Timelines Revisited: A Design Space and Considerations for Expressive Storytelling

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Abstract—There are many ways to visualize event sequences as *timelines*. In a storytelling context where the intent is to convey multiple narrative points, a richer set of timeline designs may be more appropriate than the narrow range that has been used for exploratory data analysis by the research community. Informed by a survey of 263 timelines, we present a design space for storytelling with timelines that balances expressiveness and effectiveness, identifying 14 design choices characterized by three dimensions: representation, scale, and layout. Twenty combinations of these choices are viable timeline designs that can be matched to different narrative points, while smooth animated transitions between narrative points allow for the presentation of a cohesive story, an important aspect of both interactive storytelling and data videos. We further validate this design space by realizing the full set of viable timeline designs and transitions in a proof-of-concept sandbox implementation that we used to produce seven example timeline stories. Ultimately, this work is intended to inform and inspire the design of future tools for storytelling with timelines.

Index Terms—Timelines, storytelling, narrative visualization, design space, animated transitions.

1 Introduction

Timelines have been used for centuries to communicate sequences of events [77]. Biographies, historical summaries, and project plans are often distilled as timelines to tell a story, where the goal of the storyteller is to present known information in an appropriate and engaging way. From the hand-drawn illustrations of centuries past to contemporary infographics, people have employed a wide range of visual forms for telling timeline stories. In recent years, a number of authoring tools for presenting interactive and animated timelines have emerged, and the presentation of timelines is a concern that is being actively discussed within the data journalism community [42]. In contrast, the visualization research community has primarily focused on a narrow slice of the timeline design space: variants of the linear representation pioneered by Joseph Priestley in 1765 [74]. This representation can be powerful and effective when used in the context of exploratory data analysis, where the goal of the analyst is to interact with a visual analysis tool to discover new information. However, in a storytelling context, more *expressiveness* is desirable: to make a single narrative point in multiple ways as well as to support different kinds of narrative points.

While the visualization research community has devoted attention to articulating the general principles of visual data-driven storytelling design [7], [47], [82], the question of how to tell expressive stories with timelines in particular has not been directly addressed. Visual storytellers who wish to present a variety of narrative points require a rich palette of design choices. Many existing timeline designs beyond those in the linear Priestley tradition are both expressive and sufficiently effective for a storytelling context, incorporating non-linear representations of time and non-chronological time scales. However, some of the more exotic visual timeline designs employed by storytellers can be difficult to interpret (e.g., [17], [25], [50]). Currently, those who want to tell expressive stories with timelines lack guidance with respect to balancing perceptual and narrative effectiveness.

Given a timeline story comprised of a sequence of narrative points, there may not exist a single timeline design that adequately communicates all of these points; as a consequence, a storyteller might incorporate multiple timeline designs into a single story. Smooth animated transitions can help maintain the coherency of a story by maintaining context from one narrative point to the next [86], and by assisting the audience in their interpretation of unfamiliar visual encodings [79]. Though animated transitions have been used in existing timeline stories (e.g., [35], [58], [78], [84]), there is a lack of guidance with respect to transitioning between different timeline designs. Those who typically tell timeline stories with manually-illustrated static infographics have yet to realize this potential, and tools that support interactive and animated visual storytelling could open the door to previously unexplored opportunities.

Our efforts are a first step toward answering this question: How can storytellers tell expressive stories with timelines while maintaining an underlying concern for perceptual and narrative effectiveness? Figure 1 summarizes our proposed design space for storytelling with timelines along the three dimensions of *representation*, *scale*, and *layout*. As our goal is to provide guidance to storytellers, we first examine whether each combination of these dimensions results in a viable timeline design that is *purposeful* for a known narrative point, *interpretable* by the audience of the story, and *generalizable* across datasets.

While our design space does not explicitly distinguish between static and interactive timelines, we anticipate storytelling use cases involving timelines realized in the form of interactive presentations or data videos [7]. To this end, we also provide design consider-

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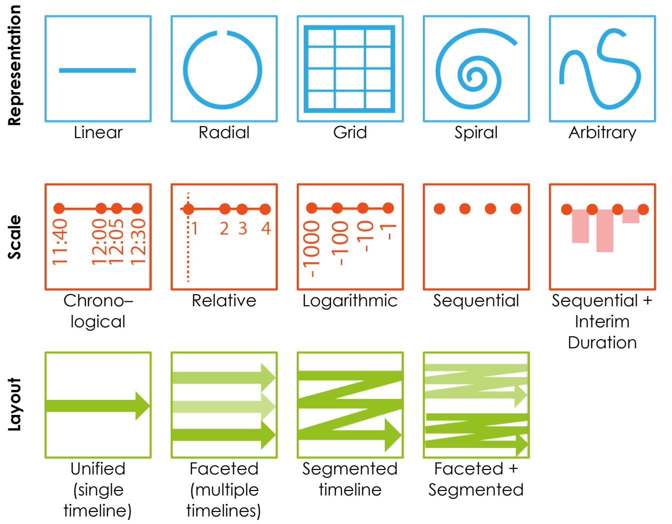

Fig. 1. The three dimensions of our design space for expressive storytelling with timelines: representation, scale, and layout.

ations with respect to using different timeline designs in coherent stories, including whether and how smooth animated transitions are appropriate for presenting a series of varied narrative points.

The contribution of this paper is twofold. The first contribution is the introduction and analysis of a design space for storytelling with timelines. Our analysis ties together five disparate threads of previous work for the first time: the history of timelines over the centuries, bespoke interactive timelines presenting a specific dataset, manually illustrated static timeline infographics, the currently deployed set of software tools for timeline authoring, and the visualization research literature. Our second contribution is a realization of viable timeline designs from our design space within a sandbox environment, which we used to produce seven example timeline stories; these stories feature a variety of narrative points and illustrate the benefits of incorporating multiple timeline designs linked together by animated transitions. Ultimately, our work is intended to both ground and inspire the design of future interactive tools for producing visual timeline stories.

2 Background and Related Work

This section provides background information with regards to timelines, data-driven storytelling, and the use of animated transitions for preserving context.

2.1 Timelines

A timeline depicts a sequence of events, or *interval event data* using the precise terminology of Aigner et al. [5], which is to be distinguished from *instant* or continuous quantitative time-series data. A simple timeline indicates the types of events being depicted, the number of events, and the order in which they occurred. A more detailed timeline may indicate when the events occurred in chronological time, how long they lasted, and whether any of the events overlapped. Typically, an event is visually encoded using some graphical mark, such as a line or an icon. The placement of this mark in relation to an axis representing time and to other event marks will indicate when the event occurred.

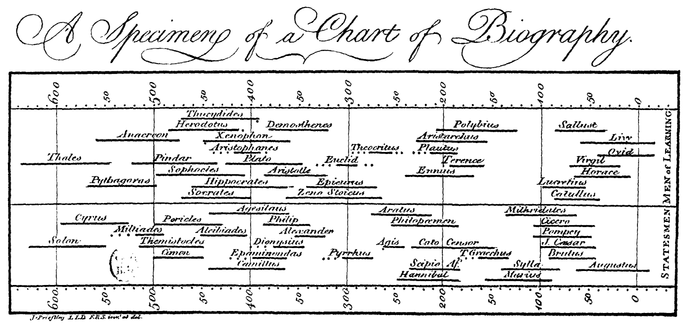

Fig. 2. The linear, chronological form of Joseph Priestley's *Chart of Biography* (1765) dominates the design of contemporary timelines.

2.1.1 Historical Context

Consider Joseph Priestley's *Chart of Biography* [74], first published in 1765, which is shown in Figure 2. Priestley has drawn lines along a horizontal chronological axis, running from left to right, indicating the lifespans of nearly sixty people, and he has annotated these lines with their names. The vertical positions of these lines are not meaningful: the lines and annotations are placed to avoid overlap.

Though most timelines appearing since the late 18th century bear some resemblance to Priestley's form, it is by no means the only and best timeline design [76]. By broadening the scope to consider timelines produced throughout history [77], one may encounter a number of visual representations that differ from Priestley's design: timelines have taken the form of circles, spirals, grids, tabular ledgers, pictographic unit charts, and even arbitrary shapes that evoke spatial metaphors; consider, for instance, the phrase "an event that changed the *course* of history." The events themselves have also been represented with a variety of graphical marks, including dots, lines, arcs, icons, or polygons. We reconsider several of these representations in our discussion of the design space below. While many narratives involving timelines follow the linear chronological progression of time, some narrative points refer to patterns or differences in the duration, distribution, or periodicity of events, or to event sequences and synchronicities. For example, linear representations can better support points relating to chronology and sequence, while representations that evoke analog clock faces or calendars can be more effective in supporting points about periodic repetition.

2.1.2 Timeline Authoring

Timeline infographics often appear in newspapers, magazines, textbooks, or online. Unlike the hand-drawn timelines produced in previous centuries [77], most timeline infographics today are produced using illustration software. This production medium allows for considerable expressiveness, and while many timeline infographics adopt aspects of Priestley's linear chronological form, many infographics deviate from this tradition (e.g., [3], [75], [91]). However, these timelines remain static, and thus it is difficult to integrate them into larger data-driven stories comprised of multiple narrative points.

As an alternative to static infographics, timeline authoring tools (e.g., [13], [39], [45], [48], [65], [68], [83], [98]) allow a storyteller to easily generate a curated interactive timeline. TimelineJS [68] and TimelineSetter [83] are two of these tools that go a step further in that they generate a slideshow presentation of the timeline with full text descriptions for each event; with

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TimelineJS, a peripheral linear chronological timeline serves as an interactive navigation aid, and panning transitions are used between successive narrative points.

However, a slideshow presentation that follows the chronological order of events supports only a single form of narrative point, one referring to the order of events. There is no existing timeline authoring tool that approaches the level of visual expressiveness encompassed by static timeline infographics and timelines produced throughout history. With our design space and our proof-of-concept implementation, we hope to rectify this gap and inform the design of the next generation of timeline authoring tools.

2.1.3 Timelines in the Visualization Research Literature

Many timeline visualization tools discussed in recent research publications [5] are intended primarily for exploratory data analysis rather than presentation or storytelling. Despite this difference in purpose, these tools nevertheless informed the dimensions of our design space and we refer to many of them in our discussion of the design space below. Many of these tools incorporate the familiar Priestley form: events are encoded as lines or glyph-based marks, and placed horizontally along a linear chronological axis [8], [72], [101], [102]. Some exceptions include tools that incorporate logarithmic [54] or relative [97] time scales, or those that incorporate non-linear representations such as calendars [94].

One key difference between exploratory timelines and those intended for storytelling relates to the size of the underlying dataset. Many research tools address use cases where an analyst must sift through raw data containing thousands of events, and thus make use of some form of visual aggregation or clustering [60], [66]. In a storytelling context, however, it is assumed that the storyteller has already distilled and reduced the size of the dataset to best support their narrative points and to the extent that is appropriate for their audience. Accordingly, our design space does not address large datasets, aggregation, or clustering.

2.2 Visualization and Storytelling

Several recent research efforts have focused on understanding and defining the scope of data-driven storytelling with visualization. Reviewing visualization in the domain of data journalism, Segel and Heer [82] introduced the term *narrative visualization* and identified seven distinct genres. Hullman and Diakopoulos [46] then investigated the types and forms of rhetorical techniques used in narrative visualization. Since then, Kosara and Mackinlay [53] and more recently Lee et al. [57] have provided a concise, high-level review of storytelling with visualization and discussed future research directions.

Other research efforts were specifically aimed to inform the design of visualization storytelling tools. Hullman et al. [47] explored the effect of sequencing in narrative visualization, focusing on linear, slideshow-style presentations. Amini et al. [7] looked into professionally created data videos and identified high-level narrative structures. Through an analysis of a curated collection of data-driven stories shared on the web, Stolper et al. [86] identified the spectrum of techniques that data-storytellers are using to inform the design of data-storytelling tools. Finally, Satyanarayan and Heer [80] introduced a model of storytelling based on state-based scene structures and used it to realize Ellipsis, an data storytelling authoring tool. Findings from these projects informed our own research and motivated a need to transition between scenes that communicate different narrative points with respect to the timelines being shown.

Much of the previous research on storytelling with visualization is agnostic to the type of data being presented. In this paper, we provide a detailed analysis of the challenges and opportunities that are specific to timelines.

2.3 Animated Transitions

Linking narrative points together and preserving context via animated transitions is an emerging trend in data-driven storytelling [86], in both interactive stories and data videos [7], and they are employed in several timeline stories found in our survey (e.g., [35], [58], [78], [84]). Heer and Robertson [44] effectively demonstrated how context can be preserved with animated transitions between different visual encodings such as bar charts and scatterplots; we now consider this approach with regards to timelines for storytelling. Animated transitions can also assist in learning unfamiliar visual encodings by smoothly animating from a more familiar visual encoding to a less familiar one [79]. Our survey revealed that some of the 20 viable timeline designs that we identify are more prevalent than others (see Table 2); if a storyteller intends to include a less familiar timeline design in their story, such as one incorporating a logarithmic scale, they might do so by first transitioning from a more familiar timeline design, such as the common chronological linear design of the Priestley tradition.

The visualization research community has identified several considerations for ensuring the effectiveness of animated transitions; these considerations include staging a transition to reduce cognitive load [11], [16], [71], determining whether to stagger the animation of elements or move them en masse [26], bundling visual elements along a common trajectory during a transition [33], and easing the speed of an animated transition [31]. Many of these considerations informed the design of our transitions for storytelling with timelines, discussed in Section 5.2.

3 METHODOLOGY

We began this project by gathering a representative corpus of timelines from a broad range of sources, including timeline visualization tools or techniques from the research literature, dataset-specific interactive timelines and timeline infographics, as well as existing timeline authoring tools, such as TimelineJS [68] and TimeLineCurator [39]. Our analysis also incorporated two existing comprehensive surveys: 78 timelines from a book tracing timeline usage from antiquity to the present from a historical perspective [77], and 19 timeline visualization techniques or tools from a book on time-oriented visualization from a research perspective [5] that includes timelines as a subset of its scope. To the best of our knowledge, this paper is the first to integrate and structure the knowledge from these disparate communities. Altogether, our initial survey included 145 timelines or timeline visualization tools prior to developing our design space.

Our initial survey encompassed a wide variety of timeline designs, and the underlying data represented in these timelines was similarly varied in terms of the number, chronological distribution, and category of events. To analyze this corpus of timelines, we attempted to iteratively identify a set of dimensions that would explain this variation by grouping timelines together and selecting exemplars, and by sketching dozens of design alternatives with pen and paper.

Our analysis process resulted in a design space with three dimensions: *representation*, *scale*, and *layout* (Figure 1). A single timeline can be described as a tuple of values, one from each dimension. The analysis of this design space involved considering each combination of values. Based on our analysis, described in detail below, we identify 20 viable timeline designs to support expressive storytelling.

In the spirit of the machine learning approach of validating whether a classification based on an initial training set generalizes appropriately, we tested against a new set of items to validate the dimensions of our design space. Thus, our validation set included 118 additional items, including 113 dataset-specific timelines and 5 additional timeline authoring tools. To accumulate the 113 timelines, we consulted three curated lists of example timelines [38], [42], [62] as well as visual.ly's visual content gallery [95], the collection of nominee entries for the 2012–2015 Kantar Information is Beautiful Awards [49], and the Massachusetts (Massive) Visualization Dataset [18]. The supplemental website[1] for this paper includes our corpus of 263 timelines described using the dimensions of our design space, along with links to original sources. All of the 263 timeline items in our survey could be described along our three dimensions, and 253 (96%) out of the 263 items in our survey could be characterized as one of the 20 viable timeline designs that we identify below in Section 4.4. Table 1 and Table 2 summarize the coverage of the dimensions of our design space and the 20 viable timeline designs with respect to the 263 items in our survey.

To realize this design space and the 20 viable timeline designs, we implemented a sandbox storytelling environment that incorporates these designs. While our sandbox environment may provide a strong foundation for a full-fledged authoring tool for storytelling in the future, the focus of this paper is not on an authoring system. Rather, our goal is to motivate, introduce, and analyze the design space; to present and explain the rationale for this set of timeline designs; and to present considerations for authoring cohesive stories containing a variety of narrative points, including transitioning between different timeline designs.

We tested these timeline designs with 28 datasets; 12 of which were adapted from existing timelines from our survey. Within this environment, we also iteratively developed and tested animated transitions that promote a cohesive storytelling experience. As a result of this process, we offer design considerations for transitions that maintain context across successive narrative points. Finally, using this environment, we produced seven example stories featuring a variety of datasets and narrative points accommodated by different timeline designs and animated transitions.

4 Design Space

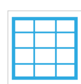
Informed by our survey, we propose a design space for timelines with the following dimensions: *representation*, *scale*, and *layout*, which are orthogonal in terms of the narrative points they support. This section presents the design choices within each dimension, along with their corresponding narrative points and supporting examples from our survey.

4.1 Dimension 1: Representation

The representation of a timeline is its most visually salient aspect, its guiding visual metaphor. Representation refers to the overall form or shape of the path that time takes across the display. As indicated in the first row of Figure 1, we have identified five timeline representations:

Linear representations, such as in Figure 2, are the most common way to represent a timeline; 192 (73%) of the 263 items in our survey use this representation. All of the interactive timeline presentation tools and nearly all of the tools from the surveyed visualization research literature use this representation. Each event on the timeline is encoded using a line, glyph, or icon mark; text labels adjacent to the event mark are also common. Linear representations have the additional attribute of *orientation*: for example, while Priestley's timeline is horizontal, one timeline authoring tool generates a vertical timeline [13], and an interactive timeline published by *The Guardian* includes 3D depth cues to appear as though it recedes into the display [17]. In the remainder of this paper, we will assume a horizontal orientation for linear representations for the sake of simplicity, though all that matters is that a linear representation maintains a single orientation. *Narrative point*: these representations ensure that the story is presented in a way that follows typical reading direction, such as with successive events proceeding from left to right. *Examples*: timeline authoring tools such as TimelineJS [68] or TimeLineCurator [39], data analysis tools such as Continuum [8], Lifelines [72], or Cousins and Kahn's timeline browser [29], and timelines such as those depicting the lives of famous painters [4] or the constitutions of nations [2].

Radial representations typically encode events as arc, glyph, or icon marks. *Narrative point*: these representations are appropriate for presenting the periodic nature of time, such as the natural cycles of people, weather systems, and ecosystems [100]. *Examples*: timelines such as those depicting the recurring daily routines of creative people [9] or the publishing history of literary masterpieces and their authors [3].



Grid representations such as the standard Month-Week-Day calendar are ubiquitous. However, grid representations are only appropriate for timelines that reflect these granularities of time. Proposed in the mid 19th century, Peabody's *Polish-American System of Chronology* [77, p.203-5] is an alternative grid-based representation that uses a 10×10 grid reflecting a entire century, wherein each row is a decade; conceivably, this representation could also be applied to any base-10 granularity of time. *Narrative point*: these representations are appropriate for presenting the cyclical nature of time according to culturally agreed-upon calendar systems. *Examples*: visualization tools such as TimeFlow [94] or DateLens [15].

Spiral representations are dense, space-filling shapes that radiate to or from a centre point. Spiral timelines are often playful or amusing [77, p.194], evoking a hypnotic engagement. *Narrative point*: these aesthetically appealing representations are appropriate for presenting many events within a single dense display. *Examples*: spiral visualization techniques for time-oriented data by Carlis and Konstan [24] or Weber et al. [99], timelines such as those depicting geological epochs [40] or the Greek debt crisis [75], and an interactive spiral timeline depicting an educational curriculum [78].

Arbitrary representations are, like spirals, playful and amusing in nature, in many cases reminiscent of the design of popular board games [59] (e.g., *Life*, *Snakes & Ladders*). Arbitrary timeline representations may appear visually similar to connected scatterplots [43], time curves [12], and

1. http://timelinesrevisited.github.io/supplemental/

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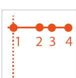
Tanahashi and Ma's storyline charts [87], though in each of these instances, the path depicting time is determined by time-varying quantitative or relational attributes, thereby resulting in a non-arbitrary representation; at present, our focus remains on truly arbitrary representations that encode no additional quantitative or relational attributes. *Narrative point*: like spiral representations, these representations may be useful for presenting many events within a single dense display. These representations may improve the memorability of a story told with timelines, as drawing timelines as arbitrary shapes was proposed by polymath Mark Twain over a century ago as a mnemonic for teaching and learning history [89]. *Examples*: timelines such as those depicting the Arab Spring [59] or the 2011 NBA lockout [92].

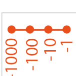
4.2 Dimension 2: Scale

The scale of a timeline refers to the correspondence between temporal distances and distances on the display. The scale is used to communicate relations between events, such as order, duration, and synchronicity. As indicated in the second row of Figure 1, we have identified five timeline scales:

Chronological scales correspond to actual dates; depending on the granularity of events, these may be coarse dates such as *2015* or *the 21st century*, or more precise dates such as *12:00pm on June 20th, 2016*. 148 (56%) of the 263 items in our survey use this scale. *Narrative point*: chronological scales can be used to present the distance between events, as well as event duration, with respect to absolute points in time, such as dates or years. *Examples*: timeline authoring tools such as TimeRime [45] or TikiToki [98], visualization tools such as EventRiver [60] or TimeSlice [102], and timelines such as those depicting history's largest empires [58] or the detainment of Guantánamo inmates [1].



Relative scales involve the notion of a baseline event at time zero. *Narrative point*: relative scales allow for the comparison of multiple timelines, where events are positioned with respect to a common baseline event, rather than with respect to absolute dates. *Examples*: visualization tools that align patient hospitalization timelines to the time when a patient is admitted to the hospital [66], [97], [101], which allow for comparisons of different patients' experiences; timelines such as those depicting the creative output of directors, musicians, and novelists [69], or relative timelines of Google search trends in response to recent terrorist attacks [96].



Logarithmic scales transform a chronological scale to emphasize either early or recent events [54], depending on what is considered to be the chronological origin of the timeline. *Narrative point*: logarithmic scales are appropriate for presenting timelines with long extents and a skewed distribution of events. *Examples*: Cloudlines [54], or timelines such as one depicting the history of the universe [50], or one depicting the emergence of life on Earth with an emphasis on historical events in human history [55, p.20].

Sequential scales are those in which the distances between successive events do not correspond to chronological distances; events are often equally spaced, or may be positioned to accommodate annotations or images. Though chronological dates are often included in the annotation layer of a timeline, chronological distances and durations are not directly encoded. *Narrative Point*: sequential scales are appropriate for communicating solely the order of events. *Examples*: a vertical timeline authoring tool [13] and timelines such as one depicting the history of Hong Kong [10], or a timeline depicting the history of coinage [85].

Sequential + Interim Duration is a hybrid combination of the sequential and chronological scales. *Narrative point*: this combination is particularly effective for presenting timelines with large chronological extents and a non-uniform distribution of events. It reflects a need to express chronological distances; however, when one attempts to visualize these events faithfully using a chronological scale, large swaths of the timeline are empty. *Examples*: this scale was largely inspired by cartographer Gerardus Mercator's chronology (1569) [77, p.64], a tabular ledger which expanded periods of history having a high event density, while contracting periods of history in which no recorded events occurred. Another inspiration was Blanchet's *Catholic Ladder* [77, p.154], [88], a timeline used by missionaries in the early 19th century in which the time elapsed between events was encoded either as lines (indicating centuries) or dots (indicating single years).

4.3 Dimension 3: Layout

The layout of a timeline describes whether and how the timeline is partitioned into separate regions of the display. The layout is used to communicate relations between groups of events. As shown in the third row of Figure 1, we have identified four timeline layouts:

A **Unified** timeline is a single timeline. *Narrative point*: this layout is used to present a single timeline of events. *Examples*: timeline authoring tools such as TimelineSetter [83] or Dipity [90], and timelines such as those depicting apocalyptic predictions [37] or the tenures of women in the American Senate [35].

A **Faceted** timeline is one that has been partitioned according to some categorical attribute, effectively resulting in multiple timelines. *Narrative point*: this layout prompts the audience to compare these timelines. *Examples*: timeline authoring tools such as TimelineJS [68] and Preceden [63], tools such as Cloudlines [54], Similan [101], EventRiver [60], or TimeSlice [102], as well as timelines such as one depicting America's involvement in wars faceted by world region [64], or the example shown in Figure 2, which is faceted vertically, with "*men of learning*" above and "*statesmen*" below.

A **Segmented** timeline is one that has been partitioned according to meaningful temporal divisions of time: consider a common calendar, which segments time by months, weeks, and days. *Narrative point*: segmented timelines allow for another form of relative comparison; for instance, the audience can compare major world events of the past decade to those of the same decade in previous centuries. *Examples*: visualization tools such as TimeFlow [94] or DateLens [15], and timelines such as those depicting the lifespan of a typical American person [91] or the history of films featuring extraterrestrials [93].

A **Faceted + Segmented** timeline is one that has been partitioned twice: first into categorical facets, and within these facets, it is partitioned again into temporal segments; the reverse ordering is also conceivable. *Narrative point*: faceted and segmented timelines allow for two forms of relative comparison, across multiple categorically distinct timelines and across multiple segments of time. *Example*: Beard et al.'s EventViewer visualization tool [14].

TABLE 1
Coverage of the 263 items in our survey with respect to the dimensions of our design space. Note that sums within cells may be greater than the row's count, as some timelines incorporate multiple representations, scales, or layouts.

Survey	Count	Representation					Scale					Layout			
Initial	145	118	6	5	11	8	106	12	3	34	2	60	79	9	1
Validation	118	74	5		1	39	42	4	3	70		87	31	3	
Total	263	192	11	5	12	47	148	16	6	104	2	147	110	12	1

4.4 Analysis of the Design Space

To our knowledge, our design space is the first classification specific to timelines, whereas Aigner et al.'s classification of time-oriented visualization techniques [5] encompasses all time-oriented data; like our design space, their classification discerns between linear and cyclic arrangements of time, the latter combining radial and spiral representations. In addition, Aigner et al.'s distinction between univariate and multivariate data roughly corresponds to our distinction between a unified and faceted timeline. However, Aigner et al. do not characterize other representations beyond linear or cyclic, nor do they characterize time scales or account for a segmented timeline.

Table 1 indicates the coverage of the 263 items in our survey with respect to the dimensions of our design space. Our survey corpus contains instances of all five representations, all five scales, and all four layouts. Some design choices are more prevalent than others, namely linear representations, chronological scales, and unified layouts. Out of the 100 possible combinations of representation, scale, and layout, this corpus contains only 24 unique combinations. Table 2 shows that some of these combinations are more prevalent than others.

We did not assume that these 24 combinations necessarily represent the complete palette of viable timeline designs. To assess the viability of combinations of representation, scale, and layout, we posed the following three questions in our analysis:

- Is the design ***purposeful***? Does the timeline design correspond to a meaningful narrative point?
- Is the design ***interpretable***? What perceptual task [27] is imposed upon the audience? Will the audience be capable of this task and therefore understand the timeline?
- Is the design ***generalizable***? Does the timeline design generalize across different datasets? A design should be robust to variation in terms of the number and distribution of events, the chronological extent of events, and the number of event categories.

By asking these questions for each combination of representation, scale, and layout, we identified 20 viable timeline designs, many redundant combinations, and several possibilities that should be investigated further in future work. Of the 24 combinations represented within the corpus, we argue that 18 are viable; also, 2 of the combinations that we consider viable did not appear in our survey corpus.

4.4.1 20 Viable Timeline Designs

We identify 20 viable timeline designs within this design space; Figure 3 shows thumbnails of our implementation of these designs along with the narrative points they support. Note that some of these timeline designs support the same narrative point. This overlap is intentional and is perhaps where the goals of data storytellers diverge from those of data analysts: given a set of timeline designs that support the same narrative point, one timeline design might promote the most perceptually accurate judgments, while another might be considered to be the most aesthetically appealing [21], [22], [52]. For instance, a linear representation will promote a more accurate perceptual judgment [27], but it may lack the aesthetic appeal of radial, spiral, or arbitrary representations. A storyteller could conceivably draw audiences' attention with an aesthetically pleasing timeline and transition to another timeline should the audience be expected to make a more accurate judgment. In addition, a multiplicity of designs may benefit a storyteller who faces constraints in terms of the medium of presentation, including restrictions upon the aspect ratio of a timeline view, or whether the audience is permitted to navigate a timeline via panning or zooming interactions. Figure 3 includes commentary about the trade-offs inherent in these designs, as well as the types of perceptual judgments that the audience would be expected to make.

Table 2 indicates the coverage of 263 items in our survey with respect to these 20 timeline designs; 253 of which (96%) can be characterized as being one of them. We encountered 80 instances of the most prevalent timeline design: a linear representation with a chronological scale, faceted by event category, which corresponds to the design popularized by Priestley shown in Figure 2. Unified linear chronological, linear sequential, and arbitrary sequential timelines are also well represented with over 30 instances each. The latter of these designs is prevalent among static timeline infographics, and we are unaware of any timeline authoring tool or visualization tool from the research literature that allows a storyteller to quickly generate an interactive timeline featuring an arbitrary representation. All but 2 of these viable timeline designs are represented in our survey, as indicated by the empty columns in Table 2. Though we did not encounter precedents for the radial chronological segmented timeline or the radial sequential faceted timeline, we have made use of them in our own timeline stories: we use the former ( ) in a story about the periodic pattern of major hurricanes over several decades, and we use the latter ( ) in a story about the creative routines of famous creative people; these timelines are also shown in Figure 4.

4.4.2 Redundant Timeline Designs

We also identify combinations of representation, scale, and layout that are redundant, being equivalent to special cases of one of the 20 viable timeline designs. These combinations can be grouped into three sets; to describe these sets, *, *, and * respectively stand in for any representation, scale, and layout:

* + + **Segmented** layouts partition a timeline using meaningful chronological divisions of time, but chronology is irrelevant when using a **sequential** scale. Alternatively, one could treat these chronological divisions of time as a categorical attribute to generate a faceted sequential timeline, such as in one timeline depicting the history of government policy relating to fracking [41].

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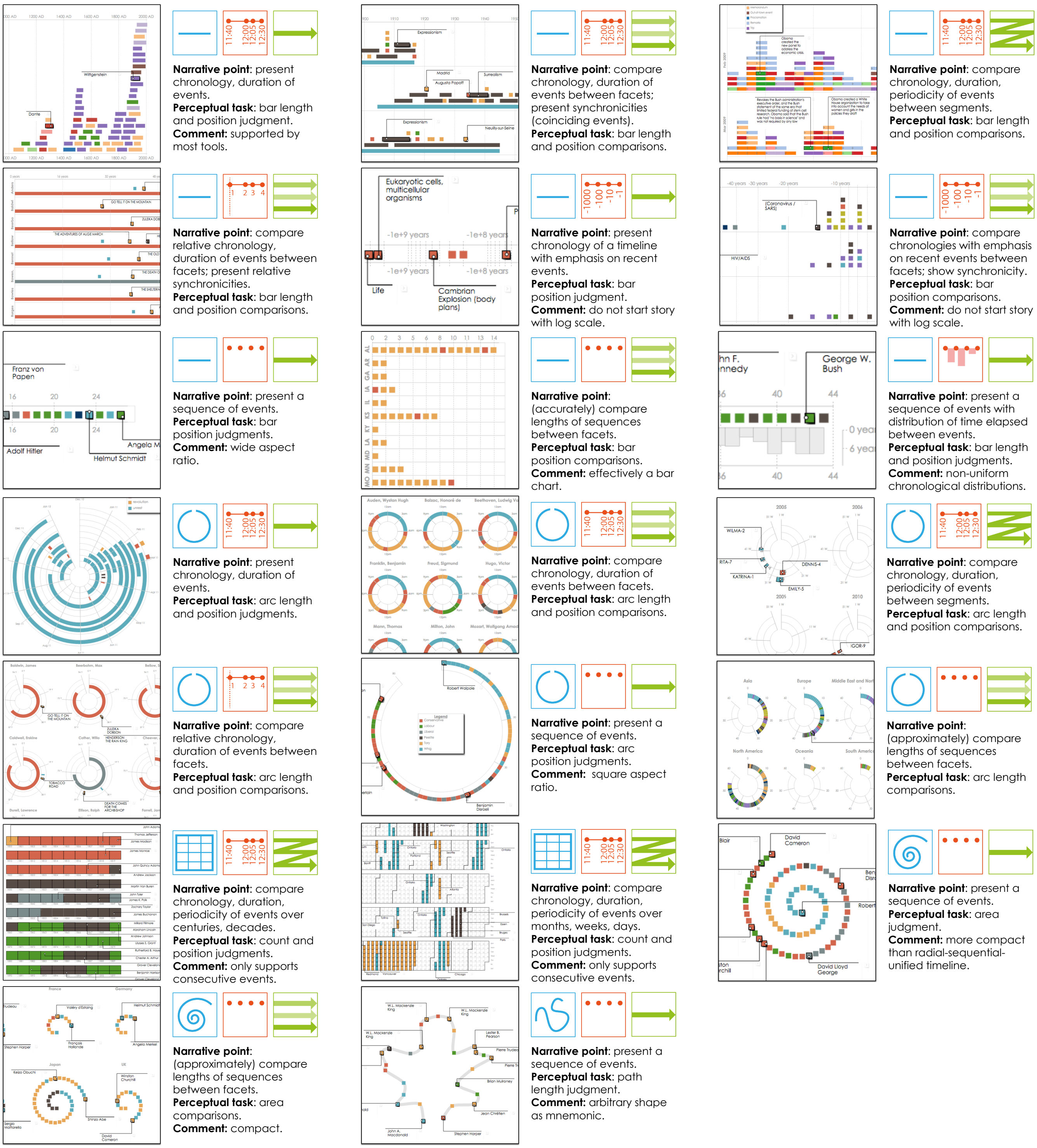

Fig. 3. Detail thumbnails of the 20 viable timeline designs generated within our sandbox environment, ordered left-to-right, top-to-bottom by representation, scale, and layout. In each timeline, individual events are encoded with rectangle or arc marks; their fill colours correspond with dataset-dependent event categories. The narrative point, perceptual task, and comments for each timeline design are also provided. Larger, high-resolution images of these timelines are available on our supplemental website along with descriptions of the visualized datasets and event categories: `http://timelinesrevisited.github.io/supplemental/gallery/`.

TABLE 2
Coverage of the 263 items in our survey with respect to 20 viable timeline designs that we identify. Note that some visualization tools may be capable of producing multiple timeline designs according to our classification. The final column indicates items that cannot be characterized as one of the 20 viable timeline designs that we identify.

Survey	Count																					
Initial	145	31	60	3	8	1	2	9	10	2	3	3		1			2	3	6		8	6
Validation	118	21	20	2	2	1	1	26	3		1			1	2					1	35	5
Total	263	52	80	5	10	2	3	35	13	2	4	3		2	2		2	3	6	1	43	11

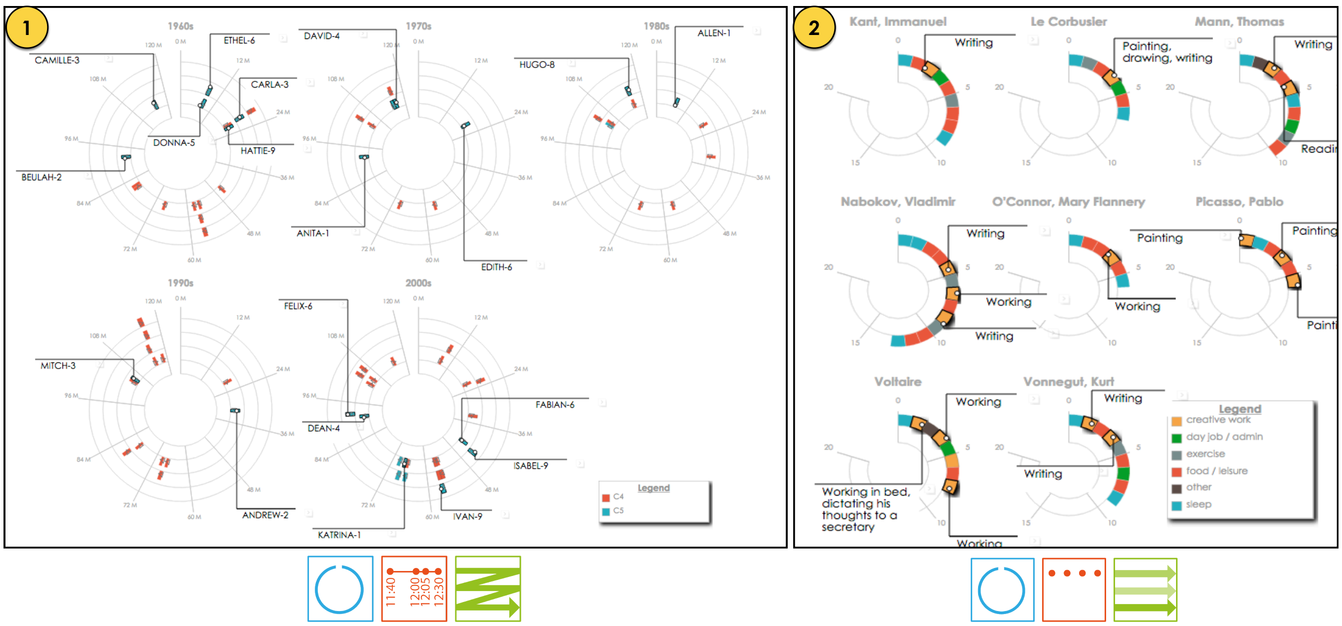

Fig. 4. Two viable timeline designs that we did not encounter in our survey. 1: A segmented radial chronological timeline of Category 4 and 5 hurricanes between 1960 and 2010, affording comparisons of hurricane severity and periodicity between decades. 2: Faceted radial sequential timelines depicting the daily routines of famous creative people, affording comparisons of the number and variation of events between people.

+ + (||) **Relative** scales are particularly appropriate when combined with a faceted layout to facilitate the comparison of categorically distinct timelines aligned to a common baseline event, such as a person's birth or a patient's admittance to a hospital. A **unified** or **segmented** relative timeline is functionally equivalent to a corresponding chronological timeline, albeit one that begins at time zero, such as in Neurath's timeline indicating the average lifespan of various animals [67].

+ + **Grid** representations are inherently segmented; consider the common Month-Week-Day calendar, which has been segmented into these granularities of time. Without segmentation, a **unified** grid is reduced to a single cell corresponding to a single granule of time, being functionally equivalent to a unified linear sequential timeline.

4.4.3 *Opportunities for Innovation in Timeline Design*

The remaining combinations of representation, scale, and layout present opportunities for future research and design innovation. They provide many potential opportunities for researchers to propose and evaluate purposeful, interpretable, and generalizable implementations for these points in the design space. Among them are 6 combinations represented by 10 items in our survey corpus that did not satisfy our interpretable or generalizable criteria. The other combinations that we did not encounter in the survey may fail to address all three criteria.

(|| ||) + + **Logarithmic** scales are notoriously difficult to interpret [36, p.200], and with the exception of one particularly dense radial infographic depicting the evolution of the known universe [50], we have yet to encounter a logarithmic scale used in combination with a non-linear representation. In a storytelling context, it cannot be assumed that the audience has seen a logarithmic time scale before and knows how to interpret one. As a consequence, future research is needed to identify purposeful and interpretable non-linear timelines that incorporate logarithmic scales.

+ + A timeline that is both **faceted** and **segmented** such as those generated by Beard et al.'s EventViewer [14] involves a nested partitioning of the timeline into rows of facets and columns of segments, or vice versa. As a result, this layout may require a very large display to accommodate the nested timelines or rely upon navigation via panning and zooming. In a storytelling context, large displays and navigation may not always be possible, and thus additional research is needed to identify generalizable techniques for partitioning timelines into facets and segments that remain interpretable and appropriate for a storytelling context.

! ( ) + + We have yet to encounter a timeline incorporating a **interim duration** scale aside from two linear timelines by Mercator and

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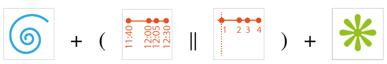
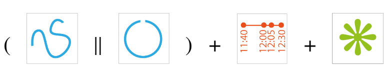
Blanchet found in Rosenberg and Grafton's historical survey [77, p.64,154]. Our own implementation of the interim duration scale (see Figure 3, third row, right column), involves juxtaposing a bar chart adjacent to the sequential timeline, in which the bars encode the interim duration or time elapsed between events. This approach works well for a unified linear timeline, where there is a common horizontal baseline from which to compare bar lengths. There would be no such common baseline in faceted or segmented layouts, nor would it be present in non-linear representations. A generalizable design for interim duration that is compatible across representations and layouts is another open technical question.



It is difficult to gauge **chronological** or **relative** distances along a **spiral** timeline (e.g., [24], [32], [70], [99]), and we are unaware of work that investigates the interpretability of this combination. Furthermore, a generalizable implementation for spiral chronological timelines is non-trivial. Consider SpiraClock [32], an interface which visualizes upcoming events on a chronological spiral clock face. SpiraClock handles cases where events do not overlap chronologically. Now consider cases of substantial event overlap; in Priestley's linear timeline (see Figure 2), events are drawn on another vertical "track" to avoid overlap with other events. It is not clear to us how multiple-track timelines could be realized with spiral and arbitrary representations; we consider this technical question to be open.

If each facet in a **faceted** timeline contains a unique **arbitrary** path, it may be difficult to compare ordinal positions across these paths, such as in an infographic depicting the history of web analytics [30]. If the arbitrary paths depicting time are homogeneous across all facets, such comparisons may not be as challenging to perform. Regardless, future research could assess the viability of these designs by investigating how people compare positions across multiple arbitrary paths.



As with the comparison of position across faceted **arbitrary** timelines, it is currently unclear as to whether people can readily gauge and compare lengths and distances along an arbitrary path. We are aware of one timeline infographic [28] that combines a simple arbitrary shape with a **chronological** scale for a small number of events. An interpretable design that generalizes to complex paths and across datasets would be a welcome response to this open problem.

5 The Realization of Timeline Stories

To realize the potential of our proposed design space and to validate the viability of the 20 timeline designs identified above, we implemented all 20 of these designs in a proof-of-concept interactive sandbox environment. This environment allows its user to load a JSON-formatted timeline dataset where each event is specified by a start and end date, a text description, and categorical attributes. Once an event dataset is loaded, the user can interactively select a combination of representation, scale, and layout; to realize an arbitrary representation, the user can draw any arbitrary shape using the cursor, and event marks will be interpolated along this shape. We implemented this browser-based environment using D3.js [20]; we also used the Moment.js [23] and d3-time [19] libraries for time parsing and arithmetic. The timelines shown in Figures 3 - 6 are partial screenshots taken within this environment.

We tested these 20 timeline designs with 28 datasets to demonstrate that our designs generalize to support a range of dataset sizes, temporal granularities, and timeline extents. A complete directory of these datasets along with descriptive metadata is available on our supplemental website[2]. Twelve of these datasets were adapted or extracted from existing dataset-specific timelines [2], [3], [4], [34], [51], [55], [58], [61], [73], [74], [81], [91], so we had a sense of what narrative points the original designer had intended to convey. The remaining datasets included both publicly available data and those from our personal and professional networks. These datasets vary considerably in terms of subject matter, from biographical timelines, to the consecutive tenures of heads of state, to periodic tornado and hurricane timelines. These timeline datasets have extents that range between hours (e.g., [73]) to those that extend between the big bang and today (e.g., [61]). Some contain a handful of events, while others contain many hundreds. Some of these datasets include categorical attributes for events, which can be used to facet a timeline or to encode event marks; for instance, the middle timeline in the top row of Figure 3 depicts the lifespans of great 20th century painters [4], which has been faceted by painter, and features event marks coloured according to event category, which include artistic periods, travels, and relationships.

5.1 Annotation, Highlighting, and Captioning

A palette of timeline designs is insufficient for storytelling on their own, as each timeline design is comprised merely of marks and axes, communicating little without additional context. To successfully communicate narrative points relating to the timeline, a storyteller should be able to highlight specific events, annotate these events with text and images, and add titles or captions to the timeline. For example, in Priestley's timeline, shown in Figure 2, a title appears above the timeline while textual annotations are added above each event mark. Our sandbox environment incorporates controls for highlighting events, hiding or showing an event category legend, adding and arranging annotations, and captioning, demonstrated in our gallery of timeline designs (Figure 3) as well as in the timeline stories described below. Rectilinear event annotations and event category legends are particularly prominent in Figures 4 and 5.

5.2 Animated Transitions for Cohesive Stories

Many data-driven stories contain a series of narrative points [7], [47]. Figure 3 demonstrates that no single design serves all possible narrative points relating to timelines. As a consequence, a single story may make use of more than one of these timeline designs. Furthermore, a storyteller may progressively disclose or hide parts of a timeline, either focusing on particular regions of the timeline's chronological extent or on particular categories of events. As an example, the timeline in Figure 5 depicts the durations of history's great empires spanning three millennia (adapted from a timeline by Lee [58]); a storyteller may choose to begin by focusing on the most recent millennium before revealing the entire timeline, or she may remove events to focus solely on the empires that achieved a worldwide reach.

A storyteller could present a series of timelines as static images on a single printed page or on a website, or she could prepare

2. http://timelinesrevisited.github.io/supplemental/datasets/

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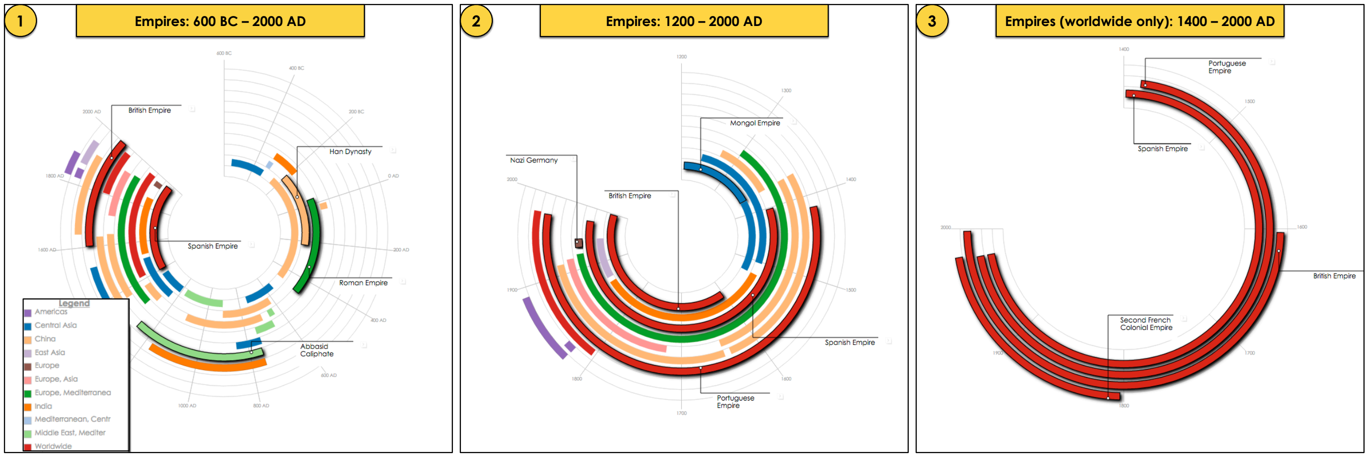

Fig. 5. A radial chronological timeline depicting the durations of history's great empires, colored by world region. An example of disclosing all or selected parts of a timeline via transitions: (1) all empires since 600 BC; (2) all empires since 1200 AD; (3) only empires with worldwide reach.

a linear slideshow. However, with either of these approaches, context may not be preserved from one timeline to the next, such as how the location of an event mark changes between them. Because tracking these changes between timelines is critical for the effective synthesis of successive narrative points, context-preserving animated transitions between timelines are an essential counterpart to our design space.

Animated transitions are already being used in the context of storytelling with timelines: many of the timeline presentation authoring tools we encountered incorporate panning and zooming animations, and animated transitions are employed by several dataset-specific timelines in our survey [35], [58], [78], [84]. For instance, in Fairfield's timeline of female representation in the US Senate [35], an animated transition is used when hiding or showing events corresponding to the tenures of male and female senators; the representation and scale of this timeline remains unchanged across this transition. An example in which the scale of the timeline changes during an animated transition is in Lee's timeline of history's great empires [58]: the viewer can interactively toggle between a chronological scale and a relative scale. Finally, an example in which the layout of the timeline changes during an animated transition is in Stauber's Histography [84]: the viewer can interactively toggle between a unified layout and a faceted layout by selecting event specific categories from a sidebar menu.

Since we anticipate that designers and storytellers will continue to use and experiment with animated transitions in interactive timeline stories and in timeline data videos [7], several forms of animated transitions are realized within our sandbox environment implementation. These transitions are triggered when switching between representations, scales, or layouts, as well as when disclosing or hiding parts of a timeline; our example stories discussed below feature both forms of animated transition.

5.3 Guidelines for Animated Transitions with Timelines

We can incorporate animated transitions into a timeline story in many ways. For instance, if we consider our set of 20 viable timeline designs, there are 190 possible bidirectional transitions between pairs of timeline designs (where n is the number of timeline designs and $\frac{1}{2}n(n - 1)$ is the total number of bidirectional transitions). We must also consider the space of possible animated transitions when progressively hiding or revealing parts of a timeline, transitions that do not result in a change of representation, scale, or layout, such as in Figure 5. We now discuss the lessons that we learned during the development of our sandbox environment and the production of our own timeline stories.

Staging: In our implementation, some transitions are more pronounced than others; transitions that involve a change in representation result in highly salient changes to a timeline, changing the shape of the timeline and by extension the direction that time takes across the display. To simplify these transitions, animation should be staged to reduce cognitive load, as demonstrated in previous studies [11], [16], [71]. We experimented with several possible staged transitions before identifying a design that generalizes across transition types:

(1) Drawing from traditional animation principles [56], begin by providing a visual signal that a transition is about to occur by reducing the opacity of event marks on the timeline and updating, removing, or adding axes to the timeline;
(2) Translate the event marks to their new location;
(3) If the scale and extent of the timeline has changed, adjust the size of the event marks corresponding to their duration with respect to the visible scale;
(4) Restore the full opacity of the event marks to complete the transition.

Staggering: The translation and scaling stages are also staggered [44]; the event marks move individually following a slight delay from one another, instead of moving as a single mass, which can result in occlusion and appear rigid. In our experience, a duration of 6 to 8 seconds per transition tends to be a good trade-off between maintaining a story's momentum and ensuring an interpretable transition. Our judgment was that these staggered transitions are visually pleasing and helpful in providing object tracking [6], in contrast to the findings of Chevalier et al. [26] that cast doubt on staggered animations in the case of 2D point clouds. We conjecture that animated transitions between timelines correspond to the case of structured data and motion paths that Chevalier et al. identified as being beneficial; future research would be required to confirm or refute this hypothesis by analyzing these animations according to their proposed metric of crowding.

Single-dimension transitions: We observed that transitions that vary more than one dimension of our design space at a time can be overwhelming, such as changing both scale and representation

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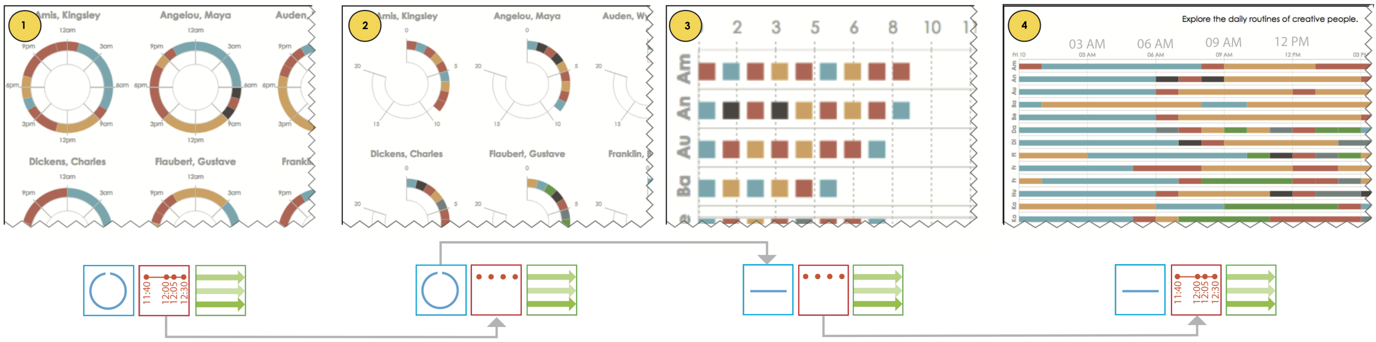

Fig. 6. This sequence represents scenes from our timeline story depicting the daily routines of famous creative people realized in our sandbox as an example story, which can be viewed as a video on our supplemental website: `http://timelinesrevisited.github.io/supplemental/stories/`. The initial narrative point (1) emphasizes the cyclical nature of a daily routine and compares the chronology and duration of events between the radial facets, where each facet corresponds to a famous creative person. This point is followed by a scale transition from chronological to sequential (2) and a representation transition from radial to linear (3). This narrative point involves a comparison of the length and heterogeneity of event sequences between the facets. Since these narrative points differ on more than one dimension of our design space, an intermediate scale transition (2) is required prior to the representation transition (3). Finally, another scale transition from sequential back to chronological (4), where the narrative point once again involves a comparison of chronology and duration of events between the facets, however the linear representation additionally affords the presentation of synchronicities (coinciding events) across the facets.

simultaneously. We therefore recommend that a single transition involve at most only one dimension that changes. Two consecutive narrative points may thus require more than one transition between them. Our supplemental website[3] contains looped animated GIFs of 33 single-dimension transitions, and Figure 6 shows an example timeline story that features three transitions.

Exceptions: Despite our recommendations to simplify transitions by staging, staggering, and restricting transitions to within a single dimension of our design space, we found that several single-dimension transitions were visually jarring; we offer specific recommendations to address these cases.

One type of jarring transition is between faceted and segmented layouts, as they impose a different partitioning on the timeline dataset and on regions of the display; in these cases, an intermediate transition to a unified layout is less jarring.

It is also difficult to follow transitions between scales, which can be resolved via intermediate transitions to the simpler chronological and sequential scales.

Another jarring transition involves grid representations such as the Month-Week-Day calendar, which impose a temporal segmentation that may be different from the segmentation used in a corresponding segmented linear or radial timeline. As a consequence, transitions to or between grid representations can be overwhelming; a generalizable solution for interpretable grid transitions is another open research question.

Finally, it is possible that some narrative points in a timeline story could be analogous to a change in subject in a spoken narrative. To support such pronounced changes, a storyteller could fade out the outgoing timeline and introduce the new one after a short delay, rather than attempt to transition between them.

5.4 Example Timeline Stories

Our realization of the design space through a sandbox implementation allowed us to produce and record seven example stories, each featuring a different dataset. While these stories span our design space, we did not attempt to exhaustively feature all 20 viable timeline designs and all possible animated transitions. To express these stories, our sandbox includes a minimal set of storytelling controls, including the ability to assign a timeline design to a "scene" of the story, to progressively disclose or hide events, and to record and replay a story. Figure 6 shows three scenes from one of our example stories, one that depicts the daily routines of famous creative people, adapted from an existing infographic [73]. The full story video, and six others, are available at the supplemental website for this paper[4]. These stories range between 90 seconds and 5 minutes in length and feature various animated transitions, captions, and annotations.

6 Conclusion and Future Work

This paper introduced a design space and considerations for presenting timeline stories with the aim of balancing expressiveness and effectiveness. Our work takes a different approach than previous work in the visualization research community that strongly focused on exploratory data analysis: leveraging timelines to gain insights on the data. In contrast, our focus is on communicating these insights to others. In our analysis of this design space, we identified a set of 20 viable timeline designs matched to a variety of narrative points, as well as considerations for using these designs in stories with the aid of animated transitions, allowing a storyteller to form a cohesive story across a series of different narrative points. Our analysis uncovered several technical questions that could lead to interesting future innovations in the design of timelines and animated transitions.

Our initial validation of this design space took the form of a proof-of-concept sandbox implementation that allowed us to verify the utility of these 20 viable timeline designs, and we produced seven stories using this environment to showcase the expressiveness of this design space. This sandbox allowed us to verify the applicability of these timeline designs and transitions across a broad set of 28 datasets, many of which were adapted from existing timelines found online. We also validated our design space through a coverage analysis of the 263 items in our survey, which included timeline authoring tools, timeline visualization tools or techniques from the research literature, as well as dataset-specific timelines, including interactive timelines and static timeline infographics. All of these items can be described using the

3. `http://timelinesrevisited.github.io/supplemental/transitions/`

4. `http://timelinesrevisited.github.io/supplemental/stories/`

dimensions of our design space, and 96% of the items in our survey can be classified as one of the 20 viable timeline designs that we identified. Additional future validation of our design space includes asking infographic designers and data journalists to impose their own categorization upon our survey corpus and comparing these categorizations to our own.

Our efforts lay the groundwork for years of future work and many possible experiments, including a set of experiments that will systematically compare possible timeline designs along with the possible transitions between them. These experiments might validate, expand upon, or refute our classification of viability by examining cross-sections of our design space. Other experiments might investigate animated transitions for timelines in greater detail; for instance, one study could focus solely on representation transitions, while another could examine scale transitions.

It is our vision that our palette of viable timeline designs and animated transitions between them be integrated into a full-featured authoring environment for storytellers. An ideal authoring tool would provide guidance in the form of recommendations and constraints based on properties of the timeline data and the intended narrative points, informed by our current findings. We also plan to demonstrate our sandbox environment, example gallery, and example stories to infographic designers and data journalists as a means to gather requirements for future authoring tools. Once an integrated authoring tool exists, it would be interesting to determine whether the way that authors use individual timeline designs to support specific narrative points matches our analysis. Deploying such a system would allow us to study both storytelling by authors and story interpretation by their audiences in the wild, and observe to what extent their narrative goals and interpretive capacities are supported or constrained by the principles embodied in our proposed design space.

It is our intent that our work will inform and inspire the design of the next generation of visualization storytelling tools, so that storytellers can present a wide range of narrative points with timelines in more expressive and engaging ways.

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