A taxonomy of temporal data visualization techniques

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Résumé

Plusieurs techniques de visualisation et d'interaction avec des espaces de données temporelles ont été proposées dans la littérature. Toutes ces techniques ont été conçues indépendamment les unes des autres. Dans ce contexte, il est difficile d'explorer l'ensemble des possibilités de conception de ce type de technique de visualisation. Dans la perspective de résoudre ce problème, cet article présente une taxonomie des techniques de visualisation de données temporelles. Sur la base de l'étude de trente sept techniques et systèmes de visualisation de données temporelles, notre taxonomie structure l'espace de conception selon les étapes du processus de visualisation de Chi.

***Mots-clés** : Techniques de Visualisation, Données Temporelles, Processus de Visualisation, Taxonomie.*

Abstract

A wide range of visualization techniques have been designed to assist users to visually analyze and manipulate temporal data. All the proposed techniques have been designed independently. In this context it is therefore difficult to systematically explore the set of possibilities as well as to thoroughly envision visualization techniques of temporal data. Addressing this problem, we present a taxonomy of visualization techniques of temporal data. Based on a study of thirty-seven visual tools and visualization techniques of temporal data, our taxonomy structures the design space according to the Chi's visualization process steps.

***Keywords:** Visualization Techniques, Temporal Data, Visualization Process, Taxonomy.*

1. INTRODUCTION AND RELATED WORK

An object property is said to be temporal if its successive values are meaningful and thus recorded. A value of a temporal property is a history or a set temporal data, e.g. a function from a finite set of instants observed at a fixed granularity (i.e. a time unit), to a set of values of a given type. The domain and the range of a history are respectively called its temporal and structural domain [11]. In the study reported in this paper, we focus on histories whose structural values are of a quantitative type. Examples of such history are the salary of an employee or the daily productions of a firm. In the following, the expressions "temporal data" and "histories" are considered to have the same meaning.

Many visualization techniques of temporal data have been proposed in various application domains including the display of clinical data [26], geographical data [20], hydrometric data [18], personal histories [23], and for different purposes as for searching trends and patterns [12], exploring program traces [25], analyzing log data [13], representing temporal abstractions [27] or visualizing temporal association rules [24]. All the proposed techniques have been designed independently. Within this context, it is therefore difficult to compare the existing visualization techniques and explore new designs. In this paper, we present a classification space based on the steps of the Chi's visualization process to provide a systematic classification process of visualization techniques of temporal data. The contribution of our classification space is two-fold:

- The ability of our framework to compare/classify existing visualization techniques has great promise, especially in light of the rapid progress that we are experiencing in the domain.
- By identifying and organizing the various aspects of visualization, our framework should also help the designer to address the right design questions and to envision future visualization techniques of temporal data.

Few design and classification spaces have been proposed in the literature. Silva et al. [29] classify the visualization techniques according to two classes of features: visualization and interaction features. Visualization features include the data characteristics (e.g. complex entity, entity-relation, periodic pattern, pattern/trend) and the rendering (snapshot view, focus+context, multiple calendars, user-defined display). Interaction features are derived from Shneiderman's taxonomy of tasks [28] that is general and not dedicated to interaction with temporal data. Complementary to this classification scheme, several time-specific interaction tasks (e.g., merging two timelines in order to obtain a new one, juxtaposing two timelines) for visualization techniques of temporal data are proposed in [19]. Another taxonomy of temporal data visualization techniques is described in [22]. The taxonomy identifies two classes of visualization techniques: static versus dynamic. A technique is called dynamic if the associated visual representation is time-dependent, otherwise it is called static. In static techniques, the visual representation of objects does not change, unless a modification is required by the user. By contrast, in dynamic techniques the visual representation of objects evolves according to the time of modification of their values.

Although these studies identify classes of visualization techniques, they do not extend enough so as to be used as guidelines during the design phase. Addressing this issue in the context of data visualization in general, Chi [3] structures the visualization process into steps described in section 2, from the data to their rendering. Techniques are then classified according to the visualization process they implement: Doing so, Chi shows the similarities and differences between them. However, the Chi's study does not consider the specific role of time in visualizing temporal data. In this paper we present a classification scheme of techniques dedicated to histories (e.g. temporal data) visualization. The classification criteria are based on the steps of the Chi’s visualization process. To validate these criteria, we studied thirty-seven tools and techniques dedicated to temporal data visualization [7]. However, in this paper only a few of them are used as illustrations.

The rest of the paper is organized as follows. In Section 2, we describe the Chi’s visualization process and in Section 3 we explain how we apply this process to temporal data. Section 4 introduces our taxonomy of temporal data visualization techniques. Finally, in section 5, we conclude and sketch some further studies.

2. ED CHI’S VISUALIZATION PROCESS

As shown in Fig. 1, Chi [3] decomposes the visualization process into three types of transformations manipulating four types of data. In this paper, we adopt the point of view of Vernier [31] that structures the visualization process of Chi into four steps namely: (1) data, (2) point of view on the data, (3) visualization space and (4) point of view on the visualization space.

Data. For example, as illustrated in Fig. 1, the data could be a set of URLs.

Point of view on the data. At this stage of the process, the data are transformed onto an analytical representation. This transformation is generally dependent on the data structures. Indeed the point of view on the data is obtained by defining an analytical abstraction, in other words by obtaining meta-information, information related to the data such as their organization (hierarchical, sequential, etc.) and by filtering the initial space. For example, in Fig. 1, the web pages are retrieved from the list of URLs (initial data space), then an image is generated for each web page.

Visualization space. The visualization space is defined by a transformation of visualization, which maps an analytical representation onto values ready to be displayed. In the visualization process shown in Fig. 1, the images (the point of view on the data) are ordered (an ordered list of images). Moreover, this transformation fixes the characteristics of the graphical space in which the data are visualized in terms of the number of its dimensions.

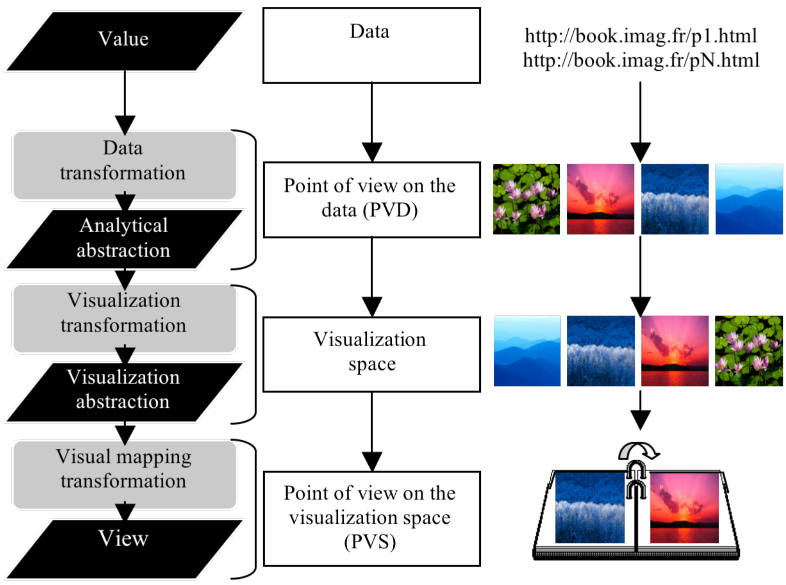


FIG. 1 – *Chi's visualization process.*

Point of view on the visualization space. This step produces the perceptible rendering. It results from a visual mapping transformation which maps the directly displayable values onto a graphical representation (a view). In the example of Fig. 1, a book is defined for presenting the list of web pages. So, at the visualization space step, the designer decides on the characteristics of the graphical space. According to these characteristics, the data values of the previous step are mapped onto graphical signs. Moreover, at this step, a deformation function of the graphical space could be applied, for example to visualize a large amount of data.

In addition to the decomposition of the visualization process into three types of transformations manipulating four types of data, Chi defines operators dedicated to each step. For instance, operators related to the "data" step include data filtering, adding new sets of data and the Fourier transformation of images. Operators for the "point of view on the visualization space" step include rotation, translation, enlargement of graphical objects and the positioning and orientation of a camera in a 3D scene. Other operators are defined for the two steps "point of view on data" and "visualization space".

Having presented the Chi's visualization process, we now apply this process to visualize temporal data.

3. VISUALIZATION PROCESS OF TEMPORAL DATA

As explained in Section 1, histories or temporal data are defined by two domains, i.e., the temporal and structural domains. Based on these two domains, we define the visualization process of a temporal data space as an association between two visualization processes: one is dedicated to the temporal domain of the history to be visualized, while the other is related to the structural domain of the history. The visualization process of structural values depends on the type of these values. Studying this process consists of studying the visualization process of data in general, which is out of the scope of this paper. We therefore only focus on the visualization process of the temporal domain. Fig. 2 shows how we apply the Chi's visualization process to the temporal domain of histories: four steps are defined namely time, point of view on time, time space and point of view on the time space.

Time. This step represents the time values to be visualized. In the example of Fig. 2, we consider a discrete, linear and bounded time model in which the time line is structured in a multi-granular way by means of time units (Year, Month, Day, Hour, etc). Time values are then observed at a particular granularity fixed by a time unit [32] (in the example of Fig. 2, the time unit is Day).

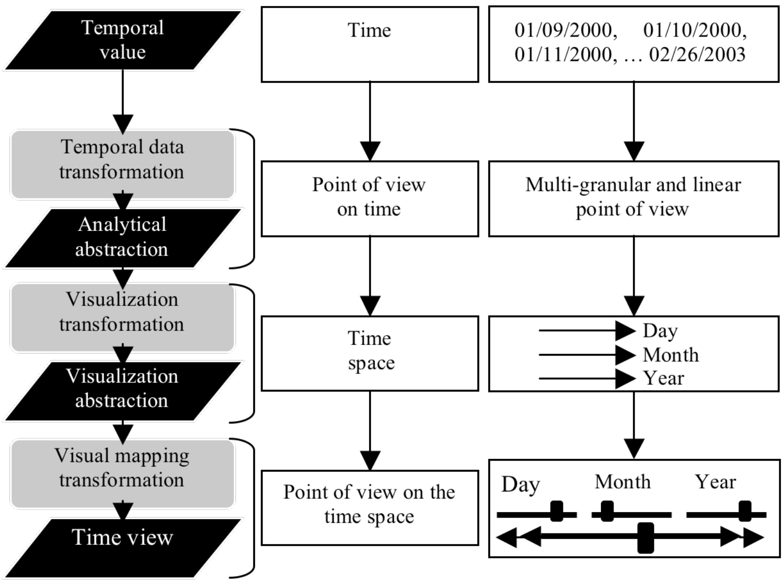


FIG. 2 – *Visualization process of a temporal domain.*

Point of view on time. This step is defined by a transformation of time values. This transformation extracts from the time values the way time is represented: (i) in which time unit are the time values observed? (ii) are the time values expressed in a particular unit system? A unit system is a sequence of comparable[1] units ordered from the coarsest one to the finest one, e.g. [Year, Month, Day]. In the example of Fig. 2, time is considered as multi-granular and linear.

Time space. At this step, displayable space of the time values is defined. For example, if time values are observed at unit Hour and expressed in unit system [Day, Hour] (the analytical representation of "the point of view on time" step), they could be mapped onto a two-dimensional representation. One dimension represents the days (Day is a

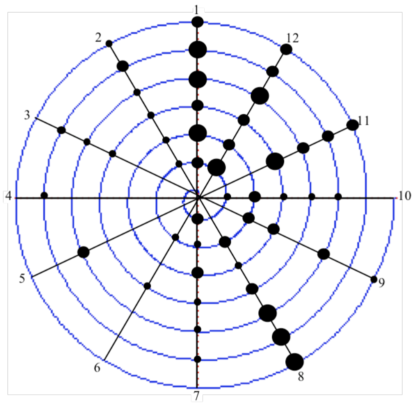
[1] One time unit U1 is said to be comparable to another time unit U2, only if each value of U1 is composed of a fixed number of U2. The time unit U1 is said to be coarser than the time unit U2, and U2 is finer than U1. A concrete example of regular units is Year (coarser unit) and Month (finer unit). Each year contains twelve months.

unit coarser than Hour, and comparable with Hour), while the other represents the hours. In the example of Fig. 2, each time unit is considered as linear: one time axis is then associated with each of them.

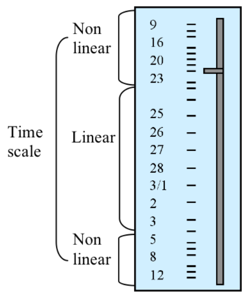
Point of view on the time space. The point of view on the time space refers to the rendering of the temporal domain of the history to be visualized. At this step, the perceptible forms of time are implemented. These forms must be studied according to the human perception of time. For instance, as pointed out by Tufte [30, p. 186], human eyes are able to detect deviation of the horizon, making easier the perception and interpretation of the horizontal representations of temporal data.

The choice of a form is strongly influenced by the point of view on time that has been adopted (Step 2 “Point of view on time”). Indeed, the point of view on time identifies the characteristics of the temporal values to be visualized. For example, a graphical representation of time in a cyclic form as illustrated by the spiral shown in Fig. 3-a could be used because the history is observed at a given unit system and could be viewed as periodic: this characteristic was identified during the step “Point of view on time”. In Fig. 3-a, the time line is shown as a spiral and a temporal value corresponds to the intersection between the spiral and one of the twelve radii (one for each month). Each structural value is represented by a circle, whose size depends on the value it is associated with (higher is the value, larger is the circle). Fig. 3-b (a simplified representation of the TimeSlider technique [16]) illustrates another representation of time where points of time are distributed irregularly on an axis in order to render a logarithmic perception of time [5]. Indeed in Fig. 3-b the time scale is linear at the central part of the timeline and is based on a uniform time unit (e.g., a day in Fig. 3-b) whereas the time scale is non-linear (time steps are exponential) at the edges. Finally a linear representation is another classical way to represent time as depicted in Fig. 2 where four timelines [10] are used to interact with the time space: one timeline for each time unit.

Some visualization techniques rely on various forms of time used simultaneously. For example the Spiral Calendar Visualizer [21] includes two points of view on time: multi-granular and cyclic. The values of each time unit are represented as a calendar (multi-granular representation of time). Thus, years are first represented in a view, then one selected year is displayed in another view and a month of this year is displayed in another view and so on. All the views are represented in a spiral form (cyclic perception of time). Using simultaneously these two forms of time reinforces the user’s perception of the multi-granular structure of time while highlighting cycles.



-a- Spiral representation of time [2]



-b- TimeSlider [16]

FIG. 3 – *Time representations.*

4. A TAXONOMY BASED ON THE STEPS OF THE VISUALIZATION PROCESS

Our taxonomy of temporal data visualization techniques is based on the different anchoring points between the visualization processes of the temporal domain (as described in the previous section) and that of the structural domain. Considering the different anchoring points between the two visualization processes enables us to define seven classes of visualization techniques, described in Fig. 4. These configurations range between two extremes: the total fusion of the two processes (Fig. 4-a) and the total splitting of the two processes (Fig. 4-g).

A point of contact (i.e., the first common step) between the two visualization processes is defined according to the operators that are applied at the corresponding step. These operators, as defined by Chi, are specific to each of the four visualization process steps. For example translation or rotation are operators dedicated to the step "point of view on the visualization space". If at a given step, one operator has an impact on the data manipulated by both processes then we consider the corresponding step as a point of contact. One operator is a condition sufficient to declare the corresponding step point of contact. It is worth noting that some operators may remain specific to only one of the two processes. Once a step is defined as a point of contact, all the following steps in both processes are then merged. Indeed, to the best of our knowledge there does not exist any approach corresponding to the configuration of Fig. 5.

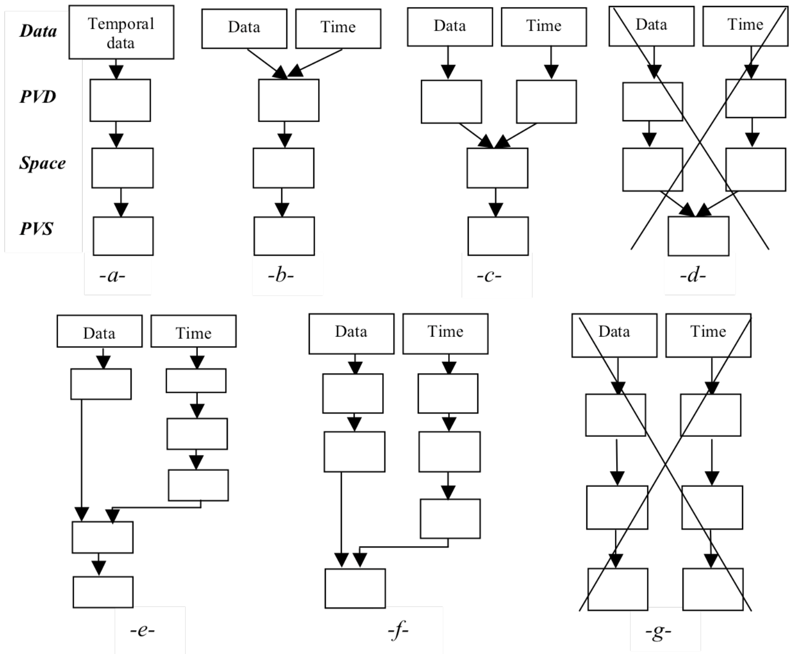


FIG. 4 – *Five classes of temporal data visualization techniques according to their visualization process.*

Total fusion or fusion at the step "point of view on the data". Some visualization techniques of temporal data result from a total fusion of both visualization processes. We distinguish two cases respectively shown in Fig. 4-a and Fig. 4-b. The configuration depicted in Fig. 4-a is often used to visualize data whose temporal domain is implicit: the representation of time is then implicit. Examples of such histories include videos. Conversely, the configuration shown in Fig. 4-b is used to visualize histories whose temporal domain is explicit. Time is then explicit, enabling the dissociation of the two history domains (i.e. the temporal and structural domains). Visualization techniques could then be classified depending on whether the time representation is implicit or explicit.

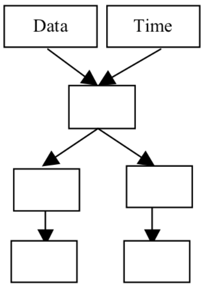


FIG. 5 – *The separation of the two visualization processes after a crossing-point: No existing visualization technique corresponds to this configuration.*

Considering the visualization techniques whose representation of the temporal domain is implicit, we distinguish two categories of techniques, dynamic vs. static [22] as defined in Section 1: (i) dynamic techniques whose visual representation changes automatically. Campos et al. [1] propose an animation model to support exploratory analysis of dynamic environments. Animation is frequently used to visualize spatio-temporal data as with the TimeMap data viewer [14]; (ii) static techniques whose visual representation does not change automatically over time. The information mural technique [15] (Fig. 6) is a static representation of temporal data that belongs to this latter class.

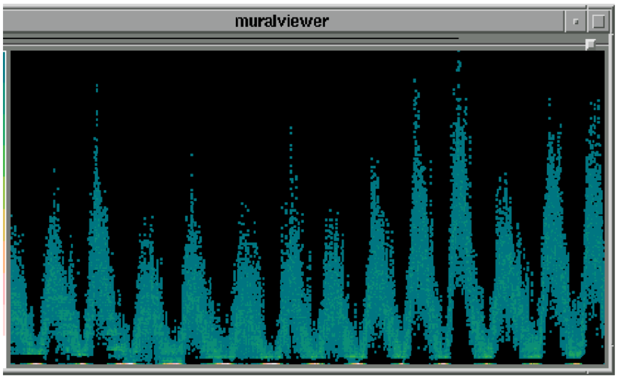


FIG. 6 – *Information Mural [15], from http://www.cc.gatech.edu/gvu/softviz/infoviz/information_mural.html.*

The information mural technique supports visualizations of large amounts of data: the number of data values is greater than the number of pixels available on screen. This technique transforms the initial data space which is defined with M*N pixels into a smaller space of I*J pixels while preserving a similar global view of the initial data space. Based on this technique, Fig. 6 presents a visualization of the number of daily recorded sun spots observed between 1850 and 1993 which is over 52,000 readings. As the temporal domain is not explicitly represented, both the "time space" and the "point of view on the time space" steps of the temporal domain visualization process are not considered.

The diagram representation of Fig. 7 is yet another static technique, but with an explicit representation of the temporal domain. It is commonly used to visualize quantitative data, temporal intervals and temporal relations [4] [17]. In these representations, time is usually represented on the horizontal axis and structural values on the vertical axis. In the example of Fig. 7, the technique visualizes the air pollution measures over time of NO (nitric oxide) and NO2 (nitrogen dioxide). Structural values are represented as a curve. Fig. 8 represents its corresponding visualization process (configuration –b- in Fig. 4): the visualization process of the temporal domain and that of the structural domain are combined at the "point of view on the data" step. Consequently, the representation of the structural domain (the curve) and that of the temporal domain (the time axis) belong to the same graphical space: both domains are visualized within a two-dimensional graphical space. In the visualization process of the temporal domain of Fig. 8, time is implicitly considered as linear. The linear human perception of time is used to guide the design of the representation of the temporal domain as a horizontal axis.

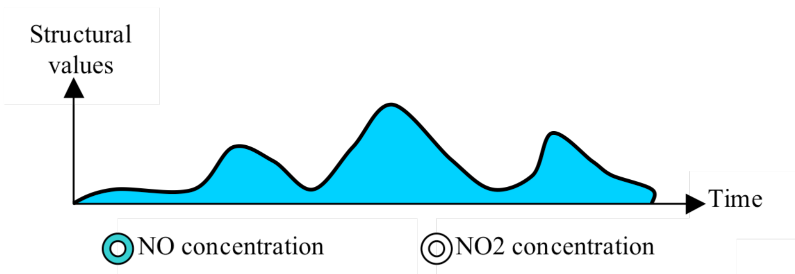


FIG. 7 – *Diagram representation: a curve represents the structural values.*

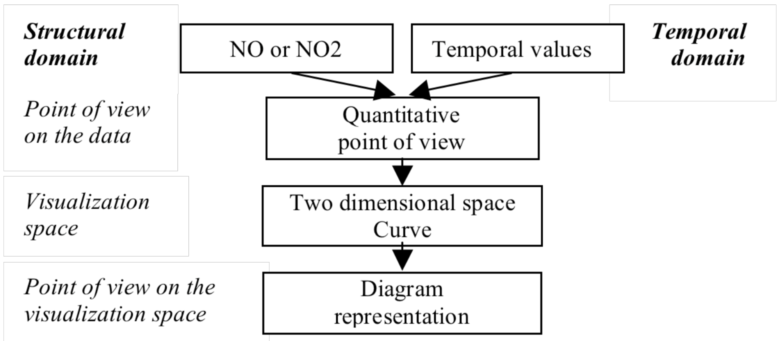


FIG. 8 – *Visualization process of the diagram representation of Fig. 7.*

Fusion at the step "visualization space". The fusion of the two visualization processes at the step "visualization space" (Fig. 4-c) implies that the graphical space of the structural domain depends on the temporal one. Thus, the characteristics of the graphical space of the temporal domain and some operators applied on this domain, directly affect the graphical space of the structural domain, and conversely. We distinguish two classes of visualization techniques defined by the process of Fig. 4-c according to whether the graphical space of the structural domain is merged with the graphical space of the temporal domain, or not.

In the first class, there is one single space representing both domains. If the temporal domain (respectively the structural domain) is represented in a three-dimensional space, the structural domain (respectively the temporal domain) must then be represented in a three-dimensional space. The spiral representation [2] depicted in Fig. 3-a is an example of technique that belongs to this group. Fig. 3-a could represent the air pollution measures of NO (nitric oxide) per month during the period January 1980 – October 1988. In [25], a spiral representation is used for visualizing traces of program execution. In both examples, the structural and temporal domains are visualized into the same graphical space, in this case, a two-dimensional graphical space. The visualization process of the representation of Fig. 3-a is presented in Fig. 9: the visualization process of the structural domain and that of the temporal domain are joined at the "visualization space" step. In the visualization process of the temporal domain of Fig. 9 only the cyclic perception of time is considered at the "point of view on time step. Consequently, time is represented as a spiral.

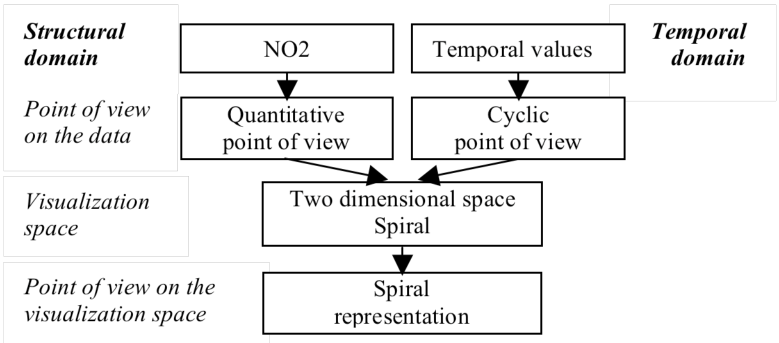


FIG. 9 – *Visualization process of the spiral representation of Fig. 3-a.*

In the second class of techniques, both temporal and structural domains are represented separately in the same graphical space. For example, our TimeVis technique of Fig. 10, showing the history of the investments (in millions of dollars) of a country in agriculture, services and industries, distinguishes the representation of time from the representation of structural values. Temporal and structural domains are separately represented but in the same graphical space. As in the previous example illustrated in Fig. 3-a, rotating the representation (graphical space) of the temporal domain (the perspective wall timeline in the example of Fig. 10) implies a rotation of the representation (graphical space) of the structural domain.

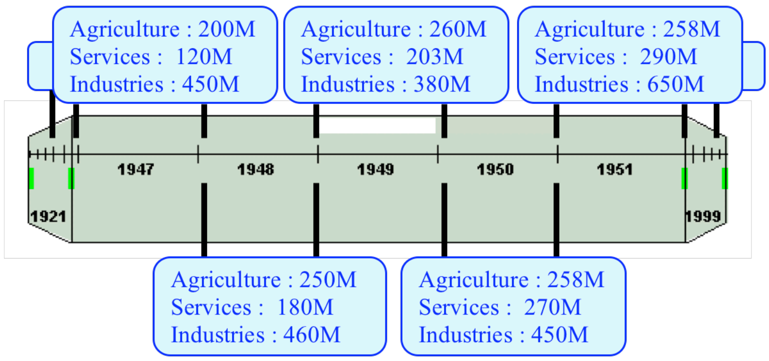


FIG. 10 – *TimeVis technique.*

Fusion at the step "point of view on the visualization space". This configuration (Fig. 4-d) of the two visualization processes is impossible because the structural domain is always associated with the temporal one, which implies that the point of view on the visualization space of the structural domain is defined only once the point of view on the time space is defined. Thus, the points of view on the visualization spaces must be fixed sequentially, considering first the time and then the structural values. Respecting this ordering constraint we identify two cases depicted in Fig. 4-e and Fig. 4-f.

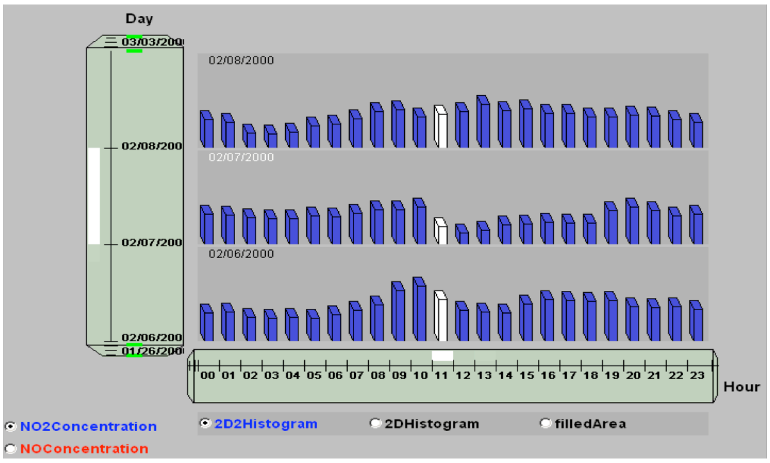


FIG. 11 – *Superposed Histograms technique [6].*

Time and then the step "visualization space of the structural domain". Some visualization techniques of temporal data use the graphical space of the temporal domain as a support for the representation of the structural domain. The main advantage is the direct association of structural values with the corresponding temporal values. This direct association reduces the visual discontinuity between both representations. As a result, the temporal values and the structural values are visualized in the same graphical space. First, the characteristics of this graphical space are all fixed by the temporal domain and second, the structural values are then visualized within this space. If time is represented in a two-dimensional space, the structural values will be too. For this reason, the representation of the structural domain is defined once the visualization process of time is completely achieved (see Fig. 4-e). It is worth noting that this configuration is different from that where the fusion proceeds at the "visualization space" step (see Fig. 4-c). Indeed, based on this configuration, the visualization process of the temporal domain is fully independent of that of the structural domain. This latter could be modified or replaced by another one while keeping the same visualization process of the temporal domain.

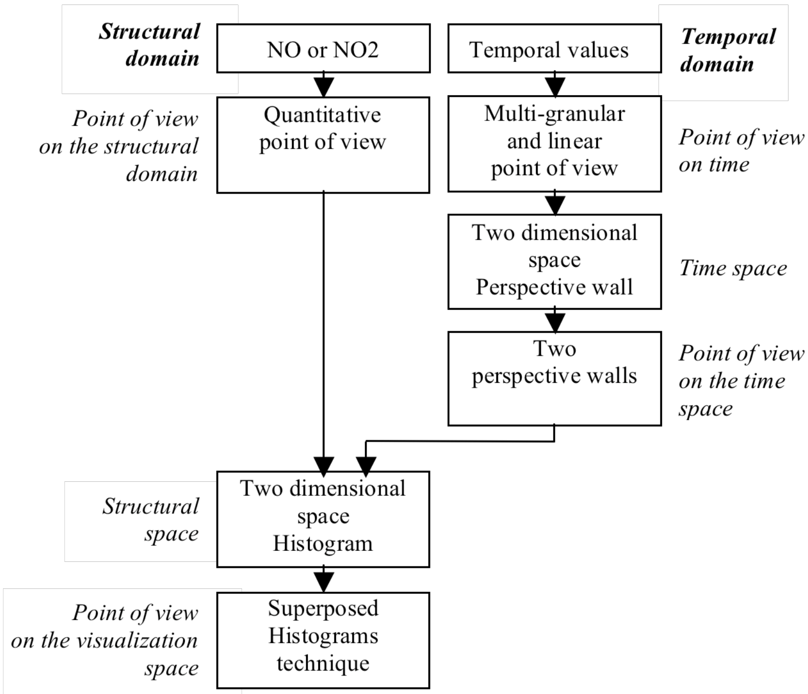


FIG. 12 – *Visualization process of the Superposed Histograms technique of Fig. 11.*

The Superposed Histograms Technique (SHT) [6], shown in Fig. 11 illustrates this configuration of the two visualization processes. SHT visualizes two histories one at a time, allowing the user to switch from one history to the other. Fig. 11 shows air pollution measures and the user can switch from NO2 measures to NO ones. In SHT, structural values have been mapped to 2.5D graphical objects (in the form of cubes). Time is represented in two dimensions: SHT includes two time-sliders, one vertical and the other horizontal. Fig. 12 represents the visualization process (configuration -e- in Fig. 4) of SHT. The visualization process of the temporal domain is achieved independently from that of the structural domain, whereas the visualization process of the structural domain depends on that of the temporal domain. In the visualization process of the temporal domain, as shown in Fig. 12, two points of view on time are considered: multi-granular and linear points of view ("point of view on time" step). The linear point of view on time is used to guide the design of the perspective wall timeline, whereas the multi-granular point of view leads us to define two timelines: one, horizontal, to represent hours and the other, vertical, to represent days. At the "visualization space" step of the structural domain, a histogram is used to denote the evolution of the visualized data. The choice of the histogram representation is strongly influenced by the fact that the data are quantitative. Moreover, histograms are visualized within a two dimensional graphical space defined by the visualization process of the temporal domain: this link between the two visualization processes is represented in Fig. 12 by the arrow from the "point of view on the time space" to the "structural space" step.

Time and then the step "point of view on the visualization space of the structural domain". The process corresponding to this case is shown in Fig. 4-f. The temporal domain is visualized in a graphical space independent from the structural domain. On the one hand this distinction allows an explicit separation between the user tasks referring to each of the two domains of temporal data, for example by navigating through time versus navigating along the structural domain. On the other hand, visual discontinuity may occur, for example making difficult the identification of a value at a given time.

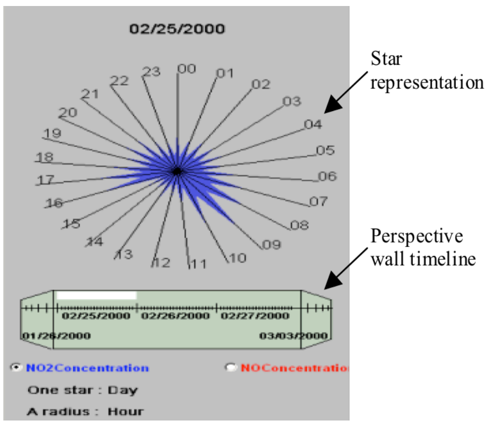


FIG. 13 – *Star Representation technique [8].*

The Star Representation Technique (SRT) [8] of Fig. 13 illustrates the process of Fig. 4-f.

In the same way as with the Superposed Histograms technique (Fig. 11), SRT supports the visualization of two histories. Fig. 13 shows the visualization of NO2 concentration measures.

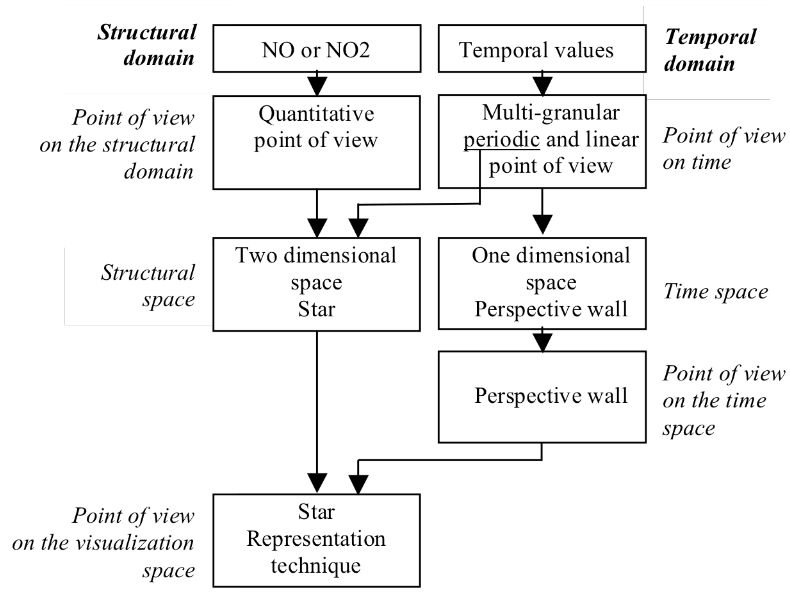


FIG. 14 – *Visualization process of the Star Representation technique of Fig. 13.*

Fig. 14 represents its visualization process (configuration -f- in Fig. 4). The visualization process of the temporal domain of the SRT is achieved independently from that of the structural domain, and as in SHT the opposite does not apply. As shown in Fig. 13, SRT relies on two representations of time used simultaneously (the perspective wall timeline and the star representation). In the visualization process of the temporal domain shown in Fig. 14, three points of view on time are considered: multi-granular, linear and periodic points of view ("point of view on time" step). The multi-granular point of view leads us to distinguish the representation of hours from the one of days. The linear point of view on time is used to visualize days as a perspective wall timeline. The choice of the star representation ("structural space" step) is strongly influenced by the fact that we considered the periodic point of view on time: this link is represented in Fig. 14 by the arrow coming from the "point of view on time" to the "structural space" step. The star representation could be visualized within a two-dimensional graphical space as in the example of Fig. 13 or within a three-dimensional graphical space. In contrast to the Superposed Histograms technique discussed above (Fig. 11) the structural space is defined independently from the characteristics of the time space.

As the complete temporal domain visualization process is independent from the structural domain visualization process in the two configurations -e- and -f- of Fig. 4, the resulting representation defines a reusable software technique for interacting with temporal data. For example the perspective wall timeline software component of the Superposed Histograms technique (Fig. 11) has been reused for developing the Star Representation technique (Fig. 13). Moreover we developed a multi-surface version of the Star Representation Technique by displaying the perspective wall timeline on a dedicated interaction surface using a PDA while the star representation is displayed on screen or projected on a wall [9]. We therefore obtain a generic physical device for interacting with temporal data.

Process fully separated. Finally the configuration of Fig. 4-g is impossible as the structural values are always associated with the temporal values.

5. CONCLUSION AND FUTURE WORK

In this paper, we presented a taxonomy of temporal data visualization techniques based on the steps of the Chi's visualization process [4]. Our taxonomy is useful for systematically exploring the set of possibilities as well as for thoroughly envisioning visualization techniques of temporal data. Indeed in [7] we classified thirty-seven visual tools and visualization techniques of temporal data according to our taxonomy. Most of the existing techniques fit into the three classes of Fig. 4-a, Fig. 4-b and Fig. 4-c of our taxonomy. It is therefore interesting to further explore and envision new visualization techniques that would fit in the two other classes identified in our taxonomy.

Our taxonomy of temporal data visualization techniques is based on the possible points of contact between two visualization processes, one dedicated to the temporal domain and one to the structural domain. As future work, this study could be generalized to any type of data by considering the visualization of two data spaces or coordinated and multiple views of the same data space. However, for the case of temporal data, the two data spaces are linked: indeed the structural values are stamped by temporal values. For the case of two independent data spaces, additional configurations should be considered. For instance, the configuration of Fig. 4-d, which is impossible for temporal data, becomes possible for two independent data spaces.

6. ACKNOWLEDGMENTS

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