



HAL
open science

TimeSplines: Sketch-Based Authoring of Flexible and Idiosyncratic Timelines

Anna Offenwanger, Matthew Brehmer, Fanny Chevalier, Theophanis Tsandilas

► **To cite this version:**

Anna Offenwanger, Matthew Brehmer, Fanny Chevalier, Theophanis Tsandilas. TimeSplines: Sketch-Based Authoring of Flexible and Idiosyncratic Timelines. IEEE Transactions on Visualization and Computer Graphics, In press, VIS'23, 10.1109/TVCG.2023.3326520 . hal-04236691

HAL Id: hal-04236691

<https://hal.science/hal-04236691>

Submitted on 11 Oct 2023

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

TimeSplines: Sketch-Based Authoring of Flexible and Idiosyncratic Timelines

Anna Offenwanger , Matthew Brehmer , Fanny Chevalier , and Theophanis Tsandilas 

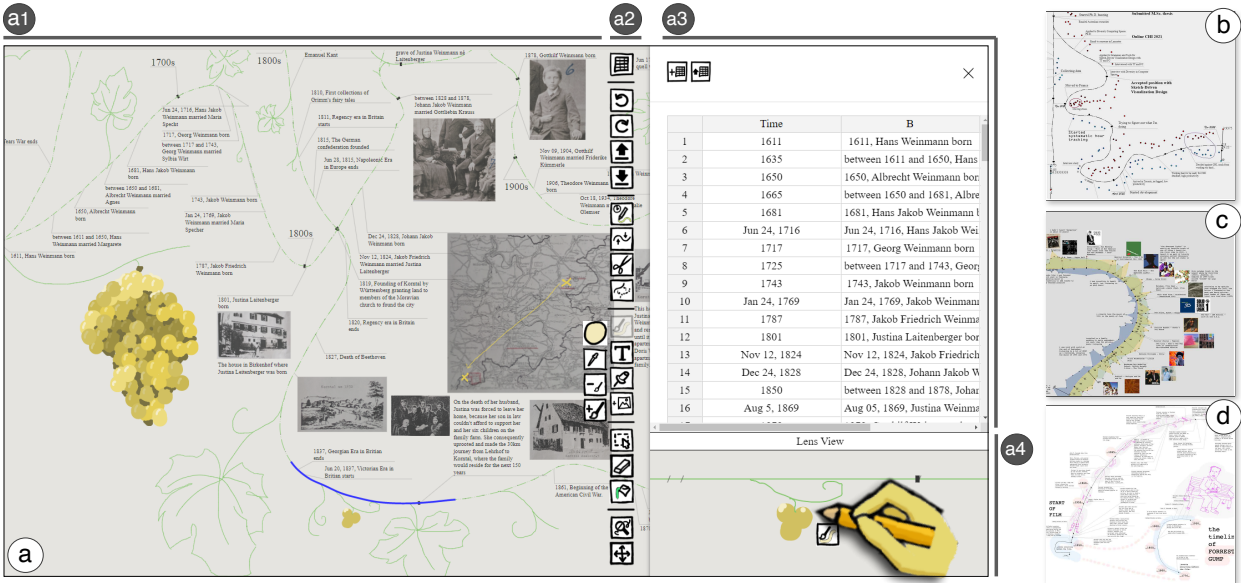


Fig. 1: TimeSplines allows people to sketch idiosyncratic timelines to document or reflect on their data. (a) Here, an example of a family timeline intertwined with a world history timeline. The author can choose from various tools (a2) to sketch and manipulate flexible temporal axes in the canvas (a1) while preserving the temporal integrity of the underlying event data (a3) through lazy data binding. TimeSplines offers the ability to sketch along a timeline through a lens view that shows a linear projection of its path (a4). Examples of visualizations created with timesplines include (b) the path of one author's academic career, including event descriptions, mood data, and work hours data; (c) a compressed music listening timeline, showing counts of songs and the average release year of songs as a streamgraph, along with text and image annotations; and (d) the plot of the 1994 film *Forrest Gump*, featuring illustrative annotations and an inset timeline of historical events occurring prior to the birth of the titular character. For more examples, visit our interactive gallery at exsitu-projects.github.io/timesplines.

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 expand 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, while our curated gallery of images demonstrates the expressive potential of our approach.

Index Terms—Temporal Data, interaction design, communication / presentation, storytelling, sketch-based interface, lazy data binding.

1 INTRODUCTION

Timelines allow people to represent temporal data visually. They are used to tell stories [13, 61], to teach history [33], to identify temporal patterns [42], or to reflect on one's own life [63]. Reflecting on and communicating with timelines can be challenging because many people have idiosyncratic and subjective mental models for time, ranging from "minimalist abstractions to complex symbolic forms" [64]. These mental models often blend simple geometric shapes with figurative and metaphorical elements: in the examples of Fig. 2, we see loops, spirals, disjoint line segments, and mnemonic doodles. Visualizing data along an idiosyncratic representation of time presents a challenge, particularly as many existing tools for creating timelines are rigid, representing time as a single straight line with a consistent chronological scale. As a consequence, many people still turn to illustration tools, from pen and paper to applications like Adobe Illustrator, but these tools do not retain any mappings to time-oriented data. Moreover, authors are compelled

- Anna Offenwanger and Theophanis Tsandilas are with the Université Paris Saclay, CRNS, Inria, LISN.
E-mail: {anna.offenwanger | theophanis.tsandilas}@lisn.upsaclay.fr
- Matthew Brehmer is with Tableau Research.
E-mail: mbrehmer@tableau.com
- Fanny Chevalier is with the Departments of Computer Science and Statistical Sciences at the University of Toronto.
E-mail: fanny@dgp.toronto.edu

Manuscript received xx xxx. 201x; accepted xx xxx. 201x. Date of Publication xx xxx. 201x; date of current version xx xxx. 201x. For information on obtaining reprints of this article, please send e-mail to: reprints@ieee.org.
Digital Object Identifier: xx.xxxx/TVCG.201x.xxxxxxx

to commit early to a specific layout or coordinate space because of “*the cost in effort and time of manual encoding*” [8]; with time-oriented data, this means committing to the shape of a temporal axis and its time scale. Experimentally plotting data along different shapes and scales would require great patience.

In practice, creative visualization often involves iterating between making representation choices, identifying and reflecting on the relative importance of visual patterns, and adding contextual annotation, a process that typically requires multiple tools [9]. Recent research projects [35,52,75] have been exploring the potential of integrating data visualization and manual illustration functionality within a common tool, accelerating this iterative process. However, prior research has yet to focus on the unique challenge of integrating the visualization of temporal data with expressive and idiosyncratic illustrations of time.

In this paper, we introduce TimeSplines, a tool for supporting rich, idiosyncratic visualization of time-oriented data. The design of this tool is grounded in three considerations that descend from a design space for communicating with timelines [13], a study on the use of timelines for personal reflection [61], and insights from the development of prior visualization authoring tools [54]. These considerations include providing affordances for flexibly representing and manipulating time, accommodating the incremental encoding of heterogeneous temporal data, and a palette of expressive multimodal annotation options. We describe a workflow in which *sketch-based interaction* performed on flexible temporal substrate supports idiosyncratic representations of time as well as annotation. This workflow employs *lazy data binding*, where graphical elements are first created and later bound to data [40], which allows authors to reference data from multiple sources.

We evaluated TimeSplines using three established methods [50]: a reproduction study with 12 participants to evaluate both the concept and the system’s usability and learnability, a free-form study with four participants to evaluate creative workflows, and a gallery of material produced with TimeSplines to demonstrate the expressive power of our approach. We found that participants were able to appropriate the concepts behind TimeSplines and express themselves in a variety of ways. We documented multiple workflows and use cases that included the mapping of spatiotemporal and periodic relationships, the use of metaphors to visualize historical fiction, and a reflection on journeys of personal growth and accomplishment. Finally, our gallery documents the expressive range of TimeSplines, encompassing various timeline shapes, manipulations of temporal scale, and approaches to annotation.

Our **contributions** are as follows: (1) a novel approach of sketch-based interaction on a flexible temporal substrate for supporting idiosyncratic timeline authoring, encapsulated in the TimeSplines application; and (2) results and reflections from a multi-pronged evaluation of TimeSplines, revealing opportunities for future explorations of how to effectively represent the compression and expansion of time while balancing readability, as well as how to broaden the role of annotation in sketch-based visualization design.

2 RELATED WORK

The design considerations underpinning TimeSplines are grounded in prior literature on temporal visualization as well as prior tools leveraging sketch-based interaction and lazy data-binding.

2.1 Timeline Visualization

Timelines have been used to visualize event sequences for hundreds of years [53]. Today, they are used in the analysis of health records [42, 74, 77], in history education [33], in storytelling [13], and in practices of self-reflection [22, 61] and therapy [7].

The varying shapes of time. Particularly when using timelines to communicate or reflect on time-oriented data, a familiar linear representation of time with a consistent chronological scale is not always desirable [13]. Cyclical, spiral, and calendar-based [70] representations of time are viable alternatives that “*emphasize the cyclic character of time*” [3]. Apart from these basic and symmetric shapes, the path of time through space can convey temporal relationships between quantitative values, such as in connected scatterplots [29], and time curves [5]. Kim et al.’s Story curves [34] can also result in unusual shapes for

time, as these curves encode the relationship between chronological time and sequential narrative order in works of film or other media, explicitly showing non-linearity as well as the use of ellipsis or montage sequences to compress or elide intervals of time. Time can also assume unusual shapes when subsumed in the representation of spatial relationships, from route maps [2, 47] and long-distance flight paths [25] to egocentric maps of personal movement patterns [44] and multi-character storylines [60]. In each of these cases, the shape that time takes either observes a consistent and symmetric coordinate space or is bound to other non-temporal values, such as speed [47]. The prospect of unbounded shapes for time is comparatively under-explored.

Free-form shapes for time can also impart meaning through metaphorical or figurative mnemonic cues [69]; some are idiosyncratic to the point of being uniquely meaningful to whoever has drawn the timeline [31, 64]. Unusual timeline shapes appear frequently when people are asked to sketch their own personal perspective on time [28, 31, 64]. In one study, Thiry et al. [61] found that “*an appearance of evenness, although desired, [is] incongruent with the way that events unfold over a lifetime.*” This is unsurprising, as Snyder et al. [58] describe how “*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.*” A linear conceptualization of time can also be a major obstacle for some individuals; for instance, Snyder et al. reported how those suffering from bipolar disorder struggled to draw a timeline that extends linearly into the future, opting instead for “*visual geometries that did not have such explicit beginnings, middles, or ends.*” Egocentric time perception is also affected by factors including cultural trends [26, 68] and the availability bias, which places greater significance to recent events [67].

Binding data to time. When plotting data along a representation of time, flexibility is necessary for authors to “*emphasize what [one] subjectively considers important to communicate and share in the data*” [46] and accommodate the annotations, captions, and images that contextualize this data [13]. Unfortunately, programmatic data visualizations often entail rigid rectilinear coordinate spaces containing consistent, symmetric, and often polygonal representations of data, along with consistent scale mappings. In previous research in the context of personal data, timelines are constrained to a single linear representation of time, such as in the Timeline Collaborations project for parental leave planning [10]. Our work therefore responds to the call for “*visual techniques [that] accommodate the completeness of story elements and shape flexibility*” [1]. While individual visualization projects have been used to tell personal stories with creative timeline shapes [19, 46, 62], it is difficult to achieve these results without a programming background, so they remain “*the privilege*” of programmers [46]. Interactive computer-supported authoring options are needed to support these use cases, and TimeSplines aims to fill this gap.

Tool support for non-linear representations. While prior surveys [3, 13] list many interactive visualization and analysis tools capable of producing linear timelines, there are fewer tools that visualize time-oriented data around circles or spirals, and fewer still that support the use of free-form shapes. Timeline Storyteller [14] is rare in this capacity, but even it reinforces a consistent scale along a free-form sequential axis, as well as a consistent representation when multiple timelines appear within the same canvas. Other interactive visualization tools for time series analysis offer the ability to expand and compress temporal axes or zoom in on specific intervals. Kronominer [78] supports compressing or expressing sections of time in a pop-out ring view on a circular axis. Similarly, TimeNotes [71] and Chronolenses [79] support an interactive focus plus content display of time series at diverse temporal granularities. Our work takes inspiration from these systems by allowing visualization authors to easily stretch and compress time along free-form axis shapes within a sketch-based interface.

2.2 Sketch- and Pen-Based Interaction for Visualization

Paper sketching is often used in visualization design [16, 32, 45], as it affords a flexibility that is especially necessary for creative visualization, where it is often necessary to iterate through multiple variations

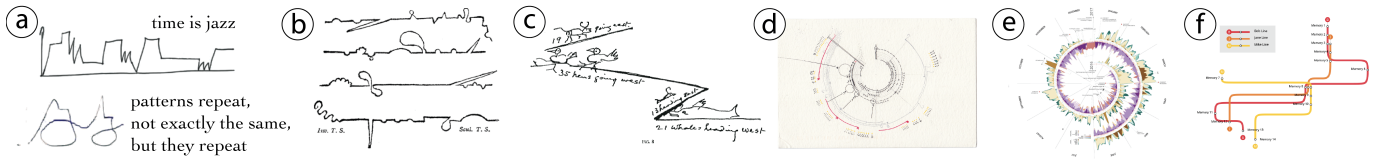


Fig. 2: Examples of idiosyncratic representations of time: (a) sketches drawn by people from the prompt “How do you see passage of time?”, curated by Camilla Torna [31]; (b) Laurence Sterne’s non-linear plot lines from *The Life and Opinions of Tristram Shandy, Gentleman* [59]; (c) Mark Twain’s zig-zagging representation of monarchs’ reigns [69]; (d) Giorgia Lupi’s nested semi-circles in “Week in our past” from *Dear Data* [41]; (e) Charles Perin’s spiral-shaped “Symmetry of my life” [46]; and (f) three people’s separate and shared memories visualized according to a metro map metaphor from memoryunderground.com.

before the final result. Lupi and Posavec’s *Dear Data* project [41] is the canonical demonstration of this process. Sketching facilitates an idea transformation process [27, 72] and is accessible to non-expert visualization designers [57, 73]. However, in interviews with designers, Bigelow et al. [8] found that “inferences about data behavior were often inaccurate” while sketching, which can be a costly problem if adding data reveals the need for a major design overhaul late in the process. Tools that interleave the ingestion of data with sketching could therefore save time by revealing these issues early.

Sketch-based input for visualization design. Flexible sketch-based input via a pen or stylus interface can serve to avoid prescriptive workflows [8, 20] and enable multiple stages of development within the same tool. Earlier works like NapkinVis [21], SketchStory [37], and SketchInsight [38] explored sketch-based gestures to trigger chart generation, while more recent tools like DataToon [35] and DataInk [75] allowed for the sketching of bespoke visual encodings. Sketch-based visualization tools have also targeted specific application domains, such as Knotation [24], a tool for sketching and manipulating spatiotemporal relationships in dance choreography, and Visualization-by-Sketching [56], a system for sketching and annotating animated illustrations of time-varying data. TimeSplines continues this line of research with the sketching of free-form temporal axes.

Sketching to annotate. Prior work has also incorporated sketching to annotate charts and visually differentiate between structured data and personal knowledge externalization [36, 52]. TimeSplines also supports sketch-based annotation, along with the option to bind these annotations to the shape of a temporal axis via transmogrification [15].

Pen-based direct manipulation for visualization. Beyond sketching to add data elements and annotations directly, prior work has also explored the use of pen-based interaction to ensure manipulations are as direct as possible. Examples include DataQuilt [76], in which a pen is used to select and copy visual elements from existing image media, TaleBrush [23], where users can sketch a narrative curve to generate text for a corresponding story plot, and SketchSliders [66], which leverages personalized sketch-based interaction on a tablet to manipulate visualization on a wall display. While TimeSplines does not incorporate specific pen-based gestures, we do allow the pen to be used beyond sketching and annotation (Fig. 3).

2.3 Lazy Data Binding

Interactive visualization construction tools struggle to accommodate design experimentation [54], which includes the ability to flexibly alternate between data binding and annotation [9], or between macro-level layout choices and micro-level data mark specifications [49]. In the context of scientific visualization, the *ink-data settling* approach [55] addresses this struggle by letting the artists freely draw illustrative marks, while the system automatically infers associations between these marks and the data. A different approach is *lazy data binding*, first demonstrated in Liu et al.’s Data Illustrator [40], in which marks are drawn before being parameterized, split, or duplicated via data binding. Like other recent projects incorporating this technique (e.g., [65, 75]), we too incorporate lazy data binding in the mapping of events to a previously sketched temporal axis.

3 DESIGN CONSIDERATIONS

We now outline design considerations for tools that support the authoring of idiosyncratic temporal visualizations. These considerations are based on our analysis of prior work and motivated by historical and recent examples where time is represented in creative ways (see Fig. 2).

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 familiar shape as having an *arbitrary* curve representation of time. However, these curves are hardly arbitrary to the author, often reflecting a personally meaningful and idiosyncratic perception on time. These curves can accommodate rich textual and illustrative annotation, as seen in Fig. 2c. Further, these multiple representations of time should not only be able to appear in juxtaposition, such as in Fig. 2b, but potentially also in sequence, such as in Fig. 2a, where straight lines are connected by curves. It is not only necessary to support custom curves, but also the ability to split and merge them.

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 [34], 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 should 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 Fig. 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. We therefore recognize the need to reconcile these differences and assign imprecise chronological or ordinal data to positions on a temporal axis.

Incremental data curation. Creative visualization workflows rarely involve a prescribed sequence of iteration and ideation [54]. Initial design ideas could be sketched before any or all of the data is gathered [8], and visualization process often informs which data is included [39, 61]. 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 can affect the design in unpredictable and undesirable ways, such as by inducing visual clutter, requiring a redesign of the layout. We must minimize the complexity of any redesign and avoid disrupting the placement of existing elements.

D3: Multimodal Annotation

Annotation is essential to data-driven storytelling [48], adding critical orientation and context for viewers, especially when showing time-oriented data [17,30]. Annotation is particularly important if the choice of representation is unconventional (D1) or if the data is personal in origin [43,63], 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 [36] and develop hunches based on a personal connection to the data [39].

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 [18] 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 emotional and thematic impressions at a glance.

Annotations can be explicitly linked to data elements or placed freely on the canvas to provide a broader contextualization. It is critical that linked annotations be responsive to changes that affect the position of data elements, such as modifying axes shapes or temporal scales.

4 TIMESPLINES

In this section, we describe TimeSplines, a browser-based authoring tool that 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 [6]. The interface is depicted in Fig. 1.a: it encompasses the substrate (a1), and a container of tables corresponding to temporal data bound to the substrate via lazy data binding (a3). We outline the functionality of TimeSplines with a usage scenario (Fig. 3):

Eve wants to create a timeline depicting her activities on Mondays during the month of January to reflect on her work habits and to share with her friends. She has her activities, work hours, and productivity data recorded in separate spreadsheets.

4.1 Sketching a Timeline (Fig. 3.1 — 3.2)

Eve has a rough idea of what she wants her creation to look like: a loop-shaped timeline which emphasizes the Mondays, compressing other days of the week since they are not the focus. Eve draws an initial axis: a loop-shaped stroke using the timeline drawing tool (Fig. 3.1).

Free-form drawing of a temporal axis. Temporal axes can be sketched on the substrate via free-form pen or mouse input, akin to drawing in vector graphics tools (D1). TimeSplines 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.

Eve copies and pastes her data from a spreadsheet into TimeSplines’s datasheets drawer. This data is timestamped textual description of when she started and ended work each day in January.

Loading data. Data can be pasted directly to sheets in the drawer (Fig. 1.a3) or uploaded from a CSV. The drawer can contain any number of tables with any number of columns (D2). Each row is optionally associated with a single point in time, specified by a timestamp in the first column. No single format for the timestamp is required; it can accommodate sequential numerical values as well as dates and

date-time values, which are all coerced to a millisecond timestamp. If the first column is left blank or has a value that cannot be parsed, data bound to an axis is placed at the start of the axis and can be positioned manually. The data in the rest of the table is treated as numeric data if it can be parsed as a number and is otherwise treated as text data.

To populate her axis with these events, Eve selects events from January, clicks the binding tool, and selects her axis (Fig. 3.2.)

Binding data to a temporal axis. Time-oriented data can be bound to axes in increments by selecting subsets of data and the desired axis (D2). TimeSplines automatically maps the earliest bound time value to the start of the axis and the latest time to the end. The positions of intermediate events are interpolated along the length of the line. Textual values are rendered as labels with an offset from the interpolation point. Numeric values are represented as circle marks positioned perpendicular to the interpolation point, with an offset determined by a numeric axis, as described in Section 4.3.

4.2 Manipulating the Scale of Time (Fig. 3.3)

Next, Eve expands Mondays and compresses the other days of the week. To compress time between the first and second Monday of the month, she 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 (Fig. 3.3). She repeats for each consecutive Monday.

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 through direct manipulation compresses time on one side and expands it on the other (D1). TimeSplines provides visual feedback for expansion and compression with variable dashing along the axis, with longer dashes in expanded intervals and shorter in compressed ones. We also considered variable tick marks, as recommended [47], but we found these ticks visually compete with the visual marks corresponding to temporal events, so we opted for a more subtle dashing. We restrict pin placement to maintain a unidirectional mapping of time. Pins cannot be moved to form reversals in the direction of time, as this would result in ambiguity with respect to where timestamped data should be bound. Whenever a pin is dragged beyond the placement of another pin, the second pin is removed, and any events on the axis are redistributed accordingly.

4.3 Iterate on Data and Representation (Fig. 3.3 — 3.13)

With an initial axis in place, Eve can now manipulate it and add data. Using the same flow as before, Eve imports and binds a second table which contains work activity event data and productivity values (Fig. 3.4). Eve re-positions the text labels via dragging such that they radiate from the loop (Fig. 3.5).

Merging data and two-way binding. Data can be added in increments (D2) via *lazy data binding* [40]. When more rows of data are added to an axis, the temporal domain of the corresponding events are evaluated in relation to the axis’s current domain. If events with numerical timestamps are bound to a line with a relative time scale, the line shifts from a relative to a chronological scale using the updated temporal domain. If the axis is already chronological, its domain will expand automatically whenever a new event with a timestamp outside of the current domain is added to the axis.

TimeSplines allows for 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 Fig. 1.a, the first 17 rows can be bound to one axis while subsequent rows could be bound to another. Conversely, a selection of events from one table are bound in Fig. 3.2, while a selection of events from a second table’s first and second columns are bound in Fig. 3.11 and Fig. 3.4, respectively.

Event text labels can be directly manipulated in several ways. When added, labels are initially positioned such that they do not overlap, however they can be freely moved via dragging. These labels remain bound to the tables, so updating the text in the table will update the text on the substrate and vice versa. We allow for additional text labels to be individually created directly on the substrate, either bound to an axis or

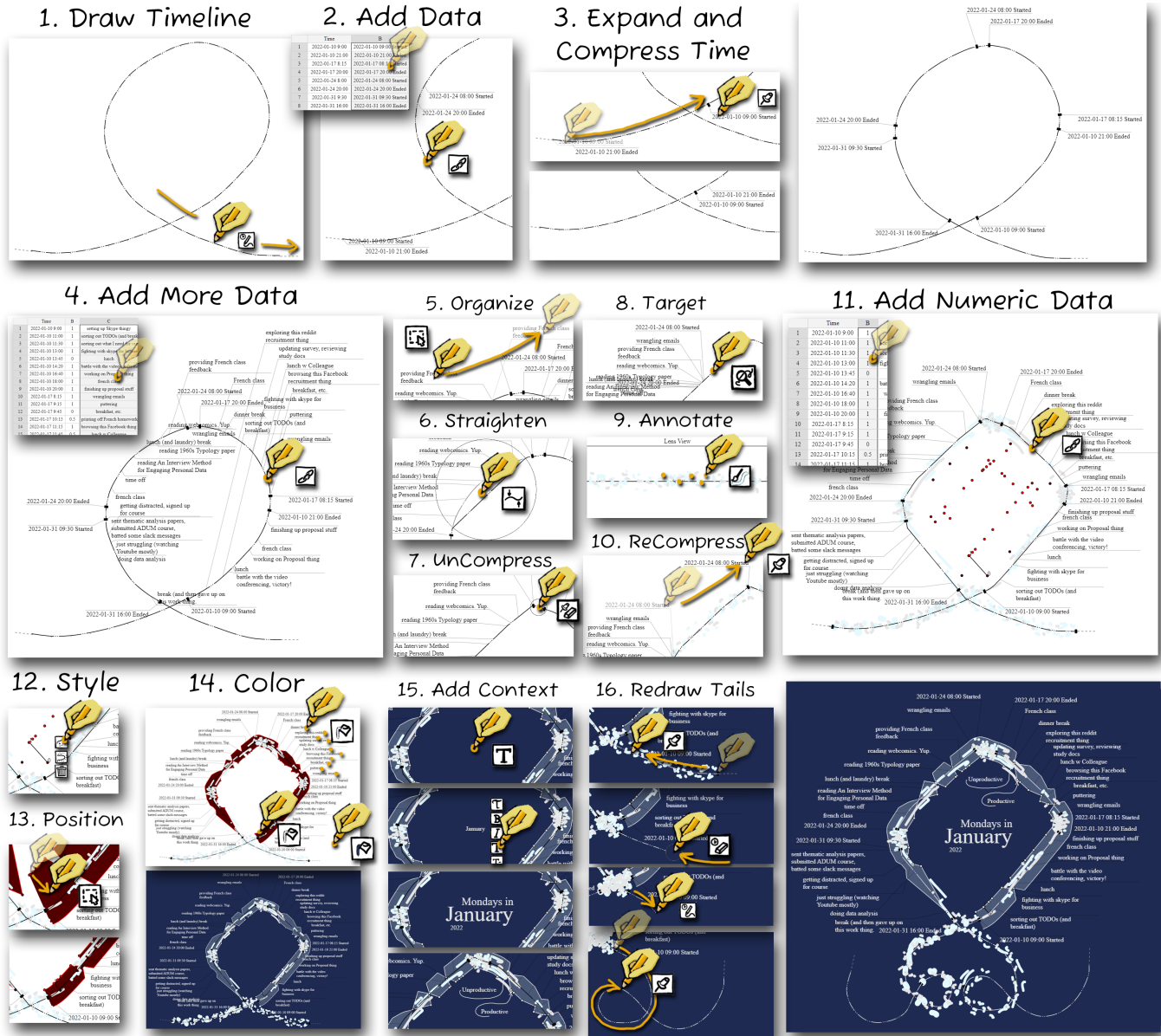


Fig. 3: Using the (1) pen tool to draw an initial axis, (2) a binding tool to add a small set of initial data, (3) a pin tool to expand and compress time, (4) the binding tool again to add additional text data, (5) a selection tool to rearrange text data, (6) a straightening tool to modify the line shape, (7) an eraser to remove time compression, (8) a lens tool to reveal a linear projection of the axis, (9) an annotation pen to add figurative illustrations within the lens, (10) the pin tool again to re-compress the time, (11) the binding tool once again to add categorical numeric data, (12) an encoding palette to select a representation for numeric data, (13) axis controls to specify the positional mapping of numeric data points, (14) a color bucket tool to style the visualization, (15) a text palette to add styled contextual labels, (16) and the pin, eraser, and timeline drawing tools to redraw the tails.

placed freely (Fig. 3.15). These newly created labels are automatically added to a table as new rows. When a label is bound to an axis that has a chronological scale, the timestamp in the table is assigned to the time corresponding to the label's position on the axis. However, if the label is placed freely or on an axis without a chronological scale, the timestamp is left empty.

After organizing her data, Eve determines that the smooth curves joining Mondays are too subtle. She takes the line deformation tool and straightens the sections between the start and end of subsequent Mondays (Fig. 3.6). The new shape reminds Eve of a snowflake, which inspires her to adopt a winter theme.

Adjusting the axis. Axes can be resized, translated, and rotated, and any data bound to the axis will transform accordingly. The deformation tool can also deform lines, moving segments of the line around, resulting in a more jagged path. The time pins are agnostic to deforming and straightening; unless a pin is within the area affected by the deforma-

tion, it will not move. As a result, changes in the temporal scale caused by deforming segments of the axis will be local to that interval.

Eve wants to further develop her wintry theme while also drawing attention to the temporal scale distortion. She wants to add a snowstorm feel to the Mondays. She uses the eraser to remove some pins, restoring a linear time scale, then selects an interval to reveal in the lens view (Fig. 3.8). Here she draws a snowstorm illustration (Fig. 3.9), and then re-compresses time on the axis with new pins (Fig. 3.10).

Responsive annotation. Annotations bound to an axis will stretch and compress according to the axis' scale (D3). However, drawing an annotation for a specific interval can be particularly challenging when the axis is curvy or self-intersecting (e.g., where the loop crosses in Fig. 3). To this end, TimeSplines offers a lens view which displays a linear projection of the axis (Fig. 1.a4). In annotating here, there is less ambiguity as to where the annotation will bind, and there is no need to mentally rotate an envisioned annotation while drawing. Annotations

are transmogrified [15] to the shape of the axis.

Eve now wants to see how her productivity varies across Mondays in January. In the same way as she added the last two datasets, she adds her numeric productivity data (Fig. 3.11). Eve chooses a streamgraph encoding for this data (Fig. 3.12), and positions it to be centered on her axis (Fig. 3.13). The timeline now provides a visual overview of her productivity rhythm, and exhibits a cool crystalline aesthetic. She extends her wintry theme by coloring the streamgraph to pair well with her snowstorm illustration.

Adding numeric data. Numeric data is mapped according to two axes: the temporal axis and a numerical axis. Numerical axes extend either vertically or orthogonally from the temporal axis (D2) and their scale and position can be adjusted by dragging the endpoints. TimeSplines provides four encoding choices for numeric data: scatterplot points, a connected scatterplot [29], an area chart, or a streamgraph. When choosing an area chart or streamgraph encoding, the numeric scale domain is automatically set to start from zero. Alternatively, for other encodings, the numeric scale domain is determined by the range of values in the corresponding data column. To preserve authors' creative freedom, we place no restriction on the extent to which numerical axes can span across temporal axes. This approach may lead to overdrawing, which authors can choose to mitigate or ignore.

4.4 Adding Context and Style

Eve completes her winter theme and adds contextual annotation to the substrate. She changes the background and text colors to suit her theme (Fig. 3.14). She then uses the text annotation tool to add and size a title, as well as annotations to explain the numeric productivity data (D3) (Fig. 3.15), along with thin lines to the label referents.

Styling the visualization. Text on the substrate can appear in various fonts and be recolored or resized. Similarly, the annotation tool offers controls for brush size, color, and opacity (D3). TimeSplines also offers the ability to annotate the substrate with external images, which can in turn be resized and optionally bound to a point on an axis.

4.5 Extending, Merging, and Splitting Axes

Finally, Eve decides that she is dissatisfied with the tails of her axis. She would prefer a more figurative shape that evokes a sense of continuity, but she doesn't want to lose her snowstorm annotation. She uses a pin to compress the snowstorm illustration into the start of the tail. She then removes the axis tails with the eraser and redraws them with the pen tool. She then moves the snowstorm illustration back into the tails, positioning it to have the appearance of trailing off gradually (Fig. 3.16). Still dissatisfied with the size and position of one of her tails, she decides to cut the tail with the scissors tool. Eve then rotates and resizes the cut section and then reconnects it with the main axis. She now considers her work to be complete.

TimeSplines provides affordances to easy transition between a single axis and multiple axes (D1).

When using the drawing tool, a ● anchor appears at the start of an axis and the ● anchor at its end. The axis can be extended from either anchor, maintaining the direction of time.

When multiple axes appear on the substrate, each axis has an independent temporal scale determined by the direction that each was drawn in. When extending an axis from a start anchor ●, the system will hide all other start anchors and only show end anchors ●. If the new stroke terminates at an end anchor ●, the two axes will merge. Conversely, 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. TimeSplines merges data in such a way as to change the mapping as little as possible. When two axes are connected, we add pins to ensure that the data remain in close proximity to prominent line features. Should the temporal domain of two merged axes overlap, TimeSplines removes and creates pins to preserve the placement of data to the extent that is

possible. Any data corresponding to overlapping time intervals will be redistributed as a result of the merge. If the domains of the two axes overlap totally, or if one domain is a subset the other's, TimeSplines adds pins greedily, dropping those that are incompatible with the merged domain.

Finally, axes can also be split with the scissors tool or the eraser. When separated, data remains in the same position relative to prominent line features, albeit now split across two axes.

4.6 Implementation

We implemented TimeSplines in JavaScript, and render the contents of the temporal substrate to SVG using d3.js [11]. The application runs locally within a web browser. We provide a link to try TimeSplines along with its source code in the supplementary material.

5 EVALUATION

In line with previous evaluation strategies for visualization authoring systems [50] 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 [51], which respectively refer to: (1) users can quickly understand how to use the tool's features; (2) the tool is powerful enough to create sophisticated, complete solutions; and (3) the tool can support a wide range of explorations. This study was approved by Inria's ethics review board (COERLE n° 2022-60).

5.1 Reproduction Study

Our first study investigated TimeSplines' learnability and usability.

5.1.1 Method

Participants. We recruited 12 participants (6 women, 6 men) via university mailing lists and community message boards. Nine of the participants were students studying topics ranging from politics and medicine to cinema and economics, two were post-docs, and one was a project manager.

Apparatus and context. Participants were provided with a (1920 × 1080) Wacom Cintiq 16 pen display connected to a Dell laptop running Windows 11 with a copy of TimeSplines running on Google Chrome. The slides with the tasks were open on the computer screen next to the tablet. Each study took place in a quiet meeting room, with the first author was present throughout.

Procedure. The entire study took around an hour for each participant. After explaining the study and having participants fill out the survey (15 min), we asked participants to reproduce a variation of a person's timeline relating to long-distance running (Fig. 4-left). We provided them with the slide deck containing tasks interspersed with tutorial videos, a representative yet fictional dataset, and Mark Twain's cartoon mnemonic [69] as inspiration: a zigzag line representing periods in English history (see Fig. 2c). Participants were instructed to read through slide deck and complete the tasks. 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. 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 (30–40 minutes). We encouraged participants to think aloud as they interacted with the interface. We reminded 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. 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 (10 min).

Data collection and analysis. We collected and transcribed audio and screen recordings for each session. We conducted a thematic analysis of the transcripts, along with notes taken by the researcher during each session, and the survey results. Of particular interest were episodes in which participants struggled, patterns of interaction common across participants, and responses to the interview questions.

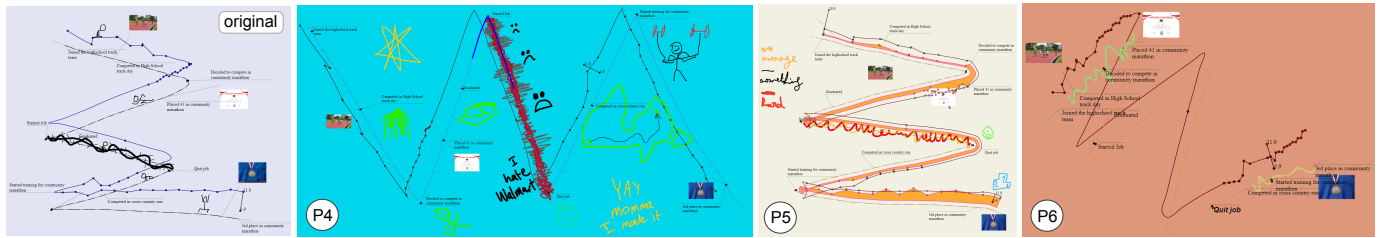


Fig. 4: In the reproduction study, participants reproduced a variation of a zig-zag timeline of events associated with an individual's progress as a long-distance runner (left). Following this are three of the resulting reproductions (P4, P5, P6).

5.1.2 Results

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

Sketching temporal axes. Participants appreciated the flexibility that free-form axis drawing afforded them (D1), with 8/12 mentioning flexibility as a strength of the system. P11 described the shape of a timeline as having traits: “[...] like these zigzags, for example, they're very responsive to change.” P7 contrasted this flexibility to the rigidity of existing tools: “[TimeSplines] is really nice because it does fluid lines; in lots of these software, the only way you can connect things is only in a linear manner.” 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). However, just as many 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 due to an incorrect data selection.

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.

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 Fig. 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 Fig. 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). Unsurprisingly, participants also 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 for 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 women, 1 man), 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. The study was designed to last 2–4 hours. We first conducted a 30-minute interview to introduce TimeSplines, to review the tutorial videos produced for the earlier study, to learn about the participants data of interest, and to ascertain any goals 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 several 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.

We then conducted a second semi-structured 30-minute interview where we discussed the participant's experience, focusing on their design goals and how the tool supported or impeded 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, and requested participants to upload this logging when they had finished their visualization. From only these logs we could review participants' interaction sequences next to a time lapse of their creation process, which we did prior to the second interview, so as to ground questions in observed behavior and interactions. We recorded and transcribed the interviews, which the first author thematically analyzed.

5.2.2 Results

Fig. 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 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

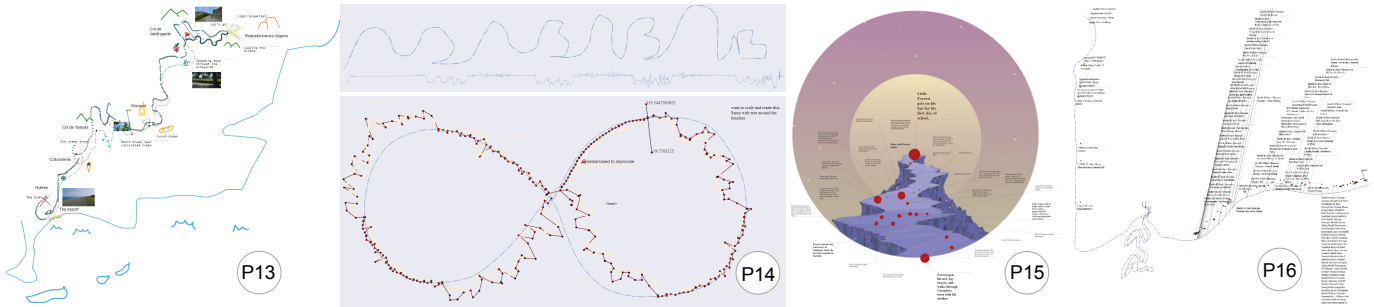


Fig. 5: The final results of the free-form study (L→R): P13’s timeline of a cycling trip; P14’s dual representations of wrist accelerometer data from a dance class (as a series of A and B shapes and as a lemniscate); P15’s rendition of the the plot of the 1994 film *Forrest Gump*; P16’s timeline of video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

“worked out well visually.” However, parts of the timeline were becoming unreadable, and P13 reflected 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 found “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” (Fig. 5.P14) but later switched to the shape of a lemniscate, a metaphor for the quality of the movement 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 the perfect way of doing this, and quite simple [...] because now I’m plugging in my data in 3D modeling, [...] which 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 eventually used the lens tool “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*. P15 used a dataset we had prepared 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’: “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” (Fig. 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.” During P15’s first attempt to add the data to the life path they found the process frustrating to move so many events with a laptop mousepad. They also observed that the

large number of events made it difficult to interpret the graph, “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 removed data points in Excel and copied 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. In other words, authors could encode data using initially symbolic elements at any stage of the workflow.

P16 - Visualizing a dance journey. P16 has been posting videos online associated with their personal journey as a dancer. They worked in an iterative process where they “would draw a line and then I’d 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.” In the iterative process, P16 quickly realised their initial idea would not work with their data, “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 hover over and it does show the text.”

5.3 Gallery

Finally, to evaluate the expressive potential of TimeSplines, we used it for creative visualization projects with data of our own choosing and without time constraints. We generated nine visualizations demonstrating a range of temporal representations and data types in an interactive gallery, which we provide as supplementary material. The gallery demonstrates the use of segmented, parallel (Fig. 1.a), branching (Fig. 1.b), and inset timelines (Fig. 1.d), as well as examples featuring multiple time scales (Fig. 1.d). It further demonstrates the use of illustrative images (Fig. 1.c), illustrative (Fig. 1.a, d) or temporal annotations (Fig. 3.8-10), data images (Fig. 1.a), and multiple datasets, as many as six tables, with event, numeric, and categorical data (Fig. 1.b). We found that the size and complexity of timelines were partly constrained by the time required to manually position data items such as text. To overcome this issue, future work should incorporate automated layout functionality, as well as bulk formatting features that propagate stylistic changes across different levels of scope.

6 DISCUSSION AND FUTURE WORK

This paper examines the potential of idiosyncratic timelines to enable visualizing data with personal conceptions of time. We discuss the balance to be struck between expressivity in temporal axes and data readability, and the blurry line between annotation and data.

6.1 Balancing Expressivity and Readability

Multiple uses for expressive and manipulable axes. Beyond the ability to reflect personal and idiosyncratic experiences of time [28, 64], we identified several additional reasons for using flexible and manipulable temporal axes. P14 and P15 both incorporated metaphorical figurative elements into the shape of their axes, thereby creating what Byrne et al. [18] 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 (Fig. 1.a, c), and compressing unimportant or empty intervals of time (Fig. 1.b). Finally, Fig. 1.a 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 [60], 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 offset from an expressively-shaped axis. Similarly, it can be difficult to determine the precise duration of intervals on an axis with intervals compressed and expanded by the placement of pins. Authors often have to compromise to have expressive axes, such as, for example, by losing some readability in favour of communicating the overall gestalt of event distribution more compactly than is possible on a rectilinear axis as demonstrated in Fig. 1.a. Here, the last two centuries are expanded because of the larger number of events compared to the preceding two centuries. While the use of non-uniform scales can complicate precise comparisons of value or chronology at a *macro* level, the ability to perform sequential and local value comparisons at a *micro* level can be preserved. For instance, in Fig. 1.b, it can be difficult to make temporal comparisons along the axis, but readers can still make distribution judgments (i.e., frequency, regularity, sparsity) in local areas. In addition, affordances for viewers to perform precise value retrieval and comparison may not always be desirable. In Fig. 1.b, the author communicates a general sense of their work patterns (light blue vs. dark blue points) without revealing the exact number of hours spent working in a given week. In instances of personal data visualization like this, we echo Perin's call [46] "*to maintain privacy, the visualization must obscure sensitive data and discourage the precise reading of individual values.*"

During our free-form study, we observed that readability was important at different stages of the process. The use cases of P13, P14, and P16 involved a reflection on their personal data. While their outcomes were personally interpretable and supported their reflection and design iteration goals, we needed them to provide us explanations in order to read them. Although it may not be necessary for viewers to retrieve or compare specific values and intervals, we saw that authors performed these tasks during the design process. P13 and P15 initially drew a straight line for their axis and bound their event data without any scale manipulations to review it. As they progressed and determined their desired representation, they deleted these original structures and drew more expressive axes. P14 took a different approach, in which they used TimeSplines' inset rectilinear lens canvas to identify key points in the data in order to place them on specific axis features. Although we introduced the lens tool as a convenient way to add annotations to a nonlinear axis, here we see it being used is to simplify data reading, an action that could take place at any stage of the authoring process.

Future work - representing compressed and expanded time clearly. In TimeSplines, directing viewer attention to intervals of compressed or expanded time relies upon the salience of pins, the variable dashing along the axis, and the placement of explanatory annotations (Fig. 3.9–10). However, since the dashing is subtle, it can easily go unnoticed, placing an additional burden on the author to explain temporal expansion and compression through additional annotations. An ongoing challenge is the automatic generation of more salient visual cues that effectively convey the compression and expansion of time. These cues

need to be compatible not only with varying axis shapes but also with different degrees of compressed and expanded time. Lastly, these cues should align with the authors' overall aesthetic direction.

6.2 Distinguishing Annotation and Data

From an author or a 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 original structured data, hunches about that data [39], marginalia, and other forms of insight externalization [36].

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 substrate, but only text annotations are promoted as data. Another inconsistency is that only drawn annotations bound to an axis are projected along the curve of the axis. Unifying the treatment of annotation and data across the system could provide a consistent and therefore conceptually simpler interaction flow. The treatment of drawn annotation 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 transmogripher approach for warping images along a spline [15]. The treatment of text could be applied to both images and annotations by allowing all data types to appear in the tabular representation, giving a unified interface to control temporal bindings, and elevating all visual elements to the status of data.

6.3 Risks and Limitations

The risk of flexible and manipulable axes. As with other visualizations, the use of TimeSplines by negligent or nefarious authors could deceive viewers. In particular, the use of expressive axis shapes or non-uniform time scales could obfuscate periodic event patterns, or indicate temporal patterns where there are none. Distant events could be made to appear close together, misleading viewers by indicating spurious sequential or causal relationships between these events. An author could also expand intervals that contain events that flatter either themselves or the timeline's subject, while suppressing intervals containing events that they want overlooked. While this is impossible to entirely prevent, the future work suggested above on more salient visual cues for compressed time could provide viewers better means to assess the author's intent with respect to (de)emphasizing intervals.

Study participation. Although their subjects of expertise varied, all of our study participants had post-secondary education experience, and many were students. Future studies should consider a broader population or collect results from a wider deployment.

7 CONCLUSION

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

SUPPLEMENTARY MATERIAL

The supplementary materials, including the code of TimeSplines, tutorials, the gallery, and the study apparatus for both studies can be found at exsitu-projects.github.io/timesplines, also available as a zip file at osf.io/r8sjx.

FIGURE CREDITS

Fig. 2a courtesy of C. Torna; Fig. 2b-c Public Domain; Fig. 2d courtesy of G. Lupi; Fig. 2e courtesy of C. Perin.

ACKNOWLEDGEMENTS

The work is supported by the CNRS-University of Toronto Ph.D. Mobility Funding program, the French National Research Agency under grant ANR-21-CE33-0002 GLACIS, and NSERC under grant RGPIN-2018-05072.

REFERENCES

- [1] Z. Abidin, D. H. Widyantoro, and S. Akbar. A survey on visualization techniques to narrate interpersonal interactions between sportsmen. In *Proc. IEEE Intl. Conf. Smart Technology and Applications (ICoSTA)*, 2020. doi: 10.1109/ICoSTA48221.2020.1570614056 2
- [2] M. Agrawala and C. Stolte. Rendering effective route maps: Improving usability through generalization. In *Proc. ACM SIGGRAPH*, 2001. doi: 10.1145/383259.383286 2, 9
- [3] W. Aigner, S. Miksch, H. Schumann, and C. Tominski. *Visualization of Time-Oriented Data*, vol. 4. Springer, 2011. 2, 3
- [4] F. Amini, M. Brehmer, G. Bolduan, C. Elmer, and B. Wiederkehr. Evaluating data-driven stories & storytelling tools. In N. H. Riche, C. Hurter, N. Diakopoulos, and S. Carpendale, eds., *Data-Driven Storytelling*. A K Peters/CRC Press, 2018. 6
- [5] B. Bach, C. Shi, N. Heulot, T. Madhyastha, T. Grabowski, and P. Dragicevic. Time curves: Folding time to visualize patterns of temporal evolution in data. *IEEE TVCG (Proc. InfoVis)*, 22(1), 2015. doi: 10.1109/TVCG.2015.2467851 2
- [6] M. Beaudouin-Lafon. Information Substrates: Interacting with Digital Matter. Technical report, Université Paris-Saclay, 2017. 4
- [7] L. Berends. Embracing the visual: Using timelines with in-depth interviews on substance use and treatment. *Qualitative Report*, 16(1), 2011. 2
- [8] A. Bigelow, S. Drucker, D. Fisher, and M. Meyer. Reflections on how designers design with data. In *Proc. AVI*, 2014. doi: 10.1145/2598153.2598175 2, 3
- [9] A. Bigelow, S. Drucker, D. Fisher, and M. Meyer. Iterating between tools to create and edit visualizations. *IEEE TVCG (Proc. InfoVis)*, 23(1), 2016. doi: 10.1109/TVCG.2016.2598609 2, 3
- [10] M. Bohøj, N. G. Borchorst, N. O. Bouvin, S. Bødker, and P.-O. Zander. Timeline collaboration. In *Proc. ACM CHI*, 2010. doi: 10.1145/1753326.1753404 2
- [11] M. Bostock, V. Ogievetsky, and J. Heer. D³: Data-driven documents. *IEEE TVCG (Proc. InfoVis)*, 17(12), 2011. doi: 10.1109/TVCG.2011.1856
- [12] R. Brath and E. Banissi. Microtext line charts. In *Proc. IEEE Intl. Conf. Information Visualisation (IV)*, 2017. doi: 10.1109/IV.2017.82 9
- [13] M. Brehmer, B. Lee, B. Bach, N. H. Riche, and T. Munzner. Timelines revisited: A design space and considerations for expressive storytelling. *IEEE TVCG*, 23(9), 2016. doi: 10.1109/TVCG.2016.2614803 1, 2, 3
- [14] M. Brehmer, B. Lee, N. H. Riche, D. Tittsworth, K. Lytvynets, D. Edge, and C. White. Timeline Storyteller: The design & deployment of an interactive authoring tool for expressive timeline narratives. *Proc. Computation + Journalism (C+J)*, 2019. 2
- [15] J. Brosz, M. A. Nacenta, R. Pusch, S. Carpendale, and C. Hurter. Transmogrification: Casual manipulation of visualizations. In *Proc. ACM UIST*, 2013. doi: 10.1145/2501988.2502046 3, 6, 9
- [16] J. Brown, A. Cesal, J. K. Dru, Z. Furnas, S. B. Robinson, L. Valade-DeMelo, and C. Harrison. The Data Visualization Society State of the Industry Survey, 2022. Accessed 2023-03-30. datavisualizationsociety.org/survey. 2
- [17] C. Bryan, K.-L. Ma, and J. Woodring. Temporal summary images: An approach to narrative visualization via interactive annotation generation and placement. *IEEE TVCG (Proc. InfoVis)*, 23(1), 2017. doi: 10.1109/TVCG.2016.2598876 4
- [18] L. Byrne, D. Angus, and J. Wiles. Figurative frames: A critical vocabulary for images in information visualization. *Information Visualization*, 18(1), 2019. doi: 10.1177/1473871617724212 4, 9
- [19] S. Carpendale, A. Thudt, C. Perin, and W. Willett. Subjectivity in personal storytelling with visualization. *Information Design Journal*, 23(1), 2017. doi: 10.1075/idj.23.1.07thu 2
- [20] G. Chalhoub and A. Sarkar. “It’s freedom to put things where my mind wants”: Understanding and improving the user experience of structuring data in spreadsheets. In *Proc. ACM CHI*, 2022. doi: 10.1145/3491102.3501833 3
- [21] W. O. Chao, T. Munzner, and M. van de Panne. Rapid pen-centric authoring of improvisational visualizations with NapkinVis. In *Proc. InfoVis Posters*, 2010. 3
- [22] E. K. Choe, N. B. Lee, B. Lee, W. Pratt, and J. A. Kientz. Understanding quantified-selfers’ practices in collecting and exploring personal data. In *Proc. ACM CHI*, 2014. doi: 10.1145/2556288.2557372 2
- [23] J. J. Y. Chung, W. Kim, K. M. Yoo, H. Lee, E. Adar, and M. Chang. TaleBrush: sketching stories with generative pretrained language models. In *Proc. ACM CHI*, 2022. doi: 10.1109/TVCG.2017.2743918 3
- [24] M. Ciolfi Felice, S. Fdili Alaoui, and W. E. Mackay. Knotation: Exploring and documenting choreographic processes. In *Proc. ACM CHI*, 2018. doi: 10.1145/3173574.3174022 3
- [25] N. Elmqvist, Y. Riche, N. Henry-Riche, and J.-D. Fekete. Mélange: Space folding for visual exploration. *IEEE TVCG*, 16(3), 2009. doi: 10.1109/TVCG.2009.86 2
- [26] O. Fuhrman and L. Boroditsky. Cross-cultural differences in mental representations of time: Evidence from an implicit nonlinguistic task. *Cognitive Science*, 34(8), 2010. doi: 10.1111/j.1551-6709.2010.01105.x 2
- [27] V. Goel. Creative brains: designing in the real world. *Frontiers in Human Neuroscience*, 8, 2014. doi: 10.3389/fnhum.2014.00241 3
- [28] C. Hammond. *Time Warped: Unlocking the Mysteries of Time Perception*. House of Anansi, 2012. 2, 9
- [29] S. Haroz, R. Kosara, and S. L. Franconeri. The connected scatterplot for presenting paired time series. *IEEE TVCG*, 22(9), 2015. doi: 10.1109/TVCG.2015.2502587 2, 6
- [30] J. Hullman, N. Diakopoulos, and E. Adar. Contextifier: automatic generation of annotated stock visualizations. In *Proc. ACM CHI*, 2013. doi: 10.1145/2470654.2481374 4
- [31] Icastic Consulting. ICATIME: What does time look like? <https://www.icatime.net/>. Accessed 2023-03-16. 2, 3
- [32] D. F. Keefe, D. Acevedo, J. Miles, F. Drury, S. M. Swartz, and D. H. Laidlaw. Scientific sketching for collaborative vr visualization design. *IEEE Transactions on Visualization and Computer Graphics*, 14(4):835–847, 2008. 2
- [33] R. Khulusi, J. Kusnick, J. Focht, and S. Jänicke. An interactive chart of biography. In *Proc. IEEE PacificVis*, 2019. doi: 10.1109/PacificVis.2019.00038 1, 2
- [34] N. W. Kim, B. Bach, H. Im, S. Schriber, M. Gross, and H. Pfister. Visualizing nonlinear narratives with story curves. *IEEE TVCG (Proc. InfoVis)*, 24(1), 2017. doi: 10.1109/TVCG.2017.2744118 2, 3
- [35] N. W. Kim, N. Henry Riche, B. Bach, G. Xu, M. Brehmer, K. Hinckley, M. Pahud, H. Xia, M. J. McGuffin, and H. Pfister. DataToon: Drawing dynamic network comics with pen+ touch interaction. In *Proc. ACM CHI*, 2019. doi: 10.1145/3290605.3300335 2, 3
- [36] Y.-S. Kim, N. Henry Riche, B. Lee, M. Brehmer, M. Pahud, K. Hinckley, and J. Hullman. Inking your insights: Investigating digital externalization behaviors during data analysis. In *Proc. ACM ISS*, 2019. doi: 10.1145/3343055.3359714 3, 4, 9
- [37] B. Lee, R. H. Kazi, and G. Smith. SketchStory: Telling more engaging stories with data through freeform sketching. *IEEE TVCG (Proc. InfoVis)*, 19(12), 2013. doi: 10.1109/TVCG.2013.191 3
- [38] B. Lee, G. Smith, N. H. Riche, A. Karlson, and S. Carpendale. SketchInsight: Natural data exploration on interactive whiteboards leveraging pen and touch interaction. In *Proc. IEEE PacificVis*, 2015. doi: 10.1109/PACIFICVIS.2015.7156378 3
- [39] H. Lin, D. Akbaba, M. Meyer, and A. Lex. Data hunches: Incorporating personal knowledge into visualizations. *IEEE TVCG (Proc. VIS)*, 29(1), 2023. doi: 10.1109/TVCG.2022.3209451 3, 4, 9
- [40] Z. Liu, J. Thompson, A. Wilson, M. Dontcheva, J. Delorey, S. Grigg, B. Kerr, and J. Stasko. Data Illustrator: Augmenting vector design tools with lazy data binding for expressive visualization authoring. In *Proc. ACM CHI*, 2018. doi: 10.1145/3173574.3173697 2, 3, 4
- [41] G. Lupi and S. Posavec. *Dear Data*. Princeton Architectural Press, 2016. 3
- [42] M. Monroe, R. Lan, H. Lee, C. Plaisant, and B. Shneiderman. Temporal event sequence simplification. *IEEE TVCG (Proc. InfoVis)*, 19(12), 2013. doi: 10.1109/TVCG.2013.200 1, 2
- [43] J. Moore, P. Goffin, M. Meyer, P. Lundrigan, N. Patwari, K. Sward, and

- J. Wiese. Managing in-home environments through sensing, annotating, and visualizing air quality data. *Proc. ACM UbiComp*, 2(3), 2018. doi: 10.1145/3264938 4
- [44] H. Otten, L. Hildebrand, T. Nagel, M. Dörk, and B. Müller. Shifted Maps: Revealing spatio-temporal topologies in movement data. In *Proc. IEEE VIS Arts Program (VISAP)*, 2018. doi: 10.1109/VISAP45312.2018.9046054 2
- [45] P. Parsons. Understanding data visualization design practice. *IEEE TVCG (Proc. VIS)*, 28(1), 2022. doi: 10.1109/TVCG.2021.3114959 2
- [46] C. Perin. The symmetry of my life: An autobiographical visualization. In *Proc. IEEE VIS Arts Program (VISAP)*, 2017. hal.inria.fr/hal-01587944/ 2, 3, 9
- [47] C. Perin, T. Wun, R. Pusch, and S. Carpendale. Assessing the graphical perception of time and speed on 2d+ time trajectories. *IEEE TVCG (Proc. InfoVis)*, 24(1), 2017. doi: 10.1109/TVCG.2017.2743918 2, 4
- [48] D. Ren, M. Brehmer, B. Lee, T. Höllerer, and E. K. Choe. ChartAccent: Annotation for data-driven storytelling. In *Proc. IEEE PacificVis*, 2017. doi: 10.1109/PACIFICVIS.2017.8031599 4
- [49] D. Ren, B. Lee, and M. Brehmer. Charticulator: Interactive construction of bespoke chart layouts. *IEEE TVCG (Proc. InfoVis)*, 25(1), 2018. doi: 10.1109/TVCG.2018.2865158 3
- [50] D. Ren, B. Lee, M. Brehmer, and N. H. Riche. Reflecting on the evaluation of visualization authoring systems: Position paper. In *Proc. IEEE Evaluation and Beyond (BELIV)*, 2018. doi: 10.1109/BELIV.2018.8634297 2, 6
- [51] M. Resnick, B. Myers, K. Nakajoji, B. Shneiderman, R. Pausch, T. Selker, and M. Eisenberg. *Design Principles for Tools to Support Creative Thinking*. Carnegie Mellon University, 2005. 6
- [52] H. Romat, N. Henry Riche, K. Hinckley, B. Lee, C. Appert, E. Pietriga, and C. Collins. Activeink: (th)inking with data. In *Proc. ACM CHI*, 2019. doi: 10.1145/3290605.3300272 2, 3
- [53] D. Rosenberg and A. Grafton. *Cartographies of Time: A History of the Timeline*. Princeton Architectural Press, 2013. 2
- [54] A. Satyanarayan, B. Lee, D. Ren, J. Heer, J. Stasko, J. Thompson, M. Brehmer, and Z. Liu. Critical reflections on visualization authoring systems. *IEEE TVCG (Proc. InfoVis)*, 26(1), 2019. doi: 10.1109/TVCG.2019.2934281 2, 3
- [55] D. Schroeder, D. Coffey, and D. Keefe. Drawing with the flow: A sketch-based interface for illustrative visualization of 2d vector fields. In *Proceedings of the Seventh Sketch-Based Interfaces and Modeling Symposium*, pp. 49–56, 2010. 3
- [56] D. Schroeder and D. F. Keefe. Visualization-by-sketching: An artist's interface for creating multivariate time-varying data visualizations. *IEEE transactions on visualization and computer graphics*, 22(1):877–885, 2015. 3
- [57] E. Shen, S. Li, X. Cai, L. Zeng, and W. Wang. Sketch-based interactive visualization: a survey. *Journal of Visualization*, 17:275–294, 2014. 3
- [58] J. Snyder, E. Murnane, C. Lustig, and S. Voida. Visually encoding the lived experience of bipolar disorder. In *Proc. ACM CHI*, 2019. doi: 10.1145/3290605.3300363 2
- [59] L. Sterne. *The Life and Opinions of Tristram Shandy, Gentleman: In Four Volumes*, vol. 9. Steudel, 1805. 3
- [60] Y. Tanahashi and K.-L. Ma. Design considerations for optimizing storyline visualizations. *IEEE TVCG (Proc. InfoVis)*, 18(12), 2012. doi: 10.1109/TVCG.2012.212 2, 9
- [61] E. Thiry, S. Lindley, R. Banks, and T. Regan. Authoring personal histories: Exploring the timeline as a framework for meaning making. In *Proc. ACM CHI*, 2013. doi: 10.1145/2470654.2466215 1, 2, 3
- [62] A. Thudt, S. Carpendale, and D. Baur. Autobiographical visualizations: challenges in personal storytelling. In *Proc. ACM DIS PVA Workshop: A Personal Perspective on Visualization and Visual Analytics*, 2014. 2
- [63] P. Tolmie, A. Crabtree, T. Rodden, J. Colley, and E. Luger. "This has to be the cats": Personal data legibility in networked sensing systems. In *Proc. ACM CSCW*, 2016. doi: 10.1145/2818048.2819992 1, 4
- [64] C. Torna. Visualizing time. In O. Ast, ed., *Infinite Instances: Studies and Images of Time*, pp. 42–51. Mark Batty Publisher, 2011. 1, 2, 9
- [65] T. Tsandilas. StructGraphics: Flexible visualization design through data-agnostic and reusable graphical structures. *IEEE TVCG (Proc. VIS)*, 27(2), 2021. doi: 10.1109/TVCG.2020.3030476 3
- [66] T. Tsandilas, A. Bezerianos, and T. Jacob. SketchSliders: Sketching widgets for visual exploration on wall displays. In *Proc. ACM CHI*, 2015. doi: 10.1145/2702123.2702129 3
- [67] A. Tversky and D. Kahneman. Availability: A heuristic for judging frequency and probability. *Cognitive Psychology*, 5(2), 1973. doi: 10.1016/0010-0285(73)90033-9 2
- [68] B. Tversky, S. Kugelmass, and A. Winter. Cross-cultural and developmental trends in graphic productions. *Cognitive psychology*, 23(4), 1991. doi: 10.1016/0010-0285(91)90005-9 2
- [69] M. Twain. How to make history dates stick. *Harper's Monthly Magazine*, 130(775), 1914. <http://www.twainquotes.com/HistoryDates/HistoryDates.html>. 2, 3, 6
- [70] J. J. van Wijk and E. R. van Selow. Cluster and calendar based visualization of time series data. In *Proc. IEEE InfoVis*, 1999. doi: 10.1109/INFVIS.1999.801851 2
- [71] J. Walker, R. Borgo, and M. W. Jones. TimeNotes: a study on effective chart visualization and interaction techniques for time-series data. *IEEE TVCG (Proc. InfoVis)*, 22(1), 2016. doi: 10.1109/TVCG.2015.2467751 2
- [72] J. Walny, J. Haber, M. Dörk, J. Sillito, and S. Carpendale. Follow that sketch: Lifecycles of diagrams and sketches in software development. In *Proc. IEEE Intl. Workshop Visualizing Software for Understanding and Analysis (VISSOFT)*, 2011. doi: 10.1109/VISSOFT.2011.6069462 3
- [73] J. Walny, S. Huron, and S. Carpendale. An exploratory study of data sketching for visual representation. *Computer Graphics Forum (Proc. EuroVis)*, 34(3), 2015. doi: 10.1111/cgf.12635 3
- [74] K. Wongsuphasawat, J. A. Guerra Gómez, C. Plaisant, T. D. Wang, M. Taieb-Maimon, and B. Shneiderman. LifeFlow: visualizing an overview of event sequences. In *Proc. ACM CHI*, 2011. doi: 10.1145/1978942.1979196 2
- [75] H. Xia, N. Henry Riche, F. Chevalier, B. De Araujo, and D. Wigdor. DataInk: Direct and creative data-oriented drawing. In *Proc. ACM CHI*, 2018. doi: 10.1145/3173574.3173797 2, 3
- [76] J. E. Zhang, N. Sultanum, A. Bezerianos, and F. Chevalier. DataQuilt: Extracting visual elements from images to craft pictorial visualizations. In *Proc. ACM CHI*, 2020. doi: 10.1145/3313831.3376172 3
- [77] Y. Zhang, K. Chanana, and C. Dunne. IDMMVis: Temporal event sequence visualization for type 1 diabetes treatment decision support. *IEEE TVCG (Proc. InfoVis)*, 25(1), 2010. doi: 10.1109/TVCG.2018.2865076 2
- [78] J. Zhao, F. Chevalier, and R. Balakrishnan. Kronominer: using multi-foci navigation for the visual exploration of time-series data. In *Proc. ACM CHI*, 2011. doi: 10.1145/1978942.1979195 2
- [79] J. Zhao, F. Chevalier, E. Pietriga, and R. Balakrishnan. Exploratory analysis of time-series with chronolenses. *IEEE TVCG (Proc. InfoVis)*, 17(12), 2011. doi: 10.1109/TVCG.2011.195 2