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Timeline Design Space for Immersive Exploration of Time-Varying Spatial 3D Data

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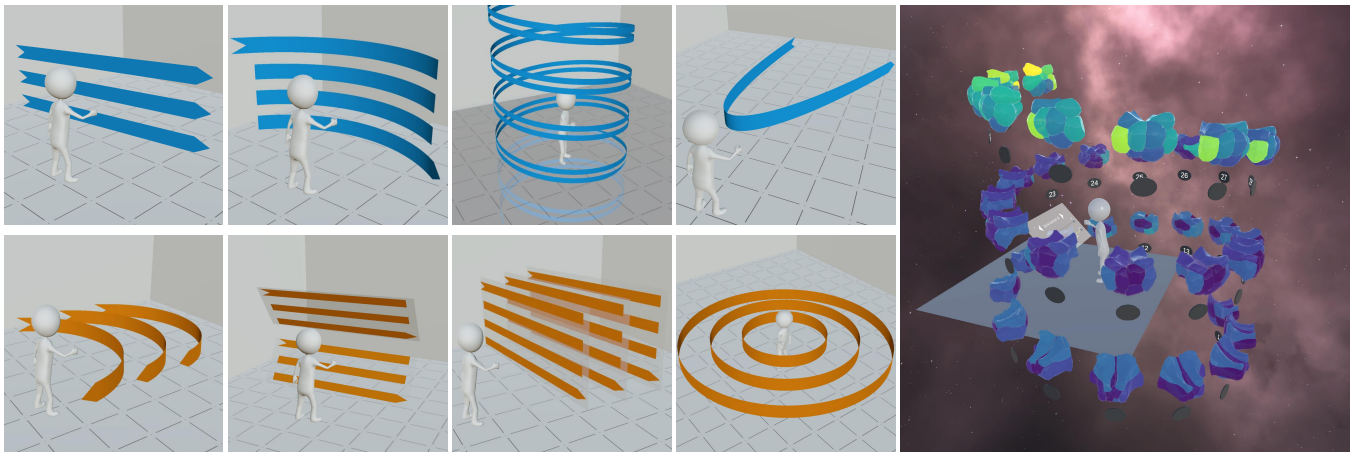


Figure 1: Illustration of the proposed 3D timeline design space for immersive exploration of time-varying spatial 3D data. The first row showcases different timeline representations, i.e. guiding curve of the timeline; while the second row showcases different support configurations. The rightmost image illustrates the use of an helicoid representation for the exploration of an time-varying embryo imaging dataset. The viridis colormap is used to encode the elongation ratio of cells involved in morphogenetic movements.

ABSTRACT

Timelines are common visualizations to represent and manipulate temporal data. However, timeline visualizations rarely consider spatio-temporal 3D data (e.g. mesh or volumetric models) directly. In this paper, leveraging the increased workspace and 3D interaction capabilities of virtual reality (VR), we first propose a timeline design space for 3D temporal data extending the timeline design space proposed by Brehmer et al. [7]. The proposed design space adapts the scale, layout and representation dimensions to account for the depth dimension and how the 3D temporal data can be partitioned and structured. Moreover, an additional dimension is introduced, the *support*, which further characterizes the 3D dimension of the visualization. The design space is complemented by discussing the

interaction methods required for the efficient visualization of 3D timelines in VR. Secondly, we evaluate the benefits of 3D timelines through a formal evaluation (n=21). Taken together, our results showed that time-related tasks can be achieved more comfortably using timelines, and more efficiently for specific tasks requiring the analysis of the surrounding temporal context. Finally, we illustrate the use of 3D timelines with a use-case on morphogenetic analysis in which domain experts in cell imaging were involved in the design and evaluation process.

CCS CONCEPTS

• **Human-centered computing** → **Visualization techniques**; *Virtual reality*.

KEYWORDS

Timelines, 3D temporal data, Multidimensional data, Virtual Reality

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1 INTRODUCTION

In the biology and medical domain, 3D imaging breakthroughs have notably increased the availability of time-varying spatial 3D data creating roadblocks and new challenges for researchers in image analysis, and visualization in order to fully exploit the large amount of data being produced [28, 32]. However, while automatic and semi-automatic methods can be used to analyze such datasets, the direct exploration by domain experts remains a necessary step during the analysis process. The most common approaches for the visualization of time-varying spatial 3D data, remain the use of temporal sliders [22], animation [26] or juxtaposition of time points [34]. However, such method presents a number of limitations, such as relying on the short-term memory to assess the temporal changes, and the limit of time points that can be juxtaposed due to the limitations of display size. One potential solution is to consider timeline visualizations to represent the evolution of the temporal dimension, however, while timelines are powerful visualizations for temporal events, they are less adapted for 3D spatial data.

This paper proposes an extended timeline design space for 3D temporal data, inspired from the design space described by Brehmer et al. [7]. Our design space extends the original design space, adapting them to additional workspace dimension, defining how data can be partitioned and structured in a 3D environment. Moreover, due to the specific characteristics of interaction of immersive contexts and in order to take full advantage of 3D timelines, we discuss the basic set of interaction techniques to explore and manipulate them, relying on methods of the field of Immersive Analytics [24], and propose a set of design criteria to drive the design process.

In order to explore the potential benefits of 3D timelines, we conducted two evaluations. The first evaluation was a formal summative evaluation, which explored how 3D timelines could improve data exploration tasks. For this evaluation, mainly VR experts were considered, and we focused on performance and usability. The second evaluation was a qualitative evaluation conducted in collaboration with experts in biology. The objective was to gather feedback on how 3D timelines could be included in their analysis workflow, i.e. how they could take advantage of 3D timelines to ease the exploration and validation process on their 3D temporal imaging data.

2 RELATED WORK

2.1 Visualizing Time-Varying Spatial 3D Data

Kim et al. [27] define spatial 3D data as “data with an inherent, meaningful width, height, and depth, where the relative position of things, their length, surface size and shape, etc. all might matter to a user”, and extend this definition to time-varying spatial 3D data, shortened respectively as S3D and S4D. S3D data considers four main categories: 3D paths (e.g. curves, trajectories), glyph or point clouds, surface data and volumetric data [27]. Moreover, categorical or numerical data are often present in such datasets, added through automatic or manual annotation processes, which increase the complexity of the data and the representation. The visualization of S4D data is challenging, as their large size, high resolution and high density imply not only potential technical difficulties with rendering, but also issues with level-of-detail [35] and occlusion [23], that can disturb the exploration of the data.

Juxtaposition is an approach used to represent and explore high dimensional data, by displaying different views and projection of the data separately [4]. Al-manee and Roberts [3] notably reported that more than half visualization systems, among the 491 reviewed, had 2 to 5 views. Munzner [39] proposed various design recommendations to juxtapose and coordinate multiple dimension-reduced views of high dimensional data. On the issue of S4D data, Duran et al. [22] propose a tool to visualize 3D temporal datasets of molecule simulations, juxtaposing a 3D data render with charts to display one-dimensional information. The small multiple approach goes further by coordinating a partition of the data. Bento Box [26] juxtaposed multiple instances of a volumetric dataset under different parameters. Relying on an immersive environment, the different views are displayed as a grid, and 3D interactions on time and rotation are coordinated. More recent work by Liu et al. [33] explored further how to display and interact with small multiples in VR. On the other hand, while the visualization of S4D data typically considers individual time-steps, visualizing multiple time-steps could enable a better identification of temporal events. Thus, we considered the timelines to complement the previous methods described.

2.2 Timelines

Timelines are a classic visualization for temporal data, which are mainly used to represent series of events linearly or in form of a tree. Timelines have a wide range of design choices [7], thus allowing to create expressive representations. Hence, they are often used for summarizing events, storytelling or historical summaries, but also for planning, using calendars or Gantt charts for instance. Narrative visualizations are often used to present data and information in an attractive yet understandable way, and timelines can be designed to balance perceptual and narrative effectiveness for this purpose. For example, TimelineJS [2] and TimelineSetter [42] are tools used in general media to generate slideshow timelines to describe long narratives, gathering numerous major events. In a context of data analysis, Lifeflow [46] and TimelineTrees [10] aggregate data using tree structures and use timelines to explore the temporal aspect.

Brehmer et al. [7] proposed a classification of timelines based on a review of 263 timeline designs, proposing a 3-dimension design space. The first dimension is the *Representation* of the timeline, i.e. its “most visually salient aspect, its guiding visual metaphor”. The most common and versatile representation of a timeline is linear, yet radial or spiral representations can be more adapted for periodic data. The second dimension is the *Scale*, which determines the reference and the relation between temporal and displayed distance (e.g. linear or logarithmic). The third dimension is the *Layout*, which describes if the display shows one or multiple faceted timelines, and if they are segmented or not. Following this work, Di Bartolomeo et al. [18] evaluated different representations on classic visualization tasks and proposed additional design recommendations. Nonetheless, 3D timelines are not approached in this design space, and are only lightly explored in the literature. The few examples include Beedocs [1], an authoring tool using 3D animations to explore a 2D timeline, or HeloVis [11] which displays radar data on a helicoid.

To help the exploration of timelines, interaction methods adapted to the visualization have been developed. The most common interaction is based on scrolling or sliders to move in time, which is

notably recommended by Blaschek et al. [6], for the familiarity with which the user will approach it. For example, works by Charles et al. [13] or Card et al. [12] use timelines to give an overview of events while using sliders to explore data in time. TimeZoom [16] also relies on horizontal scrolling to move in time, and base several other navigation methods on *regions of focus*. Such classic methods as sliders or pan and zoom were evaluated by Schwab et al. [41], to give creators more guidance to adapt the navigation on their visualizations. Yet, the need for enhanced interactivity led to the use of various user interfaces for timelines. As such, Morawa et al. [38] and Drossis et al. [20] proposed respectively to touch user interface to enhance interaction with time points, and a *time-tunnel*, displayed in an immersive 3D environment.

However, S4D data is rarely considered on timeline visualizations. A few examples can be found in contexts of 3D model editors, as proposed by Denning et al. [17] or Doboš et al. [19], that use timelines to display the step-by-step construction of the model. Although, S4D visualization tools sometimes use timelines as sliders, juxtaposing 1-dimension additional information with the 3D spatial data, as in Duran et al. [22] work, or RubberSlider [14] which uses a VR adjustable slider to explore a timeline and display 3D data. The lack of design guidelines for the visualization of S4D data using timelines motivated the extension of the design space from Brehmer et al. [7]. Yet, the visualization of such 3D timelines would require large displays to ensure that a reasonable number of time points can be explored and visualized efficiently. Thus, we leveraged the increased workspace size, depth cues [36] and navigation techniques [30] provided by immersive virtual reality systems to provide efficient visualization methods.

3 A TIMELINE IN A 3D ENVIRONMENT

This section introduces our design space for 3D timelines, which extends the 2D timeline design space [7] for 3D environments, and notably immersive environments. The extension considers the additional spatial dimension in which data can be laid enabling the direct display of the temporal dimension of the data. As mentioned in the introduction, we focus on S4D datasets. We assume that the temporal component of such datasets is discrete, or at least it can be discretized. As such, we can construct a timeline in which every time point is populated by a **3D snapshot**, i.e. the state of the 3D temporal dataset at an instant. We consider that some datasets are composed of a set of objects, i.e. shapes with the own semantic value, and define, assuming sufficient tracking information, **4D objects** that span along multiple time points. Finally, in order to exploit the interaction capabilities provided by IVR and to leverage 3D timelines, we detail the set of interaction tasks needed for their exploration.

3.1 Extending a 2D Timeline Design Space to 3D

Brehmer et al. [7] proposed a design space for 2D timelines with the three following dimensions: *scale*, *layout* and *representation*. The two first characteristics are mainly similar for 2D and 3D timelines, we added those parts for completeness, and to discuss them in the context of 3D temporal data. Then, we extend the *representation* dimension proposing additional types of guiding curves adapted to a 3D environment. Finally, due to the use a 3D display, we introduce

a fourth dimension, which describes the supporting plane on which timeline branches are laid: the *support* dimension.

3.1.1 Scale: Displaying Time. The *scale* dimension represents the relation between the displayed distance and the temporal distance. The *scale* dimension remains similarly characterized for 3D timelines, as defined by Brehmer et al. [7]:

- A **chronological** scale spaces time points according to the actual temporal distance, either **linearly** or **logarithmically**, depending on the distribution of the events.
- A **relative** scale arranges the time points according to a baseline event. It can notably be used to compare multiple timelines regarding this event.
- With a **sequential** scale, the distance between time points is fixed and does not correspond to the temporal distance.

3.1.2 Layout: Arranging Time Points. The layout dimension corresponds to how the timeline is partitioned in the display. Brehmer [7] describes several characteristics of a 2D timeline layout. First, a layout can be **segmented** or not. Segmentation is used to cope with spatial organization issues, such as the limitation in size of a 2D display, but also for analytic purposes, for example to separate the timeline to make periodic events more salient. The layout can also be qualified as **unified** or **faceted**, i.e. showing a timeline with one or several lines; the latter can be useful for comparing data from different sources over time. Whether derived from segmentation or faceting, we refer to timeline parts as *branches*.

These two characteristics can describe 3D timelines as well. Segmentation helps in solving issues of optimization of the large workspace offered by 3D environments, or to make periodicity salient. On the other hand, the choice between faceted or unified layout relies on the nature of the data and use case. A unified timeline design is more suited to focus on the dynamic features of one region of interest or group of objects, while a faceted layout allows the comparison of several ones. Faceted layouts are also adapted to juxtapose multiple datasets, as in such cases, the most common task is comparison. In any case, faceting or segmenting the layout tends to clutter the workspace. Attention should be given to properly indicate the origin and characteristics of each facet or segment as not to overwhelm the user.

3.1.3 Representation: Shaping the Timeline. The representation of a timeline corresponds to the shape, i.e. the guiding curve along which are placed the time points, which is equivalent to a time axis. In most cases, timelines are represented linearly [7]. This type of representation maintains a single orientation, often horizontal and following reading direction, and make for a good timeline readability [18]. Other designs use radial representation, to emphasize cyclic repetitions, or spirals, often used to get compact visualizations. Depending on the goal of the author of the timeline, some other types of representation can be designed for aesthetic, density or pedagogic purposes. From these representations used in 2D designs, we propose representations that take advantage of the 3D environment. First, the linear representation could be extended to a **3D curve**. Three main possibilities emerge:

Flat curve. The most direct extension of the linear representation in 2D would be to use a simple flat curve, as seen in Figure 2-A.

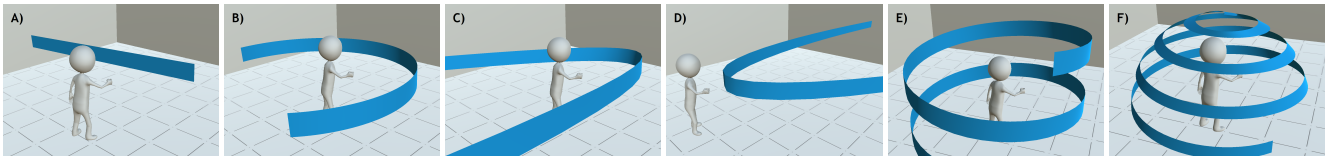


Figure 2: Third person views of options for the representation dimension of the 3D timeline design space. These illustrations show A) linear, B) convex arc of circle, C) convex parabola, D) concave parabola, E) helicoid and F) spherical representations.

There is no limit to the amount of time points displayable, yet the further the curve goes, the harder they are to reach or interact with.

Convex curve. This representation displays the time points around the user. Several types of curve could be considered. An arc of a circle centered on the user (Figure 2-B.) would place all time points at the same distance, enabling the same capacity of interaction and observation for each time point. This counters the primary issue of the flat curve representation, yet the radius of the circle will increase with the amount of time points, limiting the proximity required for interaction. To compromise between proximity and amount of time points, the user could navigate or move the arc of circle. Another approach would be to use a parabolic curve, as in Figure 2-C. In both those cases, a local temporal context is brought close to the user for interaction and observation, yet the other time points remain at a reasonable distance.

Concave curve. As opposed to the previous ones, a concave curve can be used to display close from the user a few time points, and sending the other ones that are farther in time, even farther in the environment. This representation emphasizes a local temporal context, frees some radial space around the user and decreases the density of information in their field of view. In this sense, the amount of time points displayed is potentially unlimited, yet harder to access. Similarly to convex curves, concave curves could rely on parabolas, as in Figure 2-D, or arc of circles, depending on the amount of time points that need to be close to the user.

Other designs for 2D timelines rely on circular or spiral representation. These representations are particularly adapted to provide an insightful representation of periodicity in time, as demonstrated with the spiral timeline from Weber et al. work [45]. However, because of the varying radius of a spiral loop, the number of periods have to be limited. Nonetheless, spirals are also intrinsically space-filling, thus producing dense representations, and can be engaging or even playful. Consequently, we propose two additional representations adapted to the design of a 3D timeline:

Helicoid. This representation coils the time points around a cylinder base. It can be centered on the user, displaying every time point close from the user, as shown in Figure 2-E. Similarly to the 2D spiral representation, this shape invites the display of periodic data, without the drawback of a varying radius between each period. The circular periods of the helicoid could be aligned to the occurrences of a particular event, for comparison purpose.

Spherical. Similarly, a spherical representation, as shown in Figure 2-F, coils around a sphere base. The time points are thus displayed around the user at the same distance, reducing distortions implied by distance or perspective and facilitating interaction. This representation shares similar advantages and drawbacks with the

2D spiral. It is aesthetically interesting, but the varying radius between two circular periods restrains its use for periodic data.

These two representations share several other characteristics. The exploration of the timeline is no longer horizontal as in the curve representation, but rather radial and vertical, allowing fast jumps in time. It is compact and takes full advantage of the 3D work space. Other representations using either different curves or volume could be used, that may be tailored for specific analysis use cases, for aesthetics or to create mnemonic designs.

3.1.4 Support: Exploiting the 3D Environment. In usual displays, timeline branches are most usually laid out on the display plane. As mentioned in Section 2.2, few works have explored displaying timelines in 3D environments. Beedocs [1] includes 3D perspective to animate and display the timeline at a different orientation for aesthetic purpose, while Kullberg et al. [29] even lays the timeline on the horizontal plane of a 3D environment, using the vertical plane to display the content of the time points.

As we propose to display 3D timelines in VR, we introduce an additional dimension, the *support*, to refer to the 3D shape that supports the timeline branches in such 3D environment. We describe here the main choices that will mostly influence the timeline design. This includes shape, size, position, and also count of supports on which the timeline branches are displayed. We propose the following choices for this dimension:

Vertical plane. The branches are laid on a plane vertically in front of the user, like a classic 2D display.

Horizontal plane. The branches are laid on a plane parallel to the floor. Horizontal head movements and field of view are usually preferred over vertical ones, thus this design choice could be better than a vertical plane support in some cases, such as comparison at one time point of multiple branches. The main drawback is occlusion, since branches are displayed one in front of the others.

Multiple Planes. As opposed to the previous design choices involving a single plane, here the branches are displayed on several ones. This can be useful to optimize application design, or separate clearly facets and segments.

Cubic. The branches are laid along multiple vertical or horizontal planes. Such layouts can be useful to organize branches along 2 parameters, much like a 2 dimensional array. While very meaningful in this purpose, this design might result with dense and cluttered visualizations hindering its manipulation and exploration.

Concentric cylinders. The branches are displayed on multiple isoradial planes centered on the user. In terms of exploration, it is quite similar to horizontal planes, yet fills the space around the user, which can serve aesthetic purpose.

Each of these dimension choices is illustrated in Figure 1, second line, in order. While this dimension is unnecessary for timelines with a unified layout, these design choices can be useful for some specific use cases, for application design, notably in terms of workspace usage, or for aesthetics. Yet, some of these designs can also involve significant occlusion issues. Adapted navigation and application controls might be required when using these design choices.

3.2 Interacting with 3D Timelines

This section discusses the interaction methods required for the exploration and manipulation of a 3D timeline. First, we consider methods enabling the free exploration of the timeline, supporting consume and search tasks. Then, we consider tasks that allow the manipulation of the timeline, in order to modify its arrangement. The discussed interactions consider that the user is using an immersive VR setup, in which the user can move physically to explore the timeline and that additional input capabilities are provided by hand-held controllers. For the sake of generalization, we will not discuss how the interactions can be implemented, but which parameters could be modified. The timeline is arranged in the environment in such a way as to have one time point, referred hereinafter *central time point*, that is the closest from the user (see Figure 5).

3.2.1 Exploring the Timeline. First, the user can physically move in order to approach the time point of interest. However, the range of time points that can be explored will be dependent on the shape of the timeline and the workspace of the VR setup. Timeline designs able to fit in the VR workspace, for example when using convex curves or spherical representations, will enable the direct exploration of all time points. In contrast, linear or parabolic representations can spread far away for the user, and faceted or segmented layouts might display data too high, limiting the number of time points users can access directly. To overcome this limitation, virtual navigation methods can be considered [30], which enable the user to virtually navigate. Potential good candidates are scene-in-hand methods [44] or virtual steering [9] which will allow users to reach time points arbitrarily far away from them. Yet, the choice in the virtual navigation method could depend on the implementation of the timeline, the data represented and the end user profile.

Finally, an alternative method to enable a full exploration of the timeline is to slide the timeline along its time axis, thus changing the *central time point*. This can be done continuously by scrolling the time points (e.g. using a temporal slider), or directly by selecting a time point from afar (e.g. using ray-casting selection [5]).

3.2.2 Manipulating the Timeline. There are numerous continuous parameters involved in the display of the timeline, such as the space between time points, the center and radius of curvature for curved representations, the height for helicoid representations or the distance between branches for faceted and segmented layouts. These values can strongly vary, notably depending on the amount of time points displayed in the timeline. For simplicity, the user could be able to choose among pre-defined configurations of designs. Nonetheless, to increase the flexibility of the visualization, the user should be able to adjust the parameters of the timeline in order to better fit their use-case requirements. The modification of these

values can be done using graphical user interfaces or dedicated 3D widgets [15]. Moreover, level-of-detail options are also relevant to control the information contained in the environment. The user should be able to choose to display only a proportion of the time points selected regularly along the timeline, and to directly choose time zones to collapse or extend via manual selection.

3.2.3 Manipulating the Content of the Time Points. The final interaction category relies on how the content of the time points could be modified. First, the 3D objects at each time point can be rotated and scaled, in order to enable the user to explore them from different orientations. To ensure consistency, we advocate linking the rotations and scale for all time points, thus obtaining a consistent orientation for all time points. Such manipulation could be achieved using uni- or bi-manual manipulation methods [37].

Second, operations to reduce the information at each time point can also be considered. Object and value filtering operations. These operations will be highly dependent on the available data in the S4D. For example, if the data for each time point is composed by a set of 3D objects (e.g. different 3D meshes, segmented 3D volume), individual 3D objects (or 4D objects if there is tracking information) could be removed from the timeline by selecting them. On the other hand, if additional categorical, ordinal or numerical attributes are available for each object (e.g. volume of a given object), filtering operations could also be defined (e.g. threshold, interval). These operations to reduce the displayed information could be of great relevance to reduce the amount of displayed information, reducing clutter. These interactions could be designed considering existing 3D selection methods [5] and 3D graphical user interfaces [15].

4 EVALUATION

The previous section discussed a wide range of potential 3D timeline representations, yet, from the design on itself, it remains unclear how users leverage the 3D timeline to explore S4D data. Thus, we conducted a user evaluation in order to determine the benefits of 3D timelines for the exploration of S4D data and assess how users perform exploration tasks with representative 3D timeline designs. This experiment included 21 participants, 5 women and 16 men, aged from 22 to 42, mostly recruited from our laboratory. Two of them had low experience with VR; the others were expert VR users.

4.1 Dataset

The S4D dataset used in the evaluation was generated procedurally in order to control the complexity of the dataset and limit the potential bias between users (see Figure 3). The dataset was composed of 6 objects evolving over time, and depending on the task (see below) having either 40 or 80 time points. Objects were represented by spheres, and their position did not change over time. The dataset was enriched by annotating objects with two attributes. First, a categorical attribute encoded with different colors and describing the affiliation to one of 5 **groups**, which could change over time (see Figure 3, center). We randomly introduced several occurrences of a specific pattern in the group information, on which we can evaluate success and error rates for the related task. Second, a continuous attribute (float **value**) evolving over time, encoded using the *viridis* color map (see Figure 3, right). This value was generated by adding 4 random Gaussian functions, one on each 20-time-point segment.

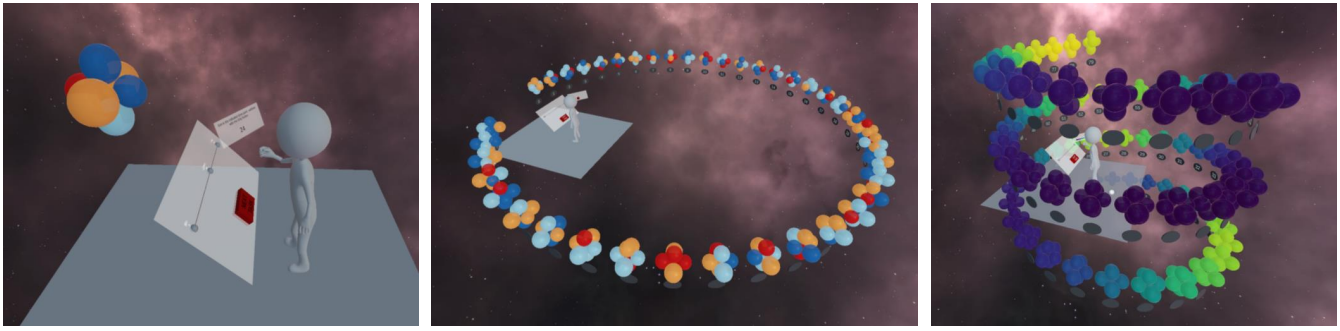


Figure 3: Environment for the user experiment. The right image shows the Lookup task in the *No timeline* condition; the middle one shows the Browse task in the *Curved* condition; the left one shows the Compare task in the *Helicoid* condition, where the objects are colored using the *viridis* colormap.

4.2 Task Design and Hypotheses

Participants had to explore the dataset and perform four common visualization tasks [39], adapted for the exploration of time-varying data: Lookup, Browse, Locate and Compare. For the **Lookup task**, a dataset of 80 time points was used. Participants had to find random time points between 0 and 79. They had to reach the indicated time point by using the time exploration technique available, described below. For the **Browse task**, a dataset of 40 time points, annotated with the group information was used. Participants had to count the number of object occurrences of a given group in all time points. The task was limited to 3 minutes. For the **Locate task**, a dataset of 40 time points, annotated with the group information was used. Participants had to identify the occurrences of a specific 3-time-point-long temporal pattern. The task was also limited to 3 minutes of exploration. Finally, for the **Compare task**, a dataset of 80 time points, annotated with the continuous information was used. Participants were instructed to compare the objects and identify the one exhibiting the maximum value. For simplicity, all objects from the same time point had the same value.

The two first tasks (Lookup and Browse) did not require temporal context. Indeed, the information to find was punctual in time, thus any method allowing scrolling through time could be sufficient. Thus, we did not expect timelines to be particularly efficient for this type of task. On the other hand, the two other tasks (Locate and Compare) required information from previous or following time points. While we expected better outcomes using timelines, the result could also be dependent on the timeline design, as how the information accessed. We expect that denser timeline designs will allow to access a larger temporal context also being useful to handle more time points. In overall, providing better performance of Locate and Compare tasks. Accordingly, we chose different timeline designs, which are detailed in the following section. In summary, our hypotheses were:

- H1a** Tasks that did not require exploring temporal context will be achieved at similar performance with or without timeline.
- H1b** Tasks that did not require exploring temporal context will be achieved more comfortably with a timeline.
- H2** Tasks that require temporal context will be achieved better using a timeline.

- H3** Access to more information through denser timeline designs will improve task performance.

4.3 Independent and Dependent Variables

The experiment followed a within-subject design in which participants had to perform the different tasks using 3 different visual conditions. The first one was the *No timeline* condition, in which only a snapshot of the dataset at an instant was displayed. The two others used timeline designs to take advantage of the 3D workspace, a helicoid unified (*Helicoid*) and a circular convex unified (*Curved*) timelines. The unified layout was chosen for there are few objects with little spatial complexity, and the representations were adapted for the amount of time points to observe. The support dimension corresponded to respectively a vertical plane and a cylinder, as the characteristics of the data did not require additional support planes. The two designs can be explored similarly, yet the helicoid design exploits the vertical axis and thus corresponds to a denser timeline design. For all conditions, object selection and task validation was done using a virtual laser pointer. Object manipulation was done using a bi-manual control. In contrast, time exploration was adapted to each timeline condition. In the *No timeline* condition time exploration was done by scrolling on the controller touchpad or using a through a 2D slider (see Figure 3, left). For the timelines, scrolling made the timeline slide along its directing curve. Moreover, users could also select at time point by orienting their heads towards it and pressing the trigger button.

Regarding the collected data, for all tasks, we measured the time to complete the task, as well as the movements and the time using the different available VR interaction tools. For the Lookup task, we also computed the difference between the selected time point with the target time point. For the Browse task, we also computed the error rate. For the Locate task, we further evaluated the precision and recall. Finally, for the Compare task, we evaluated the accuracy.

4.4 Experimental Protocol

At the beginning of the experiment, participants signed a consent form and filled a demographic information questionnaire. Participants received an explanation of the VR system and the available

interactions. Then, they could get used to the tools and the application layout for 10 minutes. The participant then proceeds to the tasks in the following order: Lookup, Browse, Locate, Compare. The display condition was counterbalanced using a Latin Square design. The order of the tasks was not counterbalanced as they were presented with increasing complexity.

After each condition, participants filled the SUS [8] questionnaire to evaluate usability. Finally, to subjectively assess the timelines, for each task and condition we asked the following questions: “What condition felt the most comfortable for this task?” and “What condition seemed the most efficient for this task?”.

4.5 Results

Analysis was mainly conducted using a one-way repeated measures ANOVA, using post-hoc tests (Bonferroni correction) when needed. When normality assumption was violated (Shapiro-Wilk normality test), we used the non-parametric Friedman test, using pairwise-wilcoxon tests when needed. We report the partial eta square (η_p^2) for ANOVA analyses and the Kendall’s W for the Friedman analysis. Only significant post-hoc tests are reported ($\alpha = 0.05$).

Lookup task. The first two trials of each condition and participant were removed due to their large variability (learning). In general, participants made almost no **errors** ($M=0.018$; $SD=0.077$), showing that they were able to perform the task accurately. However, the Friedman test condition vs **average time** showed a significant effect $\chi^2(2)=13.24$; $p < 0.01$; $W = 0.32$. Post-hoc tests showed that users were significantly faster with the *No timeline* condition ($M=7.12$; $SD=1.86$) compared to the *Curved* ($M=8.75$; $SD=2.38$) and *Helicoid* ($M=9.57$; $SD=4.13$) conditions. This result **does not support H1a**.

Browse Task. Participants never reached the time limit and did a small number of **errors** ($M=0.04$; $SD=0.06$). The Friedman test condition vs **time** showed a significant effect ($\chi^2(2)=18.29$; $p < 0.001$; $W = 0.43$). Post-hoc tests only showed that the *No timeline* condition ($M=106.8$; $SD=40.4$) required significantly higher times compared to the *Curved* ($M=76.8$; $SD=42.2$), *Helicoid* ($M=68.4$; $SD=32.7$) conditions. This result **does not support H1a**.

Locate task. Participants achieved the task with a reduced number of **errors** ($M=0.99$; $SD=0.03$). The one-way ANOVA condition vs **recall** showed a significant effect ($F(1.66,33.13) = 5.41$; $p < 0.01$; $\eta_p^2=0.21$). Post-hoc tests showed that only the *No timeline* condition ($M=0.652$; $SD=.201$) had lower recall compared to *Curved* ($M=0.798$; $SD=0.15$) and *Helicoid* ($M=0.818$; $SD=0.17$). This result **supports H2**. Finally, the one-way ANOVA condition vs **time** showed a significant main effect ($F(1.93,38.64) = 9.53$; $p < 0.001$). Post-hoc tests showed that the *Helicoid* condition ($M=157$; $SD=38.8$) had the lowest task completion time compared to the *No timeline* ($M=192$; $SD=20.9$) and the *Curved* conditions ($M=180$; $SD=28.5$). This result **supports H3**.

Compare task. The measured **error** rate was always close to 1 ($M = 0.997$, $Min=0.98$), participants were able to accurately perform the task with all conditions. The Friedman test condition vs **time** showed a main significant effect ($\chi^2(2)=8$; $p < 0.05$; $W = 0.190$). Post-hoc tests showed that *No timeline* condition ($M=32.5$; $SD=10.54$) required significantly more time than the *Helicoid* ($M=26.1$; $SD=9.12$) and *Curved* conditions ($M=22.8$; $SD=9.19$). This result **supports H2**.

Questionnaires. The one-way ANOVA condition vs **SUS score** showed a significant main effect ($F(1.57,31.43) = 5.78$; $p < 0.05$; $\eta_p^2=0.22$). Post-hoc tests only showed that the *Curved* condition ($M=81.9$; $SD=11.7$) obtained higher scores than the *No timeline* condition ($M=70.4$; $SD=12.2$). Then, Figure 4 provides a summary for the comfort and efficiency assessment. In overall, in terms of comfort, the users generally preferred the *Curved* condition for every task. The *No timeline* condition was second only in the Lookup task, for the other tasks the *Helicoid* condition was preferred. About subjective estimation of efficiency, the *Curved* condition was still preferred in all tasks, except in the Finding Lookup task, for which the *No timeline* condition was arguably even. However, the second place was more clearly attributed to the *Helicoid* condition for this criteria. Overall, we can argue that participants preferred the use of timelines but more simplified representations were preferred.

4.6 Discussion

The results from the two first tasks, that did not essentially require temporal context, were mitigated, so we must **reject H1a**. The results from the questionnaire however **support H1b**, as users did report preference for timelines for these tasks. Several results from the Locate and Compare tasks **support H2**, that we can accept. Finally, results from the Locate task **supports H3**.

Overall, these results showed significant benefits of using timeline designs over classic visualization for temporal exploration tasks, in terms of time and quality of completion, yet also in user experience. Nonetheless, we expected a more significant difference between the two timeline designs, notably regarding the different number of time points between the tasks. We explain this lack of differences due to the choice of using a Latin Square ordering: in two out of three orderings, the *Curved* condition was tested after the *Helicoid*. As learning effects did disturb some results, we think that extending this study with the 6 other ordering possibilities might make such effect appear clearly, but would require a large number of participants.

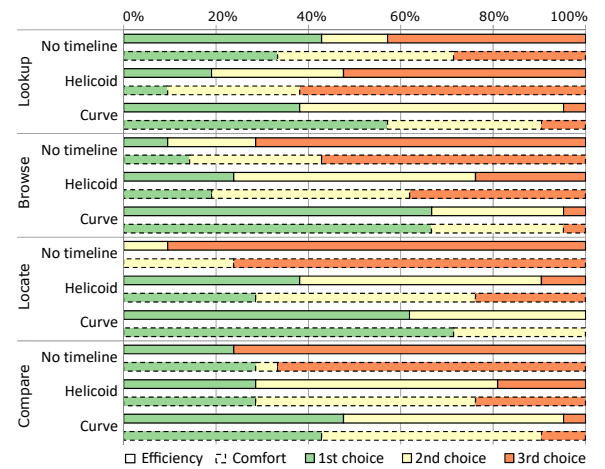


Figure 4: Ranking for perceived comfort and efficiency for each display condition and task.

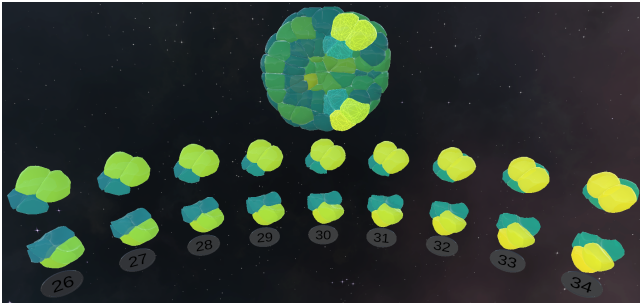


Figure 5: Embryo at the 30th time point. The snapshot at the central time point shows 2 groups of are selected symmetrically as to compare their individual evolution. They are displayed on a Circular Convex Faceted timeline, linear scale, vertical plane. The information color-mapped is the remaining lifespan before division (colormap *viridis*).

5 USE CASE: MORPHOGENETIC ANALYSIS

We illustrate the use of 3D timelines in an example from the biology domain, and in particular on the visualization of 3D spatio-temporal datasets acquired through live embryo microscopy imaging. Our goal was to gather insights from domain experts, generally unfamiliar with VR, on how 3D timelines could be used for their needs.

5.1 Dataset

A live recording of the embryonic development of a *Phallusia Mammillata*, a tunicate of the ascidian class (see Figure 5) was chosen as the main dataset (available on the MorphoNet website [31]). The ascidian embryos are characterized by their fast development and low number of cells (a few hundreds). The acquisition was made using confocal multiview light-sheet microscopy and then processed to obtain a surface-based spatio-temporal dataset of a few hundred megabytes with 180 time points [25]. Categorical and numerical information were added through automatic and manual process by the community of biologists working with these data.

The visualization of the post-processed dataset is an important part of the analytical process. Initially, as most of the image processing and annotations are automatic, biologists need to validate, correct and add data manually, for instance to check for errors in segmentation which could lead to abnormal cell shapes. Then, the 3D nature of the data and high temporal resolution allows a general observation of the main dynamics involved in biological processes through different angles, giving insight and understanding of the evolution of the embryo.

5.2 Application and Timeline Design

The application used in the experiment was extended in order to better support the analysis of the S4D dataset. First, the user could choose the annotated information displayed through a 3D GUI. Their choice will change the color-mapped information. Second, we also implemented an object filter operation to decrease the amount of information displayed on the timeline. Users could select a cell on the 3D snapshot to select the whole **4D object**, i.e. each

occurrence of the cell (including parent and child cells) at each time point. Only the selected 4D objects were displayed (see Figure 5).

From the dataset and the different analyzed scenarios, we proposed the following timeline design. As the dataset observed comes from imaging taken at regular time step, the scale dimension of our design is thus intrinsically **chronological and sequential**. Considering the tasks described in the previous section, we considered two layout choices, **faceted** to allow comparison between cells, and **unified** for an analysis of the spatial context. For the representation, we chose a *helicoid* for the unified layout in order to maximise the number of time points accessible, and a **curved** for the faceted layout, to manage the upward dimension more easily. Finally, we end up with two 3D timeline designs: (1) helicoid unified, chronological and sequential, cylinder support and (2) curved faceted, chronological and sequential, vertical plane support.

Finally, taking advantage of the large work space offered by the immersive environment, we juxtaposed the 3D timeline with the 3D snapshot at an instant or interest, as shown in Figure 5. The timeline provides temporal context, and the 3D snapshot provides spatial context. In the following, we describe examples of processes for analysis relying on the timeline visualization, further illustrated in the accompanying video.

5.3 Data Analysis using 3D Timelines

Finding Regions of Interests. Defining a region of interest is a classic visualization task, especially difficult when exploring large multidimensional datasets. We propose an iterative process to define and refine them, both in time and in space, using the 3D timelines. Initially, the user selects a few objects via ray-based selection as well as an adapted layout for the 3D timeline. The first step of the exploration consists in a broad overview of the objects and color-mapped values displayed over the timeline. This global exploration allows to eliminate non-relevant data, through value filtering or by collapsing temporal regions, allowing to identify the main regions of interest. In a second step, a user can focus on individual time points allowing the refinement of the objects of interest, i.e. of the local spatial context. Further refinement of the spatio-temporal context can be done by repeating this process, adjusting successively the spatial dimensions, then the time dimension.

Comparing Objects. Comparison is also a usual analysis task in visualization, yet Kim et al. [27] report that this topic is quite underexplored in the case of S4D datasets. Timeline visualizations intrinsically juxtapose and allow a comparison between the selected objects or regions of interest at various time points, supported by the interactive level-of-detail and timeline collapse methods described in Section 3.2.2. However, the task of comparing 4D objects is more complex, requiring to compare both temporal and spatial features that need to be identifiable in each of the compared objects. Notably, using a faceted layout, the 3D timeline visualization allows the comparison of selected 4D objects or regions of interest, extracted from one or more datasets. For example, the considered dataset includes the notion of lifespan, as cell fusion and fission events will modify the number of 3D objects in a given time point. We approached this issue considering that selected 4D objects comprise all of the 3D objects involved in the event, creating different branches depending on the type of event. For this use case and

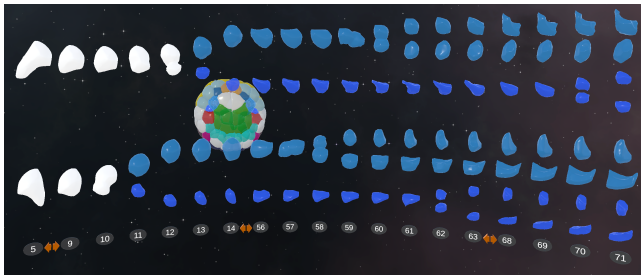


Figure 6: Two sister cells are selected and displayed on the timeline. The information color-mapped corresponds to the fate of the cells. The selected ones start without annotation and are determined after a first division. The tree-like structure of the timeline shows the asymmetry of the division, with one cell significantly larger than the other.

dataset, we propose an adaptation of the faceted layout for the 3D timeline design to represent the branches, inspired by the lineage tree [43], emphasizing those events and allowing comparison of the cells, as shown in Figure 6.

5.4 Testing and Expert Feedback

We gathered feedback and insights from a total of 20 biology experts participated, among which 5 were familiar with the dataset or experts in embryology, and the others are specialized in other domains. They participated in sessions of about an hour by groups of 2 or 3, in order to try the application and discuss potential application of 3D timeline visualizations in their respective fields. We presented them the dataset used and the application controls, and let them explore the data using the timeline designs proposed and the analytic techniques described previously.

The embryology specialists were overall positive about the visualization. They could analyse easily value evolution over different cells, as in Figure 1, identify outlier behaviors, and obtain information about a cell differentiation, as shown in Figure 6, where an undetermined cell is selected and differentiate itself after division. They also considered how such visualization could be beneficial in comparing multiple embryos, which they can difficultly do with their current visualization tools. The specialists from other domains could not go into such details with this dataset, yet they projected how they could benefit from 3D timelines for their own data. They quoted several examples of adapted use case with other S4D datasets such as imaging of organoids [21], in context of immunology or cancer research. They also mentioned how 3D timelines could be helpful to visualize colocalization over time of objects of different nature in multi-channel imaging.

Most of the negative feedback was about improving the application design to integrate it in the analysis workflow. Several key points in the analysis process should be included to answer completely the use case, including raw data visualization, standard data formatting or annotation options. The integration of VR equipment is also an obstacle, yet several people mentioned they would be willing integrate it in their work stations if the mentioned options were implemented.

6 GENERAL DISCUSSION AND CONCLUSION

In this paper, we proposed an extension of the 2D timeline design space proposed by Brehmer et al. [7] into a 3D timeline design space, focusing on their use for S4D dataset visualization. To do so, we extended the *representation* dimension, using 3D curves as guiding lines for timelines, and introduced an additional dimension describing the 3D geometry on which several timeline branches could be displayed, named *support* dimension. We proposed to use these timelines in a VR environment, leveraging the benefits of the material to enhance the exploration and interaction with such structures. We tested two 3D timeline designs against a baseline visualization based on a 3D render and time slider, on tasks oriented toward the exploration of a S4D dataset. The experiment results led us to conclude that 3D timelines significantly improved the achievements of tasks requiring large temporal context, yet could not conclude on the benefits of one or the other timeline. Finally, an application implementing 3D timelines and adequate interaction methods on a embryo S4D dataset was tested by 20 biologists. Their feedback was very positive, both for this specific dataset but also opening to various use cases in other biology domains.

As opposed to the design space proposed by Brehmer, we are not classifying existing examples of timelines. By extending the 2D design space, we could propose a mostly usable and general 3D design space, yet it also implies our design space might be less exhaustive. We expect that both the representation and support dimension could be even further explored, as they exploit the 3-dimension space, and could be used for more innovative or use-case specific timeline designs. Furthermore, if our evaluation showed the usability of 3D timelines in general cases, a comprehensive evaluation of the design space would be interesting to properly evaluate the benefits and drawbacks of each component of the design. Nonetheless, S4D data are extremely varied, and the different topology, resolution, temporal characteristics might be obstacles in the encoding of such data as time point information. Yet, this variety in the data and in the associated analysis use-cases could inspire other design choices, which would enrich our design space.

Similarly, future works could improve the interaction pallet we provided. The use of 6-degree-of-freedom 3D interface allowed us to implement efficient yet basic interactions for S4D datasets for general tasks. However, the literature proposes finer techniques, notably for selection and navigation [30], that could be more adapted depending on the characteristics of the data or the 3D timeline design choices. Our interaction pallet allows to approach most of the Immersive Analytics tasks described by Fonnet and Prié [24], yet some of them were left out. Notably, the biologist who tested the application regretted the lack of annotation functionalities, as such task is key in the analysis process. We suggest that such limitation, as well as the obstacle of integrating VR material in analysts workspace, could be overcome through asymmetric collaborative visualization systems, as described by Reski et al [40], with one user on a desktop application and the other in VR.

To conclude, future works should investigate the implementation of 3D timelines as a part of a complete visualization application designed for analysts. More than the goal for novel visualization methods in general, this could also help exploring, extending and evaluating this method which is yet to be applied in a real 3D temporal data analysis scenario.

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