# TimeSplines: Sketch-Based Authoring of Flexible and Idiosyncratic Timelines

Category: Research

Paper Type: application/design study

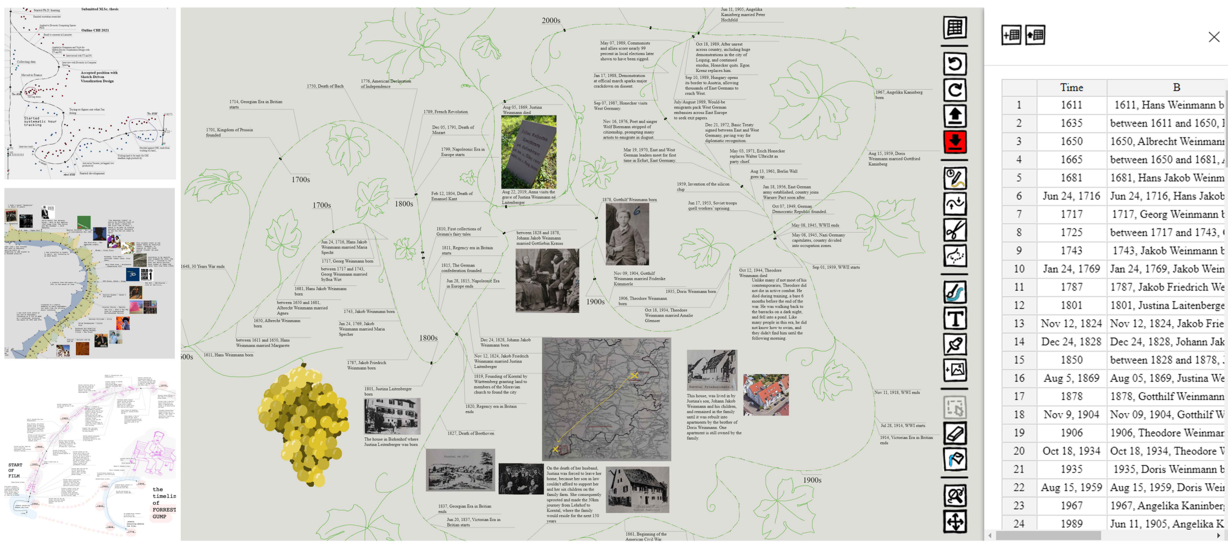

Fig. 1: A sample of the gallery with the TimeSplines interface. See supplementary materials for full gallery. a) Academic career, path direction indicates career direction, and includes text events, author mood data (red points), and work hours data (blue points). b) Music listening data, showing counts of songs added to various playlists, features heavy use of multimedia. c) timeline of Forrest Gump, featuring inset paralell timelines, and expressive annotation. This visualization uses the same dataset as P15. d) TimeSplines showing the Family History visualization. Authors can specify and manipulate flexible temporal axes in the canvas through sketch interaction (left), while preserving temporal integrity of the underlying sequence event data (right) through lazy data binding. The Family History visualization features an intertwined family timeline and a world history timeline. Anna: the a, b, c, d labels are missing, they're supposed to go top to bottom, left to right

**Abstract**—Timelines are essential for visually communicating chronological narratives and reflecting on the personal and cultural significance of historical events. Existing visualization tools tend to support conventional linear representations, but fail to capture personal idiosyncratic conceptualizations of time. In response, we built TimeSplines, a visualization authoring tool that allows people to sketch multiple free-form temporal axes and populate them with heterogeneous time-oriented data via incremental and lazy data binding. Authors can bend, compress, and stretch temporal axes to emphasize or de-emphasize intervals based on their personal importance; they can also annotate the axes with text and figurative elements to convey contextual information. The results of two user studies show how people appropriate the concepts in TimeSplines to express their own conceptualization of time. Our curated gallery of images demonstrates the expressive potential of our approach.

**Index Terms**—Timeline, Time-series data, Sketch-Based Interface, Lazy Data Binding

## 1 Introduction

Timelines are a popular visual way to represent time data for telling stories [14, 55], reflecting on historical data [29], analysing how data evolves over time [40], and documenting personal data [57]. However, current tools for creating timelines are often rigid, providing only single, straight, constant, linear representations of time (e.g. spreadsheets software, LucidChart [38]) or do not retain a mapping of time (e.g. Adobe Illustrator, pen and paper).

Many people have idiosyncratic and subjective mental representations of time, "proved to range from minimalist abstractions to complex symbolic forms." [58] They are often a mix of alternative conventional representations including loops, spirals, straight lines, and disjointed segments (Figure 2). Only pen and paper can truly accommodate these representations today [5]. Creative authoring tasks often involve iterating on the visual as well as what data to represent because the process of visualization can reveal the relative importance of different elements. Amplifying salient elements can involve including more details or context for certain items, removing less important items, and complete changes in the style of visualization.

Available visualization tools, such as Tableau, often target a quantitative analysis workflow, where data is gathered prior to analysis and modifying it during analysis is bad practice. Consequently, the iterative workflow of creative tasks is not well supported. Tools to support both flexibility of representation and flexibly of workflow are needed.

In tools that better support visual expressivity, such as Adobe Illustrator and plain paper, it is difficult to work with data because representing data manually is tedious and error prone. Authors must commit to a specific layout because changing is a lot of work, making it difficult to reflect and iterate on personal data. Tools which support automatic data layout while retaining expressivity and flexibility similar to drawing tools could enable more people to work with their data.

To address these issues, we have developed TimeSplines, a tool for supporting rich idiosyncratic visualizations of time. TimeSplines targets data sketching and storytelling, supporting reflection and documentation. We present the key design considerations (D1-D3) (§3) drawn from literature [13, 55] and observed use cases which underpin TimeSplines. We outline a complete workflow in TimeSplines (§4) which demonstrates (D1) how *sketching* on the flexible temporal substrate supports idiosyncratic time representation, (D2) how *lazy data binding* supports a flexible workflow, and (D3) how freehand annotation, styling and multimedia annotation support expressivity. We evaluated TimeSplines using three established methods [47]: a reproduction study with 12 participants to evaluate the system's usability; a free-form evaluation with four designers and visualization researchers to evaluate different use cases and creative workflows; and a gallery of visualizations produced with TimeSplines to demonstrate the expressive power of our approach (§5). From the reproduction study, we found participants were able to understand and sometimes appropriate the concepts of idiosyncratic representations within TimeSplines, such as by creating a number of variations of the line they were asked to reproduce (Figure 4). From the freeform study, we were able to observe how the tool supported participants in a variety of contexts, including creating person histories, reflecting on personal metrics, and visualizing fictional data. The system supported iteration in the participants' different workflows, showing how the tools sketchiness supports developing ideas. Finally, our gallery shows a number of unique time mappings that are not possible in standard timeline visualizations, proving the value of these visualizations, which we discuss along with directions for further enriching rich idiosyncratic timeline visualizations.

Our contributions are: a novel approach of sketching on a flexible temporal substrate for supporting idiosyncratic timeline authoring, embodied in the TimeSplines system; and an evaluation of the system which opens interesting questions around authoring idiosyncratic timeline visualizations, providing evidence for the power, utility, and limitations of such visualizations.

## 2 Related Work

In this section, we outline relevant literature on temporal visualization, and rich corpus of sketch-based systems and systems supporting lazy data-binding which inspire our approach.

### 2.1 Timeline Visualization

Timelines have been used for data visualization for hundreds of years [29, 50] and are still a staple representation today [14, 29, 43], used for analysis of electronic health records [40, 66, 70], for conveying historical events [45, 50], for telling stories [14], for self-reflection on personal data [21, 55], or even for addiction treatment [8].

When dealing storytelling and time related information, direct mapping of linear time to space is not always desirable. Classic visualizations of time generally have time running along a linear, straight, uniform axis (horizontal axis) and the data distributed along the vertical axis [45]. Cyclic and spiral shapes, as well as cluster and calendar-based representations [64] are also common to "emphasize the cyclic character of time" [3]. Expanding beyond set shapes, the path of time through space can be used to convey temporal relationships between quantitative values which are plotted on other representations, such as in connected scatterplot [27], time curves [6], or story curves [30]. Timelines whose shape is used to encode meaning through metaphors [63], can also be the result of aesthetic choice intended either to be memorable in its own right, suggestively figurative, or drawn to accommodate annotations, captions, and images (e.g. Figure 2). Such expressive timelines, however, appear to be less common [13], arguably because few tools support their creation.

Free-form timelines appear most frequently in narrative and personal contexts, for example, in many personal time visualizations [26, 58], and are recommended for mnemonic purposes as far back as 1914 [63]. This is unsurprising as "experiences of time vary depending on contextual factors. They are not always perceived, remembered, or interpreted as linear; they can be abstract, and they can draw heavily on social and cultural metaphors" [52]. Under certain highly personal contexts, the need to use a linear mapping of time can be a major obstacle, such as in [52] when many participants with bipolar disorder declined to participate in a task which required them to project a timeline into the future, opting instead for "visual geometries that did not have such explicit beginnings, middles, or ends" [52]. Flexibility in the representation of time is important as different representations might be more suitable to "emphasize what [one] subjectively considers important to communicate and share in the data" [44] in different contexts.

Programmatic data visualization elicits associations of rigid rectilinear coordinate spaces; consistent, symmetric and often polygonal representations of data and axes; and consistent scale mappings that afford data analysis. We know that personal and idiosyncratic experiences of time do not adhere to these characteristics [26, 58]. The timeline design space [13] was a step toward acknowledging this contrast, but tools like Timeline Storyteller [14] still reinforce consistency of scale and representation.

Egocentric time perception is affected by factors, such as cultural trends [24, 62], and biases such as the availability bias which places greater significance to recent events [61]. In the creation of personal timelines, it was found that "an appearance of evenness, although desired, [is] *incongruent with the way that events unfold over a lifetime"* [55]; motivating the need for 'distorted' chronological time representations which may better represent the human perception of these events [13]. Supporting the use of ellipses to cut out sections of the timeline that are light on narrative content, as used in popular narrative [30], and the ability to compress or expand periods will enable data to best serve the narrative. While time distortion or warping has been examined in a few contexts, such as warping time to fit spatial distance [2, 23, 42], the idea of warping time to enable the expression of personal perceptions of time and significance appears to be comparatively under-explored. We explore this in our work.

Interactive visualization tools designed for time series analysis offer the ability to stretch, compress, and zoom time. Kronominer [71] supports squeezing or stretching sections of time in a pop-out ring view on a circular timeline. Similarly, TimeNotes [65] and Chronolenses [72] support interactive focus+content display of time series at diverse temporal granularities. Our work takes inspiration from these systems by allowing visualization authors to easily manipulate time in a sketch-based interface which also supports timelines with creative shapes.

Previous research has looked into personal data timelines, such as in Timeline Collaborations [11], which for creating parental leave plans by projecting events into the future with collaborative manipulation. However, most of these tools focus on a single representation of time. We still need "to develop visual techniques to be able to accommodate the completeness of story elements and shape flexibility" [1]. While previous work has investigated how to tell personal stories through timeline visualizations [18, 44, 56], when it comes to computer-supported authoring, it is hard to get the desired personalization without a programming background, making these visualizations "the privilege of computer scientists only" [44]. We still need tools to support these use cases, a gap which our approach aims to fill by leveraging sketch-based and lazy-data-binding interaction paradigms.

### 2.2 Sketch-based Visualization Creation

When approaching a creative visualization task, an author often needs to iterate through multiple variations before reaching a final result. Sketching facilitates this idea transformation process [25]. Paper sketching is often used to iterate on visualization designs[1] because of its flexibility. However, in interviews with designers, it was noted that "inferences about data behavior were often inaccurate" [9], which can be a costly problem if adding data reveals the need for a major overhaul late in the process. Providing tools that incorporate data in the sketching process could save both time and resources.

Enabling flexibility in tools can be done through a range of approaches, including avoiding prescriptive workflows [9, 19], enabling multiple stages of development within the same application [31, 60], and making manipulations as direct as possible [68, 69]. Post-hoc visualization and annotation manipulation is difficult in multi-tool workflows which are often necessary to enable customization [10].

[1] datavisualizationsociety.org/survey

DataToon enables flexibility by combining data visualization creation with story composition, and SketchSliders [60] combines manipulation and exploration via visualization controllers that can take personalized forms. DataInk [68] and DataQuilt [69] offer flexibility in the form of direct data manipulation. Directly sketching timelines has been investigated, specifically with respect to documentation, with Knotation [22] enabling choreographers to both develop and document their work through timelines visualizations.

Another dimension of flexibility is the ability to externalize contextual knowledge, often in the form of data annotation [33]. Paper, again, offers flexibility which software often fails to capture, such as in the diverse examples produced in the *Dear Data* project [39], as well as NapkinVis [20]. Some software, however, has targeted this flexibility, with ChartAccent [46], SketchStory [34], and Temporal Summary Images [16] supporting narrative and storytelling via annotation, and SketchInsight [35] and ActiveInk [49] targeting knowledge externalization.

Avoiding prescriptive workflows while at the same time providing support for data manipulation is challenging, and the visualization community has been pushing towards tools that allow for a strong partnership between the author – who draws graphics on a canvas – and the computer – which automates a lot of the copy-paste operations (typical of vector graphics) and ensures that graphical elements are in line with the underlying data through precise data-to-graphical-feature mappings. Liu et al. [37] refer to this general approach as *lazy data binding*. The concept has been implemented in both structured [32, 37, 59] and playful [68, 69] applications. Our approach follows this body of work, enabling visualization authors to freely sketch on a canvas to specify a time representation and then bind data to that representation. Like previous work on visualization transmogrification [15], we also let users manipulate the shape of their time representation, split it, join multiple representations, and alter data bindings either via multiple embedded tables or the representation on the canvas. This lazy-data-binding approach supports rapid iteration by connecting the data and the representation in a two-way direction.

Fanny: Add Jagoda.

## 3 Design Considerations

Based on our analysis of prior work and motivated by historical and recent examples where time is represented in creative ways (see Figure 2), we outline design considerations for tools that support the authoring of idiosyncratic temporal visualizations.

### D1: Flexible Representation and Manipulation of Time

First and foremost, we need to accommodate both multiple heterogeneous representations of time and non-uniform transformations to one or more temporal axes appearing within a common workspace.

**Heterogeneous representations of temporal axis shape.** In their survey of timelines, Brehmer et al. [13] categorized instances that did not incorporate a conventional shape as having an *arbitrary* curve representation of time. However, these shapes are hardly arbitrary to the author, often reflecting a personally meaningful and idiosyncratic perception on time. These custom shapes can accommodate rich textual and illustrative annotation, as seen in Figure 2c. Further, these multiple representations of time should not only be able to appear in juxtaposition, such as in Figure 2b, but potentially also in sequence, such as in Figure 2a, where straight lines are connected by curves. It is not only necessary to support non-conventional curves, but also the ability to segment and connect such curves.

**Non-uniform manipulations of temporal scale.** Two equal duration intervals on a temporal axis do not necessarily require the same visual salience, particularly if one interval is of greater importance to the author and their audience. In other words, there is no strict need for a linearly-scaled correspondence between the duration of time and distance along an axis. Distortions of temporal scale may also be non-uniform, alternately expanded or compressed to emphasize important intervals and de-emphasize unimportant ones. Visual temporal distortion is analogous to similar narrative devices in film, which include ellipses that skip unimportant intervals between important scenes, montage and time-lapse sequences to show gradual developments quickly, and slow motion sequences to show rapid events slowly. We must allow for these manipulations of chronology to be applied locally to a single temporal axis, without affecting other axes.

### D2: Heterogeneous and Accumulative Temporal Data

**Reconciling differences in data type and fidelity.** Multiple types of data can be drawn in reference to a temporal axis [3]. Both instances and intervals of time can be associated with one or more event categories, rich text descriptions, or numerical values. In some cases (such as Figure 2e), all three types are employed to convey a sequential narrative. However, combining multiple types of data along a common temporal axis can be hindered by the lack of a common temporal referent. Some data may be associated with a precise point in time, whereas other data may be associated with a coarser interval or an ordinal sequence having no fixed temporal coordinate. Reconciling these differences and assigning imprecise chronological or ordinal data to positions on a temporal axis is necessary.

**Incremental data curation.** Creative visualization workflows rarely involve a prescribed sequence of iteration and ideation [51]. Initial design ideas could be sketched before any or all of the data is gathered [9], and visualization process often informs which data is included [36, 55]. For example, an author may begin their process with a table of timestamped events, only later realizing the need to append a numerical value to each item. There may also be a need to append individual and unstructured data points to a design, or an entirely new table of structured temporal data to the workspace. Late-stage data curation runs the risk of affecting the design in unpredictable and undesirable ways, such as resulting visual clutter requiring a redesign of the layout, so we must mitigate any effects of adding new data through flexible graphical and temporal editing.

### D3: Multimodal Annotation

Annotation is essential to data-driven storytelling [46], adding critical orientation for viewers. Annotation is particularly important if the choice of representation is unconventional (**D1**) or if the data is personal in origin [41,57], as it helps to establish a shared context between author and viewer. Irrespective of whether these annotations are ever shared with viewers, the ability to annotate also allows authors to externalize their interpretations of visual patterns [33] and develop hunches based on a personal connection to the data [36].

Depending on their salience and placement relative to data-bound elements (i.e., marks and axes), text-, illustration-, and image-based annotation can emphasize features and contextualize the data. Illustrative or figurative elements and frames [17] can complement abstract marks bound to structured data by providing metaphorical or semantic cues, and reinforce the message of figuratively shaped temporal axes (**D1**). This latter form of annotation is seldom employed just for ornamental or aesthetic appeal; it can also communicate an intended affect, one that establishes an emotional and thematic impressions at a glance.

Annotations could be explicitly linked to data elements or alternately be contextual. It is critical that linked annotations be responsive to visualization design choices that affect the position of data elements, such as changing the axis shape or the temporal scale, whereas other annotations should be agnostic of such changes.

## 4 TimeSplines

In this section, we describe our authoring tool TimeSplines, which embodies the design considerations introduced above. The core of TimeSplines is a canvas that can accommodate any number of temporal axes, each with an independent shape and scale. We refer to this canvas as the *temporal substrate*, which corresponds to a structural substrate in Beaudouin-Lafon's conceptual model [7]. The interface is depicted in Figure 1: it encompasses the canvas (left), where the author can sketch and manipulate their flexible and idiosyncratic timelines, and a tabular view of the underlying temporal data which is bound to the visualization through lazy data binding (left).

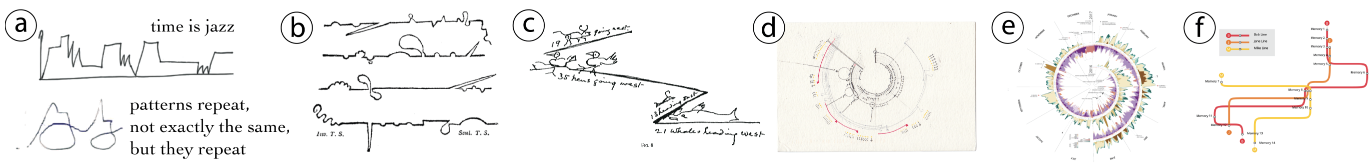


Fig. 2: Examples of idiosyncratic representations of time: (a) sketches drawn by people from the prompt “How do you see passage of time?”, curated by Camilla Torna [28]; (b) Laurence Sterne’s non-linear plot lines from *The Life and Opinions of Tristram Shandy, Gentleman* [53]; (c) Mark Twain’s zig-zagging representation of monarchs’ reigns [63]; (d) Giorgia Lupi’s nested semi-circles in *“Week in our past”* from *Dear Data* [39]; (e) Charles Perin’s spiral-shaped *“Symmetry of my life”* [44]; and (f) three people’s separate and shared memories visualized according to a metro map metaphor from `memoryunderground.com`.

We outline the functionality of TimeSplines through a usage scenario documented in Figure 3: Eve wants to create a timeline featuring her activities on Mondays during the month of January to reflect on her work habits, as well as share with her friends. She has her activities, hours, and productivity data recorded in separate spreadsheets. Eve gets started with a single main timeline as follows.

### 4.1 Creating a Timeline

Eve has a rough idea of what she wants her creation to look like: a loop-shaped timeline which emphasizes the Mondays, with other days of the week on a compressed time-scale since they are not the focus.

**Free-form drawing of a temporal axis.** Temporal axes can be sketched on the substrate via flexible, free-form mouse or pen input, akin to drawing arbitrarily-shaped strokes on vector graphics tools (D1). Eve draws a loop-shaped stroke using the timeline drawing tool (Figure 3.1) as her initial axis. In the back-end, the system interprets this stroke as an oriented temporal axis with an independent temporal scale determined by the direction of drawing, spanning from relative time $t = 0$ from the start of stroke to $t = 1$ at the end of the stroke.

**Loading data.** Eve imports her data containing records of work start and end time for each day in January from a CSV file into TimeSplines’s datasheets drawer (copy-paste tabular-formatted data is also supported). This drawer (featured in Figure 1.right) can contain any number of tables with any number of columns (D2). Each row is associated with a single point in time, specified by the first column, which is optional, but restricted to be a timestamp. No single format for the timestamp is required; it can accommodate sequential numerical values as well as dates and date-time values to varying degrees of specificity (e.g., `YYYY`, `YYYY-MM-DD`, `YYYY-MM-DD HH-MM`, etc.). In the absence of a timestamp, data is placed at the start of the line and can be positioned manually. The remaining columns may contain either text strings or numerical values associated with events. Eve has timestamped textual description of when she started and ended work each day (Figure 3.2).

**Binding data to a temporal axis.** To build her personal timeline, Eve now wants to populate her axis with these events. Time-oriented data can be bound to the substrate in increments by selecting subsets of data and the desired axis (D2). Eve selects events from January, clicks the linking tool, and selects her axis. TimeSplines automatically maps the events such that the earliest bound time value is mapped to the start of the axis and the latest time to the end: a line connecting to the axis is added for each event with the corresponding event label (Figure 3.2). Eve now has an initial timeline, which she can also manipulate as a regular graphical object on the canvas by resizing, translation, and rotation transformations.

### 4.2 Personal Conceptualization of Time

Eve’s story is about how she starts her work week so she wants to emphaisize the Mondays, and has little interest in showing details for the days in-between and so wants to compress that time.

**Using pins to compress and expand scale intervals.** The time interval of an axis can be manipulated through the metaphor of *pinning time*: placing a pin on the axis binds it to the corresponding timestamp, and moving the pin along compresses time on one side and expands it on the other (D1). To compress time between the first and second Monday of the month, Eve places two pins: one at the end of the first Monday, one at the start of the second Monday, then she drags these two pins close to one another through direct manipulation, which results in the axis time mapping redistributing accordingly (Figure 3.3). She repeats for each consecutive Mondays. TimeSplines provides visual feedback through dashes which are more or less spaced out, depending on whether time is expanded or compressed.

Pins are restricted to maintaining a unidirectional mapping of time, as enabling time reversal would result in time points mapping to multiple line points, and therefore ambiguity in how data should be placed; if a pin is dragged across another pin such that the mapping of time would be reversed, that pin is instead removed, and the time mapping redistributed accordingly. Pins can used to expand and compress certain time frames (Figure 3.3), or bind data features to specific line features (Figure 3.16).

### 4.3 Iterating on Data and Temporal Representation

With her base temporal substrate in place, Eve proceeds to iterate.

Fanny: Try to integrate more of the intent, i.e. the goals for her story. "Eve wants to see how productive she was. She has data xxx; she wants to add it to the timeline."

**Merging data and two-way bindings.** Data can be added in increments (D2), characterizing this process as one of *lazy data binding*, as first demonstrated in Data Illustrator [37]. Each time additional rows of data are bound to an axis, the temporal domain of the corresponding events are evaluated with respect to the current domain of the axis. Binding events with numerical timestamps to a line with a relative time scale will promote the mapping from a relative to a chronological time scale using the new time values. If the axis is already chronological, the domain of the axis will be expanded whenever a new event is added to the axis that has a timestamp that is outside of this domain.

Using the same flow as before, Eve imports her second table which contains the work activity event data and productivity values. She adds the event data to the graph. Because the temporal domain of the events is a subset of the timelines current mapping, the mapping does not change and the events are automatically distributed based on it, with labels arbitrarily positioned so they do not overlap (Figure 3.4).

Event data, specifically text data, can be directly manipulated via the canvas. Eve repositions the text data via dragging so it flares out from her loop (Figure 3.5).

Eve can now update or correct her event data via direct manipulation. Data items are linked to the tables in a two way binding, updating text in the table will update the text on the canvas and vice verse. Additional text items can also be created. Created items can either be bound to a line or placed on the canvas (3.15). Each created item will be added to a table; if the items was bound to a line with a temporal mapping, the table item will have the timestamp set to the time at the point on the line the text was added to. For text bound to a line with a relative mapping or the canvas the time cell is left blank.

**Fine tuning temporal representation.** After organising her data, Eve finds that the Mondays are not salient enough, the smooth curves merges one into the other too much; she wants it to be less continuous. She takes the line deformation tool and straightens the sections between the start and end of the Mondays. The line length in now shorter, but the

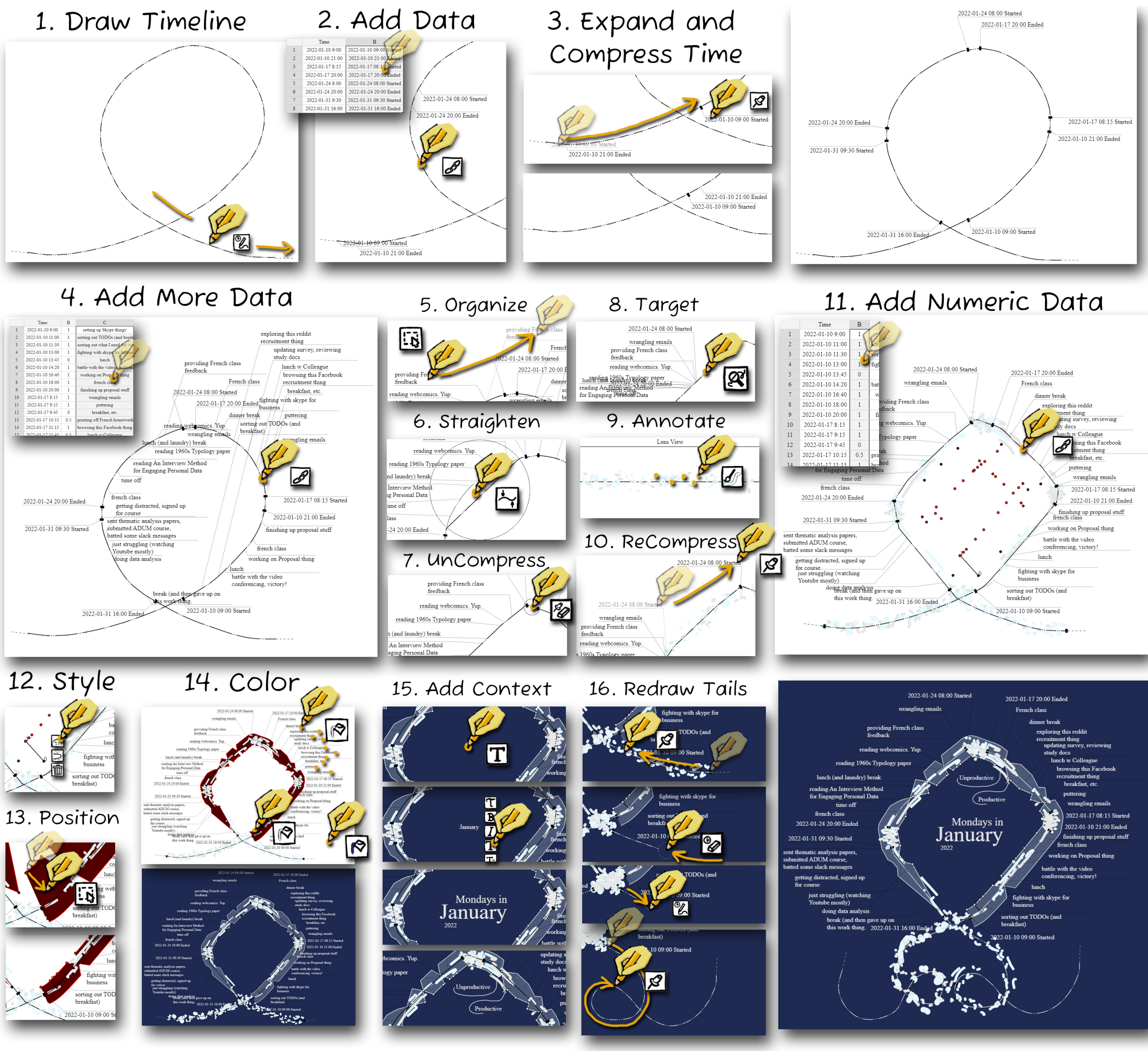


Fig. 3: Using the (1) timeline drawing tool to create the initial line, (2) linking tool to add a small set of initial data, (3) pin tool to expand and compress time, (4) linking tool to add additional text data, (5) selection tool to rearranging text data, (6) straightening tool to modify the line shape, (7) eraser to remove time compression, (8) lens tool to display the line in the linear view, (9) annotation pen to draw a temporal representation, (10) pin tool to recompress the time, (11) linking tool to add categorical numeric data, (12) data style button to choose a numeric representation, (13) axis controls to set the data's positional mapping, (14) color bucket tool to style the visualization, (15) text tool and settings to add styled contextual labels, (16) and the pin, eraser, and timeline drawing tools to redraw the tails.

pins remain in place so the event data remains on the correct segment, and shifts slightly to stay with the new shape (Figure 3.6). The new shape makes Eve think of branch of a snowflake, which she finds be an inspiring theme to further develop.

The deformation tool can also deform lines, moving sections of the line around to give it a more jagged appearance. The time pins are agnostic to deform/straitening, unless the pin is within the area affected by the transformation, it will not move, meaning changes in the time mapping caused by deforming sections of the line will be local to that interval.

**Deconstructing and reconstructing time mapping.** Inspired by the snowflakes shape, Eve wants her time axis to be convey a wintery theme. She has an idea to both convey this theme and the time distortion. Eve knows that if she annotates her line, the annotation will map to the lines time, so then if she compresses time, her annotation will be compressed (D3). She selects the eraser in pin mode and removes the pins to return to a constant time mapping.

As drawing an annotation that is intended to map to a line could result in ambiguity with regard to where on the line the drawing is meant to map, e.g. the place Eve's loop crosses, TimeSplines offers a *lens view* which represents the axes in linear form. Eve targets her line, opening it in the lens view (Figure 3.8), which removes ambiguity as to where the annotation will bind to. This has the added advantage that she can draw her annotation straight and doesn't need to to mentally bend it around her loop. She then draws her snowstorm (Figure 3.9), and recompresses time (Figure 3.10).

**Enriching event data on timelines: adding the quantified-self.** Eve now wants to see how her productivity looks for her Mondays. In the same way as she added the last two datasets, she adds her productivity data, which is an ordinal categorical value encoded at a numeric value (D2) (Figure 3.11). In TimeSplines, numeric time oriented data is placed based on two axis, the first being the length along the line, and the second being distance from the line. The direction for the distance from the line can be either orthogonal to the line, or it in a fix direction specified by the data axis. There are four encoding for numeric data, points, line, area chart, and stream graph. The axis controls the distance from the line, specifying either the distance of the highest and lowest value for point and line representations, or the distance of the highest value and the position of 0 for area chart and streamgraph.

Eve's data automatically aligns with her existing time mapping, so she has no further work to do there. Eve chooses the streamgraph for her visualization (Figure 3.12), and positions it to be centered on her axis (Figure 3.13). She chooses with orthogonal alignment so it will be symmetric over the axis. The data graph now follows the shape of the curve, both giving a visual overview of her productivity rhythm, and having a nice crystalline appearance. She completes the winter thematic styling by coloring it to match her snowstorm.

### 4.4 Style, context, and decoration

To complete her visualization, Eve styles her visualization and adds context. She starts by changing her background color and text color to fit her winter theme (Figure 3.14). She then uses the text tool to add a title to her graph, and labels for her numeric data (D3) (Figure 3.15).

Text on the canvas can be colored, resized, and has a few options for different fonts. The annotation drawing tool offers controls for size, color, and opacity, which together offer a surprisingly expressive range of annotation (D3). Eve increases the size of her graph title, and shrinks her numeric data labels so they aren't obtrusive. She adds thin lines to indicate what the labels refer to.

TimeSplinesalso offers the ability to use external images for annotation (D3). Images can be added directly to the canvas, resized, and optionally bound to an axis. When bound, images link to the date on the line they are bound to, and will therefore change position when the time is remapped. The linked date can be directly edited.

### 4.5 Segmenting and reforming timelines

**Breaking and connecting lines.** Finally, Eve decides she is dissatisfied with the tails of her graph. She wants something that is more decorative, and evokes a sense of continuity. She wants to remove the tails, but keep her snowstorm annotation, so she first uses a pin to compress the storm into the start of the tail, and then removed the tails with the eraser. She then wants to redraw the tails. In the drawing mode, the • anchor appears at the start of the axis and the • anchor appears at the end. The line can be extended from either anchor, maintaining the direction of time. Eve extends her tails, one from each anchor. She then moves the annotation back into the tail, positioning it to have the appearance of trailing off gradually (Figure 3.16).

Eve is slightly dissatisfied with the size and position of one of her tails, and decides to tweak it. She takes the scissors tool, and cuts off the tail. This creates two separate axis with the annotation split across them (D1). The system adds pins to both axis to ensure the snowstorm mapping remains in the same place on the segments as it was when they were connected. The same happens when the eraser is used to remove a section in the middle of a line. Eve can then rotate and resize the tail independently.

Eve then uses the drawing tool to reconnect the tail. In a segmented time representation, each axis has an independent temporal scale determined by the direction the original line was drawn in. When extending a line, if extending from a line start anchor •, the system will hide all other start anchors and only show the end anchors •. If the new stroke terminates at an end anchor axis, the axes will join. If extending from an end anchor •, only start anchors • will be available, ensuring that lines can only be joined unidirectionally. We also disallow the creation of closed-loop (e.g., •A→•B→•A), diverging (•←•↔•→• or •←•↔•→•), or branching axes, as each would result in scale mappings that are ambiguous or difficult to interpret.

Extending or joining axes will redistribute the temporal scale. The system merges data in such a way as to change the mapping as little as possible. When two axis are connected, the system adds pins as necessary to ensure that the data remains in the same place relative to line features. Should the time mapping on the two connected lines overlap, the system removes and creates pins such that the maximum amount of data remains unaffected. The data on the overlapping segments is redistributed over the connected section. If the lines are totally overlapped, or one lines range is a subset the other, etc., the system adds pins greedily, dropping those that are not compatible with the built up mapping.

When Eve is happy with her tail, she reconnects it. Because she used the scissors, the lines connect without moving her annotations. She therefore removed the created pins so her annotation will fill the small gap that was created by the connection. Her visualization is now complete.

**Segmented representations.** TimeSplines allows for a an $N:M$ correspondence between tables and axes on the substrate. Events from a single table can be bound to multiple axes, for example, in Figure 1, it is possible to select the first 17 rows and bind them to one axis while subsequent rows could be bound to another axis. Conversely, in Figure 3, a selection of events from one table are bound in Figure 3.2, while a selection of events from a second table's first (numerical values) and second (text values) columns are bound in Figure 3.11 and Figure 3.4, respectively. It is also possible to bind a single data item to multiple axis.

## 5 Evaluation

In line with previous evaluation strategies for visualization authoring systems [47] and storytelling tools [4], our evaluation incorporates a reproduction study (§5.1), a free-form study (§5.2), and a gallery (§5.3). These three methods also reflect Resnick et al.'s "Low Threshold, High Ceiling, and Wide Walls" criteria [48], which respectively refer to: (i) users can quickly understand how to use the tool's features; (ii) the tool is powerful enough to create sophisticated, complete solutions; and (iii) the tool can support a wide range of explorations. This study was approved by institutional ethics review board (# xxxx).

### 5.1 Reproduction Study

Our first study considered the learnability and usability of TimeSplines.

#### 5.1.1 Method

**Participants.** We recruited 12 participants (6 ♀, 6 ♂) via university mailing lists and community message boards. All participants were young adults. Nine of the participants were students at the time of the evaluation, studying topics ranging from politics and medicine to cinema and economics.

**Apparatus.** The participants interacted with TimeSplines in Google Chrome on a $(1920 \times 1080)$ Wacom Cintiq 16 pen display connected to a Dell laptop running Windows 11.

**Procedure.** We asked participants to reproduce a variation of a person's timeline relating to long-distance running (Figure 4-left), providing them with a representative yet fictional dataset, and Mark Twain's cartoon mnemonic [63] as inspiration: a zigzag line representing periods in English history (see Figure 2c). We did not require an exact reproduction, as this allowed for flexibility in terms of the shape of axes as well as the placement and style of annotations. To acclimate participants to the functionality of TimeSplines, we provided two short video tutorials. We encouraged participants to think aloud as they interacted with the interface, reminding them of the goal of the activity and of particular functionality when it was evident that they were frustrated or stuck, without giving too much of the solution away. Participants were instructed to read through slide deck and complete the tasks, and that they would be stopped ten minutes before the end of the hour to leave time for interview questions. They were not instructed to meet speed or precision goals, though they were asked to try and complete all the tasks in the given time. After completing the reproduction activity, we conducted a brief semi-structured interview to better understand the participant's experience and asked them whether they could envision using TimeSplines with their own data.

**Data collection and analysis.** The first author transcribed and thematically analyzed the audio and screen-capture recordings from each participant's session. Of particular interest were episodes in which participants struggled, patterns of interaction common across participants, and responses to the interview questions.

#### 5.1.2 Results

All of the participants successfully completed the reproduction activity within 15 to 45 minutes ($M = 30$ min). Figure 4 shows three participants' reproductions to the right of the example timeline.

**Sketching temporal axes.** Overall, participants appreciated the flexibility that free-form axis drawing afforded them (**D1**). P11 described the shape of a timeline as having *traits*: " [...] *traits like these zigzags, for example, they're very responsive to change."* P7 contrasted this flexibility to the rigidity of existing tools: *"this thing is really nice because it does fluid lines, in lot of this software, the only way you can connect things is only in a linear manner."* P1 also found the approach to be playful, describing it as *"doodling with data, which is fun in the first place."* Conceptually, participants also appreciated a *"novel way of showing time"* (P12) and realized the creative opportunity that TimeSplines presented: *"these lines that you can free-hand* [...] *it just opens up a lot of different dimensions when it comes to data processing"* (P4).

**Binding data.** Five participants explicitly commented on the process of data binding being simple, or quick to perform (**D2**), with P6 distilling the process in three 3 steps: *"we just click on the column and we draw a line, which is a very simple task, and then we can get all the data on this line"*. However, some participants found the process of selecting and binding data confusing, with P10 and P11 being unsuccessful in adding the requested numeric data to their axis.

**Manipulating time scales.** Most (10 / 12) participants understood the concept of a non-uniform time scale and the role of pins to compress and expand the time scale along the axis (**D1**), and that manipulating pins resulted in the automatic redistributing of event data; the remaining two participants eventually were able to comprehend this aspect of TimeSplines after revisiting the tutorial material. P5 described how *"pins are indispensable,"* explaining that *"if nothing interesting happens in a period of time, I can squeeze* [the timeline]*"*. Both P9 and P10 appreciated how automatic event redistribution following pin placement spared them of tedious manual effort. On the other hand, three participants were skeptical or cautious about manipulating time scales, with P3 describing a general expectation of linear scales, and P2 suggesting that authors must *"admit that the timeline is not going to be linear."*

**Annotation.** We encouraged participants to be creative in terms of annotation (**D3**) and visualization aesthetics, and this was reflected in the results. We observed substantial usage of free-hand sketching to provide additional context (e.g., P4's result in Figure 4). In general, participants were enthusiastic about being able to apply colors to timelines elements, annotations, and the background. A notable example is P5's metaphorical color choices: a fiery palette reflecting difficulty (see Figure 4), explained in a free-hand legend.

**Reflecting on utility.** Participants envisioned various potential use cases for TimeSplines beyond general the categories of communication and reflection, including mind mapping, agenda keeping, and activity tracking, as well as applications in pedagogical (P3) and artistic practice (P9). However, others doubted the scalability of TimeSplines to large event datasets (P9), as well as its applicability to certain types of data, such as financial (P11) or scientific data (P9).

### 5.2 Free-Form Study

In our second study, we assessed the utility of TimeSplines with respect to personal data communication and reflection tasks, in which we allowed participants to select data reflecting a personal interest.

#### 5.2.1 Method

**Participants.** We solicited participation across our personal and professional networks for those with interests, vocations, or hobbies that were reflected or captured in time-oriented data, along with an interest to communicate or reflect on this type of data. We recruited four participants (3 ♀, 1 ♂), ranging in age between 25 and 44, who we will refer to as P13 — P16 (P13 participated in the reproduction study as P1). We compensated these participants at a rate of 15€/hour, including time spent using TimeSplines and time for interviews.

**Apparatus.** The participants used their own equipment and input peripherals at their own home or workplace. P13, P14, and P16 used a computer with a mouse, while P15 used a laptop with a trackpad. P13 and P16 also performed some of the activity using a tablet, and P16 used an Apple Pencil on an iPad. They were free to use any additional software to complement the functionality of TimeSplines, such as spreadsheet applications.

**Procedure.** We first conducted a 30-minute interview to introduce TimeSplines, to review the tutorial videos produced for the earlier study, to learn about their data, and to ascertain any goals that the participant wanted to achieve by visualizing their data. In three of the four cases, participants' used their own time-oriented data. P15 did not use their own data, we instead offered a range of compatible datasets and identified one that piqued their interest.

After the initial interview, we asked participants to dedicate between one and three hours over the course of two weeks to visualize and annotate their data using TimeSplines. We remained in contact during this period, responding to troubleshooting questions as they arose.

In the second interview, we discussed the participant's experience, focusing on their design goals and how the tool supported or prohibited them, as well as any breakdowns they encountered or workarounds they discovered that resulted in a change of creative direction.

**Data collection and analysis.** We instrumented TimeSplines with multimodal telemetry logging. This enabled us to review participants' interaction sequences next to a time lapse of their creation process. We reviewed these prior to meeting for the second interview so as to ground questions observed behaviour and interactions. As with the reproduction study, we recorded and transcribed the interviews, which the first author thematically analyzed.

#### 5.2.2 Results

Figure 5 shows the final outcomes of participants' use of TimeSplines, reflecting three hours of activity in the cases of P13, P14, and P16, and 90 minutes of activity in the case of P15.

**P13: Timeline of a cycling trip.** Combining timestamped elevation and location data from a past cycling trip, P13 initially drew a straight line axis just to see *"how the elevation looked like, [...] it helped me remember as well, because this was a long time ago."* They later incorporated a a map metaphor, where the temporal axis approximately followed the path of the ride. We noted the use of loops in the axis; P13 explained that these corresponded with breaks in the bike trip, or time spent *"around the same place,"* and that expressing these as loops *"worked out well visually."* However, parts of the timeline were becoming unreadable, and P13 admitted that *"it's not possible to have both of very interesting curves and the data being super readable everywhere"*. They therefore decided to break the timeline into two pieces, *"it gave me two places where I could control the alignment* so that *"places of the elevation [...] i wanted to emphasize most, I could choose the axes so that it does that*" Finally, the participant annotated their timeline with photos and free-hand sketching, such as dark strokes to emphasize switchbacks up the mountain, or figurative sweat drops to indicate physical effort. Reflecting on the process, P13 reported that *"the task captured my whole attention because it was a way for me to reminisce about the day when I captured that data, and it was really satisfying to transform those numbers into something that looked personal and told my story."*

**P14: Dance classes.** Beginning with over 20,000 timestamped accelerometer events recorded over the course of a year of dance classes, P14 whittled this down to 300 events via sampling. they initially experimented a timeline in the shape of *"literal As and Bs for fun"* (Figure 5.P14) but later switched to the shape of a lemniscate, a metaphor that the *"dance teacher asks us to imagine a lot when we're doing certain exercises."* The participant explained that visualizing their data in TimeSplines was *"was the perfect way of doing this, and quite simple* [...] *because now I'm plugging in my data in 3D modeling [...], which*

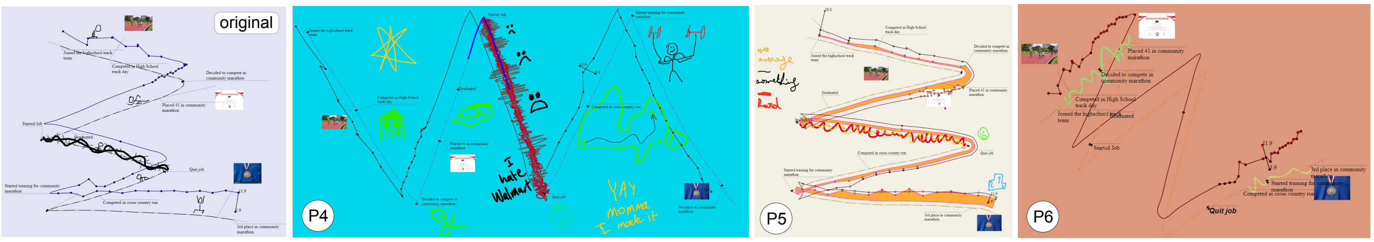


Fig. 4: In the reproduction study, participants reproduced a variation of a zig-zag timeline of events associated with an individual's progress as a long-distance runner (left). Following this are three of the resulting reproductions (P4, P5, P6).

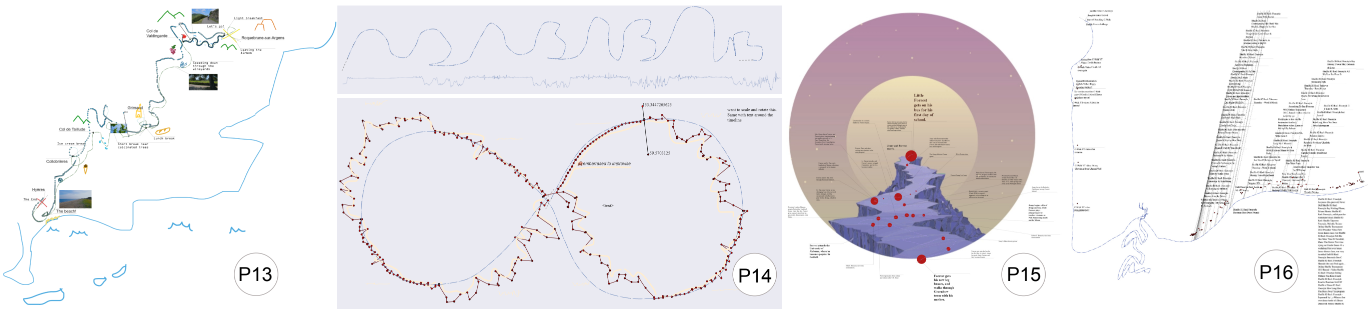


Fig. 5: The final results of the free-form study (L→R): P13's timeline of a cycling trip; P14's dual representations of wrist accelerometer data from a dance class (as a series of A and B shapes and as a lemniscate); P15's rendition of the the plot of the 1994 film *Forrest Gump*; P16's timeline of video views associated with a personal dance journey.

*is much more tedious"*. P14 wanted to view how the data changed over sections of the dance by plotting As and Bs on separate lemniscates, then stacking them in the 3D visualization. They struggled, however, in separating the different AB sections in the data, and evetually used the lens tool to *"to find the right spot between the changes of those sequences"*, because the straight line is *"how I'm used to seeing my data"*. Once P14 found the correct break, they attempted to add only that data to their line, but ran out of time before being able to complete the visualization. Overall P14 found that *"it's been actually quite helpful to be able to like lay it out next to the Rhino stuff"*, because they could try things out here that were difficult in the other tool, *"for example spreading the As and Bs on the right spots around the two circles, that's something i haven't figured out in Rhino, so that's super simple here with the pins"*.

**P15: The plot of *Forrest Gump*.** As P15 a dataset we had prepared as examples on the plot of the 1994 film *Forrest Gump*, which depicts the titular character's life story against a backdrop of real historical events spanning the latter half of the 20th century. P15 is an experienced designer with a workflow that was particularly amenable to working with TimeSplines: *"When it comes to visualizing things, sketching things, or even preparing presentations, I start by experimenting. I don't have something fixed in my mind."* They started with a simple wavy line to which they attached and reviewed the data, then envisioned and implemented the metaphor of a curvy *'life path'* to reflect the story: *"the story of Forrest Gump is a bit hilly and intense* [...] *and there is something nice of the end of his story* [...] *you have a goal, this bright bit at the end"* (Figure 5.P15). In this iteration process, P15 appreciated the ease with which data can be bound and manipulated on an axis: *"it's like boom, it's there, then you can do whatever you like with it, so that's nice."* In P15's first attempt to add the data to the life path, they started arranging the events, but found it frustrating, *"because I'm working with my mousepad of my laptop"*, to moving around so many events, and besides the events might make it hard to parse the graph, as *"some things in the timeline I thought maybe they were unnecessary if you wanted to very quickly look at visualization this story"*. This prompted an iteration where they manually remove data points in Excel and copy a smaller data table back into TimeSplines, and tried again. P15 observed that TimeSplines changed their conventional workflow: *"what this tool does well, and InDesign doesn't do, is that it gives you a structure with this tool, the data comes to the front* [...] *you get to engage with the* [table] *in parallel to engaging with the aesthetics."* Beyond an appreciation for this parallel workflow, P15 also urged us to consider more expressive axis formatting, or rather to avoid differentiating between axis and annotation ink strokes, suggesting that any spline drawn on the substrate could become an axis, even if it was initially drawn as annotation.

**P16: Video views during a dance journey.** For several years, P16 had been posting videos online associated with their personal journey as a dancer. They used an iterative process where they *"would draw a line and then out immediately try to link my data to it to see what it would look like"*. P16 experimented with different metaphors, including constellations because the data is *"bound together by some overarching meanings, like they're all stars in the sky"*, and plants because for the *"connotation that it will keep going"*. P16 ran into issues with the data quantity, partly due to a bug in the system and partly because *"I'd try to add these one hundred twenty data points and then be like shocked like okay that does not work* [...] *fitting in that much text,* [...] *I'd be kind of like overwhelmed opening it again"*. As a desired feature, P16 suggested having *"something that i can like hover over and it does show the text"*.

### 5.3 Gallery

Finally, to evaluate the expressive potential of TimeSplines, each author of this paper used it for creative visualization projects with datasets of their own choosing and without time constraints. We collected the results in an interactive gallery, see supplementary material.

## 6 Discussion and Future Work

Here we discuss the implications of supporting idiosyncratic representations of time-oriented data and directions for future work.

### 6.1 Balancing expressivity and readability

**Multiple uses for expressive and manipulable axes.** Beyond the ability to reflect personal and idiosyncratic experiences of time [26,58], we identified several additional reasons for using flexible and manipulable temporal axes between our freeform study participants' and our own creations. P14 and P15 both incorporated metaphorical figurative elements into the shape of their axes, thereby creating what Byrne et al. [17] refer to as figurative frames for data, providing a semantic association with the underlying data at a glance. We also saw how P13 integrated time and space into the shape of their axis, recalling the aesthetic of hand-drawn route maps [2] and adding using loops to signify idling in place. From our gallery, we demonstrate a pragmatic manipulation of axis shape and scale as a means to accommodate text and image annotations, compressing unimportant or empty intervals of time (Figure 1.a). Finally, Figure 1.d illustrates how multiple temporal axes can be drawn such that they intersect, intertwine, run parallel, or diverge from one another, effectively producing a multi-narrative storyline representation [54], albeit without structured data that explicitly reflects the relationships between the narratives.

**Expressive axes, non-uniform scales, and readability.** As remarked upon by P13, it can be perceptually difficult to evaluate precise values on an expressively-shaped axis. Similarly, if can be difficult to determine the precise duration of intervals on an axis with intervals compressed and expanded by the placement of pins. However, the ability to evaluate individual values is not the only form of readability of concern. Expressive axis shapes could communicate the overall gestalt of event distribution more compactly than a rectilinear axis, and although the use of non-uniform scales might complicate precise comparisons of value or chronology at a *macro* level (i.e., the scope of an entire axis), the ability to perform sequential and local value comparisons at a *micro* level can be preserved. In other cases, affordances for viewers to perform precise value retrieval and comparison may not even be desirable. For example in Figure 1.a, an author might wish to communicate an general sense of their work patterns with their colleagues without telling them precisely how many hours they spent working on a given week. In instances of personal data visualization like this, we echo Perin's call [44] *"to maintain privacy, the visualization must obscure sensitive data and discourage the precise reading of individual values."*

In the instructions for the free-form study, we did not want to limit participants' creativity, so we did not impose any requirement that anyone viewing their creations be able to perform accurate value retrievals. While their creations were personally interpretable, we required their explanations from the follow-up interviews to fully appreciate how to read their timelines. Although viewers may not require the ability to retrieve or compare individual values and intervals, authors may need to perform these tasks during the design process, particularly if they have not already explored or visualized their data using other tools. This is reflected in P13 and P15's processes in our free-form study: before drawing and manipulating expressive axes, they both initially drew a simpler axis to which they bound their event data without any scale manipulations. P14 made use of TimeSplines's inset lens canvas to inspect their data using a rectilinear projection of an axis, as the shape of the axis was substantially contorted on the main canvas.

Although expressive axes and non-uniform scales may have multiple uses, their departure form a rectilinear alignment and inconsistencies in scale may impart an impression that they are less precise than they actually are. Their sketch-based origins, particularly when paired with sketched annotations, may additionally connote informality and uncertainty [67]. These impressions may be desirable in some cases and undesirable in others, such as when visualizing time-oriented financial data, as suggested by P11. Ultimately it is left to the discretion of the author as to what impression they want to make with respect to precision, by varying the degree of sketchiness and the extent to which their axes deviate from rectilinear shapes and uniform scales.

**The risk of flexible and manipulable axes.** As with other visual representations of data, the use of TimeSplines by negligent or nefarious authors could deceive viewers. In particular, the of use expressive axis shapes or non-uniform time scales could obfuscate periodic event patterns, or give impressions of temporal patterns where there are none. Intervals could be compressed to an extent where distant events appear close together, misleading viewers by implying or explicitly indicating a sequential or causal relationship between these events. An author could also expand intervals that contain events that flatter either them or the subject of the timeline, while suppressing intervals containing events that they want the viewer to overlook. We expect that a more salient encoding of expanded and compressed time along an axis will provide viewers with cues to better assess the author's intent with respect to emphasizing some intervals and de-emphasizing others.

**Future work: representing compressed and expanded time clearly.** Directing viewer attention to intervals of compressed or expanded time currently relies upon the salience of pins and a variable dash encoding along the axis, along with the placement of explanatory annotations (Figure 3.9, 10). These former two cues can be quite subtle, particularly in the context of a densely-annotated timeline, while the latter is the authors' responsibility. We therefore must explore more salient visual cues that encode compressed and expanded time without imposing additional manual effort on the author. Any such approaches must additionally be compatible with varied axis shapes as well as different magnitudes of compressed and expanded time, and the visual result should not interfere with the authors' overall aesthetic direction.

### 6.2 Distinguishing, Annotation, Data, and Uncertainty

From an author or viewer's perspective, there is currently no visual distinction in TimeSplines between individual text annotations added manually to an axis from categorical event data added from a table via lazy data binding. The former also generates a new event row that is appended to the first table in the datasheets drawer , effectively promoting the annotation to the status of data. Whether TimeSplines is used longitudinally for reflection on personal data or for communicating with viewers, there will likely be cases where it is helpful or necessary to distinguish between the original structured data, hunches about that data [36], marginalia and other forms of insight externalization [33].

**Future work: annotation as data, annotation as uncertainty.** Currently, different forms of annotation are treated inconsistently. Text-, image-, and illustration-based annotation can be added both to the canvas or bound to positions on an axis, but only axis-bound text annotation is promoted as data. There is no compelling rationale for this inconsistency apart from a need to maintain a structured tabular inventory of images and illustrations. Another inconsistency is the special treatment of illustration-based annotation bound to an axis. Only bound illustrations are projected along the curve of the axis, responsively updating when the shape of the axis changes. The same treatment could be applied to text by setting the baseline to follow the path of the axis (e.g., [12]) or to images by adopting Brosz et al.'s transmogrifier approach for warping images along a spline [15].

Finally, another role that illustration-based annotation could play is to impart additional information on structured data already bound to an axis. Specifically, this annotation could be a way of expressing a degree of uncertainty with respect to when an event occurs, or when an interval begins or ends. Such 'fuzzy' intervals are particularly common in personal or biographical data [55], but the only way of expressing this uncertainty today is via idiosyncratic manual annotation. An alternative illustration mode that codifies this uncertainty and renders it with a sketchier or blurrier brush stroke [67] could be another way to elevate the role of annotation in TimeSplines.

## 7 Conclusion

We introduced TimeSplines, a sketch-based authoring tool for idiosyncratic timelines. TimeSplines observes three design considerations: offering affordances for the flexible and manipulable representation of time, accommodating heterogeneous and accumulative temporal data, and providing multimodal annotation input. Through two user studies and a gallery of examples, we demonstrated the expressive range of TimeSplines, summarized reactions to the concept of a flexible temporal substrate, and identified two major opportunities for future research: exploring ways of clearly representing compressed and expanded time, and resolving the ambiguity between data, annotation, and temporal uncertainty.

## Figure Credits

Figure 2a courtesy of Camilla Torna; Figure 2b-c are Public Domain; Figure 2d courtesy of Giorgia Lupi; Figure 2d courtesy of Charles Perin; Figure 2e permission pending.

## Supplementary Material

The supplementary materials, including the implimentateion of TimeSplines, the code, tutorials, the gallery, and the study apparatus for both studies can be found at exsitu-projects.github.io/timesplines.

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