The "Map" in the Mental Map: Experimental Results in Dynamic Graph Drawing

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Abstract

Preserving the mental map is frequently cited by dynamic graph drawing algorithm designers as an important optimization criterion. There have been a number of definitions for mental map preservation and many different algorithmic approaches to drive dynamic graph drawing to satisfy these definitions. One of the most frequently used definitions is that of Coleman and Parker where "the placement of existing nodes and edges should change as little as possible when a change is made to the graph." A number of experiments have been run to test the effectiveness of this definition from a usability perspective. To date, no experiment has found conclusive evidence that supports the effectiveness of the mental map in the comprehension of a dynamic graph series. In this paper, we summarize the experiments conducted on this definition of mental map preservation and provide recommendations to designers and researchers to fully understand when the mental map supports user tasks.

Keywords:
Dynamic Graph Drawing, Information Visualization, Formal Experiments, Mental Map

1. Introduction

This paper summarizes and critiques empirical results relating to the problem known as preserving the mental map in dynamic graph drawing. A graph consists of a set of nodes V, together with a set of edges E which represent relationships between the nodes. **Graph drawing** is the process of assigning co-ordinates to the nodes so that a node-link representation of the graph can be depicted in a two-dimensional plane. **Dynamic graph drawing** deals with graphs that evolve over time, whereby the structure of the graph changes as nodes and edges are added or removed. The dynamic graph is often divided into several **timeslices** that are snapshots of the graph at specific time intervals. The algorithms assign coordinates to the nodes present in these timeslices. Several algorithms have been proposed to draw an evolving graph with data structured in this way (Brandes et al., 2011). These algorithms have many application areas, including but

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not limited to: sociology (van Duijn et al., 2003) and social networks (Brandes et al., 2011), software engineering (Burch et al., 2011), computer networks (Boitmanis et al., 2007), social media analysis (Java et al., 2007; Kwak et al., 2010), and systems biology (Barsky et al., 2008).

In dynamic graph drawing, it is generally assumed that the presentation of the information should be as stable as possible as the graph evolves. This **preservation of the mental map** feature is often cited as a desired criterion for a successful dynamic graph drawing algorithm. Intuitively, the idea of mental map preservation is to keep the positions of the nodes as stable as possible as the graph changes. It is conjectured that drawing stability allows the person interpreting the diagram to **offload** cognitive effort by using an external visual representation instead of relying solely on memory and supports their ability to comprehend the information space – in this case, the dynamic graph. Thus, preserving the mental map is closely related to *cognitive maps* in psychology and *overviews* in information visualization.

The notion of a mental map has a long history in other disciplines, such as geography (Kitchin, 1994) and psychology with varied names for the same idea. Tolman (1948) provides one of the first definitions of what he calls a **cognitive map** to describe how rats, and by analogy humans, navigate an environment. The definition of mental map in this research is an internal representation of the physical environment to enable navigation. Maps are entities that externalize this information and help support this internal representation so that the human does not need to rely entirely on memory for the full representation of an object or physical space.

In the field of psychology, research into these internal representations has existed for many years using varied terminology do describe this concept. Johnson-Laird (1983) proposed the existence of *mental models* of logical propositions that facilitate reasoning and explanation, and subsequent research has mostly furthered this area along these lines (eg. Stenning (2002)). Shepard and Metzler (1971) demonstrated that internal models of diagrams were not, however, internally represented as propositions, but were instead *mental images*. Kosslyn and Pomerantz (1977) nicely summarize some of the central ideas of this theory. Quoting from this paper, we can see the possible limitations humans have when generating mental models and the need to externalize them:

"... An image is a spatial representation like that underlying the experience of seeing an object during visual perception. These images may be generated from underlying abstract representations, but the contents of these underlying representations are accessible only via generation of a surface (experienced) image. ... Only a finite processing capacity is available for constructing and representing images. This limits the amount of detail that may be activated at any one moment."

Palmer (1978) states that we cannot know the actual form of this internal representation and defines *informational equivalence* as the extent that two representations (internal and/or external) embody the same information. Subsequent research has investigated the use of such internal diagrammatic representations in reasoning/problem solving (Glasgow et al., 1995; Stenning, 2002), and the benefit of externalizing these models for learning (Cox and Brna, 1995; Ainsworth, 2006) and thinking (Blackwell, 2001; Brna et al., 2001). Asking users to externalize their mental models, usually by drawing them, provides a way we can observe the form of these models, acknowledging that the transcription process may be imprecise (Palmer, 1978).

In the field of psychology, most of this research has concentrated on cognitive models of physical environments or objects. In the field of information visualization and graph drawing, the internal representation is not based on objects in the physical world, but rather it is based on data in an abstract information space. Still, the concept of building a cognitive map, or mental model, of this information space is still relevant as users of these systems would like to understand the information landscape. Thus, it is reasonable to discuss the notion of *cognitive models of an information space* for the purposes of visualization. These models are related to the concept of overviews which can be viewed as an external representations, or maps, of data. The famous information seeking mantra of Shneiderman (1996) (*"Overview first, zoom and filter, then details on demand"*) emphasizes the need for supporting the cognitive map, or this internal representation, when browsing information. Hornbaek and Hertzum (2011) generalize Shneiderman's notion of an overview and provide a survey of overviews as used in information visualization research. The survey finds qualitative support for overviews but impact on task performance is less clear.

For dynamic data, the concept of mental models and cognitive maps is further complicated by the fact that the information space is not static and evolves over time. However, there is still a need for the internal representation to provide an overview that is consistent over time. This concept of information stability is equivalent to the concept of preserving the mental map in dynamic graph drawing. It is not enough for algorithm designers to include a *mental map preservation* feature in their dynamic graph layout algorithm; the effect of these features in supporting the comprehension of the information needs to be evaluated, usually through human-centred, empirical studies. These studies have typically been conducted by researchers in information visualization and graph drawing community versed in methods for empirically evaluating readability and usability (Purchase et al., 1996; Purchase, 1997; Ware et al., 2002; Tory et al., 2007) and memorability (Lam et al., 2006; Tory et al., 2009) of techniques in these domains. In the human-computer interaction experiments conducted on dynamic graphs, a common and repeated conclusion was that no significant positive effect was found between conditions that preserved the mental map and conditions that did not, over a variety of different tasks in the area of undirected, dynamic graph drawing. In other words, choosing to preserve the mental map did not improve the performance of participants in the experiment, either in terms of response time or error rate, when compared to a representation of the dynamic graph whereby each and every timeslice was drawn independently (Purchase and Samra, 2008; Saffrey and Purchase, 2008; Archambault et al., 2011; Archambault and Purchase, 2012). These results therefore contradict the intuition of algorithm designers who expect that the preservation of the mental map should, in some way, improve the ability of the user to understand changes to a dynamic graph.

The principal contribution of this paper is an examination of these experiments in an attempt to understand why this surprising result has been replicated in several experiments and to provide recommendations to designers and researchers alike. We seek some inspiration from the fields of psychology and geography to explain why these previous experiments have not revealed a benefit for the preservation of the mental map. We believe that in order to benefit from mental map preservation, tasks should rely heavily on the *map* properties of the dynamic data: tasks that require orientation and navigation through the data. These tasks rely heavily on external representations of the dynamic graph because they are too complicated for the participant to accomplish relying solely on their cognitive map of the information space. This notion is difficult to define in graph drawing as dynamic graphs are often abstract entities.

In this paper, we define this **map** as properties of the dynamic graph drawing that help support the orientation of the user in the data. These properties can differ from readability and memorability as they rely on the ability of the user to navigate and locate information in the larger data set relative to other information. Implicit in this definition, we suggest that for the mental map to be beneficial, the number of data elements considered in the tasks tested in our experiments should be large. This summary focuses on experiments that deal with human factors in dynamic graph drawing rather than algorithmic considerations. Further discussion of algorithmic considerations and other aesthetic criteria can be found in book chapters and surveys on the topic (Branke, 2001; Brandes et al., 2011).

2. The Mental Map and Dynamic Graph Drawing

In Section 2.1, we precisely define the types of dynamic graphs considered in this paper. Section 2.2 presents the definition of mental map preservation used. In Section 2.3, we discuss the types of mental map preservation algorithms used and present a study that sheds some light on which ones perform best with respect to the chosen definition of mental map preservation. Finally, we present the results of experiments that test the effectiveness of mental map preservation with users in Section 2.4. One of the conclusions of this section is that even with the best known algorithms to preserve the mental map, we still do not have experimental evidence that the mental map assists users in performing tasks in undirected, dynamic graph drawing.

2.1. Definitions and Scope

This paper studies undirected, dynamic graph drawing approaches where edges are drawn as straight lines, unless otherwise stated. This survey deals only with dynamic timesliced graphs. The timeslices, also known as the sequence of graphs, are placed in chronological order, demonstrating graph evolution. In this paper, we deal with graphs that evolve in terms of their structure and not in terms of changes in their attribute values (for example Barsky et al. (2008)) as that problem is less related to preserving the mental map. We use attributes only for node identification. We primarily focus on **offline** scenarios, meaning that the algorithm has access to all timeslices that will be depicted in the drawing before execution; this restriction implies that the online difference metrics, such as Bridgeman and Tamassia (1998), are not considered here. Whenever we refer to **animation**, we mean that a smooth, linear interpolation is used to move a node whose position differs in two adjacent timeslices. A **small multiples** (Tufte, 1990) representation of the graph depicts the sequence of timeslices as a matrix of static images placed in chronological order. As the focus of this paper is on mental map preservation, we refer the reader to other surveys which deal with with different ways of representing dynamic data (Moody et al., 2005) as well as the implication of many other visual parameters involved in representing an animation of a dynamic graph (Bender-deMoll and McFarland, 2006).

2.2. Preserving the Mental Map

Unless otherwise stated, we define the mental map using the definition of Coleman and Parker (1996), where *dynamic aesthetics* (essentially the concept of preserving the mental map) is defined as follows:

The placement of existing nodes and edges should change as little as possible when a change is made to the graph.

Most algorithms for the drawing of general, dynamic graphs are designed with this definition, either implicitly or explicitly, in mind (Brandes and Wagner, 1997; Diehl and Görg, 2002; Erten et al., 2003; Frishman and Tal, 2004; Brandes et al., 2005; Frishman and Tal, 2008; Boitmanis et al., 2007). Therefore, as this definition has been used by most dynamic graph drawing algorithms, it has received the most attention through human-computer interaction experiments.

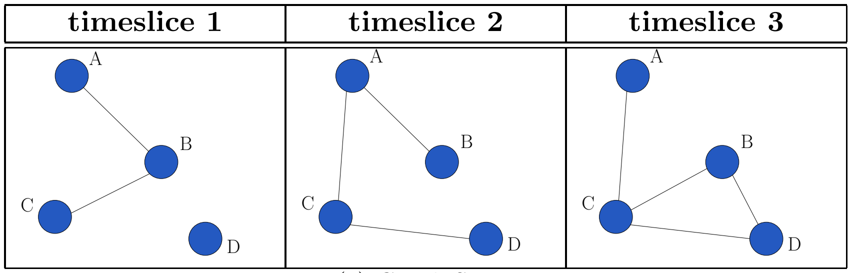
One of the first definitions of the mental map was proposed by Misue and Eades (Eades et al., 1991; Misue et al., 1995) in the context of interacting with a graph and presenting evolving graphs. The paper proposes three mathematical models for preserving the mental map: orthogonal ordering, proximity relations, and topology. If **orthogonal ordering** is preserved, the ordering of the node coordinates projected on to the x and y axes of the drawing does not change during graph evolution. **Proximity relations** are preserved if items close to each other remain close to each other during graph evolution. Perhaps, the strongest notion of proximity is if the Delaunay triangulation of the graph drawing does not change during evolution. Preserving **topology** means that the regions of the plane segmented by the nodes and edges in the drawing do not change during evolution. More precisely, if we construct a dual graph where we transform each region of the drawing into a node and connect two nodes if the regions share a boundary, the topology of this graph does not change. Precise mathematical definitions of these concepts are available in Misue et al. (1995).

Any heuristic that optimizes for as little node movement as possible between adjacent timeslices during the evolution of a dynamic graph drawing is likely to preserve orthogonal ordering, proximity relations, and topology, even though it is not guaranteed to preserve the criteria in their entirety. If nodes move short distances, their projections on to the x and y axes of the drawing, their Delaunay triangulations, and the topology of the regions of the drawing will not likely change that much. Therefore, one could view the definition of Coleman and Parker (1996) as a mental map preservation strategy that preserves all three of these models (Eades et al., 1991; Misue et al., 1995) simultaneously. However, it may be interesting to consider subsets of these models. We consider these areas future work and elaborate on possible ways implement them in section 5.

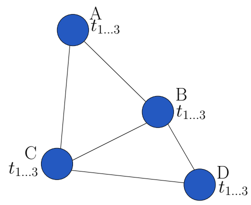
2.3. Which Algorithm Should We Use?

Most algorithms in the literature that have aimed at preserving the mental map use some form of the definition of Coleman and Parker (1996) to preserve the mental map, and therefore drive the dynamic drawing to respect all three of the criteria of Misue and Eades (Eades et al., 1991; Misue et al., 1995) simultaneously. As we have several different algorithms that aim at preserving the mental map, which algorithm should be used when conducting human perception experiments? The chosen algorithm should maximize individual timeslice quality while moving nodes a little as possible between timeslices over the course of graph evolution.

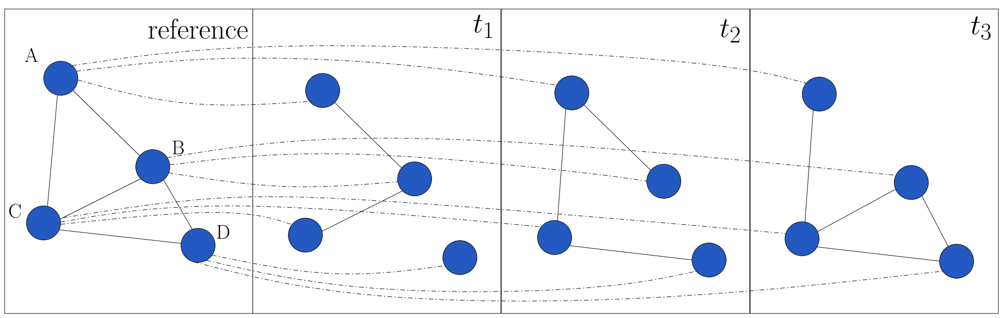
Recently, Brandes and Mader (2011) described and compared a number of strategies for preserving the mental map using the definition of Coleman and Parker (1996) and a stress minimization approach. They cite three frequently used classes of approaches to preserving the mental map in general, dynamic graph drawing and evaluate these using metrics to determine which performs the best. In an **aggregation** scenario (Figure 1(b)), all timeslices are aggregated into a single graph with a single node for each unique node over time. The layout of the dynamic graph is determined from a drawing of this aggregated graph. In **anchoring** (Figure 1(c)), a node is attracted to a reference position in the plane, keeping it in a similar area. A **linking** strategy (Figure 1(d)) joins copies of the same node in adjacent timeslices with springs, therefore keeping the same node in a similar area of the plane as the dynamic graph drawing evolves over time. To allow for a fair comparison between all three approaches, each was tested using a stress majorization strategy (Brandes and Pich, 2008; Gansner et al., 2004).



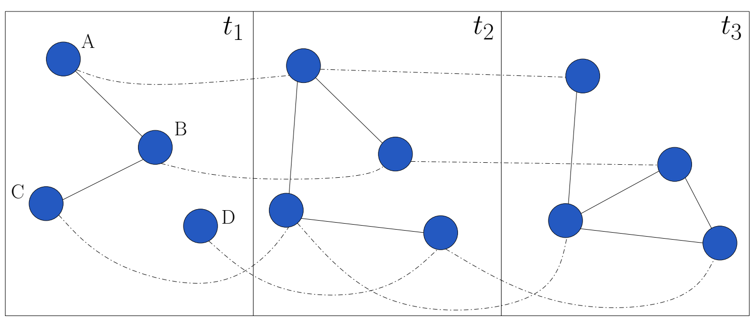
(a) Graph Series



(b) Aggregation



(c) Anchoring



(d) Linking

Figure 1: Strategies for dynamic graph drawing. **(a)** The evolving timesliced graph. **(b)** Aggregation: all timeslices are collapsed into a single supergraph which is laid out. **(c)** Anchoring: Nodes in each timeslice are anchored according to some reference layout with inter-timeslice edges. This reference layout could be the previous timeslice. **(d)** Linking: A node is created for every node in a timeslice. Nodes of the same identity in adjacent timeslices are connected with inter-timeslice edges. Dashed lines indicate links to a reference frame or inter-timeslice edges.

The metrics used to evaluate how well each dynamic graph drawing approach performed was based on the drawing quality of each timeslice and the total distance moved by nodes in the drawing between timeslices. To measure the quality of the drawing at each timeslice, the stress in the layout of each individual timeslice using the dynamic graph drawing technique was compared to the stress of the timeslice drawn without mental map preservation, as it is assumed that preserving the mental map will only increase the stress of the layout. Let P_B be the baseline layout and P_M be the layout obtained using mental map preservation strategy M. The quality of each individual timeslice is:

$$\delta_\sigma^M = \frac{\text{stress}(P_B)}{\text{stress}(P_M)} \tag{1}$$

Assuming that stress increases as an algorithm imposes mental map constraints, this value will lie in the interval $[0, 1)$ with values approaching 1 corresponding to layouts of high quality.

The quality of the mental map preservation is assessed using the sum of the squared distances moved in successive timeslices. Let p_i^t be the position of node i in the layout in timeslice t. Let $\varphi(P^{t-1}, P^t) = \sum_{i \in V} ||p_i^t - p_i^{t-1}||$ where the layouts have been aligned so that the layouts are minimal with respect to global rotation or translation. Thus, the quality of the mental map preservation is:

$$\delta_\varphi^M = 1 - \frac{\varphi(P_M^{t-1}, P_M^t)}{\varphi(P_B^{t-1}, P_B^t)} \tag{2}$$

A value for this metric can be computed for the transition between each pair of timeslices in the graph series. Assuming that any form of mental map preservation will reduce the value of $\varphi(P_M^{t-1}, P_M^t)$, this metric returns a value in $[0, 1)$ with values approaching 1 corresponding to optimal mental map preservation.

The experiment tested the aggregation, anchoring, and linking strategies on fifty graph series each ten timeslices long, using two network generation methods frequently used in social network analysis. The results found that linking achieved the best result with respect to this metric followed by anchoring, especially for δ_φ^M. The results suggest that linking strategies conform best to the Coleman and Parker definition of the mental map in a quantitative sense. The majority of experiments on undirected graphs that have tested the mental map have used a linking strategy to vary the mental map preservation condition (Purchase and Samra, 2008; Archambault et al., 2011; Archambault and Purchase, 2012).

2.4. Human Computer Interaction Experiments

Based on the results of Brandes and Mader (2011), if we would like to test the Coleman and Parker (1996) definition of mental map preservation with users, the best dynamic graph drawing strategy to use would be a linking strategy. Using this insight, we categorize the current state-of-the-art in terms of human-computer interaction experiments that test the utility of mental map preservation along these lines. Subsequently, we subdivide each experiment by the type of tasks that the user was required to perform.

The first section defines and describes our categorization of tasks on dynamic graphs. Then, we look at experiments that studied undirected, dynamic graph drawing. This section is subdivided into linking and other approaches. We then present experiments that tested dynamic, directed acyclic graph drawings with users. Finally, we discuss some related experiments on how animation can support the mental map of the user.

	Local Task	**Global Task**
Indistinguishable	Is the degree of node A increasing?	Does the number of nodes/edges in this graph increase?
Distinguishable	Do nodes P and Q appear at the same time?	What is the sequence of nodes along the shortest path from A to B?

Table 1: Examples of the types of task that can be asked about a dynamic graph series. The local/global axis refers to the number of graph elements that are involved in the question whereas the distinguishable/indistinguishable axis refers to the graph elements needing to be differentiated from each other.

2.4.1. Categorization of Dynamic Graph Drawing Tasks

The types of task tested by human computer interaction experiments on mental map preservation can be divided into three broad categories:

- **Interpretation Tasks** require the participant to read the graph and answer a question about its structural information. For example, node degrees or paths through the graph.
- **Change Tasks** ask the participants to read the graph and answer a question about how it changes over time. These tasks include appearance of nodes/edges in the graph, changes in degree, and changes in the size of the graph over time.
- **Memory Tasks** require participants to read the graph and answer a question about it from memory. For example, determining if a dynamic graph series is exactly the same as some previously presented one or reconstructing part of the graph on paper from memory.

These tasks can have local and global versions. A **local** question asks about a small number of nodes and edges distributed in the graph whereas a **global** question asks about a larger number of graph elements in the presentation. The scale between local to global is continuous ranging from a single node or edge to the entire graph. Tasks can also involve indistinguishable or distinguishable graph elements. Tasks involving **indistinguishable** graph elements tend to ask about a change in absolute quantity of nodes and edges. Often these tasks require the participant to perform a "visual sum" such as count the number of nodes incident to a node (degree) or the number of nodes or edges in a subgraph. Tasks involving **distinguishable** elements tend to involve graph elements that need to be uniquely identified. In these tasks, a participant cannot perform a visual sum such as enumerating nodes along a path. Example questions of each of these types is presented in Table 1.

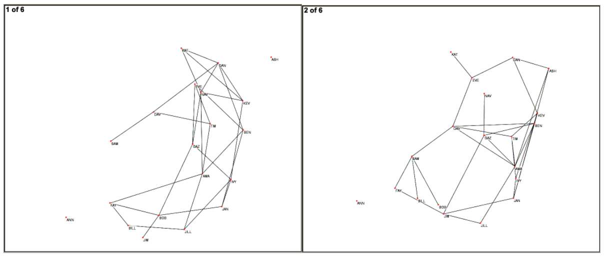
Another important factor in the experimental design is if the locations of all of the nodes and edges used in the question were highlighted preattentively (Ware, 2004) throughout the presentation of the dynamic graph series. In this paper, **preattentive highlighting** refers to highlighting conducted in this way by other means than position (colour for example). If all the elements used to solve the question are not preattentively highlighted, visual search is often required and the mental map may assist in this task.

2.4.2. Undirected Dynamic Graph Drawing

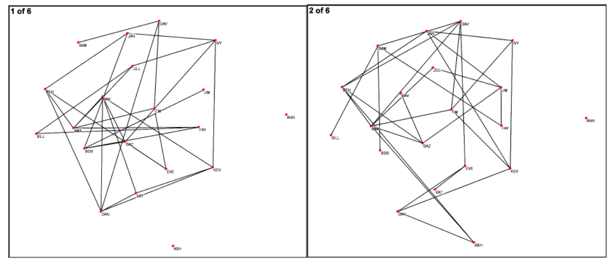
There have been a total of four experiments that have tested mental map preservation in the context of undirected graph drawing. Detailed information about these experiments is listed in the upper half of Table 2. We first discuss experiments that use graph drawing algorithms based on linking approaches followed by experiments that use anchoring approaches.

Experiment	Algorithm	TS	Highlight	Question	Task Type	Result Errors	Result Time	Result Preference
Undirected Dynamic Graphs								
Purchase and Samra (2008)	Graphael (Erten et al., 2003)	6	no	sum of degree	Interp. L & I	–	MM worst	extremes least preferred
			no	degree at instant	Interp. L & I	–	MM worse & HM worse NM	
			no	sum of degree	Interp. L & I	MM worse NM	MM worst	
Saffrey and Purchase (2008)	Saffrey and Purchase (2008)	10	yes	degree at instant	Interp. L & I	–	–	large node move helps
			no	shortest path	Interp. G & D	NM best	–	
			yes	connectivity	Change L & I	NM better HM	–	
			no	shortest path	Interp. G & D	HM is worst	–	
Archambault et al. (2011)	Graphael (Erten et al., 2003)	9	yes	change in degree	Change L & I	–	–	result not reported
			yes	node appearance	Change L & D	–	–	
			yes	edge appearance	Change L & D	–	–	
			no	edge increase/decrease	Change G & I	–	–	
			no	path decrease	Interp. G & D	–	–	
Archambault and Purchase (2012)	Graphael (Erten et al., 2003)	6	no	confirm modifications	Memory G & D	–	–	**HM preferred**
Directed Acyclic Graphs								
Purchase et al. (2006)	Görg et al. (2004)	6	yes	global change	Change G & I	–	–	results not reported
			no	sum of degree	Interp. L & I	**HM best**	–	
			yes	global change	Change G & I	HM worst	**HM best**	
			no	degree	Interp. L & D	**HM best**	–	
Zaman et al. (2011)	Zaman et al. (2011)	2	no	node insertion	Change G & D	–	–	results not reported

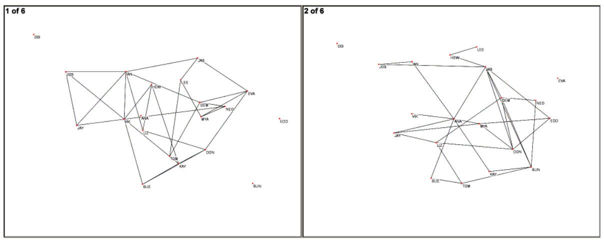
Table 2: Experiments that tested Coleman and Parker (1996) definition of the mental map. **Algorithm** indicates the graph drawing approach used. **TS** indicates the number of timeslices. **Highlight** indicates if the nodes/edges in question were preattentively highlighted. **Question** indicates the type of question asked. **Task Type** indicates the type of task with L and G corresponding to local and global and I and D corresponding to distinguishable and indistinguishable. **Result Errors** and **Result Time** indicate significant results found in terms of times and errors with NM - no mental map, MM - medium mental map, and HM - high mental map. **Result Pref.** indicates findings in the preference data, if questions pertained to mental map preservation were asked.



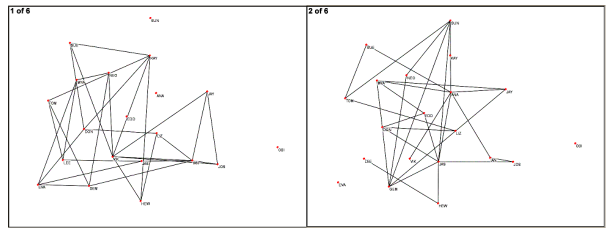
(a) Low Mental Map (Graph A)



(b) High Mental Map (Graph A)



(c) Low Mental Map (Graph B)



(d) High Mental Map (Graph B)

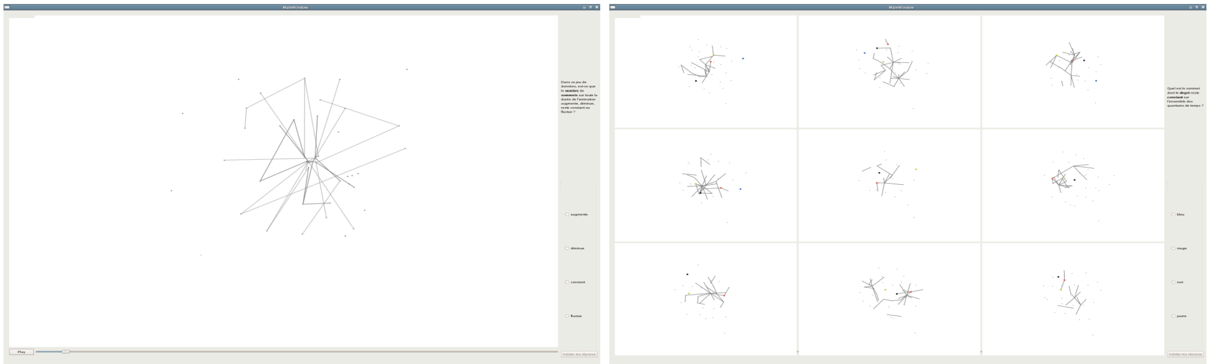
Figure 2: Dynamic graphs for Purchase and Samra (2008) when testing mental map in an animation context on degree reading tasks. The study found, surprisingly, that the extremes (low and high levels of mental map preservation) performed better for this task than the medium level of preservation.

Linking Approaches: A number of experiments have looked at graph readability and memorability tasks on dynamic graph drawings that have used algorithms with a linking approach as described previously.

Purchase and Samra (2008) performed an evaluation of the importance of the mental map in dynamic graph drawing, using Graphael (Erten et al., 2003) (Figure 2). The study compared sequences of graphs drawn with a high, medium, and low degree of mental map preservation. The tasks tested were all local, indistinguishable interpretation tasks that required participants to identify nodes of high or low degree over the course of the full graph evolution. The study found, surprisingly, that the extremes (low followed by high levels of mental map preservation) performed better for this task than the medium level of preservation.

Archambault et al. (2011) tested the mental map preservation in the context of animation and small multiples presentation methods for dynamic graphs (Figure 3). In their experiment, Graphael (Erten et al., 2003) was used and the mental map condition consisted of a high level of mental map preservation and no mental map preservation at all. Interpretation and appearance tasks were tested and both global and local questions were included: is the degree of a node increasing/decreasing (change, local & indistinguishable), are nodes or edges appearing simultaneously (change, local & distinguishable), are the number of nodes increasing/decreasing/fluctuating over time (change, global & indistinguishable), and do shortest paths between two nodes only decrease (interpretation, global & distinguishable). The shortest path questions consider path lengths of at most four nodes. The experiment found no significant difference of notable magnitude between no mental map preservation and high mental map preservation for either small multiples or animation.

Archambault and Purchase (2012) also tested the effect of preserving the mental map on the memorability of dynamic graphs in a global and distinguishable context (Figure 4). **Memorability**, in contrast to readability, tests the ability of participants at remembering a dynamic graph



(a) animation (b) Small Multiples

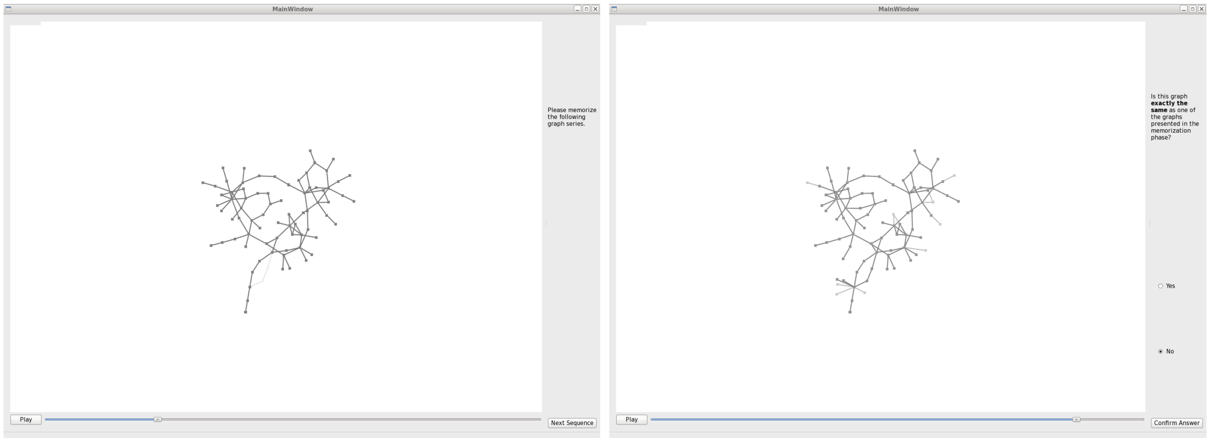
Figure 3: Interfaces for Archambault et al. (2011) when testing mental map preservation in the context of animation and small multiples. The experiment found no significant difference between mental map preservation conditions for either animation or small multiples.

sequence and identifying if it has changed in some way. A version with no, medium, and high mental map preservation was tested on three real dynamic graph series. All of the graph series were presented as an animation. Unaltered versions on the graph were presented in the memorization phase. During the recall phase, either the unaltered version of the graph was re-displayed or an altered version with a small percentage of nodes removed was displayed. The participant was asked to respond “yes” or “no” to state if the presented graph was altered or not. The experiment found no significant effect for preserving the mental map on either error rate or response time. In most cases, either a high level or no mental map preservation performed best followed by the compromise condition. Participants significantly preferred the mental map preservation condition to the other two conditions in the post experiment questionnaire. There was also some evidence that static and motion features aid in the recall of dynamic graph series. A static feature corresponds to the interconnection of nodes in a particular way while a motion feature corresponds to a particular pattern of node or edge movement in the animation during graph evolution. Static features benefit from mental map preservation while motion features do not.

Other Approaches: One experiment in the literature tested an anchoring approach to mental map preservation. Saffrey and Purchase (2008) investigated two new mental map preserving dynamic graph layout algorithms (Figure 5). These algorithms were based on force-directed approaches that limit the movement of nodes by geometric restriction. The tasks tested were all interpretation or change tasks that were either local, indistinguishable tasks (degree reading and number of edges in a component) or global, distinguishable tasks (shortest path finding). The path lengths tested in this experiment were at most two or three. The results of this study suggested that preserving the mental map by restricting node movement can actually be harmful to readability, especially when significant node overlap occurs, but did not find a benefit for preserving the mental map.

2.4.3. Dynamic Directed Acyclic Graph Drawing

Some experiments tested mental map preservation in the context of directed acyclic graphs and trees drawn in a hierarchical fashion. In this body of work, we have some evidence that the mental map can help in understanding dynamically evolving graphs for certain questions.



(a) Memory Interface

(b) Recall Interface

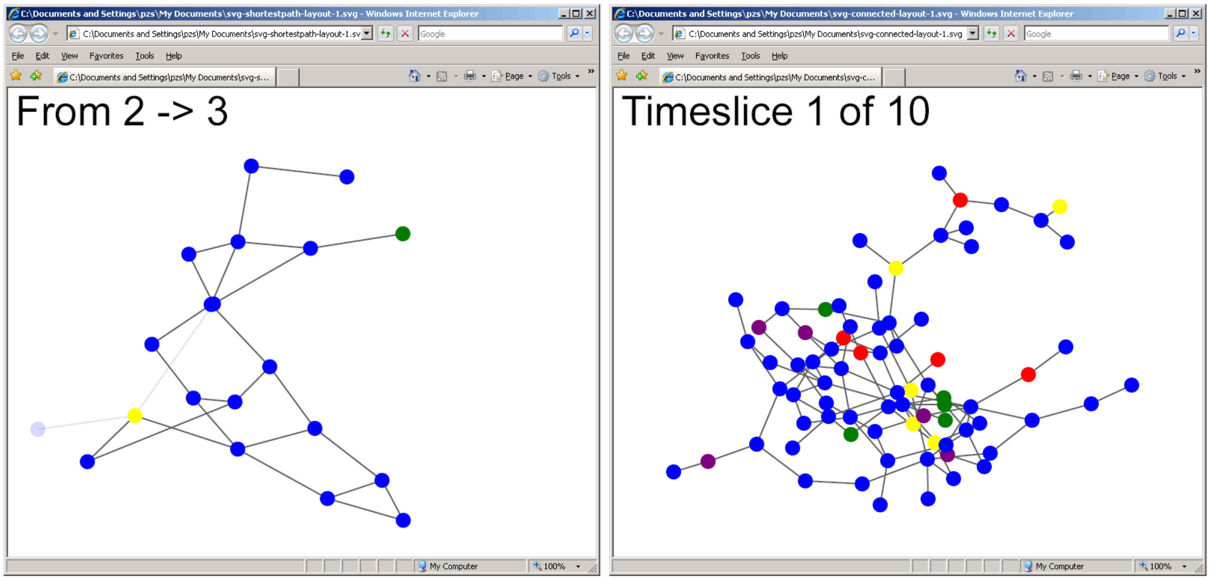
Figure 4: Interfaces for Archambault and Purchase (2012) when testing the mental map and memorability on dynamic graphs. The experiment found no significant difference between preserving, moderately preserving, and strongly preserving the mental map under animation. Qualitative feedback indicates that motion and static features of the animation may help memorization.

Purchase et al. (2006) presented a study which examined the effect mental map preservation has on dynamic graph drawing readability. In this work, the authors considered dynamically evolving directed acyclic graphs drawn in a hierarchical manner using the algorithm of Görg et al. (2004). In some ways, it tests the readability of other dynamic hierarchically drawn approaches as well (Moen, 1990; Cohen et al., 1992; North, 1995) as they share many of the same principles. The authors found that the mental map was important for questions which required specific nodes of the graph to be identified by name across time, but less important for questions that focus on edges or do not require nodes to be differentiated from each other. Both questions were degree reading questions and produced significantly fewer errors under mental map preservation.

Zaman et al. (2011) had a mental map factor when evaluating the `DARLS` system for its effectiveness to determine the difference between two hierarchically drawn, directed acyclic graphs. In the first experiment of the paper, a low mental map preservation version of the algorithm was tested against a high mental map preservation version of the algorithm on tasks that involve finding the appearance of new nodes and edges in the graph. For this task, no significant difference was found in terms of response time or error rates.

2.4.4. Animation and the Mental Map

A few experiments have examined whether animation can assist in helping preserve the mental map for graph drawings. In these experiments, mental map preservation, in terms of node movement, was not tested. Instead, this research found that smooth, animated transitions and not jump cuts, like a Powerpoint presentation without transitions, helped for some tasks. These experiments found a benefit for animated transitions when determining the connectivity of a graph when panning through one that does not entirely fit in the viewport (Shanmugasundaram et al., 2007) and when recalling parts of trees from memory (Bederson and Boltman, 1999). In a metro map reading task, it was found that animated transitions help reduce error rates in determining the number of stations where a commuter could transfer when getting from a source station to a target station (Shanmugasundaram and Irani, 2008).



(a) Small Data (b) Large Data

Figure 5: Interfaces for Saffrey and Purchase (2008) when testing the mental map readability tasks on dynamic graphs. The experiment tested degree reading, number of edges in a cluster, and paths between clusters. The results of this study suggested that preserving the mental map by restricting node movement can actually be harmful to readability, especially when significant node overlap occurs, but did not find a benefit for preserving the mental map.

In an undirected graph drawing scenario, Archambault et al. (2011) tested animation against small multiples for dynamic graph series presentation. In this regard, the study found that small multiples was significantly faster than animation for most questions and overall. For questions involving the simultaneous appearance of nodes and edges in the graph, the authors found that animation was significantly more accurate. Farrugia and Quigley (2011) compared animation to small multiples in a social network visualization scenario. The study found that small multiples was significantly faster than animation for most tasks. These experiments did not compare jump cuts to animation or small multiples. Archambault et al. (2010) tested animation, jump cuts (sideshow), and small multiples in a difference map setting. The experiment was similar to that of Zaman et al. (2011) but on undirected graphs. The experiment showed some benefits for the difference map and suggests that animation could help determine if the number of edges in a graph are increasing, decreasing, or fluctuating in number.

2.4.5. Summary

Despite extensive searching, we did not find any other experiments that tested the effectiveness of the mental map using the Coleman and Parker (1996) definition. Of these experiments, only Purchase et al. (2006) found a positive effect on user performance. In this experiment, she found that preserving the mental map helped interpret dynamic, hierarchical graph drawings when the nodes needed to be identified by name.

3. Where Mental Map Preservation May Help

In dynamic graph drawing, the environment is often an abstract information space that is evolving over time. A direct application of this navigational definition of map is therefore not always possible. Thus, the experiments to test the utility of preserving the mental map in dynamic graph drawing have stemmed from a tradition of information visualization and graph drawing readability and usability studies (Purchase et al., 1996; Purchase, 1997; Ware et al., 2002; Tory et al., 2007) as well as memorability studies (Lam et al., 2006; Tory et al., 2009).

However, inspired by the work on navigation and "cognitive maps", the value of mental map preservation could be related to the ability of the user to orient themselves in the information space. In this paper, we suggest that mental map preservation is beneficial when a task uses the *map properties of the mental map*. These tasks require users to offload information to the drawing of the dynamic graph because they are too complicated to be done solely relying on the participant's internal representation of the information space.

In this section, we begin by revisiting experiments in psychology that will assist us in identifying tasks where mental map preservation can help. Then, we will discuss these tasks in the context of local and global questions involving distinguishable and indistinguishable elements on our three question types.

3.1. Humans Can Track Three to Five Independently Moving Objects Simultaneously

In this section, we look at some key experiments in psychology that suggest a potential reason as to why no experiment has witnessed a benefit of preserving the mental map in dynamic graph drawing. One of the key observations is that humans can track three to five independently moving objects against a field of randomly moving distractors.

The first experiment to demonstrate this finding was presented in the work of Pylyshyn and Storm (1988). In this experiment, ten randomly placed crosses were placed on the screen. A subset of these crosses, ranging from one to five, would flash for a few seconds. These crosses would be the targets. The remaining crosses would serve as distractors for the task. Subsequently, the field of all ten crosses was put into motion with directions randomly selected from eight equal divisions of the compass directions. During the motion phase, crosses were visually indistinguishable and weren't allowed to pass too close to one and another. The field moved for seven to fifteen seconds. At this point, either a target or a distractor would be replaced with a flashing box. The participant was to respond by pressing a key on the keyboard to indicate if the indicated item was a target. This experiment found that participants could track with high accuracy three to five moving targets on a field of indistinguishable distractors. Although accuracy did degrade as the number of targets increased, even with five targets subjects were correct 86.5% of the time.

Yantis (1992) confirmed these results before extending them in a series of experiments. Their subsequent experiments tested points with coordinated movement in either non-ridged or ridged convex shapes. The study found that the accuracy in task response increased, possibly explained by the Gestalt law of common fate (Ware, 2004) that objects with coordinated motion tend to be perceived together.

Finally, Liu et al. (2005) replicated the results of Pylyshyn and Storm (1988) in an air traffic control scenario. Participants in this experiment tracked points under different object speed and camera motion conditions. This experiment provided evidence that participants use scene coordinates, the position of objects in the two or three dimensional virtual space, rather than image coordinates to perform the task.

These results suggest that participants are able to track up to five indistinguishable objects moving randomly on the screen in parallel against a field of distractors. Accuracy is improved if the motion of these objects is coordinated in some way. This result suggests that tasks involving three to five groups of elements of the graph moving at the same time will benefit less from preserving the mental map as participants could track them independently for the duration of the task.

3.2. The Benefits of the Mental Map

An implementation of the mental map would be more beneficial when the number of independently moving elements in the task is more than five. By increasing the number of nodes or subgraphs involved in the task, the participant would more likely be required to offload them to the diagram and preserving the mental map would be more important. In order to conveniently offload this information to the drawing, the participant would most likely be required to orient themselves in the information space. Tasks designed in this way would require participants to use the dynamic graph drawing more like a physical map. This way of using the data is similar to the *cognitive maps* of psychology and geography, but applied to a dynamically evolving graph.

3.2.1. Local Tasks

For local tasks to benefit from mental map preservation, the number of independent, local areas (consisting of a small number of nodes and edges) involved in the task should probably be greater than five. We conjecture that this is true for both indistinguishable and distinguishable tasks (Table 1). For degree reading tasks, participants should follow more than five moving nodes in the graph. For tasks involving subgraphs, as the motion of elements in these subgraphs is usually coordinated due to the spring forces on the edges, more than five subgraphs should be involved. Possibly, this conjecture may be independent of preattentive highlighting of nodes and edges for questions that involve all the timeslices of the graph series. We conjecture that this idea probably holds true for both interpretation and change tasks.

For dynamic directed acyclic graph drawing, Purchase et al. (2006) demonstrated on questions requiring nodes to be identified by name that the mental map helped. One of the reasons for this finding could be that these questions required a large number of independent nodes to be considered. The first successful task required the participant to consider almost every node in the graph independently and perform an indistinguishable, local task on each of them (change in degree). The second task had no preattentive highlighting and required the participant to find when a node identified by name, say M, became accessible by only one node. This means M is not accessible by *any* other node in the graph. The task required a large number of distinguishable elements and relied more on the mental map.

3.2.2. Global Tasks

Global tasks require a large number of elements, sometimes nearly the entire graph, to be considered in the question. If the large number of elements are indistinguishable (Table 1), where we perform a visual sum, preserving the mental map will not likely be useful. As an example, questions about the change in number of nodes or edges in the graph as it evolves over time will probably not rely heavily on the mental map.

However, if we require that the elements of a global task be distinguished from each other, the mental map will probably be more useful. For example, following a long, specific path through the graph probably would benefit, because it involves a large number of distinguishable elements that need to be tracked. We conjecture that this idea probably holds true for both interpretation and change tasks.

3.2.3. Memory

In terms of memory, we have only one experiment (Archambault and Purchase, 2012) that tests the preservation of the mental map on a global task. This experiment found no effect. Qualitative feedback indicates that both the motion in the graph and certain collections of small groups of nodes helped in the memorability of the graph series. From this qualitative data, one could conjecture that more local tasks with a large number of targets would benefit from mental map preservation, but further experimentation is required to understand the effect of the mental map on memory.

4. Possible Explanations for Experimental Results

In this section, we describe possible limitations of the ability of previous experiments to find a positive effect of mental map preservation and suggest future avenues of research.

4.1. Revisitation Tasks

Previous experiments have used a small number of focus nodes in their experimental tasks. Evidence in the previous section indicates that if this number of nodes is below five, the benefit of mental map preservation may not be realized as the participant could possibly track the targets simultaneously. By increasing the number of targets, the participant may need to rely on the map properties of the graph drawing to re-orient themselves after a given period of time.

One way to explicitly test this ability for a participant to re-orient themselves in the data is through a revisitation task. In a revisitation task, the participant attempts to re-locate a previously visited node in the visualization. A couple of experiments have looked at revisitation tasks in static graph drawings. Skopik and Gutwin (2005) examined the efficiency of revisitation under fisheye distortion. The first task of the experiment required participants to revisit a node after a fisheye visualization of the graph had been moved to a random location. The study found that task completion time significantly increased with fisheye distortion level. In the second task, the study found that visual landmarking assisted in revisitation tasks. Ghani and Elmqvist (2011) further studied the effect of visual landmarking in a static graph drawing context and found that landmarking is generally promising for graph revisitation. Revisitation could possibly benefit from the mental map because it is a local question. As long as the number of local areas of the graph considered is high, participants will probably not be able to track all of them as the data evolves and will most likely be required to rely on the mental map.

Consider a task where a set of nodes blinks before an animation of an evolving graph is shown. The participant uses the animation to view the evolving graph and, some time later, the participant is required to revisit the set of nodes that blinked at the beginning of the experiment. Under the preservation of the mental map, this set of nodes would remain in the same area of the screen and if the mental map is not preserved these nodes will likely have moved a lot during the evolution of the data set. As the task could potentially involve a large number of nodes and edges and it uses the dynamic graph drawing as a map for the revisitation of nodes, it is more likely to benefit from mental map preservation.

4.2. Orientation in a Graph

Other than a few results in directed acyclic graph drawing (Purchase et al., 2006; Bederson and Boltman, 1999; Shanmugasundaram et al., 2007), few experiments have tested dynamic graph drawings with clear orientations. It could be that the top-down nature of the hierarchical graph drawing has a clear orientation and mental map preservation helps because the drawing allows participants this direction in the drawing to navigate as the data evolves. It may be fruitful to test this property in an undirected graph drawing setting. In undirected graph drawing, orientation would, qualitatively, involve something like the compass directions on the dynamic graph (North, South, East, and West).

In an undirected graph drawing setting, consider a data set with twenty or so highly connected components. The participant is required to locate these components on the screen at various points in time during graph evolution. A task which involved only a few subgraphs, say four, probably wouldn't benefit from the mental map as the participant could probably track them in parallel as they moved. However, if the task involved a larger number of subgraphs, we conjecture that the objects could not be tracked and mental map preservation would provide more of a benefit. The participant would most likely offload memory to this evolving "map" and use these subgraphs for orientation in the data.

4.3. Specific Paths Through a Graph

Quite often, maps are used to specify directions to get between two places in a specific environment. Road and highway maps for long distance travel are one example of this type of externalization. Also, quite frequently, people sketch maps on paper with directions such as *turn right at the second set of lights, and then immediately left at the post office.* These sorts of maps help people navigate the physical space in order to trace a specific route to arrive at a destination.

In a dynamic graph drawing setting, instead of intersections and roads, we have nodes and edges. Routes through this data correspond to long paths, sequences of specific nodes and edges, that need to be traversed. So long as the number of nodes in the sequence is greater than five, preserving the mental map might provide a benefit as the participant is likely to offload the path to the dynamic drawing. Yantis (1992) noted that if the movement of the targets is coordinated, the number of targets that can be tracked in parallel increases. As the motion of the nodes along the path is likely to be coordinated, paths longer than five may need to be tested. This task is similar to tasks that involve orientation in the graph, but rely more on navigation through the data instead of locating specific targets in the data.

4.4. Tasks Involving More Data Elements

Previous experiments have usually involved a small number of nodes and edges in the task performed by the participants. If a larger number of nodes and edges are involved in the task, it would likely benefit from preserving the mental map. This consideration is particularly important for global tasks with distinguishable elements. As the number of elements increases beyond five, it is more likely that the participant will have to offload information to the diagram.

The problem with testing mental map preservation on tasks involving a larger number of elements is that these tasks are harder for participants. Therefore, we run a much greater chance of experiencing a ceiling effect. In a **ceiling effect**, the task is so hard that the error rates under all conditions and factors become very large. Under such conditions, it is harder to test several mental map preservation levels as the task could be too hard independent of the conditions and factors.

In Archambault et al. (2011), a ceiling effect was experienced on a task that involved finding a shortest path that only decreased in length. Thus, for this specific task in the experiment, the authors were not able to conclude results on the effect of the mental map.

5. Revisiting the Definition of the Mental Map

In this paper, we have argued that using the definition of Coleman and Parker (1996) preservation of the mental map will most likely be useful in situations where information must be offloaded to the drawing. This occurs in local tasks when the number of independently moving areas of the graph used in the task is high and for global tasks when the number of distinguishable nodes/edges used in the task is high. However, Coleman and Parker (1996) preserves all three mathematical models as defined by Misue and Eades (Eades et al., 1991; Misue et al., 1995): orthogonal ordering, proximity relations, and topology. It may be more interesting to consider preserving one or two of these metrics instead of all three simultaneously.

Algorithms in the graph drawing literature have considered this possibility, but no human computer interaction experiments have been run to determine the effectiveness of these approaches. Lyons et al. (1998) preserves only proximity in the definition of Misue and Eades (Eades et al., 1991; Misue et al., 1995). In this approach, the Voronoi diagram, the dual of the Delaunay triangulation, is preserved and refined using Lloyd's algorithm. Lee et al. (2006) optimize the definition of Misue and Eades (Eades et al., 1991; Misue et al., 1995) directly through simulated annealing. In this approach, the objective function optimized drives the drawing of the graph sequence to preserve orthogonal ordering and proximity. It would also be interesting to consider these definitions of the mental map to determine if subsets of Misue and Eades (Eades et al., 1991; Misue et al., 1995) perform better than when all three mathematical models are preserved.

6. Recommendations for Designers

In this paper, we present evidence that preserving the mental map is not always helpful when performing tasks on dynamic graphs. For local tasks, the number of nodes, edges, or subgraphs considered needs to be high. For global tasks, the number of distinguishable nodes and edges used in the task needs to be high. In general, preserving the mental map may not support graph interpretation (Purchase and Samra, 2008; Archambault et al., 2011; Saffrey and Purchase, 2008), change (Purchase et al., 2006; Archambault et al., 2011; Saffrey and Purchase, 2008; Zaman et al., 2011), or memory (Archambault and Purchase, 2012) tasks. However, subjectively, users may feel that preserving the mental map helps (Archambault and Purchase, 2012).

As an algorithm designer, the decision whether or not to preserve the mental map is more dependent on the tasks likely to be performed by users than previously assumed. Although experiments often observe that preserving the mental map seems to neither hurt nor help task performance (Archambault et al., 2011; Archambault and Purchase, 2012; Zaman et al., 2011), it can impact performance negatively (Purchase and Samra, 2008; Saffrey and Purchase, 2008) for certain tasks. This worsened performance is most likely due to the individual timeslice quality and drawing stability trade off that needs to be made by all dynamic graph drawing algorithms. However, further experimentation is needed and should be informed by our critique of previous experiments as well as results in the fields of geography and psychology.

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