscure patterns relative to special events (such as public holidays and recurring cultural/sport events), which may appear more fascinating to viewers.

The work is inspired by Wickham et al. (2012), which uses linear algebra to display spatio-temporal data as glyphs on maps. It is also related to recent work by Hafen (2018) which provides methods in the **geofacet** package to arrange data plots into a grid, while preserving the geographical position. Both of these show data in a spatial context.

In contrast, calendar-based graphics unpack the temporal variable, at different resolutions, to digest multiple seasonalities, and special events. There is some existing work in this area. For example, Van Wijk & Van Selow (1999) developed a calendar view of the heatmap to represent the number of employees in the work place over a year, where colors indicate different clusters derived from the days. It contrasts week days and weekends,

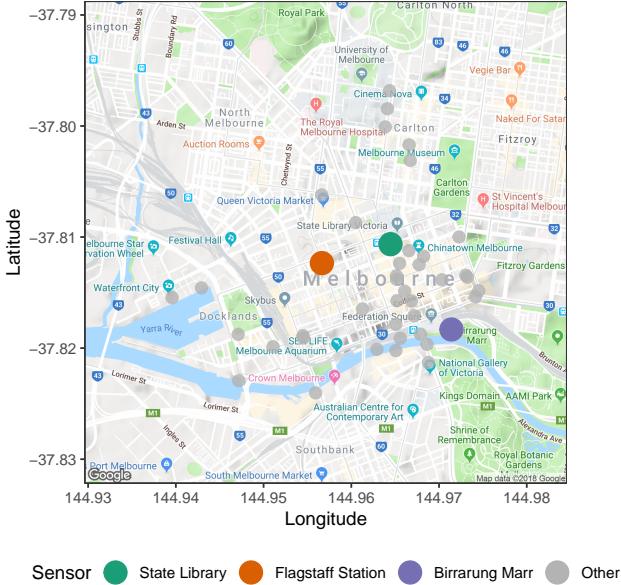


Figure 1: Map of the Melbourne city area with dots indicating sensor locations. 3 sensors have been highlighted to give a closer look at in the paper.

highlights public holidays, and presents other known seasonal variation such as school vacations, all of which have influence over the turn-outs in the office. The calendar-based heatmap was implemented in two R packages: **ggTimeSeries** (Kothari & Ather 2016) and **ggcal** (Jacobs 2017). However, these techniques are limited to color-encoding graphics and are unable to use time scales smaller than a day. Time of day, which serves as one of the most important aspects in explaining substantial variations arising from the pedestrian sensor data, will be neglected through daily aggregation. Additionally, if simply using colored blocks rather than curves, it may become perceptually difficult to estimate the shape positions and changes, although using curves comes with the cost of more display capacity (Cleveland & McGill 1984, Lam et al. 2007).

We propose a new algorithm to go beyond the calendar-based heatmap. The approach is developed with three conditions in mind: (1) to display time-of-day variation in addition to longer temporal components such as day-of-week and day-of-year; (2) to incorporate line graphs and other types of glyphs into the graphical toolkit for the calendar layout; (3) to enable overlaying plots consisting of multiple time series. The proposed algorithm has been implemented in the **frame_calendar** function in the **sugrrants** package using R.

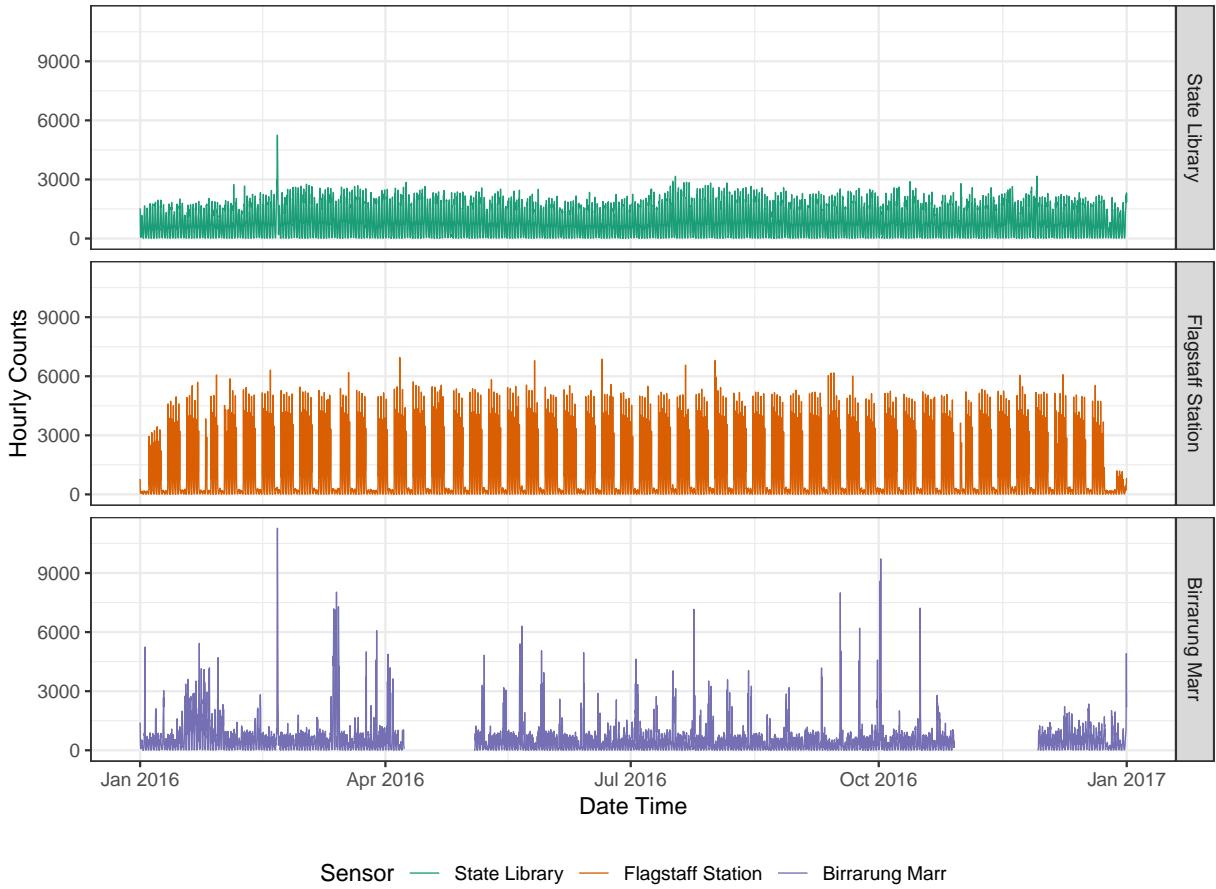


Figure 2: Time series plots showing the number of pedestrians in 2016 measured at 3 different sensors in the city of Melbourne. Colored by the sensors, small multiples of lines show that the foot traffic varies from one sensor to another in terms of both time and number. The weekly patterns look distinctive across these 3 sensors. There is an eye-catching spike which occurred at the State Library, caused by the annual White Night event on 20th of February.

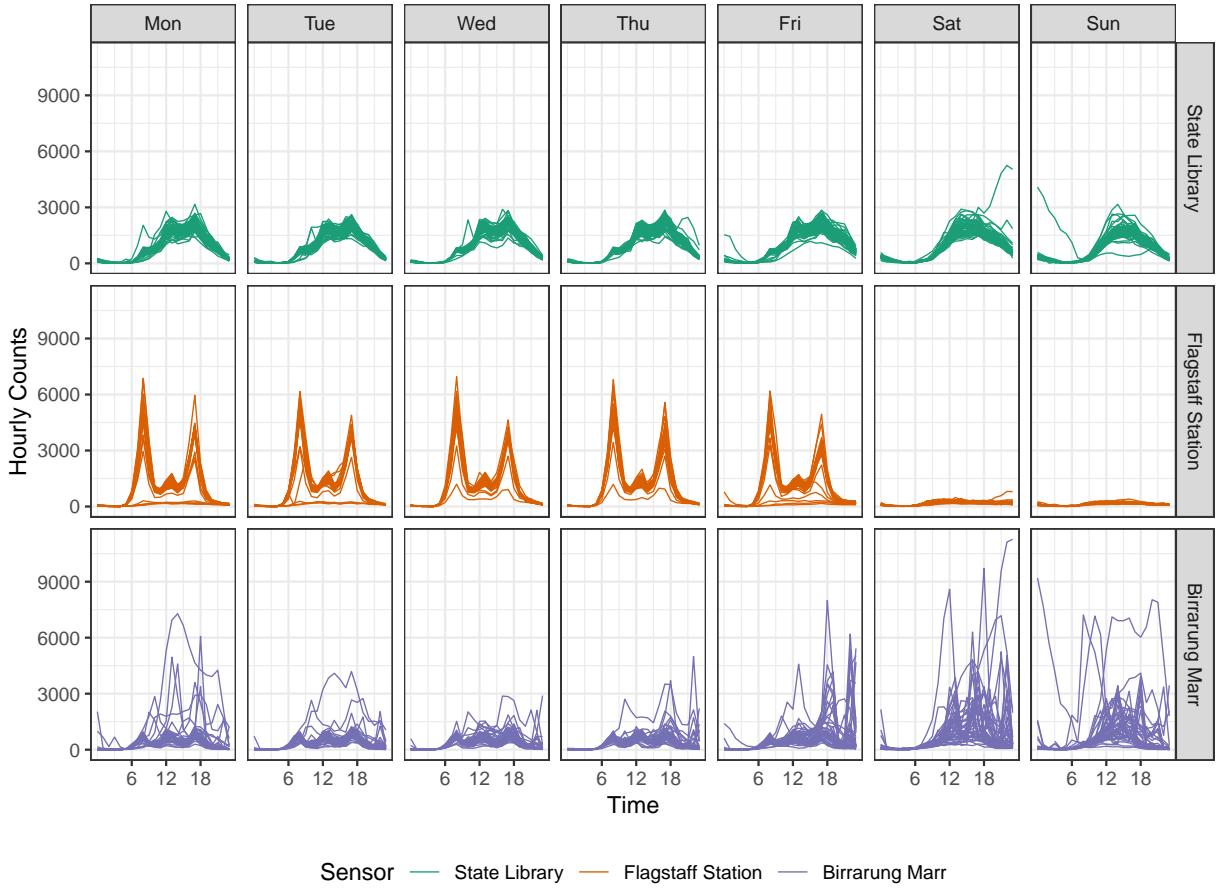


Figure 3: Hourly pedestrian counts for 2016 faceted by sensors and days of the week using lines. It features at least two types of seasons—time of day and day of week—across all the sensors. The White Night effect on increasing pedestrian counts can be seen on Saturday in February at the State Library.

The remainder of the paper is organized as follows. Section 2 demonstrates the construction of the calendar layout in depth. Section 2.2 lists and describes the options that come with the `frame_calendar` function. Section 2.3 presents some variations of its usage. Graphical analyses of sub-daily people’s activities are illustrated with a case study in Section 3. Section 4 discusses the limitations of calendar displays and possible new directions.

2 Creating a calendar display

2.1 Data transformation

Figure 4 shows the line glyphs framed in the monthly calendar over the year 2016. This is achieved by the `frame_calendar` function, which computes the coordinates on the calendar for the input data variables. These can then be plotted using the usual `ggplot2` package (Wickham et al. 2018) functions. All of the grammar of graphics (Wilkinson 2005, Wickham 2009) can be applied.

The algorithm for constructing a calendar plot uses linear algebra, similar to that used in the glyph map displays for spatio-temporal data (Wickham et al. 2012). To make a year long calendar requires cells for days, embedded in blocks corresponding to months, organized into a grid layout for a year. Each month can be captured with 35 (5×7) cells, where the top left is Monday of week 1, and the bottom right is Sunday of week 5 by default. These cells provide a micro canvas on which to plot the data. The first day of the month could be any of Monday–Sunday, which is determined by the year of the calendar. Months are of different lengths, ranging from 28 to 31 days, and each month could extend over six weeks but the convention in these months is to wrap the last few days up to the top row of the block. The notation for creating these cells is as follows:

- $k = 1, \dots, 7$ is the day of the week that is the first day of the month.
- $d = 28, 29, 30$ or 31 representing the number of days in any month.
- (i, j) is the grid position where $1 \leq i \leq 5$ is week within the month, $1 \leq j \leq 7$, is day of the week.
- $g = k, \dots, (k + d)$ indexes the day in the month, inside the 35 possible cells.

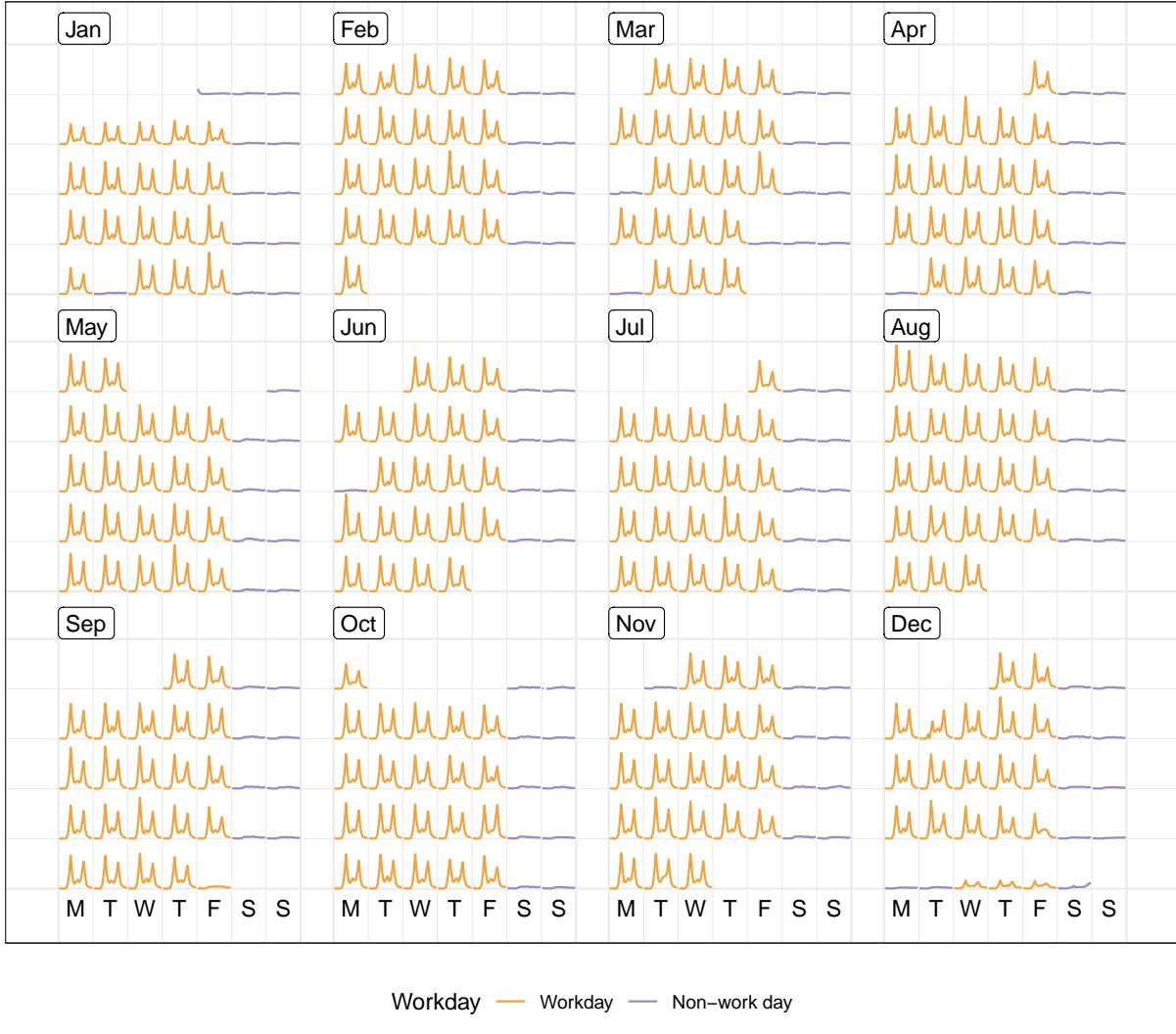


Figure 4: The calendar-based display of hourly foot traffic at Flagstaff Station using line glyphs. The arrangement of the data into a 3×4 monthly grid represents all the traffic in 2016. The disparities between week day and weekend along with public holiday are immediately apparent.

				$k=5, g=5$ $i=1, j=5$	$g=k+1$ $i=1, j=6$	$g=k+2$ $i=1, j=7$
$g=k+3$ $i=2, j=1$	$g=k+4$ $i=2, j=2$	$g=k+5$ $i=2, j=3$	$g=k+6$ $i=2, j=4$	$g=k+7$ $i=2, j=5$	$g=k+8$ $i=2, j=6$	$g=k+9$ $i=2, j=7$
$g=k+10$ $i=3, j=1$	$g=k+11$ $i=3, j=2$	$g=k+12$ $i=3, j=3$	$g=k+13$ $i=3, j=4$	$g=k+14$ $i=3, j=5$	$g=k+15$ $i=3, j=6$	$g=k+16$ $i=3, j=7$
$g=k+17$ $i=4, j=1$	$g=k+18$ $i=4, j=2$	$g=k+19$ $i=4, j=3$	$g=k+20$ $i=4, j=4$	$g=k+21$ $i=4, j=5$	$g=k+22$ $i=4, j=6$	$g=k+23$ $i=4, j=7$
$g=k+24$ $i=5, j=1$	$g=k+25$ $i=5, j=2$	$g=k+26$ $i=5, j=3$	$g=k+27$ $i=5, j=4$	$g=k+d$ $i=5, j=7$

Figure 5: Illustration of the indexing layout for cells in a month, where k is day of the week, g is day of the month, (i, j) indicates grid position.

The grid position for any day in the month is given by

$$\begin{aligned} i &= \lceil (g \bmod 35) / 7 \rceil, \\ j &= g \bmod 7. \end{aligned} \tag{1}$$

Figure 5 illustrates this (i, j) layout for a month where $k = 5$.

To create the layout for a full year, (m, n) denotes the position of the month arranged in the plot, where $1 \leq m \leq M$ and $1 \leq n \leq N$. Between each month requires some small amount of white space, denoted by b . Figure 6 illustrates this layout where $M = 3$ and $N = 4$.

Each cell forms a canvas on which to draw the data. Initialize the canvas to have limits $[0, 1]$ both horizontally and vertically. For the pedestrian sensor data, within each cell, hour is plotted horizontally and count is plotted vertically. Each variable is scaled to have values in $[0, 1]$, using the minimum and maximum of all the data values to be displayed, assuming fixed scales. Let h be the scaled hour, and c the scaled count.

Then the final points for making the calendar line plots of the pedestrian sensor data

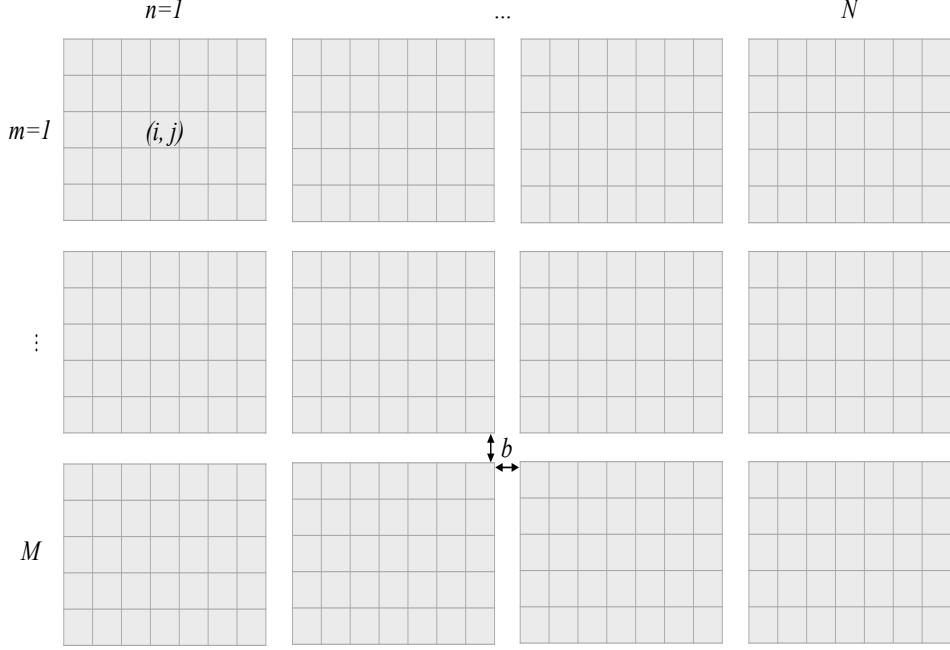


Figure 6: Illustration of the indexing layout for months of one year, where M and N indicate number of rows and columns, b is a space parameter separating cells.

is given by:

$$\begin{aligned} x &= j + (n - 1) \times 7 + (n - 1) \times b + h, \\ y &= i - (m - 1) \times 5 - (m - 1) \times b + c. \end{aligned} \tag{2}$$

Note that for the vertical direction, the top left is the starting point of the grid (in Figure 5) which is why subtraction is performed. Within each cell, the starting position is the bottom left.

In order to make calendar-based graphics more accessible and informative, reference lines dividing each cell and block as well as labels indicating week day and month are also computed before plot construction.

Regarding the monthly calendar, the major reference lines separate every month panel and the minor ones separate every cell, represented by the thick and thin lines in Figure 4, respectively. The major reference lines are placed surrounding every month block: for each m , the vertical lines are determined by $\min(x)$ and $\max(x)$; for each n , the horizontal lines are given by $\min(y)$ and $\max(y)$. The minor reference lines are only placed on the

left side of every cell: for each i , the vertical division is $\min(x)$; for each j , the horizontal is $\min(y)$.

The month labels located on the top left using $(\min(x), \max(y))$ for every (m, n) . The week day texts are uniformly positioned on the bottom of the whole canvas, that is $\min(y)$, with the central position of a cell $x/2$ for each j .

2.2 Options

The algorithm has several optional parameters that modify the layout, direction of display, scales, plot size and switching to polar coordinates. These are accessible to the user by the inputs to the function `frame_calendar`:

```
frame_calendar(  
  data, x, y, date, calendar = "monthly", dir = "h",  
  sunday = FALSE, nrow = NULL, ncol = NULL, polar = FALSE,  
  scale = "fixed", width = 0.95, height = 0.95, margin = NULL  
)
```

It is assumed that the `data` is in tidy format (Wickham 2014), and `x`, `y` are the variables that will be mapped to the horizontal and vertical axes in each cell. For example, the `x` is the time of the day, and `y` is the count (Figure 4). The `date` argument specifies the date variable used to construct the calendar layout.

The algorithm handles displaying a single month or several years. The arguments `nrow` and `ncol` specify the layout of multiple months. For some time frames, some arrangements may be more beneficial than others. For example, to display data for three years, setting `nrow = 3` and `ncol = 12` would show each year on a single row.

2.2.1 Layouts

The monthly calendar is the default, but two other formats, weekly and daily, are available with the `calendar` argument. The daily calendar arranges days along a row, one row per month. The weekly calendar stacks weeks of the year vertically, one row for each week, and one column for each day. The reader can scan down all the Mondays of the year, for

example. The daily layout puts more emphasis on day of the month. The weekly calendar is appropriate if most of the variation can be characterized by days of the week. On the other hand, the daily calendar should be used when there is a yearly effect but not a weekly effect in the data (for example weather data). When both effects are present, the monthly calendar would be a better choice. Temporal patterns motivate which variant should be employed.

2.2.2 Polar transformation

When `polar = TRUE`, a polar transformation is carried out on the data. The computation is similar to the one described in Wickham et al. (2012). Figure 7 shows star plots embedded in the monthly calendar layout, which is equivalent to Figure 4 placed in polar coordinates.

2.2.3 Scales

By default, global scaling is done for values in each plot, with the global minimum and maximum used to fit values into each cell. If the emphasis is comparing trend rather than magnitude, it is useful to scale locally. For temporal data this would harness the temporal components. The choices include: free scale within each cell (`free`), cells derived from the same day of the week (`free_wday`), or cells from the same day of the month (`free_mday`). The scaling allows for the comparisons of absolute or relative values, and the emphasis of different temporal variations.

With local scaling, the overall variation gives way to the individual shape. Figure 8 shows the same data as Figure 4 scaled locally using `scale = "free"`. The daily trends are magnified.

The `free_wday` scales each week day together. It can be useful to comparing trends across week days, allowing relative patterns for weekends versus week days to be examined. Similarly, the `free_mday` uses free scaling for any day within a given month.

2.2.4 Orientation

By default, grids are laid out horizontally. This can be transposed by setting the `dir` parameter to "v", in which case i and j are swapped in the Equation 1. This can be useful

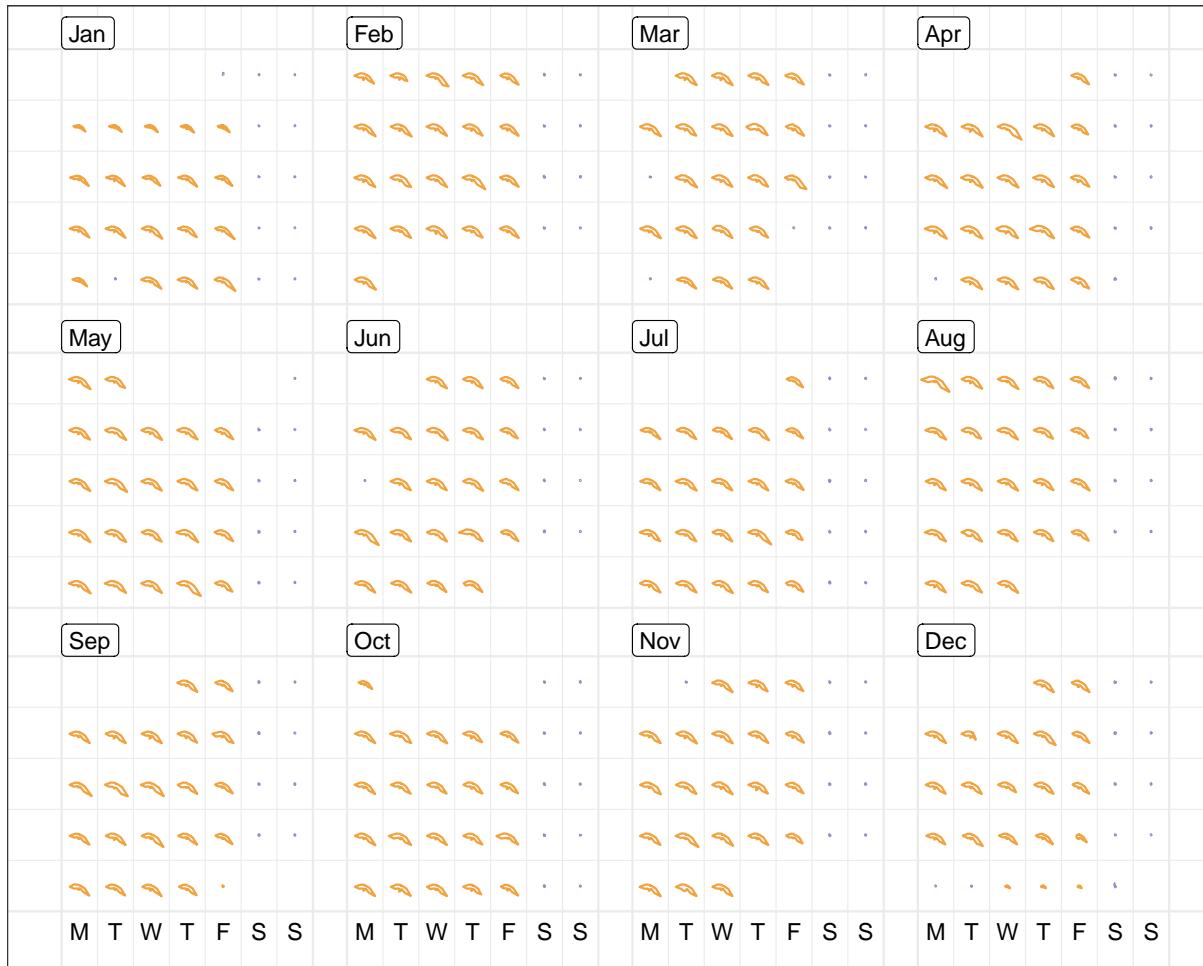


Figure 7: Figure 4 in circular layout, which is referred to as star plots. The daily periodicity on work days are clearly visible.

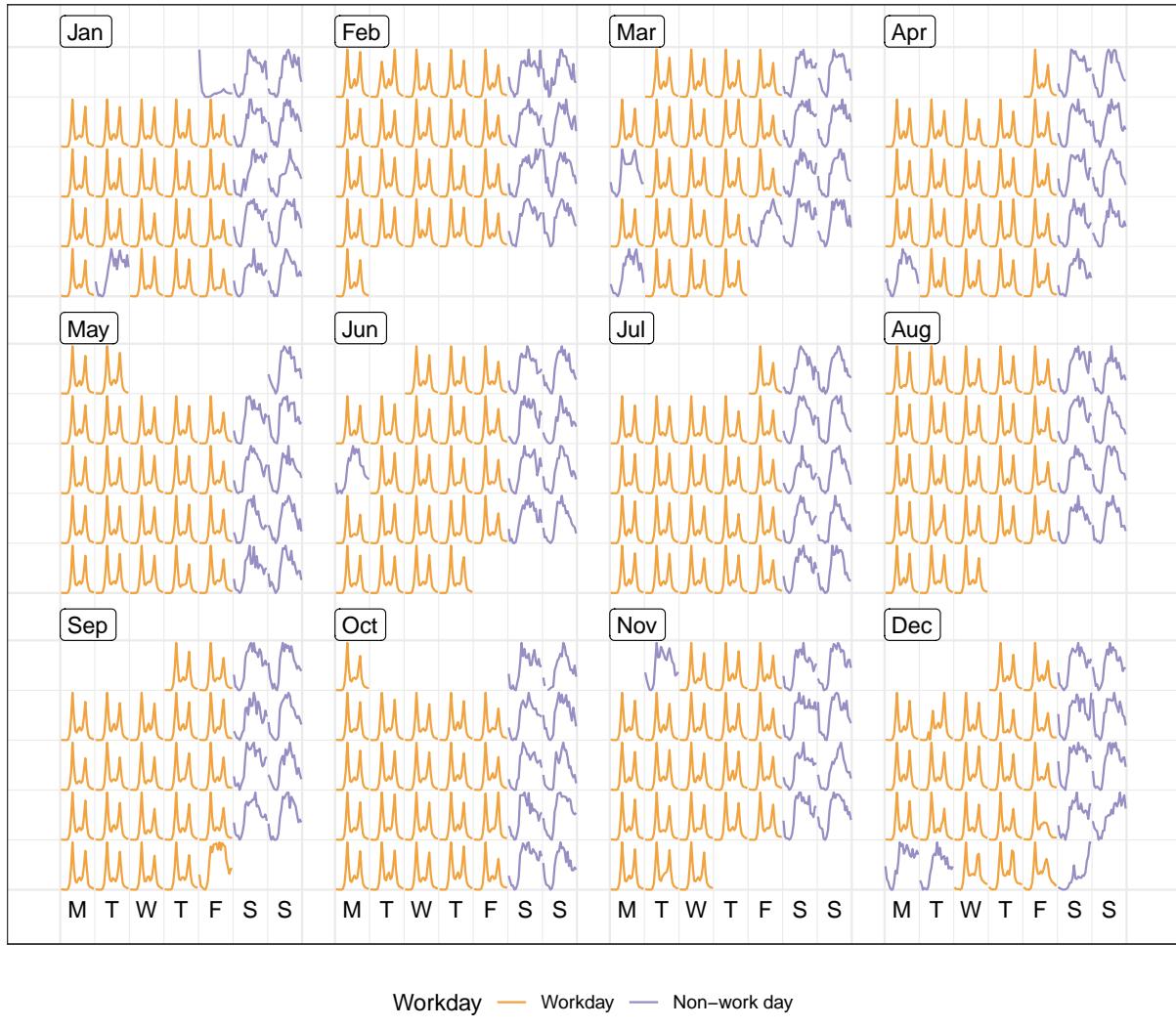


Figure 8: Line glyphs on the calendar format showing hourly foot traffic at Flagstaff Station, scaled over all the days. The individual shape on a single day becomes more distinctive, however it is impossible to compare the size of peaks between days.

for creating calendar layouts for countries where vertical layout is the convention.

2.2.5 Language support

Most countries have adopted this western calendar layout, while the languages used for week day and month would be different across countries. We also offer languages other than English for text labelling. Figure 13 shows the same plot as Figure 12 labelled using simplified Chinese characters.

2.3 Variations

2.3.1 Overlaying and faceting subsets

Plots can be layered. The comparison of sensors can be done by overlaying plot the values for each (Figure 9). Differences between the pedestrian patterns at these sensors can be seen. Flagstaff Station exhibits strong commuters patterns, with fewer pedestrian counts during the weekends and public holidays. This suggests that Flagstaff Station has limited functionality on non-work days. From Figure 9 it can be seen that the State Library has a similar temporal trend to Flagstaff Station on non-work days. The nighttime events, such as White Night and New Year’s Eve, have barely affected the operation of Flagstaff Station but heavily affected the incoming and outgoing traffic to Flagstaff Station and the State Library.

To avoid the overlapping problem, the calendar layout can be embedded into a series of subplots for the different sensors. Figure 10 presents the idea of faceting calendar plots. This allows comparing the overall structure between sensors, while emphasising individual sensor variation.

2.3.2 Different types of plots

The `frame_calendar` function is not constrained to line plots. The full range of plotting capabilities in `ggplot2` is essentially available. Figure 11 shows a lag scatterplot at Flagstaff Station, where the lagged hourly count is assigned to the `x` argument and the current hourly count to the `y` argument. This figure is organized in the daily calendar layout. Figure 11

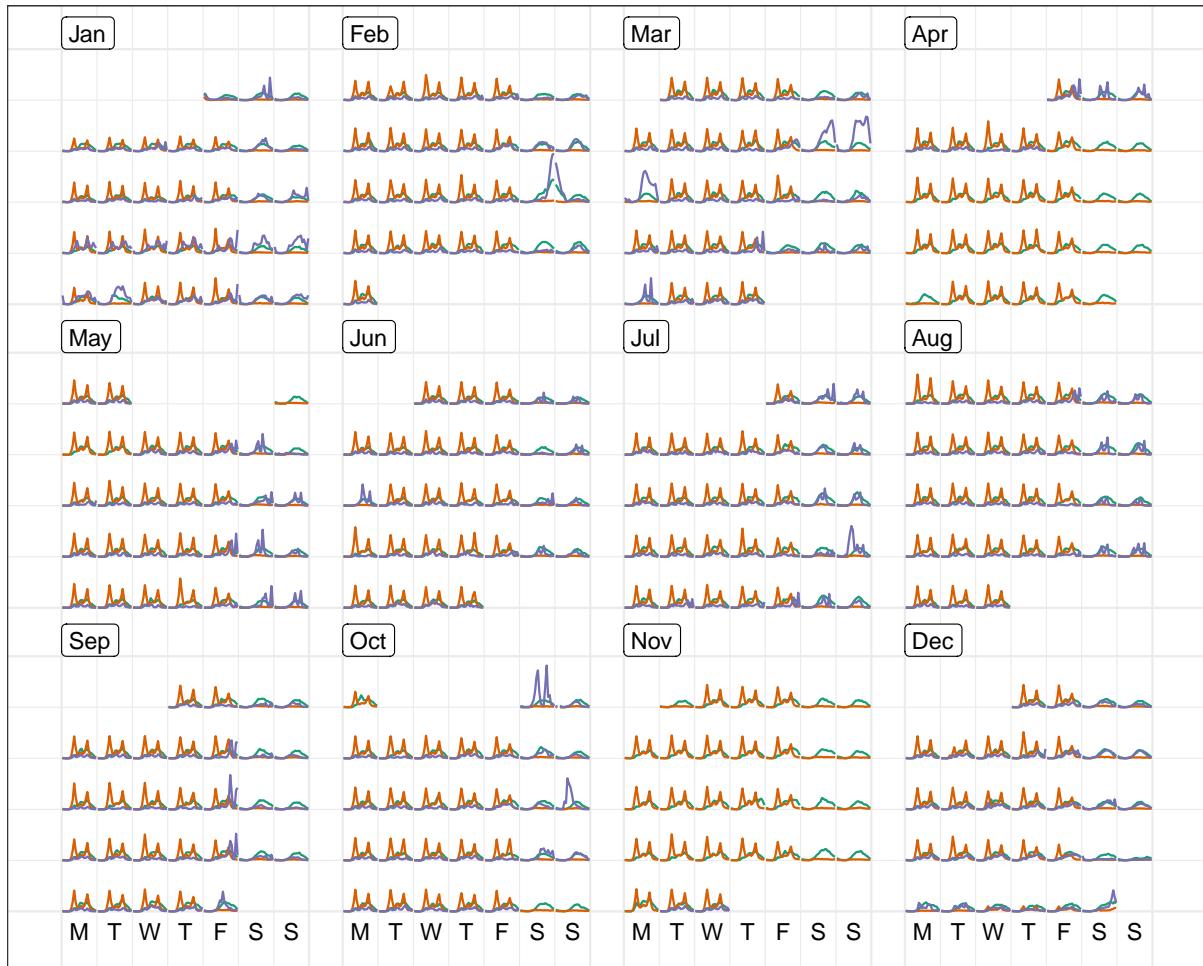


Figure 9: Overlaying line graphs of the 3 sensors in the monthly calendar. Flagstaff station is not as busy as the other two on non-work days.

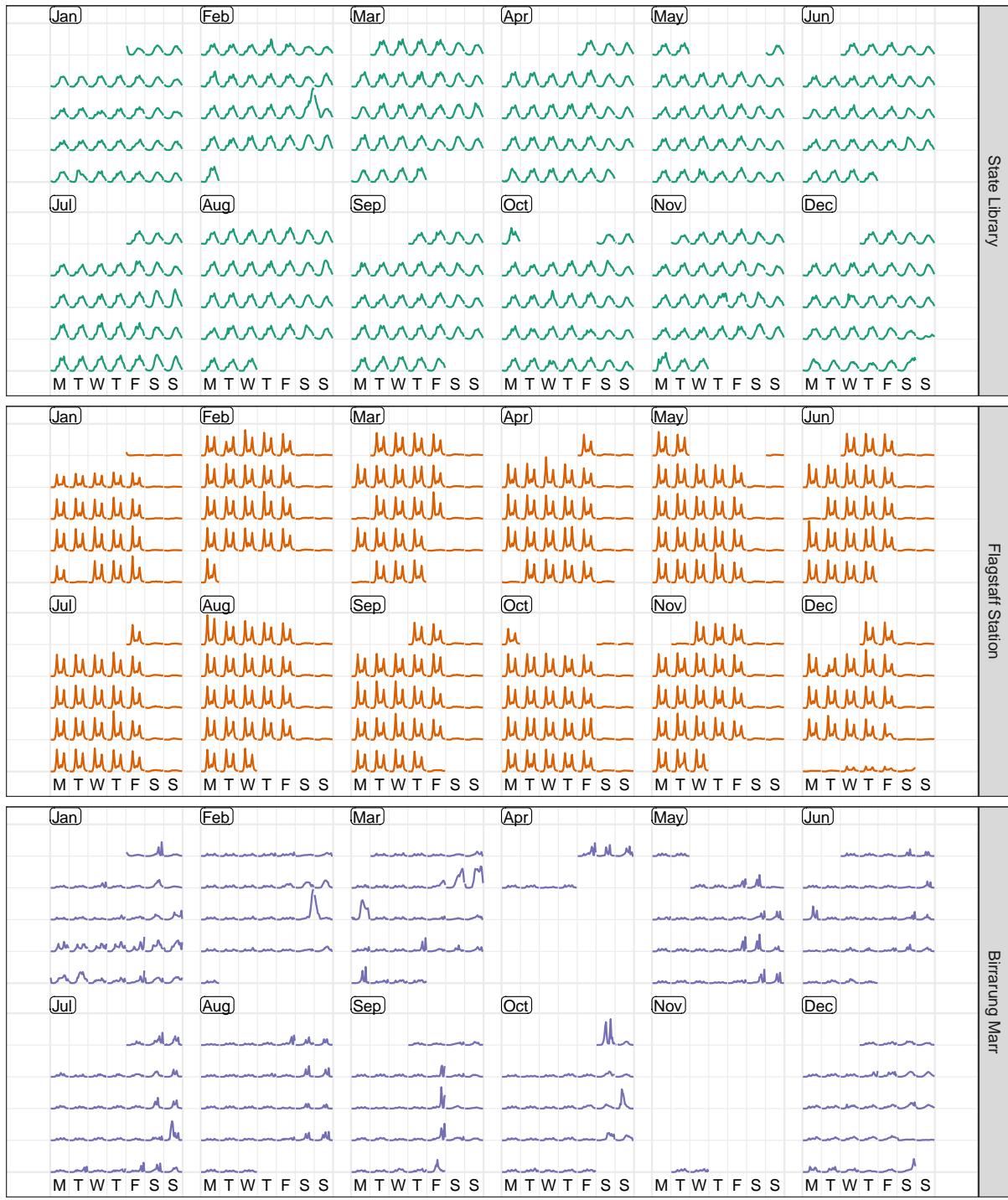


Figure 10: Line charts, embedded in the 6×2 monthly calendar, colored and faceted by the 3 sensors. The variations of an individual sensor are emphasised, and the shapes can be compared across the cells and sensors.

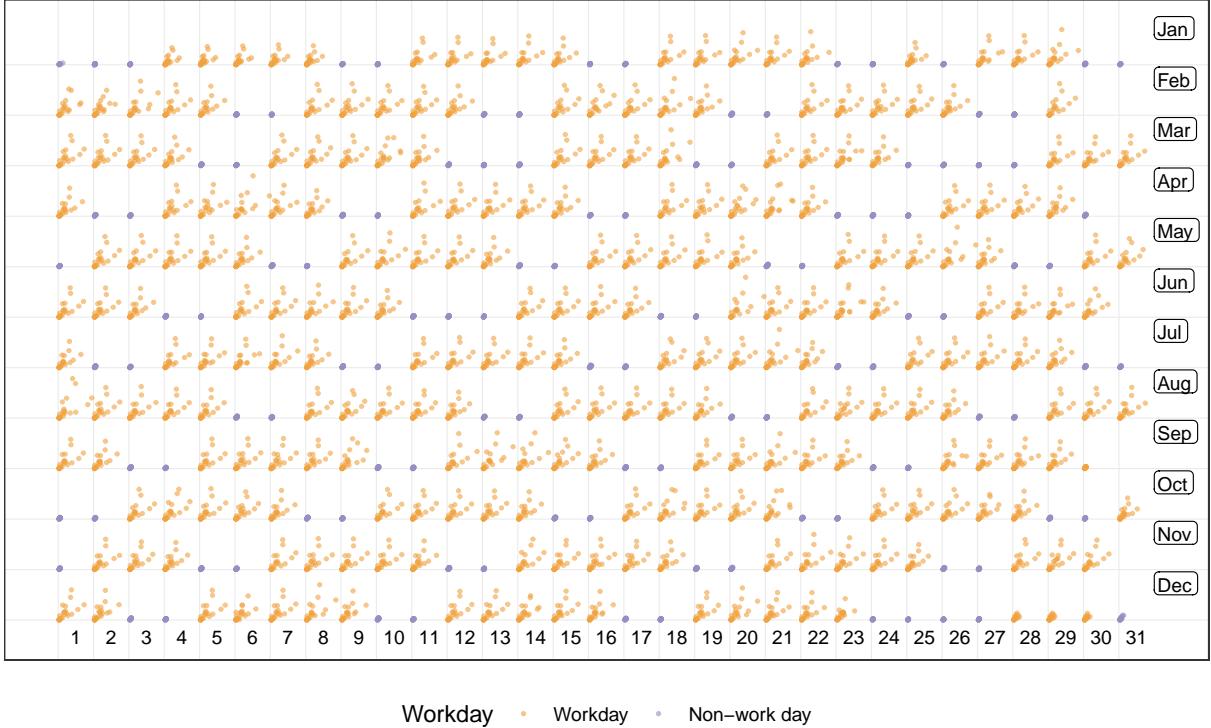


Figure 11: Lag scatterplot in the daily calendar layout. Each hour’s count is plotted against previous hour’s count at Flagstaff Station to demonstrate the autocorrelation at lag 1. The correlation between them is more consistent on non-work days than work days.

indicates two primary patterns, strong autocorrelation on weekends, and weaker autocorrelation on work days. At the higher counts, on week days, the next hour sees possibly substantial increase or decrease in counts, essentially revealing a bimodal distribution of consecutive counts, as supported by Figure 4.

The algorithm can also produce more complicated plots, such as boxplots. Figure 12 uses a loess smooth line superimposed on side-by-side boxplots. It shows the distribution of hourly counts across all 43 sensors during December. The last week of December is the holiday season: people are off work on the day before Christmas, go shopping on the Boxing day, and stay out for the fireworks on New Year’s Eve.

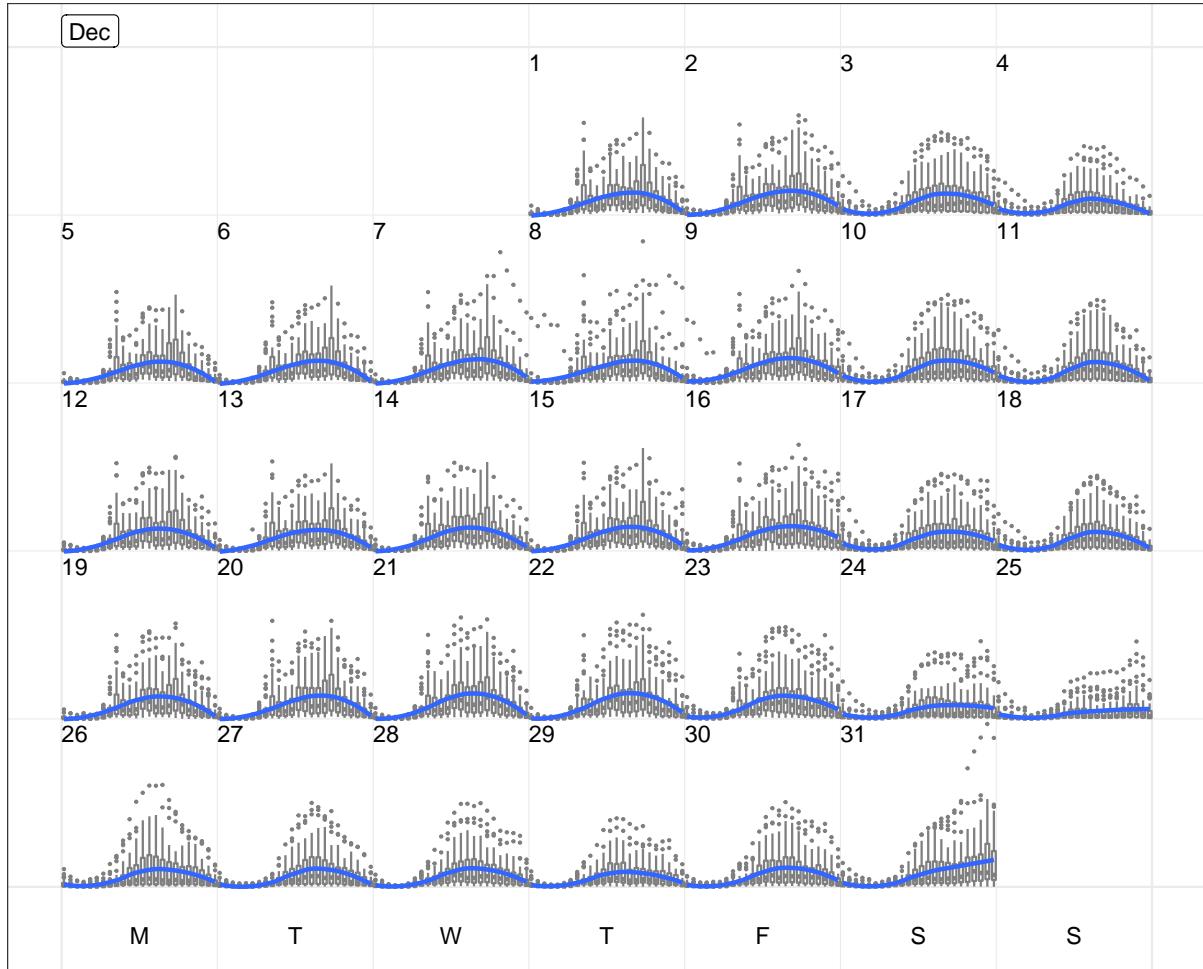


Figure 12: Side-by-side boxplots of hourly counts for all the 43 sensors in December 2016, with the loess smooth line superimposed on each day. It shows the hourly distribution in the city as a whole. There is one sensor attracting a larger number of people on New Year's Eve than the rest.

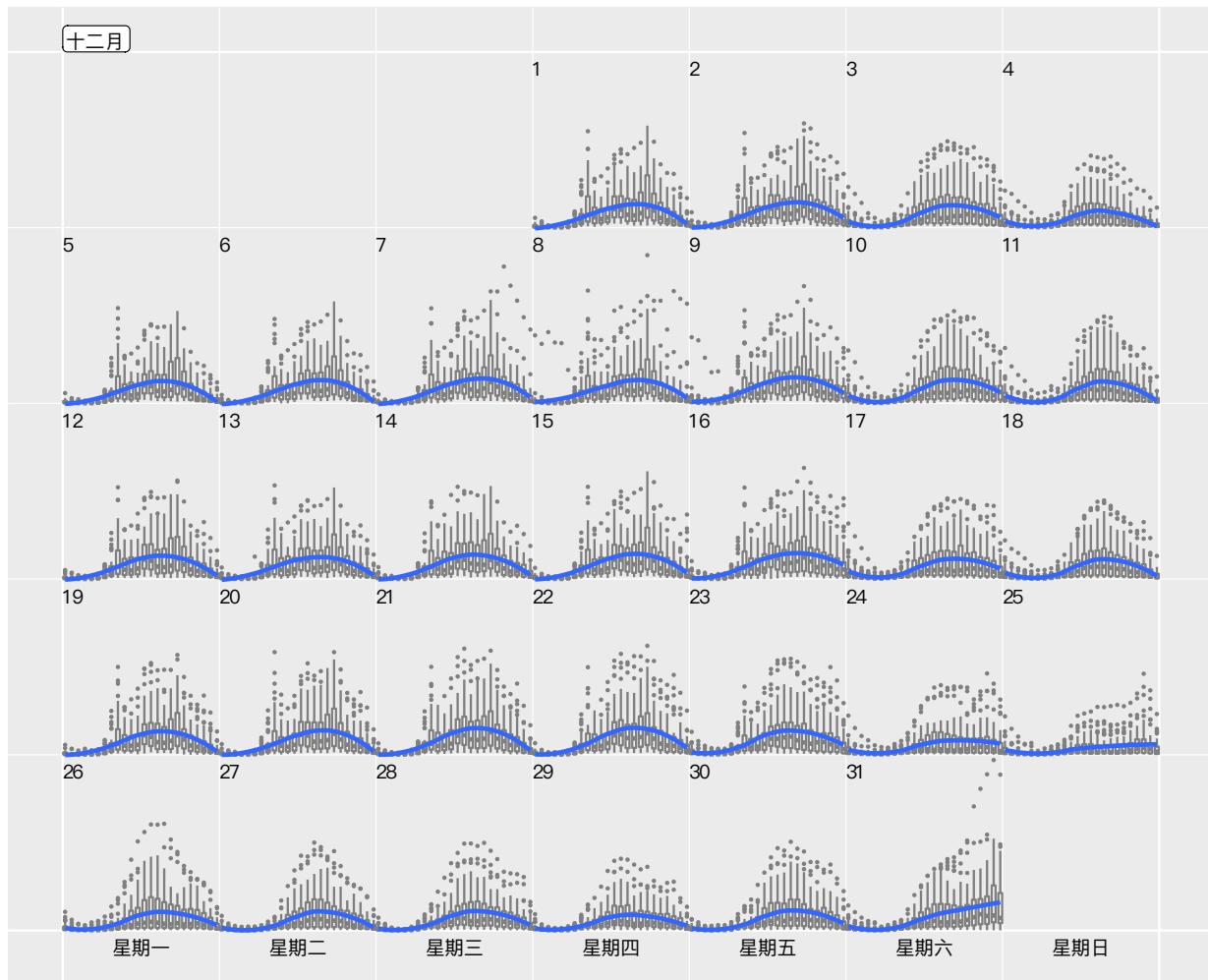


Figure 13: The same plot as Figure 12, but with the month and week day labels in Chinese. It demonstrates the natural support for languages other than English.

2.3.3 Interactivity

As a data re-structuring tool, the interactivity of calendar-based display can be easily enabled, as long as the interactive graphic system remains true to the spirit of the grammar of graphics, for example **plotly** in R. As a standalone display, interactive tooltip can be added to show the actual values of a data point when mousing over it in the calendar layout, for example the hourly count with the time of day. It is difficult to sense the values in static display, but the tooltip makes it possible. Options in function **frame_calendar** can be ported to a form of selection buttons or text input. The display will update on the fly accordingly via clicking or inputting, as desired.

Linking calendar displays to other types of charts is of great value to visually explore the interactions with many factors. It most naturally serves as a toolbox of date selection. By selecting and brushing the glyphs in the calendar, it subsequently highlights the elements of corresponding dates in other time-based plots, or vice versa. For example, it would be interesting to learn if very hot/cold days and heavy rain affect the number of people walking in downtown Melbourne, especially outdoor areas. Melbourne's daily temperatures and precipitations can be acquired, and plotted against the dates. The linking between weather data and calendar display is achieved using the common dates.

3 Case study

The use of the calendar display is illustrated on smart meter energy usage from four households in Melbourne, Australia. Individuals can download their own data from the energy company, and these four households are the data of colleagues of the authors. The calendar display is useful to help people understand their energy use. The data contains half-hourly electricity consumption in 2017 and 2018. The analysis begins by looking at the distribution over days of week, then time of day split by workdays and non-work days, followed by the calendar display to inspect the daily schedules.

Figure 14 shows the energy use across days of week in the form of letter value plots (Hofmann et al. 2017). As a variant of boxplots, letter value plots represent each pair of adjacent letter values using one box, instead of whiskers. Figure 14 demonstrates three

letter values and outliers marked as asterisks, with a line representing the median (thus M) and the innermost boxes corresponding to the fourth (F) and the eighth quantiles (E). Household 3, with a family size of one couple and two kids, uses more energy over the weekdays given the medians, compared to the others consisting of one or two people. Whereas, household 2 displays a great deal of variability in daily energy consumption with noticeable variations on Thursdays, and much higher usage over the weekends. The other two households (1 and 4) tend to consume more energy on average with increased variations during the weekends relative to the weekdays, as a reflection of work and leisure patterns.

Figure 15 provides a more detailed depiction of each household's life style, by plotting energy consumption against time of day between weekdays and weekends. Household 1 is an early bird, starting their day before 6 and going back home around 18 on weekdays. They switch air conditioning or heating on when they get home from work and keep it operated till mid-night, while learned from the tiny cluster of points below 1 kWh. On the other hand, the strips above 1 kWh tells that household 2 perhaps have air conditioning or heating on all time during the days, consuming the energy almost as double as household 1. Apart from the morning and night peak use, a third peak occurs around 3pm for household 3 only, when the kids are home from school. They also share a consistent energy pattern between weekdays and weekends. As for household 4, their home routine starts after 6pm on weekdays. Figure 14 and 15, part of traditional graphical toolkits, are useful for summarizing overall deviations across days and households.

Figure 16 and 17 apply the new calendar displays individually for each household, unfolding their day-to-day life. Glancing through Figure 16, their weekday energy use distinguishes from their weekends. We can exactly tell when their air conditioner and heater are turned on. Heating keeps functioning in consecutive hours at household 2, which is evident in the mid July; while household 1 uses them cautiously. This finding helps explain the strips and clusters in Figure 15. The calendar plots speak the stories about vacation time that are untold by previous figures. Household 1 is on vacation over three weeks of June, and household 2 was also away for holidays during Christmas and the second week of June. Figure 17 shows household 3 takes two one-month-long family trips in September till early October and in June/July, and household 4 is away over two

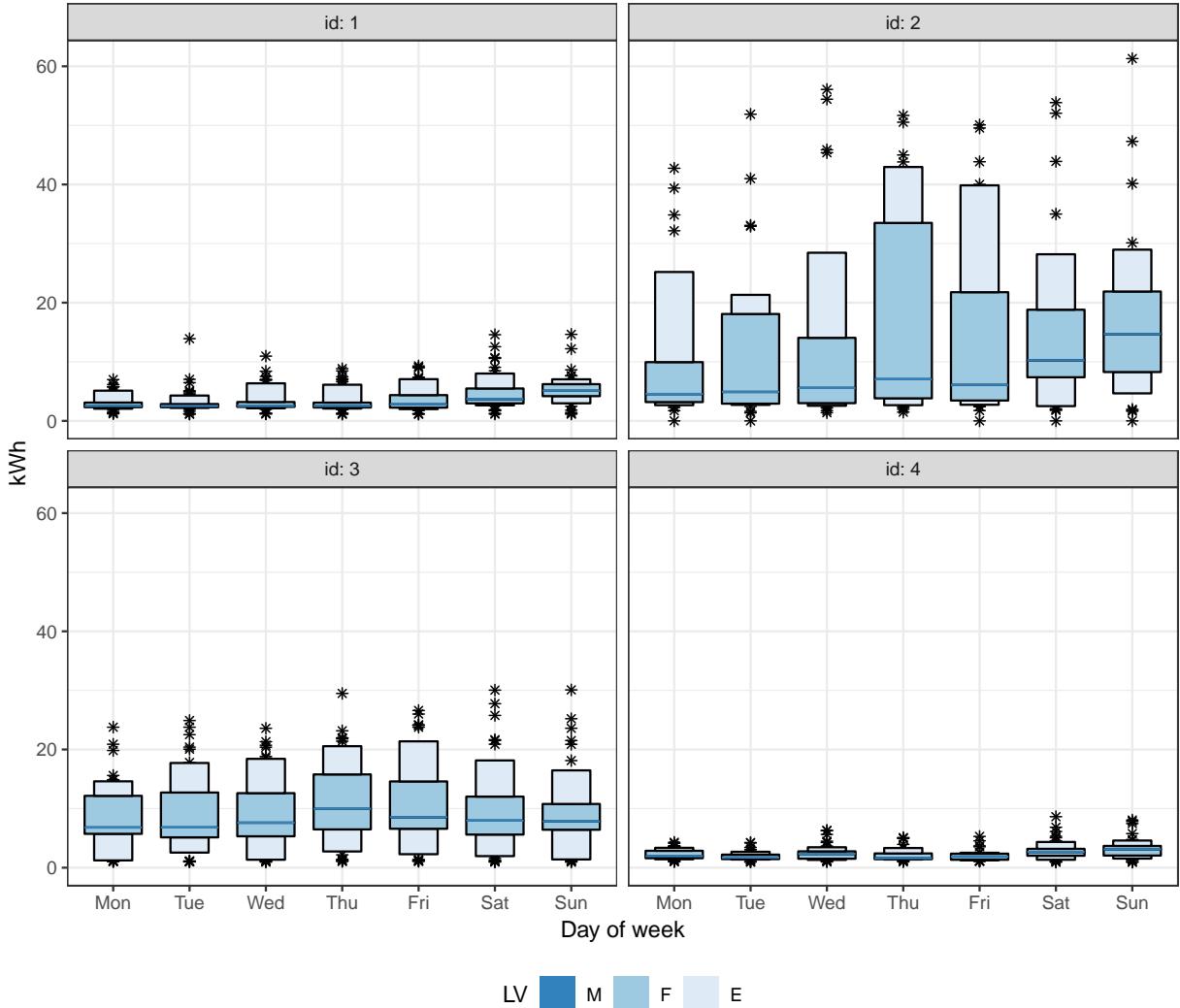


Figure 14: Letter value plots of daily energy usage against day of week for four households, with one line displaying the median (M) and each box corresponding to the fourth (F) and eighth (E) paired quantile estimates. Suggested by the medians, household 3 uses more energy than the others on the weekdays, due to a large family size. By contrast, household 2 sees considerably large variability.

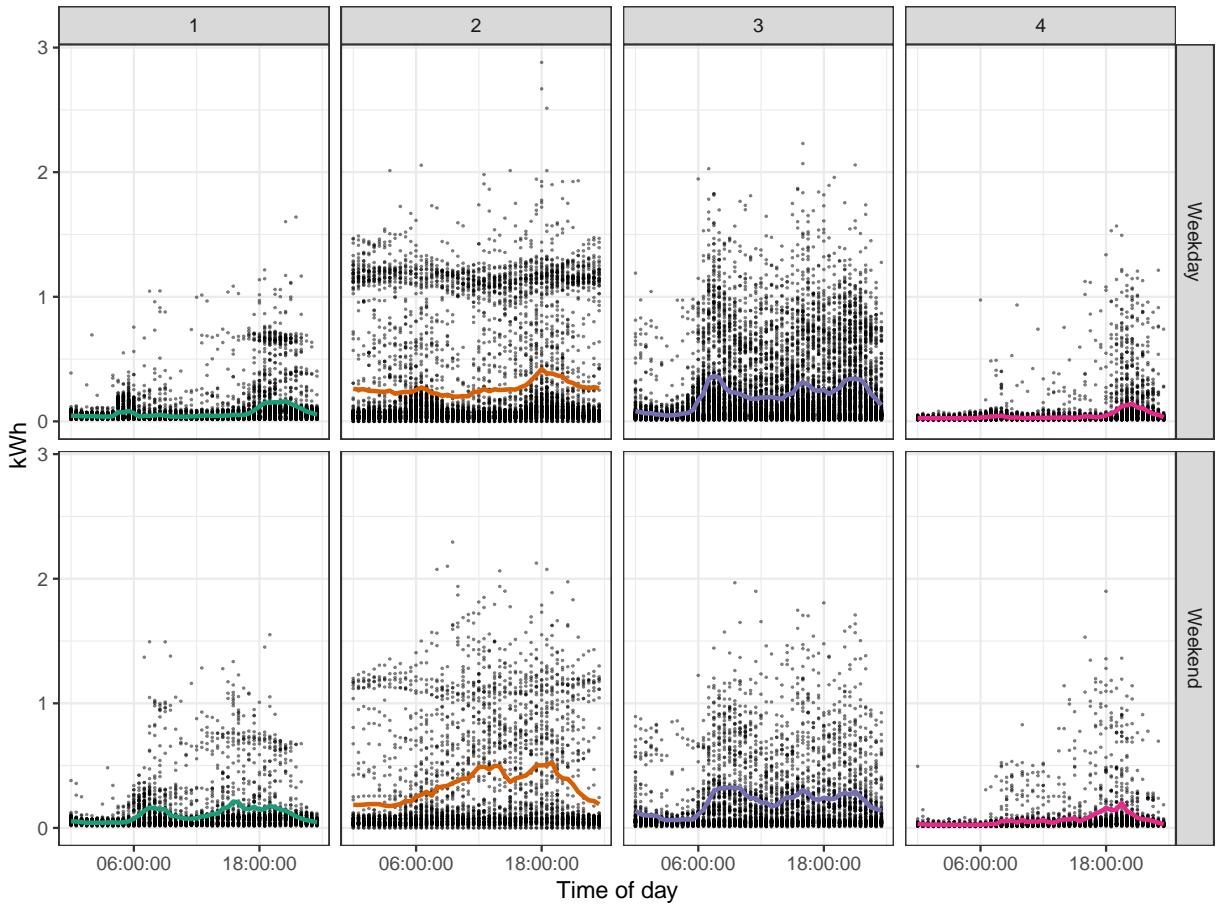


Figure 15: Scatterplot between half-hourly energy usage and time of day with the averages overlaid, contrasting weekdays and weekends for each household. All have different daily routines between weekdays and weekends, except for household 3. On weekdays, household 1 wakes up early before 6am, and household 2 around 6am, followed by household 3 and 4. The use of air conditioning and heating are noted in household 1 and 2.

or three weeks in early October, December and late June. The use of air conditioning and heating leaves no trace in these two households.

4 Discussion

The calendar-based visualization provides data plots in the familiar format of an everyday tool. Patterns on special events for the region, like Anzac Day in Australia, or Thanksgiving Day in the USA, more easily pop out to the viewer as public holidays, than they would on a more commonly used week day and month faceted layout.

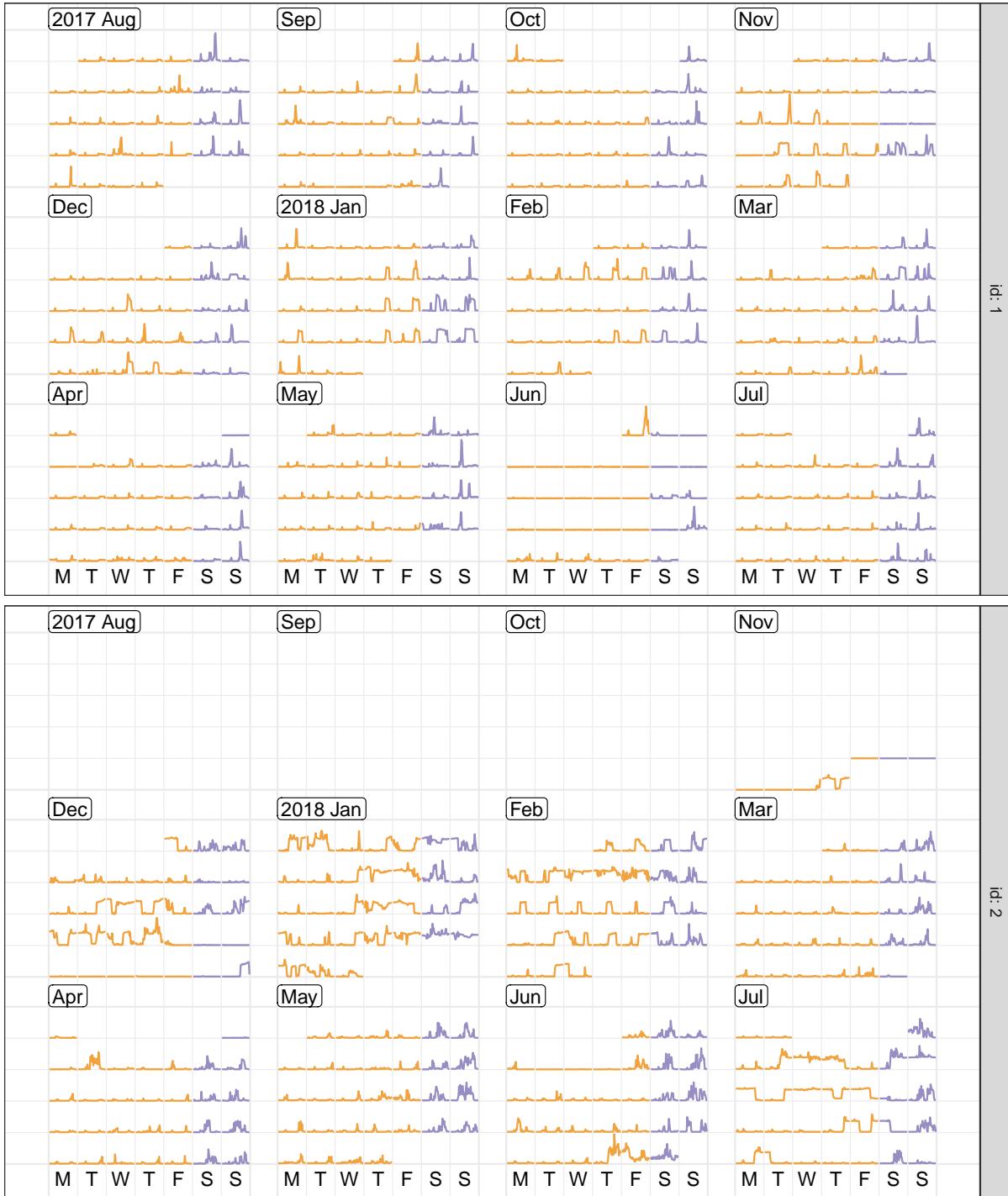
The methodology creates the western calendar layout, because most countries have adopted this format. The main difference between countries is the use of different languages for labelling, which is supported by the software. Layouts beyond the western calendar could be achieved by the same modular arithmetic approach.

The calendar layout will be useful for studying consumer trends and human behavior. It will not be so useful for physical patterns like climate, which are not typically affected by human activity. The layout does not replace traditional displays, but serves to complement to further tease out structure in temporal data. Analysts would still be advised to plot overall summaries and deviations, in order to study general trends.

The layout is a type of faceting and could be useful to develop this into a fully-fledged faceting method, with formal labels and axes. This is a future goal.

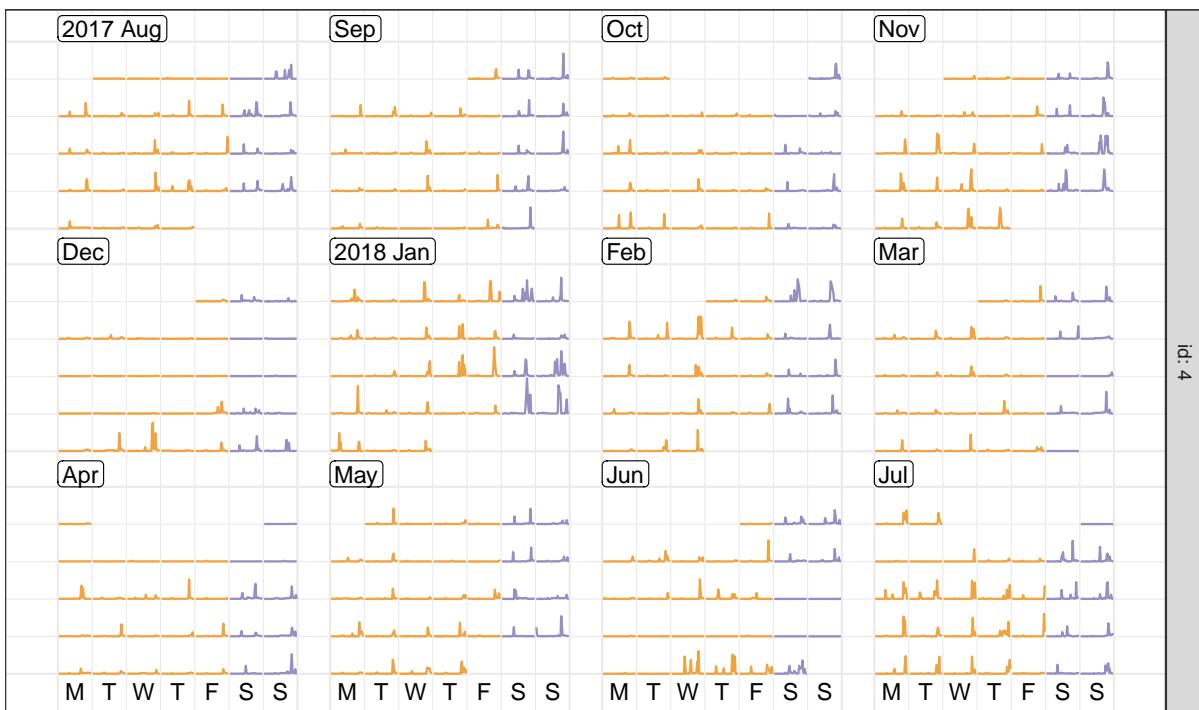
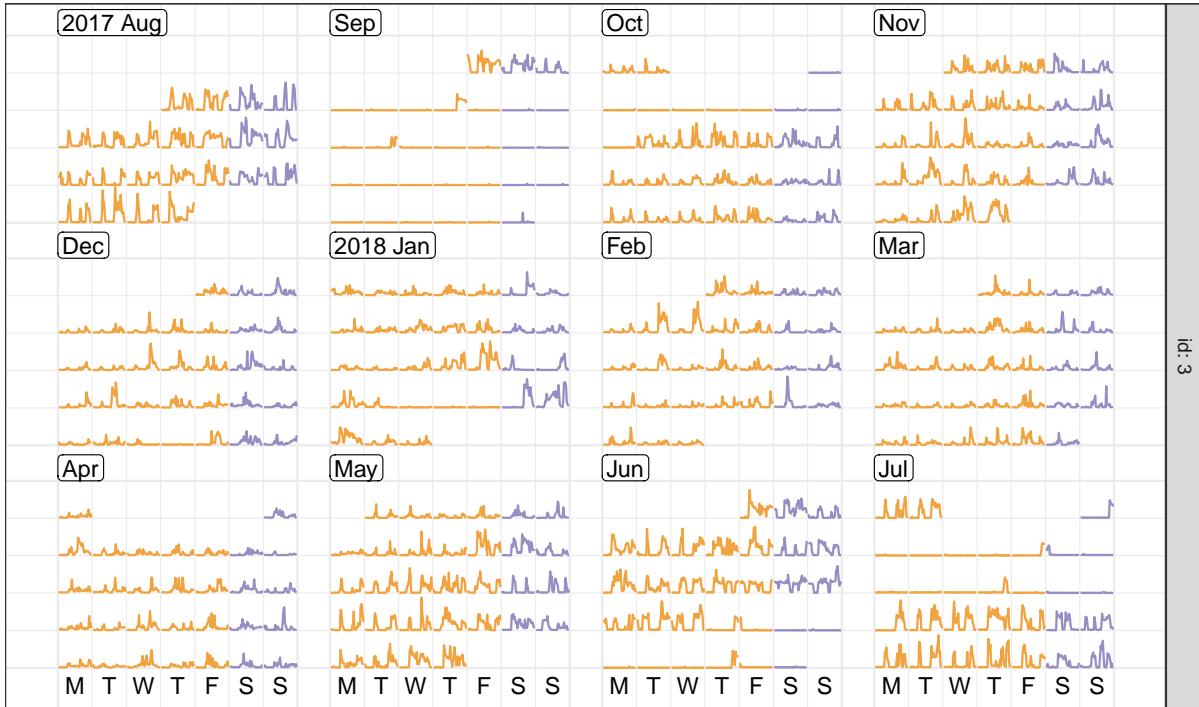
Acknowledgements

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weekday — Weekday — Weekend

Figure 16: Calendar displays for household 1 and 2. It reveals their regular tendency of using air conditioning and heating and vacation time periods. For example, household 2 leaves heating on consecutively in the mid July, is on holiday for Christmas and the second week of June.



weekday — Weekday — Weekend

Figure 17: Calendar displays for household 3 and 4. Household 3 are on long trips twice in the past year, while household 4 takes three short trips in October, December, and June. Both households leave no clue if they use air conditioning and heating.

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