Exploring Visual Stability in Dynamic Graph Drawings: A Case Study

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***Abstract*—In this paper, we present a case study about how visual stability affects the users as they track actors in dynamic graph drawings of social networks. We propose a mathematical model to measure the visual stability of such graphical representations and validate our approach through eye-tracking analyses and questionnaires. The participants of our study had to track members of a software development community over five periods of time in three different dynamic graph drawings. The results suggest that dynamic graph drawings making use of fixed positions are more efficient in the visual search but are limited in the recognition of single elements. On the other hand, dynamic graph drawings with the minimal changes or a constant structure improve the recognition of single elements but lose efficiency in the visual search.**

***Keywords*—graph visualizations, dynamic graphs, visual stability, user study, eye-tracking.**

I. Introduction

We understand dynamic graphs as sequences of networks characterized by the addition or removal of nodes and links at different points in time. Such dynamic scenarios are often visualized by capturing a sequence of "snapshots" from the graph time line based on time intervals or windows of aggregation [1]. A graph drawing is computed separately for each "snapshot" and the sequence is presented to the user in a predefined order. In the context of tracking a set of actors in a dynamic social network, there are some issues regarding drawings generated with the previous strategy. Each snapshot has a different distribution of actors and relations over the canvas. Thus, it is very likely that their position will vary as the user explores the dynamic graph. Furthermore, the actors can leave the dynamic graph without prior information and together with the addition or removal of entities from the drawing could disturb the user during the execution of this task.

In this paper, we address the problem of how visual stability affects users as they track actors in dynamic social networks. To this end, we propose a mathematical model to measure the visual stability of those drawings generated by the snapshot strategy. Our approach has been validated through a study with 15 participants involving questionnaires along with an eye-tracking device to determine the efficiency of the visual search. Before we report on details of the study we describe related work and the introduce our model.

II. Related Work

A. *Visualization of dynamic social networks*

In the last years, several metaphors have been proposed for visualizing the changes occurring in dynamic graphs of social networks. These methods represent actors as nodes, relations as lines and the notion of time is derived from the streaming of events over a given time line or by a *time window* [1]. The *time window* defines the period of time in which a network will be under observation. A common strategy to create dynamic graph visualizations make use of the time window to capture a consecutive sequence of "snapshots" from the network time line [2]. A unique graph drawing is computed for each "snapshot" and the sequence is presented to the user in a predefined order. The snapshot strategy has been used in a variety of domains. For example, *Forcoa.Net* [3] is a web-based tool designed for the analysis and visualization of co-authorship networks over time. The system has been mounted on top of the DBLP data set from the field of computer science, containing information about 913,543 authors. Forcoa.Net can display the co-authorship network of a specific actor along with statistical information about their collaboration, stability [4] and their corresponding variations at different points in time. *Weaver* [5] is a Java application, which combines two different views to visualize dynamic social graphs. A 2D view displays the actors and relations contained in a single snapshot of the sequence. On the other hand, a 3D view displays an overview of all time periods and is also possible to highlight the trajectory of a set of actors through all graph sequence. The *Visual Analytics Approach* [6] is a java-based tool combining three different views to visualize dynamic graphs. A first view presents a superimposition of the elements in the graph. The second view allows the users to select different snapshots, placing them next to each other. The last view distributes the snapshots of the dynamic graph using a metaphor similar to a "booklet". The trajectory of a single actor is illustrated as a line that goes through the "pages" of the "booklet".

B. *Layout adjustment techniques and the mental map*

The term *mental map* refers to the "structural cognitive information a user creates by observing the layout of a graph" [7]. Much of the interest about preserving the mental map in dynamic graph drawings is because it improves the user orientation over the canvas [8] and identification of single elements [9]. Modern visualization techniques incorporate different strategies to preserve the mental map. For example, a *Circular Layout* [10], focus on a shape that remains constant during the exploration of a dynamic graph. Nonetheless, actors can change their position over the circumference as the user switches between two different snapshots. Diehl [11] proposed four methods to reduce the changes in the structure of a dynamic graph drawing. *Predecessor dependent adjustment* suggest to generate the current drawing by taking as many parts from its predecessor. *Simultaneous adjustment* suggest to generate the current drawing by using as much as possible the structure from the next graph in the sequence. *Context dependent adjustment* suggests to generate the current drawing considering the structure of the predecessor and successor drawings in the sequence. The last method is called *independent adjustment* and suggest to aggregate all the elements of the dynamic graph into a global drawing which displays only those parts matching the snapshot under exploration.

The layouting method of *Foresighted Graph Layout* (FGL) [12] is based on the last approach. FGL aggregates the actors and relations of the dynamic graph into a global layout called *Super Graph*. This global layout assigns a unique position on the canvas to each actor in the dynamic graph. Due to the considerable amount of space required to display the Super Graph, a reduction process named *reduced graph animation partitioning (rGAP)* is executed afterward. The *lifetime* is an attribute describing the appearance of an actor or relation in the dynamic graph. A set of "containers" called partitions are used to store entities of the same type. All those actors with disjoint lifetimes can be placed into a same *node component* and the set of all node components form the *node partition*. The same principle also applies to the relations. All those relations with disjoint lifetimes can be placed into the same *edge component* and the set of all edge components form the *edge partition*. The *rGAP* guarantees that the actors of the dynamic graph will appear in only one location. Still, one location can contain different actors at different points in time. The partitions obtained from the compression process form the foresighted graph layout, a drawing that not only requires less space to be displayed on the screen but also has the minimal number changes on its structure during the exploration of the dynamic graph. In other words, it is a drawing that can be perceived as visually stable.

C. Visual Stability

In the literature, there are many theories on how the world can be perceived as stable despite the fact it is always in motion. For instance, the *Saccade-Target Theory* [13] suggest each saccade attempts to direct the eye gaze towards a specific object in our visual field. These *target objects* are scanned in detail as a mental representation about their location is stored. As new visual information becomes available, the next saccade initiates a search on the approximate region where the *target objects* have been located. Hence, the sense of a stable picture occurs if the *target-locating process* is successful. Other theories suggest that visual stability comes from the *constancy on the visual field* [14]. According to Colby [15], neurons react to the changes perceived in our visual field. The neurons store information in a mental representation of what is on sight and continue monitoring the approximate region where the change was noticed. This phenomena is called *remapping* and propose that visual stability is achieved when no more changes are perceived. Following some of the principles aforementioned, we designed a mathematical model to measure the visual stability of dynamic graph drawings. Our objective is to determine how layout techniques characterized by the use of *fixed positions*, a *constant structure* or *minimal changes* to the drawing affect the user as they track actors in a dynamic graph.

III. A MODEL OF VISUAL STABILITY FOR DYNAMIC GRAPH DRAWINGS

The model of visual stability operates with dynamic graph drawings generated with the snapshot strategy. Our approach is formed by nine dimensions, covering criteria like the *Euclidean Distance* between the elements of two consecutive graph drawings [16] and incorporating other indicators focused on the elements that remain on the screen.

A. Foundations of the model

Wasserman and Faust [17] define a **graph** as a structure in the form $g = (V, E)$ where V is a set of vertices and E is a set of edges $E \subseteq V \times V$. According to Tamassia [18], a graph drawing d of a graph g is a mapping of each vertex v of g to a distinct point $P(v) = (v_x, v_y)$ of a plane and of each edge (u, v) of g to a simple Jordan Curve with end points $P(u)$ and $P(v)$. A straight line drawing is a drawing in which every edge is mapped to a straight line segment; more formally, a straight line drawing is an injective function $f : v \in V \to (v_x, v_y) \in \mathbb{R}^2$. These definitions serve as the basis of our mathematical model. Nonetheless, we extend the notion of a graph drawing to cover algorithms like the foresighted graph layout in which more than one vertex can be mapped to the same position. We define a **graph layout** as a mapping of each vertex v of g to a **vertex logical position** with the function f_{pv}:

$$f_{pv} : V \to P$$

where P is a set in the form $\{p_1, p_2, p_3, ...p_n\}$. The vertex logical positions can be mapped to the two-dimensional Euclidean Space using the function f_{sv}:

$$f_{sv} : P \to \mathbb{R}^2$$

$$f_{sv}(p) = (f_{sv}(f_{pv}(v)) = (x, y)$$

The edges (u, v) of g can also be mapped to an **edge logical position**. The function f_{pe} describes this process:

$$f_{pe} : E \to P \times P,$$

$$f_{pe}(e) = f_{pe}((u, v)) = (f_{pv}(u), f_{pv}(v))$$

Each edge logical position can be mapped to a straight line drawing on the Euclidean Space. The function f_{se} allows us to perform such transformation:

$$f_{se} : P \times P \to \mathbb{R}^2 \times \mathbb{R}^2,$$

$$\begin{aligned} f_{se}(p_u, p_v) &= (f_{sv}(p_u), f_{sv}(p_v)) \\ &= (f_{sv}(f_{pv}(u)), f_{sv}(f_{pv}(v))) \\ &= ((x_1, y_1), (x_2, y_2)) \end{aligned}$$

Based on these mappings, we define a **graph drawing** $d(g)$ as a mapping of the elements of a graph g to the Euclidean Space:

$$d(g) = (f_{sv}(f_{pv}(V(g)), f_{se}(f_{pe}(E(g))))$$

A **dynamic graph** [12] is a sequence $G = [g^1, g^2, g^3, ..., g^n]$ of graphs with $G^i = (V^i, E^i)$. Given that a graph drawing is a mapping of the elements of g to the two-dimensional Euclidean Space and a dynamic graph is a consecutive sequences of graphs in the form $G = [g^1, g^2, g^3..., g^n]$, we define a **dynamic graph drawing as**:

- Let f^i_{pv} be the mapping of a vertex v of g^i to a vertex logical position.
- Let f^i_{sv} be the mapping of a vertex logical position of of g^i to the Euclidean space.
- Let f^i_{pe} be the mapping of an edge e of g^i to an edge logical position.
- Let f^i_{sv} be the mapping of an edge logical position of g^i to the Euclidean space.

Thus, a **dynamic graph drawing** is a successive sequence of drawings in the form:

$$D(G) = [d(g^1), d(g^2), d(g^3), ..., d(g^n)]$$

Each element $d(g^i)$ of $D(G)$ represents a mapping of the vertices $v \in V(g^i)$ and the edges $e \in E(g^i)$ to the Euclidean space where:

$$d(g^i) = (f^i_{sv}(f^i_{pv}(V(g^i))), f^i_{se}(f^i_{pe}(E(g^i))))$$

B. Dimensions of the model

A dynamic graph drawing in the form $D(G) = [d(g^1), d(g^2), d(g^3)..., d(g^n)]$ can be considered as visually stable if the changes during the transition from $(d(g^i)$ to $d(g^{i+1})$ are null or minimal. In our model, we consider the following dimensions to determine the visual stability of a dynamic graph drawing.

1) Vertex Set Stability: The **vertex set stability** or **VS**, determines the percentage of vertices from from (g^i) that will be present in g^{i+1} after a transition. We illustrate the **vertex set stability** next:

$$VS = \frac{|V(g^i) \cap V(g^{i+1})|}{|V(g^i) \cup V(g^{i+1})|}$$

The values obtained for the **VS** are between 0 and 1. Lower values of **VS** suggest a only a few nodes are shared between g^i and g^{i+1}. On the other hand, higher values of **VS** suggest mode nodes are shared between two consecutive graphs.

2) Vertex Set Drawing Stability: The **vertex set drawing stability** or **VDS**, determines the percentage of **vertex logical positions** from $d(g^i)$ that will be present in $d(g^{i+1})$ after a transition. We illustrate the **vertex set drawing stability** next:

$$VDS = \frac{|f^i_{pv}(V(g^i)) \cap f^{i+1}_{pv}(V(g^{i+1}))|}{|f^i_{pv}(V(g^i)) \cup f^{i+1}_{pv}(V(g^{i+1}))|}$$

The values obtained for the **VDS** are between 0 and 1. Lower values of **VDS** suggest a only a few vertex logical positions are shared between $d(g^i)$ and $d(g^{i+1})$ On the other hand, higher values of **VDS** suggest mode vertex logical positions are shared between two consecutive drawings.

3) Edge Set Stability: The **edge set stability** or **ES**, was conceived to determine the percentage of edges from g^i that will be present in g^{i+1}. We illustrate the **edge set stability** next:

$$ES = \frac{|E(g^i) \cap E(g^{i+1})|}{|E(g^i) \cup E(g^{i+1})|}$$

The values obtained for the **ES** are also between 0 and 1. The lover the values for the **ES** suggest only a few edges are shared between g^i and g^{i+1}. On the contrary, higher values of **ES** indicate more edges are shared between two consecutive graphs.

4) Edge Set Drawing Stability: The **edge set drawing stability** or *EDS*, was proposed to determine the percentage of **edge logical positions** from $d(g^i)$ that will be present in $d(g^{i+1})$. The **edge set drawing stability** is presented next:

$$EDS = \frac{|f^i_{pe}(E(g^i)) \cap f^{i+1}_{pe}(E(g^{i+1}))|}{|f^i_{pe}(E(g^i)) \cup f^{i+1}_{pe}(E(g^{i+1}))|}$$

The values obtained for the **EDS** are between 0 and 1. The lover the values for the **EDS** suggest only a few edges logical positions are shared between $d(g^i)$ and $d(g^{i+1})$. On the contrary, higher values of **EDS** indicate more edge logical positions are shared between two consecutive graph drawings.

5) Vertex Set Degree Change: The **vertex set degree change** or **VDC**, was designed to determine the changes on the degree of those vertices present in g^i after a transition to g^{i+1}. The **vertex set degree change** operates in the following way:

$$VDC = \frac{\sum_{v \in V(g^i) \cap V(g^{i+1})} |\frac{C^i_d(v)}{|V(g^i)|} - \frac{C^{i+1}_d(v)}{|V(g^{i+1})|}|}{|V(g^i) \cap V(g^{i+1})|}$$

where C^i_d stands for the **degree centrality** [17] of a vertex v of g^i. The values for the VDC are between 0 and 1. Those values closer to 0 indicate smaller changes on the degree centrality of those vertices present in g^i after a transition to g^{i+1}. On the contrary, values closer to 1 suggest drastic changes on the degree centrality of those vertices present in g^i and g^{i+1}.

6) Vertex Set Drawing Neighborhood Change: The **vertex set drawing neighborhood change** or **VDNC** detects the changes in the neighborhood of all vertex logical positions present in $d(g^i)$ after a transition to $d(g^{i+1})$. The **vertex set drawing neighborhood change** operates in the following way:

- Let $PV^i = f^i_{pv}(V(g^i))$
- Let $PE^i = f^i_{pe}(E(g^i))$
- Let $V^* = PV^i \cap PV^{i+1}$

$$VDNC = \frac{\sum\limits_{v \in V^*} \left(|\sum\limits_{e \in PE^i} \frac{f_c(v,e)}{|PE^i|} - \sum\limits_{e' \in PE^{i+1}} \frac{f_c(v,e')}{|PE^{i+1}|}| \right)}{|V^*|}$$

where f_c is a function in the form

$$f_c : P \times (P \times P) \to [0, 1]$$

$$f_c : (p1, (p2, p3)) = \begin{cases} 1, & \text{if } p1 = p2 \\ 1, & \text{if } p1 = p3 \\ 0, & \text{otherwise} \end{cases}$$

The values obtained for the **VDNC** are between 0 and 1. Those values closer to 0 indicate a small change on the neighbors of those vertex logical positions from $d(g^i)$ after the transition to $d(g^{i+1})$. The values closer to 1 indicate drastic changes on the neighbors of the vertex logical positions present in $d(g^i)$ and $d(g^{i+1})$.

7) Vertex Set Drawing Active Positions: The **vertex set drawing active positions** or **VDAP** detects the percentage of vertex logical positions that are active in $d(g^i)$. It is mainly designed for layout algorithms with a global layout rather than techniques with individual drawings in the sequence. The **VDAP** can be defined as:

$$VDAP = \frac{|f^i_{pv}(V(g^i))|}{|\cup^n_{i=1} f^i_{pv}(V(g^i))|}$$

In case the layout algorithm operates only on the individual graphs, we define VDAP as:

$$VDAP = \frac{|f^i_{pv}(V(g^i))|}{|f^i_{pv}(V(g^i))|} = 1$$

The values obtained for the **VDAP** are between 0 and 1. Values closer to 0 indicate a small number of vertex logical positions are active in the current drawing, while higher values suggest the opposite case.

8) Edge Set Drawing Active Positions: The **edge set drawing active positions** or **EDAP** detects the percentage of edge logical positions that are active in $d(g^i)$. Similar to the **VDAP**, the **VDAP** is mainly designed for layout algorithms with a global layout rather than techniques with individual drawings in the sequence. The **EDAP** can be defined as:

$$EDAP = \frac{|f^i_{pe}(E(g^i))|}{|\cup^n_{i=1} f^i_{pe}(E(g^i))|}$$

In case the layouting algorithm operates only on the individual graphs, we define EDAP as:

$$EDAP = \frac{|f^i_{pe}(E(g^i))|}{|f^i_{pe}(E(g^i))|} = 1$$

The values obtained for the **EDAP** are between 0 and 1. Values closer to 0 indicate a small number of edge logical positions are active in the current drawing, while higher values suggest the opposite case.

9) Graph Drawing Offset: The **graph drawing offset** or **GDO** detects variations variations on the coordinates of those vertex logical positions that have been mapped into the Euclidean Space. The **graph drawing offset** is illustrated next: Let $f^i_{mv} = f^i_{sv}(f^i_{pv}(V(g^i))$ be the mapping of the vertices of $d(g^i))$ to the Euclidean space.

$$GDO = \sum\nolimits_{v \in V(g^i) \cap V(g^{i+1})} dist(f_{mv}(v)^i, f_{mv}(v)^{i+1})$$

where $dist(f_c(v), f_f(v))$ refers to the *Euclidean Distance* between two points. The values obtained for the **GDO** are higher or equal to 0. Lower values suggest minimal variations on the coordinates of those vertex logical positions present in $d(g^i)$ and $d(g^{i+1})$. Higher values of **GDO** indicate drastic changes on the coordinates of these elements.

IV. Method of Study

In order to determine the effects of visual stability in dynamic graph drawings, we conducted a study combining the use of questionnaires to gather information about the user experience together with an eye-tracking study to record the eye-movements performed by the participants. The objective, was to determine how drawing techniques characterized by the use of *fixed positions*, a *constant structure* or *minimal changes* affect the user as they track actors in a dynamic graph. The research hypothesis was that *visually stable drawings improve the search efficiency and user experience while tracking actors in dynamic graphs*. A group of fifteen students from the fields of computer science and applied cognitive science aged between 22 and 28 participated in our study. All subjects had some basic knowledge regarding network analysis techniques but were not familiar with theories of visual stability nor mental map preservation. The study presented three different scenarios to the participants, which were organized in a random order. We used the model of visual stability to characterize the drawing in the different scenarios as we looked for variations in the user experience and search efficiency by comparing the collected data. *Scenario 1*, illustrated a dynamic graph with a *Circular Layout* (CL). The technique provides a drawing with *constant structure* during the exploration of the dynamic graph but changes the position of the actors on the screen. *Scenario 2*, utilized a *Circular Super Graph* (CSG) due to its mapping of the actors in the dynamic graph to a unique position. Yet, the drawing does not present a constant structure. *Scenario 3*, made use of a *Foresighted Circular Layout* (FCL) because of the *minimal number of changes* on the drawing during the exploration of the dynamic network. Despite this fact, the technique assigns several actors to the same position. There was no time limit for the completion of the scenarios. However, the average duration per user for all three scenarios, was 30 minutes.

We asked the participants to complete a series of tasks focused on tracking three actors in the different scenarios. The dynamic graph was extracted from the developer mailing list of the Asterisk open source project and contained five snapshots; each one representing a month of communication between the developers (cf. [19] for a more detailed description of the data set). In the drawings, the developers were represented as nodes and a mail exchange was illustrated with an edge (See Figure 1). By the end of the tasks, the users were requested to answer a questionnaires about their experience with the different drawings. Each question was rated with a Likert scale of five points. The value of 1 exemplified a strong disagreement, the value of 3 an agreement and the value of 5 a strong agreement. The criteria under evaluation were organized in two different groups. Positive criteria reflect better results with higher values on the Likert scale. On the other hand, negative criteria reflect better results with lower values on the Likert scale. Table I illustrates the criteria under evaluation.

The information recorded by the eye-tracking device was analyzed with the metrics proposed by Goldberg [20], [21]. Two different settings were proposed for the analysis. The

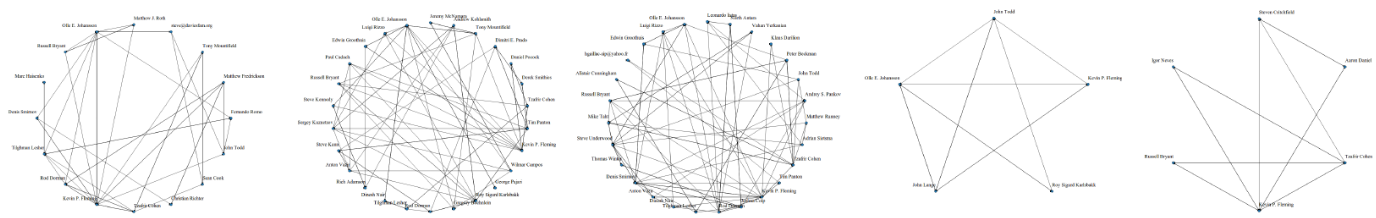

Fig. 1: Dynamic graph extracted from the mailing list of the Asterisk open source project.

Criteria ID	Description
C1	The drawing technique uses a fixed coordinate system.
C2	The drawing technique is useful to track persons in a dynamic graph.
C3	The changes on the drawing are noticeable.
C4	The drawing technique requires some effort to locate a person.
C5	The addition or removal of entities from the drawing is distracting.
C6	The addition or removal of relations from the drawing is distracting.

TABLE I: Positive and negative items evaluated by the questionnaires.

first setting applied the metrics to the overall drawing area. The second setting applied the metrics to the areas of interest (AOIs) where the three actors were located. The AOIs did not maintain a fixed position for all the drawing techniques. Instead, they were placed over the canvas respecting the rules of each drawing technique. Additionally, we compared the eye-tracking metrics for the three scenarios and looked for statistical significance with a Wilcoxon test. This strategy should allow us to determine in which drawing the metrics have a better performance. Next, we present the list of the eye-tracking metrics:

- *Number of fixations* [20] - Number of times a user observes elements on the screen.
- *Duration of fixations* [20], [22] - Time spent observing the elements on the screen.
- *Number of saccades* [20] - Number of eye movements performed on the screen.
- *Saccadic duration* [20] - Time spent for the eye movements performed on the screen.
- *Saccadic amplitude* [21] - Distance covered by the eye movements performed on the screen.
- *Scan Path Length* [20] - Distance covered by the scan path during the visual search.
- *Scan Path Duration* [20] - Time spent for the visual search.
- *Spatial Density* [20], [23] - Indicates the distribution of the visual search on the screen.
- *Time to first fixation* [20], [24] - Time spent to locate an element on the screen for the first time.
- *Fixations on target* [20] - Number of fixations over a given element.
- *Fixations/Saccade Ratio* [20] - Ratio comparing the time spent observing an elements to the the time spent searching for the elements.

V. Analysis and results

A. Model of visual stability

The model of visual stability was computed for the different scenarios under study. We preserved the order of the transitions between drawings, simulating the navigation through the dynamic graph. Additionally, we calculated the average value for each dimension of the model. This allowed us to have the overall visual stability of the drawings observed by the users. As it is illustrated in Table II, the *FCL* along with the *CSG* presented the lowest values in terms of the active positions. Both techniques make use of a global layout to maintain a constant structure during the exploration of the dynamic graph. In average, the *FCL* presented as active 48% (0.48) of the vertex logical positions (VDAP) from the global layout and 14% (0.14) of the edge logical positions (EDAP). The *CSG* presented as active 20% (0.20) of the vertex logical positions (VDAP), while only a 11% (0.11) of the edge logical positions were displayed on the screen (EDAP). The *CL* creates independent layouts for every graph in the sequence, rather than using a global layout. Therefore, 100% (1.0) of the vertex logical (VDAP) positions and edge logical positions (EDAP) were active.

Another difference noticed among the drawing techniques was related to the movement of vertex logical positions over the canvas. The *FCL* and the *CSG* had a graph drawing offset (GDO) of 0 due to the mapping of the vertex logical position to fixed location on the Euclidean Space. On the contrary, the *CL* places the vertex logical positions in different locations for every graph drawing in the sequence. Hence, the the graph drawing offset (GDO) was of 2564.68, suggesting the drawing technique has a high amount of movement.

Traditional graph visualization techniques perform a mapping of a single vertex from the dynamic graph to a unique location on the Euclidean Space. The *CL* together with the *CSG* follow this rule, acquiring a stability of 17% (0.17) for the vertex logical positions (VS, VDS) and 2% (0.02) for the edge logical positions (ES, EDS). On the other hand, the *FCL* is a drawing technique that allows several vertices from the dynamic graph to be placed on the same location. Therefore, the stability of the vertices (VS) and edges (ES) of the dynamic graph was still of 17% (0.17) and 2% (0.02) respectively. But the stability of the vertex logical positions presented on the screen (VDS) was of 41% (0.41) and up to 40% (0.40) for the edge logical positions (EDS). In other words, the foresighted strategy presents a more visually stable drawing although the graph structure is changing.

Dimensions of the model	CL	CSG	FCL
VDAP vertex set drawing active positions	1.0	0.20	0.48
EDAP edge set drawing active positions	1.0	0.11	0.14
GDO graph drawing offset	2564.68	0	0
VS vertex set stability	0.17	0.17	0.17
VDS vertex set drawing stability	0.17	0.17	0.49
ES edge set stability	0.02	0.02	0.2
EDS edge set drawing stability	0.02	0.02	0.04
VDC vertex set degree change	0.41	0.41	0.41
VDNC vertex set drawing neighborhood change	0.41	0.41	0.40

TABLE II: Average visual stability calculated for the three drawings under study.

B. *Questionnaires*

The data collected from the questionnaires provided an insight about the user experience in the different scenarios. We computed the average values of the user ratings per each criterion (Table I). The user ratings lie within [1, 5], (mean value $=$ 3). We present the average user rating for criteria 1 and 2 in Figure 2. Criteria 1 and 2 are positive, which means that a rating of of 5 is perceived as the best while a rating of 1 is perceived as the worst. In Figure 3 we present the average user rating for criteria 3 to 6. These criteria are perceived as negative, which means that a rating of 5 is the worst while a rating of 1 is the best.

In *Scenario 1* we presented the dynamic graph with the CL, obtaining *09:14* minutes as the average execution time for all the tasks. The drawing technique was received negatively, despite the use of a constant structure (see Figure 2 and Figure 3). The users did perceived any mapping of an actor to a fixed position on the Euclidean Space (C1 = 2.47). Additionally, the changes on the drawings were noticeable (C3 = 3.27) and it was difficult for users the to locate the requested actors on the canvas (C4 = 3.27). The addition and removal of elements from the drawing did not distract the users during the execution of the tasks (C5 = 2.53, C6 = 2.53). Still, the drawing technique was rated on average as not useful for tracking actors in a dynamic graph drawing (C2 = 2.67).

In *Scenario 2* we displayed the dynamic graph with the *CSG*, obtaining *09:11* minutes as the average execution time for all the tasks. According to the results (Figure 2 and Figure 3), the users noticed that the actors were maintaining their location on the canvas (C1 = 3.40) and the effort to locate an actors was less in comparison to the *CL* technique (C4 = 2.73). On the other hand, the changes on the drawing were still perceived (C3 = 3.07). The addition and removal of elements were more distracting during the execution of the tasks (C5 = 2.67, C6 = 2.67). Despite this fact, the use of position on the Euclidean Space improved the usefulness of the technique for tracking actors in a dynamic graph (C2 = 2.87).

In *Scenario 3* we used the *FCL* to visualize the dynamic graph, obtaining *09:09* minutes as the average execution time for all the tasks. According to the criteria under evaluation (Figure 2 and Figure 3), the users were aware the mapping to a fixed position on the Euclidean Space (C1 = 3.87). Also, the effort to locate a person with the *FCL* was lower in comparison to the *CSG* and the *CL* (C4 = 2.33). Moreover, the changes on the drawing were not so prominent (C3 = 2.40) while the distraction produced by the addition or removal of elements from the drawing was reduced (C5 = 2.33, C6 = 2.33). The *FCL* was considered by the users as the most useful technique for tracking actors in a dynamic graph (C2 = 3.27).

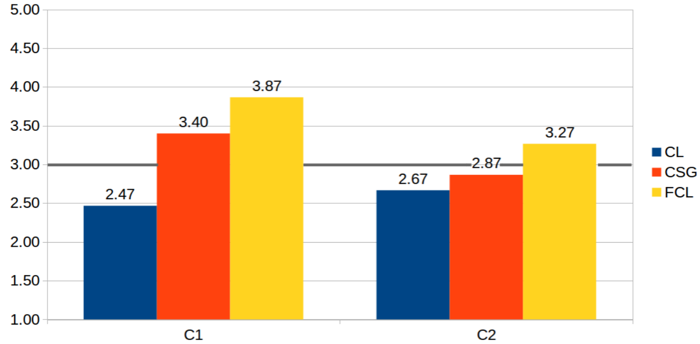

Fig. 2: Results of the user questionnaires for positive criteria (C1, C2)

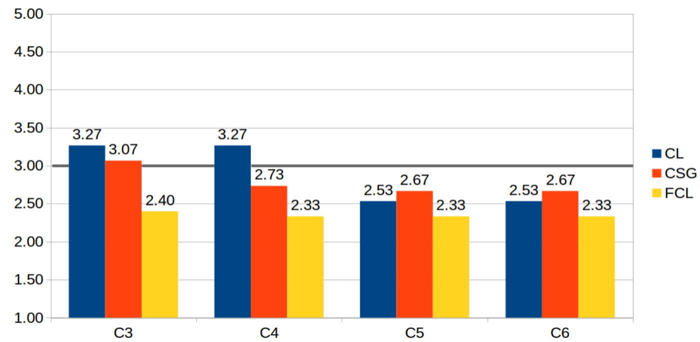

Fig. 3: Results of the user questionnaires for negative criteria (C3-C6)

C. *Eye-tracking metrics for the overall drawing area*

The data collected by the eye-tracking device revealed dissimilarities between the drawing techniques in terms of the processing of single elements and the visual search. As it is illustrated in Table III, the *CSG* presented the minimal number of fixations (OFIX1 $=$ 64.08) but it was also the technique with the longest time spent on the durations of the fixations (OFIX2 $=$ 0.28 seconds). The duration of the fixations was found to be statistically significant in comparison to the values obtained for the *CL* ($[Z = -3.010, p = .003]$) and the *FCL* ($[Z = -2.158, p = .031]$). This suggest that users using the *CSG* focused on less elements, but required more time to process the visual information. A similar pattern was observed for the saccades. The *CSG* presented the minimal number of saccades (OSAC1 $=$ 12.40) but their duration was longer (OSAC3 $=$ 0.04). In terms of the saccadic amplitude, the *FCL* was technique with the shortest distance covered by the eye movements (OSAC2 = 121.69). We found this value to be statistically significant in comparison to the *CL* ($[Z = -2.840, p = .005]$) and the *CSG* ($[Z = -2.385, p = .017]$).

The scan path covered the shortest distance when the participants used the *CSG* (OSCN1 = 3041.67 pixels) followed by the *FCL* (OSCN1=3173.70 pixels) and the the *CL*(OSCN1=3441.96 pixels). A similar situation was observed in the spatial density. The *CSG* presented the lowest density (OSD1=0.36) followed by the *FCL* (OSD1=0.38) and *CL* (OSD1=0.44). We found the density of the *CSG* to be statistically significant in comparison to the *FCL* ($[Z = -2.212, p = .0.27]$) and the *CL* ($[Z = -3.413, p = .001]$). According to Goldberg [20] and Cowen [23], a lower spatial density is an indicator for a more direct search which indicates the *CSG* has the best visual search among the drawings under study. With respect to the duration of the scan paths, the shortest time was observed in the *CL* (OSCN2 =6.44 seconds). Lastly, we calculated the Fixation/Saccade ratio (OFS1). The ratio indicates the time spent observing an elements to the the time spent searching for the elements. The smallest ratio was found in the *CL* (OFS1=8.42) while the highest ratio was observed in the *FCL* (OFS1=10.12).

Eye-tracking metric	CL	CSG	FCL
OFIX1 Number of fixations	81.79	64.08	70.45
OFIX2 Duration of fixations in seconds	0.23	0.28	0.26
OSAC1 Number of saccades	17.56	12.40	17.95
OSAC2 Saccadic amplitude	140.33	139.09	121.69
OSAC3 Saccade duration in seconds	0.03	0.04	0.03
OSCN1 Scan path length in pixels	3441.96	3041.67	3173.70
OSCN2 Scan path duration in seconds	6.44	6.85	6.96
OSD1 Spatial density	0.44	0.36	0.38
OFS1 Fixation saccade ratio	8.42	9.44	10.12

TABLE III: Average value of the eye-tracking metrics for the overall drawing area.

D. Eye-tracking metrics for the areas of interest

The number of fixations on target and the time to first fixation were two eye-tracking metrics applied to the areas of interest (AOIs). As it is illustrated in Table IV, the *CSG* and the *FCL* where the drawing techniques with the highest number of fixation on target for all areas of interest (AFOT1=0.4). According to Goldberg [20], more fixations on target suggest a higher accuracy on the visual search. The shortest time to first fixation (ATTF1) was observed in the *CL* (ATTF1=1.69) while the longest time was observed in the *CSG* (ATTF1=3.28). As it is stated by Byrne [24], a long time to first fixation indicates a possible delay or potential difficulty to locate a specific element on the screen.

Eye-tracking metric	CL	CSG	FCL
AFOT1 Number of fixations on target	0.2	0.4	0.4
ATTF1 Time to first fixation in seconds	1.69	3.28	2.02

TABLE IV: Average value of the eye-tracking metrics for the areas of interest.

VI. DISCUSSION

In order to get further insight on how visual stability affects the users in the exploration of dynamic graphs, we used Spearman's rank correlation (Spearman's ρ) as a measure of statistical dependence between the questionnaires and the eye-tracking metrics. According to the model of visual stability, the *CL* was the technique with highest amount of movement in terms of the elements on the Euclidean Space (GDO). The users had difficulties to find the requested actors, since their distribution on the canvas was always changing. Additionally, the most extensive search patterns was found with the *CL*. The length of the scan path was positively correlated to the criterion C4 ($\rho = 0.516, p < 0.05$), suggesting that longer scan paths influence the effort required to locate an actor on the canvas. The duration of the saccades was also found to be positively correlated with the criterion C5 ($\rho = 0.539, p < 0.05$), indicating that the distraction produced by the addition and removal of entities on the drawing leads to longer saccades. The fixation-saccade ratio was negatively correlated to the criterion C5 ($\rho = -0.522, p < 0.05$). In this case, the distraction produced by the addition and removal of the elements from the canvas affected negatively the efficiency of the visual search.

The *CSG* introduced a mapping of the actors in the dynamic graph to a unique position on the Euclidean space, reducing the drawing offset (GDO) to zero. The users received positively this feature and mentioned that it was easier to locate actors on the canvas. Nonetheless, the distraction factor produced by the addition and removal of elements from the drawing was still present in this technique. The *CSG* requires a global layout to display the dynamic graph. Thus, it requires more logical positions to generate the drawing. Since only a few actors appear constantly in the dynamic graph, the number of active logical positions is also reduced (VDAP and EDAP) which makes the changes in the drawing more noticeable (VDS and EDS). This was noticed in the duration of the fixations for the eye-tracking metrics, suggesting more time is required to process the changes in the drawing.

The *FCL* introduced the mapping of several actors from the dynamic graph to a unique position on the Euclidean space, as long as they do not appear in the same period of time. This characteristic allows the *FCL* not only to increase the number of active logical positions (VDAP and EDAP) but also the visual stability of the drawing (VDS and EDS). Much of the users received positively the features of the *FCL*, with some exceptions that considered it confusing. Despite this fact, the eye-tracking metrics revealed a decrease in the duration of the fixations. This means that in a visually stable drawing, the image can be processed faster. On the contrary, the length of the scan path ($\rho = 0.686, p < 0.05$), the scan path duration ($\rho = 0.592, p < 0.05$) and to the length of saccades ($\rho = 0.649, p < 0.05$) were found to correlate positively with the criterion C1. Longer scan paths are an indicator of a more extensive search. This could suggest that even the image can be processed faster, the users had to perform more searches because several actors can occupy the same position at different points in time. The fixation-saccade ratio was found to be positively correlated with the criterion C2 ($\rho = 0.649, p < 0.05$), indicating the users perceived as useful the features of the *FCL* for tracking actors in a dynamic graph. This finding was also endorsed by the negative correlation of the criterion C2 with the duration of the saccades ($\rho = -0.636, p < 0.05$).

VII. Conclusions and Future Work

In this paper, we addressed the problem of how visual stability affects the users as they track actors in dynamic graph drawings. We proposed a mathematical model to measure the visual stability of such graphical representations and validated our approach with the use of questionnaires along with an eye-tracking device. The results obtained suggest that drawing techniques with a constant structure, like the *CL*, do not provide a good user experience nor accuracy on the visual search because they change the distribution of the elements on the Euclidean Space. Drawing techniques mapping actors of the dynamic graph to a unique position on the Euclidean Space, such as the *CSG*, improve the accuracy on the visual search but the changes on the drawing require more time to be processed. Lastly, those drawing techniques mapping several actors to a unique position on the Euclidean Space improve the processing time of the image. But, this feature can confuse the user resulting in a more extensive visual search. As future work, we plan to develop an algorithm, which balanced the user experience, processing time of the image along with the visual search. We will take into consideration the dimensions of the model of visual stability and perform further studies to validate our findings.

References

[1] S. Bender-deMoll and D. A. McFarland, "The art and science of dynamic network visualization," *Journal of Social Structure*, vol. 7, 2006.

[2] J. Moody, D. McFarland, and S. Bender-deMoll, "Dynamic network visualization," *American Journal of Sociology*, vol. 110, no. 4, pp. 1206–1241, 2005.

[3] Z. Horak, M. Kudelka, V. Snasel, A. Abraham, and H. Rezankova, "Forcoa.net: An interactive tool for exploring the significance of authorship networks in dblp data," in *Computational Aspects of Social Networks (CASoN), 2011 International Conference on*, Oct 2011, pp. 261–266.

[4] M. Kudelka, Z. Horak, V. Snasel, and A. Abraham, "Social network reduction based on stability," in *Computational Aspects of Social Networks (CASoN), 2010 International Conference on*, Sept 2010, pp. 509–514.

[5] A. Harrer, S. Zeini, and S. Ziebarth, "Integrated representation and visualisation of the dynamics in computer-mediated social networks," in *Proceedings of the 2009 International Conference on Advances in Social Network Analysis and Mining*, ser. ASONAM '09. Washington, DC, USA: IEEE Computer Society, 2009, pp. 261–266.

[6] P. Federico, W. Aigner, S. Miksch, F. Windhager, and L. Zenk, "A visual analytics approach to dynamic social networks," in *Proceedings of the 11th International Conference on Knowledge Management and Knowledge Technologies*, ser. i-KNOW '11. New York, NY, USA: ACM, 2011, pp. 47:1–47:8.

[7] H. C. Purchase, E. Hoggan, and C. Görg, "How important is the "mental map"?–an empirical investigation of a dynamic graph layout algorithm," in *Graph drawing*. Springer, 2007, pp. 184–195.

[8] P. Eades, W. Lai, K. Misue, and K. Sugiyama, *Preserving the mental map of a diagram*. International Institute for Advanced Study of Social Information Science, Fujitsu Limited, 1991.

[9] D. Archambault and H. Purchase, "Mental map preservation helps user orientation in dynamic graphs," in *Graph Drawing*, ser. Lecture Notes in Computer Science, W. Didimo and M. Patrignani, Eds. Springer Berlin Heidelberg, 2013, vol. 7704, pp. 475–486.

[10] J. M. Six and I. G. Tollis, "A framework for circular drawings of networks," in *Graph Drawing*. Springer, 1999, pp. 107–116.

[11] S. Diehl and C. Görg, "Graphs, they are changing - dynamic graph drawing for a sequence of graphs," in *Proc. 10th Int. Symp. Graph Drawing (GD 2002), number 2528 in Lecture Notes in Computer Science, LNCS*. Springer-Verlag, 2002, pp. 23–31.

[12] S. Diehl, C. Görg, and A. Kerren, "Preserving the mental map using foresighted layout," in *Data Visualization 2001*, ser. Eurographics, D. Ebert, J. Favre, and R. Peikert, Eds. Springer Vienna, 2001, pp. 175–184.

[13] G. W. Mcconkie and C. B. Currie, "Visual stability across saccades while viewing complex pictures," *Journal of Experimental Psychology: Human Perception and Performance*, vol. 22, no. 3, pp. 563–581, 1996.

[14] D. Melcher and C. L. Colby, "Trans-saccadic perception," *Trends in cognitive sciences*, vol. 12, no. 12, pp. 466–473, 2008.

[15] C. Colby, M. Goldberg *et al.*, "The updating of the representation of visual space in parietal cortex by intended eye movements," *Science*, vol. 255, no. 5040, pp. 90–92, 1992.

[16] S. Bridgeman and R. Tamassia, "Difference metrics for interactive orthogonal graph drawing algorithms," in *Graph drawing*. Springer, 1998, pp. 57–71.

[17] S. Wasserman and K. Faust, *Social network analysis: Methods and applications*. Cambridge university press, 1994, vol. 8.

[18] R. Tamassia, *Handbook of Graph Drawing and Visualization*. CRC Press, 2007.

[19] S. Zeini, T. Göhnert, T. Hecking, L. Krempel, and H. U. Hoppe, "The impact of measurement time on subgroup detection in online communities," in *State of the Art Applications of Social Network Analysis*. Springer, 2014, pp. 249–268.

[20] J. H. Goldberg and X. P. Kotval, "Computer interface evaluation using eye movements: methods and constructs," *International Journal of Industrial Ergonomics*, vol. 24, no. 6, pp. 631–645, 1999.

[21] J. H. Goldberg, M. J. Stimson, M. Lewenstein, N. Scott, and A. M. Wichansky, "Eye tracking in web search tasks: design implications," in *Proceedings of the 2002 symposium on Eye tracking research & applications*. ACM, 2002, pp. 51–58.

[22] M. A. Just and P. A. Carpenter, "Eye fixations and cognitive processes," *Cognitive Psychology*, vol. 8, no. 4, pp. 441–480, 1976.

[23] L. Cowen, L. J. Ball, and J. Delin, "An eye movement analysis of web page usability," in *People and Computers XVI-Memorable Yet Invisible*. Springer, 2002, pp. 317–335.

[24] M. D. Byrne, J. R. Anderson, S. Douglass, and M. Matessa, "Eye tracking the visual search of click-down menus," in *Proceedings of the SIGCHI conference on Human Factors in Computing Systems*. ACM, 1999, pp. 402–409.