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Supporting synthesis in geovisualization

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Geovisualization tools are intended to support analysts in complex task domains like crisis management, disease surveillance, and threat analysis. It is likely that analysts in these domains will use geovisualizations to develop many analytical results over time. This calls for attention to the problem of collecting, organizing, and making sense out of groups of analytical results – a stage of analysis called synthesis. The research reported here aims to characterize the process of synthesis as it is conducted by analysts working alone, and to suggest design guidelines for new tools to support synthesis in that setting. We have developed a new experimental method for observing and characterizing the process of synthesis. This approach has participants work with a collection of physical data artifacts on a paper-covered workspace to devise hypotheses under the guise of a disease outbreak scenario. From experiment video recordings we identified and coded actions that participants undertook to complete the synthesis task. In this article we report results from synthesis experiments with analysts from Pacific Northwest National Laboratory and experts from The Pennsylvania State University. Experiment results are then distilled into a design framework that can be used to shape the development of geovisual synthesis tools.

Keywords: synthesis; geovisualization; design framework

1. Introduction

Advanced geovisualization tools are intended to support analysts in complex task domains such as crisis management (Tomaszewski *et al.* 2007), disease surveillance (Kamel Boulos *et al.* 2008), and threat analysis (Weaver 2008). We anticipate that analysts in these domains will use geovisualization tools to develop many analytical results over time. This requires attention to the problem of collecting, organizing, and making sense out of groups of analytical results – a stage of geovisual analysis called *synthesis*. The central aim of the research reported here is to characterize and suggest design guidelines for new tools that support synthesis, which until now has received limited attention in the GIScience community.

To address this challenge, we have developed an experimental approach for observing and characterizing the process of synthesis. This approach has participants work with a collection of analytical artifacts on a paper-covered workspace. Participants are asked to devise hypotheses from the collection of artifacts, and to arrange and modify artifacts and the workspace using standard office tools such as pens, post-it notes, and markers. To analyze their work, we use video recordings to identify and code actions that participants undertake to complete the synthesis task.

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This article reports synthesis experiment results from sessions with analysts at Pacific Northwest National Laboratory (PNNL) and experts at The Pennsylvania State University (PSU). Findings from these experiments are then distilled into a design framework that can be used for future development of geovisual synthesis tools to support analysts working on an individual basis. This work elaborates a key portion of the theory that describes analysis with geovisualization and provides an in-depth examination of how individuals approach part of the geovisualization research process. It also provides a novel experimental methodology for exploring and characterizing the synthesis of geovisual information.

2. Background

The basic theory driving geovisualization research was originally proposed by DiBiase (1990) and extended later by MacEachren (1995). DiBiase outlines a geovisualization research process that moves from exploration to confirmatory analysis, transitioning to synthesis, and ending with presentation (Figure 1). To date, a great deal of geovisualization research and development has focused on the goals of exploration and analysis. Little specific work has focused on characterizing or developing tools to support synthesis. DiBiase describes this stage of geovisual research as '. . . synthesis or generalization of findings'.

When viewed from the **(cartography)3** framework of cartographic visualization (MacEachren 1995), synthesis research should aim to design strategies for composing and generalizing exploratory and analytical results, as analytical tasks shift from knowledge construction to information sharing. These strategies will support the formative stages of condensing what has been discovered using geographic visualization, as analysts change goals from revealing unknowns to presenting what is known. **Q1**

A commonly referenced theoretical framework in GIScience by Gahegan and Brodaric (2002) describes synthesis in a somewhat different manner. In their framework of

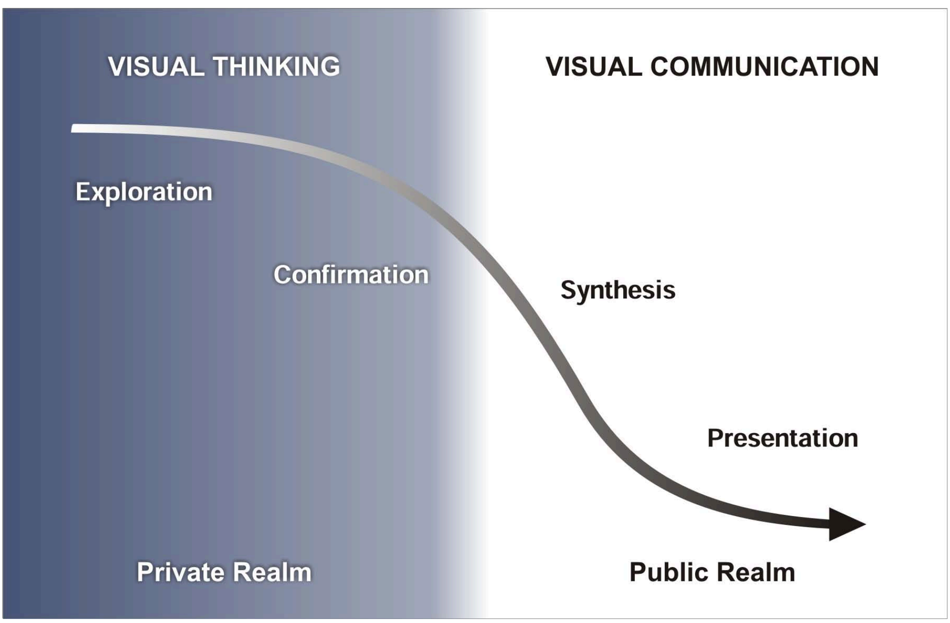

Figure 1. The geovisualization research process as conceived by DiBiase (1990).

geoscientific discovery, synthesis involves creating taxonomies from data – often in the form of classification schemes. As an example, Gahegan and Brodaric describe how analysts could visually explore and identify suitable classification schemes with land cover data – making synthesis an activity that occurs quite early in the scientific process.

Because the definition for synthesis varies in the literature, we must define it clearly for research. Our focus is on the result generalization and organization stage of the scientific process – a (thus far) largely unexplored topic in geovisualization research. Therefore, the term 'synthesis' in the sense initially articulated by DiBiase (1990) and MacEachren (1995) is appropriate, in contrast to synthesis as described by Gahegan and Brodaric (2002). We define synthesis as *the stage of an analytic process in which analysts organize and combine individual analytical results into coherent groups that are used to assign meaning and/or encapsulate complex ideas*. In any analytical process, iteration between stages is expected, so we do not define synthesis as a wholly separable, independent task.

Visualization researchers have begun to tackle the problem of supporting synthesis with new visually driven environments for collecting and adding meaning to analytical results. Current synthesis support tools include Analyst's Notebook (i2 2007), nSpace (Wright *et al.* 2005), GeoTime (Eccles *et al.* 2008), Scalable Reasoning System (Pike *et al.* 2008), EWall (Keel 2007), and Jigsaw (Stasko *et al.* 2007). These efforts have not benefited from empirical studies of what analysts do when they synthesize information. Our research helps fill that gap by exploring and characterizing the process of synthesis with geovisual information.

3. Synthesis experiments

To observe how synthesis takes place an experiment was designed for participants to simulate the real-world task of determining the source of an avian influenza outbreak in the Pacific Northwest. The following sections describe the experiment design and evaluation.

3.1. Study participants

Eighteen participants were recruited for this study, including eight disease surveillance and biological/chemical threat analysts from PNNL, five GIScience experts from the Penn State GeoVISTA Center, and five infectious disease experts from the Penn State Center for Infectious Disease Dynamics (CIDD). The Penn State experts are postdoctoral research associates and senior PhD candidates in their respective laboratories.

The strategy guiding participant selection was to explore what is needed not only to support current analysts, but also to characterize how synthesis tools should function for people who are currently receiving education and training and will enter the analyst workforce in years to come. Participant selection from PSU included geographers as well as disease biologists to further explore potential differences between expert groups that are likely to work together in real-world situations that involve multifaceted geographic problems.

3.2. Experiment design

Our experiment featured an hour-long synthesis activity in which participants work in isolation to organize and annotate a set of physical artifacts (3.5″ × 5″ laminated cards) on a 36″ × 36″ paper-covered workspace. Participants were provided markers, pens, adhesive tags, and post-it notes of multiple sizes and colors to modify the workspace and artifacts as desired. The use of physical artifacts and tools was intended to explore how synthesis occurs without the constraints imposed by current software tools, which typically offer limited types of organizational metaphors. Analog experiments have been shown to elicit new ideas for digital technology through observations of how participants make use of affordances when provided real-world tools (Sellen and Harper 1997). It has also been observed that analog methods can elicit greater creativity among users when compared to digital counterparts (Stones and Cassidy 2006).

Participants were instructed that an avian influenza outbreak had occurred in the Pacific Northwest and that their task was to develop hypotheses for the source of the outbreak using the artifacts and tools they had been provided with. During the experiment, participants were asked to provide a talk-aloud (Ericsson and Simon 1993) verbal protocol to state what they were doing. A verbal protocol provides context for participant actions during the experiment to aid post-experiment coding analysis.

In addition, participants were instructed to state whenever they had an emergent hypothesis, and to briefly describe this hypothesis so that it could be recorded. This was done to evaluate whether or not the experiment successfully elicited realistic analytical behavior.

At the conclusion of each experiment, a short debriefing session was conducted between the lead investigator and the participants. At that time, the participant was asked to describe how they had organized their information and what they had done to indicate their hypotheses on the workspace.

3.3. Analytical artifacts

A set of 48 analytical result artifacts (Figure 2) was developed for the experiments (see Supplement A for the artifacts in detail). The design of these artifacts was based in part on the Sign of the Crescent (Hughes and Schum 2003) activity, which is commonly used to train analysts. This activity contains a set of text reports that include source information and time stamps. The goal of the activity is for analysts to determine likely hypothetical outcomes of a terrorism scenario based on the information they can gather from text reports. We used this activity as a model to suggest the character of information that each artifact should include.

The artifacts used in our experiments differ from those in the Sign of the Crescent activity, in that they include maps, photos, and other graphics as well as text reports. A 2:1 ratio of graphic artifacts to text artifacts was used to develop the complete set. This choice reflects the fact that geovisual analytic tools typically generate graphical rather than textual results.

3.3.1. Embedded hypotheses

The artifacts were designed to weave a multithreaded story regarding an avian influenza outbreak in the Pacific Northwest. Each artifact features source information and a time stamp, and there are photographs, video screen captures, maps, data graphics, and text reports included in the set. Based on the information provided, there are five potential sources for the outbreak, and there are many more permutations possible given the combinations of those hypotheses. The five threads devised for the experiment include a natural occurrence based on bird migration, a person named Alex Watersby who intentionally spread the flu to wild birds and through pet stores, an Al-Qaeda operative named Waleed Al-Keval who infected wild birds, an unintentional outbreak caused by illegal pet trade activity by local pet stores, and a plot by North Korea and China to spread avian influenza to disrupt poultry commerce in America.

Figure 2. Analytical artifacts developed for synthesis experiments.

3.3.2. Geographic information

Particular attention was given to the inclusion of a variety of realistic spatial references in the artifacts to require participants to consider hypotheses in terms of their fit to the relevant geography. Flight schedules, financial transactions, and flu outbreak data provided contextual geographic references to help participants determine whether the geographic extent of the outbreak made sense in relation to where avian flu already existed, how it could get to the region, and where funding to support that effort would come from.

3.3.3. Randomization

The artifacts were assigned a number from 1 to 48 and sorted for each experiment using a random permutation. The randomized artifacts were placed on the workspace in a stack at the beginning of each experiment.

3.4. Coding and analysis

Our experiments generated 18 videos. To analyze the videos, a coding scheme was developed to describe the low-level events that users initiated to complete the synthesis experiment. Our focus was on defining which software tools and functions would be necessary to support what the user was doing with the artifacts during the experiment. Coding was completed for all actions that were separable, using the verbal protocol of the user as well as the context of the action to help guide choices. A conservative approach was taken to identify actions that involved the direct, observable use of artifacts, tools, or the workspace. Gestures or verbal declarations were not coded.

The first coding scheme was developed by the author by watching sample videos. This scheme was then further refined by a group of seven interface and software developers from the GeoVISTA Center during a meeting in which sample videos were reviewed. A final round of refinement then took place after the author completed sample coding of two videos. The final scheme is presented here, showing major types of codes and their possible subtypes. The detailed coding scheme can be found in Supplement B:

- Annotate (text, drawing)
- Group artifacts (hypothesis, category, type, time, read/unread, unknown)
- Collapse/expand group of artifacts
- Link artifacts (hypothesis, network)
- Sort (category, type, time)
- Search (category, time, read/unread, keyword)
- Tag (hypothesis, category, time, network, certainty, follow-up, place)
- Zoom (single item, multiple items).

Videos were coded using Transana (Woods and Fassnacht 2007), a software tool Q3
designed for qualitative analysis of audio and video data. Ten sample videos were selected to test coding reliability. Two GeoVISTA graduate students were each given five videos that included event markers but were stripped of the event code that the author had assigned. Code reliability was assessed using a percent agreement measure, a commonly used method of inter-rater reliability (Yawn and Wollan 2005). The percent agreement between the independent coders and the author was 88.4%.

4. Experiment results

The following sections describe results from our synthesis experiments. The graphical data presented here can be interpreted using the annotated legend provided in Figure 3. The primary glyph carries with it the color of the major category it is associated with (e.g. annotate, group, sort), and the smaller glyph attached to its bottom indicates which particular subtype of that category was assigned. A qualitative color scheme was used from ColorBrewer (Brewer *et al.* 2003). Grayscale ramps were used to fill the subtype glyphs. Although the codes are qualitatively different, visual clarity was not possible using a qualitative scheme for the higher-level categories as well as the individual subtypes.

Where noted, individual participants are referred to using the generic name for the site where the experiment took place, along with a number. A letter suffix is included with PSU participant data as those experiments were grouped into five sessions.

4.1. Cumulative results

Charts showing the cumulative results from experiments conducted at PNNL and PSU are shown in Figure 4. The top five most frequent events are group (category), annotate (text), zoom (single), zoom (multiple), and group (time line). These five codes are consistent for both PNNL and PSU groups, indicating no difference between domain backgrounds in this case.

4.1.1. Grouping

A bias toward the group code is expected, considering that participants were provided a stack of randomly sorted artifacts at the beginning of the experiment. However, the type of grouping is of interest, as the most common methods for doing this are by category or by time line. The categories users assigned to artifact groups varied widely, from broader categories like ‘historical information’ to specific categories like ‘information about Alex Watersby’.

Grouping by time line was the second most common coded grouping method. As source information and dates were provided on each artifact, it was easy for participants to sort through and group items along a time line. The way the time lines were arranged on the workspace is of interest, as there was no single dominant strategy for this. Some users arranged past to present from top to bottom, others from bottom to top, and some used left to right.

We might have expected more participants to group artifacts by hypotheses, considering the task was to develop hypotheses, but this was an infrequently coded event in our experimental evidence. Every participant developed at least three hypotheses, but few chose to group items on the workspace using hypothesis membership as the primary criterion.

4.1.2. Annotation

Annotation was the second most common coded event from the individual experiment data. Participants from both PNNL and PSU added text annotations more often than graphical annotations, with PSU participants using graphic annotations slightly more often than PNNL

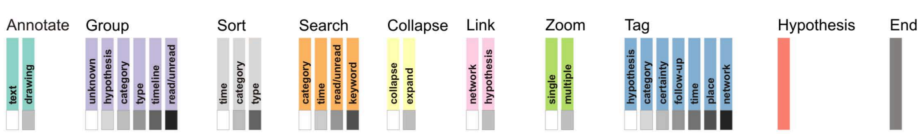

Figure 3. Legend for use with coded experiment results in Figures 4 and 5.

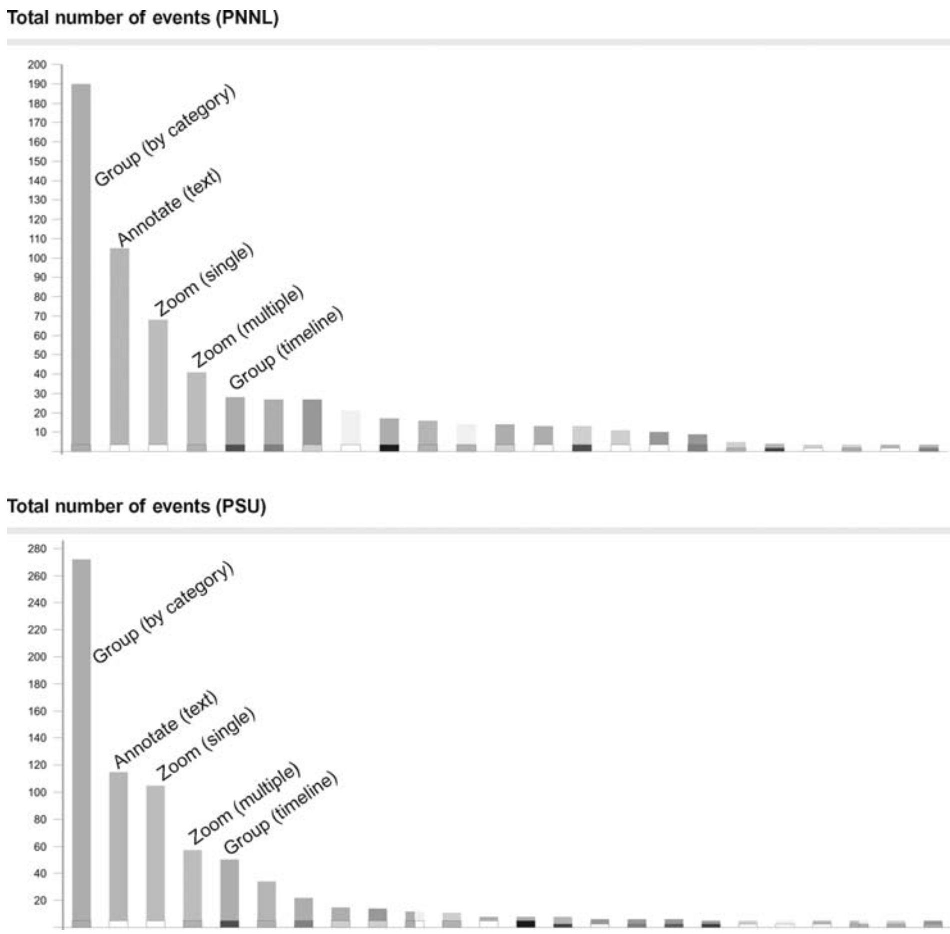

Figure 4. Cumulative charts showing total number of coded events for both the experimental groups. The top five event types for each group are labeled.

participants. Text annotations were frequently used to record key information about artifacts, to add information to tags, and to identify working hypotheses.

Drawn annotations usually took the form of regions around groups of artifacts, or arrows drawn between particular items that are related in some way. It is worth noting that not all users engaged in annotation of one kind or another; PNNL 7, PSU 2B, and PSU 5B did not choose to annotate their workspaces.

4.1.3. Zooming

Zoom events were quite common among participants from both groups. Zoom events were coded when a participant closely inspected an artifact or multiple artifacts that had been placed on the workspace. Most of the time participants picked up artifacts and brought them closer to their face to interrogate them closely. In general zooming takes place later in the process of synthesis after artifacts have already been grouped on the workspace. Participants tend to look at one item at a time, which may be due to the physical limitation associated with holding artifacts. The most common multiple item zoom was to examine two artifacts to compare their information.

4.1.4. Other events

While grouping, annotation, and zooming were the most common events that occurred during synthesis experiments, participants initiated a wide array of additional actions to develop hypotheses using the artifacts. Colored tags were used to indicate categories, hypotheses, certainty, and other attributes. These events did not occur as frequently, but frequency alone is not necessarily an indicator of importance with respect to supporting synthesis. Participants also initiated searches and sorts through artifacts to find references to particular people, and to quickly organize data based on time or other criteria.

Link events were coded whenever participants stated that artifacts were linked to each other and/or when arrows were drawn indicating as much. Most of the time links were used to indicate linkages between pieces of evidence in a hypothesis.

Finally, some participants collapsed artifact groups on the workspace. Most of the time collapsing events occurred with data artifacts that were judged to be background or historical information. One analyst at PNNL chose to begin with collapsed groups organized on a time line, and then systematically expand each group from past to present to analyze the information.

4.2. Individual results

This section focuses on patterns of events that are observable by looking at the coded results for individual participants. It also presents observations on the organizational methods that participants used to synthesize information.

Detailed results for each participant are provided in SupplementC. There each coded result is presented along with a graph that summarizes the most frequently coded events, a photograph of the final workspace, and a brief text summary of what occurred during the experiment.

4.2.1. Synthesis strategies

Participants used several different basic strategies for completing the synthesis task (Figure 5). The most common strategy begins with grouping all the artifacts following a brief examination of the artifacts one by one. After the workspace has been initially organized, a deeper look at the artifacts takes place, involving cycles of zooming one or more items, annotating about them, and regrouping into new categories or hypotheses. Participants tend to announce hypotheses shortly after the initial grouping, and then announce new or refined hypotheses during the close examination of artifacts. In this synthesis approach, annotation and tagging occur after most grouping has been completed.

Another strategy begins with thorough examination of each artifact, annotation of key information, and then collection of artifacts into groups. Figure 5 shows two sets of results that demonstrate this strategy. It is not clear in these cases how hypotheses might be related to sequences of events during synthesis. From video evidence, PSU 5A and PNNL 5 could be described as methodical in terms of how much time they spent carefully examining and annotating each artifact, and they appeared surprised that substantial time had passed by the time all artifacts had been examined.

A third approach focused on a rapid initial sort or grouping of artifacts according to generic attributes. This was followed by different secondary strategies to evaluate information. PNNL 6 began by quickly grouping artifacts onto a time line that had collapsed stacks for each day in the data set. Then they expanded each day one by one from past to present to

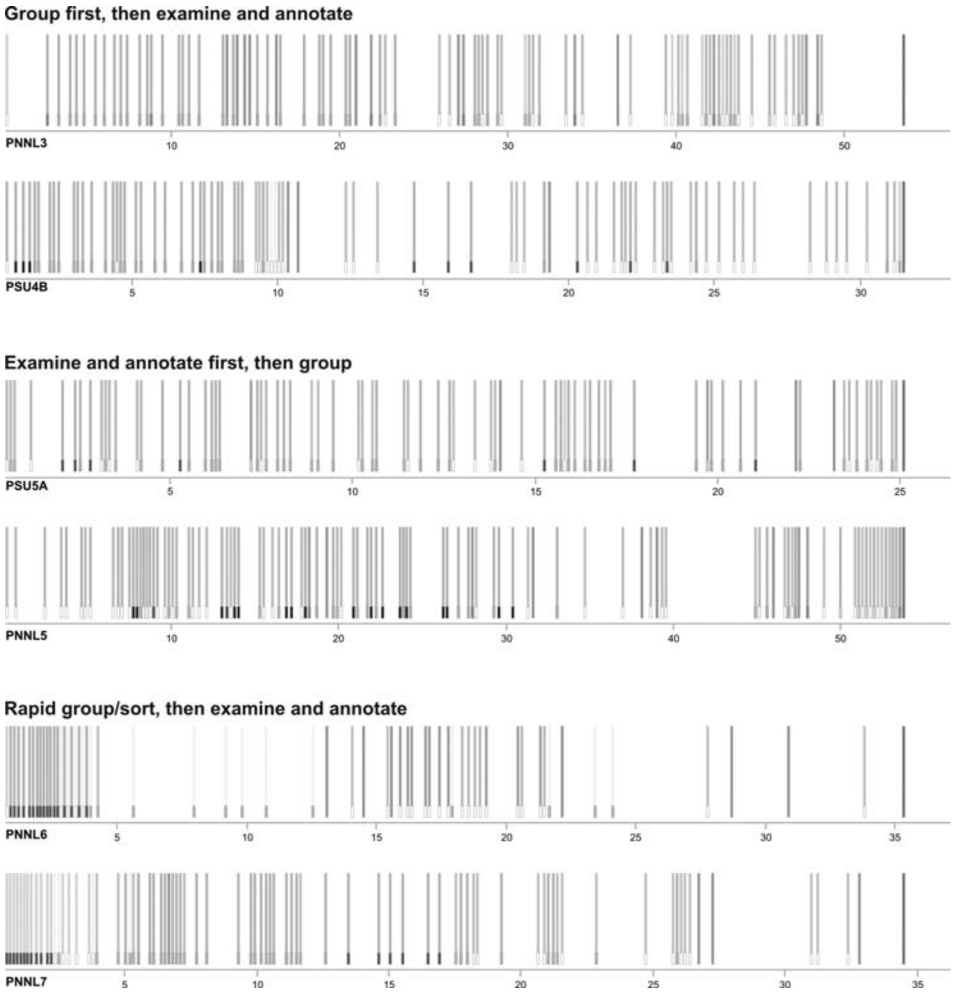

Figure 5. Three key synthesis strategies found in experiment results are shown here on time lines (measured left to right in minutes). Each time line corresponds to an individual experiment, and colored glyphs can be interpreted using the legend in Figure 3.

evaluate the information in detail. Later, colored and annotated tags were added to indicate artifacts that were important to particular hypotheses, but artifacts were kept in place according to the time line.

PNNL 7 used a similar approach by quickly sorting the stack of artifacts by the basic type of information they showed (text, graphic, photo). The objects were sorted while in hand – not grouped on the workspace. After the rapid sort was complete, PNNL 7 began evaluating the text items to create groups by category.

4.2.2. Organizational metaphors

The events initiated by participants provide substantial insights into the process of synthesis and how it might be supported with interactive visualization tools. It is also important to examine the basic organizational metaphors that participants made use of to organize their information. Video recordings of the debriefing conducted immediately following each experiment and photographs of the final workspaces inform our understanding of how participants organized the information.

In general, participants often chose to group artifacts in multiple ways on their workspace, augmenting some of them with tags or annotations, rarely in a consistent manner across all of them. This may be due in part to the fact that it is not easy with physical artifacts to quickly try out several different methods of organization. It may also indicate that complex analytical problems require multiple views to the information in order to develop some hypotheses.

A prototypical result is shown in Figure 6. Here, PSU 4B's workspace has been marked to highlight the different organizational metaphors that they use. A time line (1) has been established across the top of the workspace and hypotheses have been arranged from left to right according to where they fit in terms of time. At bottom left (2) an emerging hypothesis with sparse information has been gathered, but not included in the main time line. At the center (3) of the workspace a text report that confirms a flu outbreak has been placed near several artifacts that describe recent data about the spread and impact of avian flu around the world. Finally, along the bottom right (4) of the workspace a number of artifacts have been gathered that provide contextual and historical information.

4.2.3. Geographic information

While all participants' hypotheses required at least some attention to spatial reasoning to decide their plausibility, none in the individual experiments attempted to draw a map on the workspace to develop an explicit spatial representation of their information. A few chose to tag artifacts to indicate spatial information, but for the most part, participants did assign separate methods for spatial references. Written notes on the workspace and post-it notes that were used to summarize findings integrated spatial references with other information.

Figure 6. Workspace of PSU 4B, showing multiple organizational methods.

5. Design guidelines for synthesis support tools

Analysts currently have little in the way of interactive visual tools to help organize, annotate, and make sense out of collections of evidence. To begin addressing that need, results from synthesis experiments with analysts working on an individual basis are distilled here into design guidelines for synthesis support software. The following sections describe interface metaphors, necessary tools and functions, and general system design guidelines for supporting individuals as they synthesize geovisual information.

5.1. Synthesis interface metaphors

The experimental results reveal a wide array of organizational metaphors that can be used to synthesize analytical results. The analytical needs dictate the use of different organizational strategies at different times; for example, time lines may be useful to orient artifacts in order of occurrence, but a node-link organization may be required later during the same synthesis activity to develop a deeper understanding of the social network involved. Evidence points to organization by category, hypothesis, time line, hierarchy, report outline, and node-link methods (Figure 7).

5.1.1. Category

New synthesis support tools should allow users to assemble groups of artifacts according to category designations. In experiments, participants indicated groups by collecting artifacts in close proximity on the workspace, and often chose to draw lines around the objects to develop 'regions' to separate groups from one another. Synthesis software should detect groups of items in close proximity to one another and help users delineate them with boundary markers.

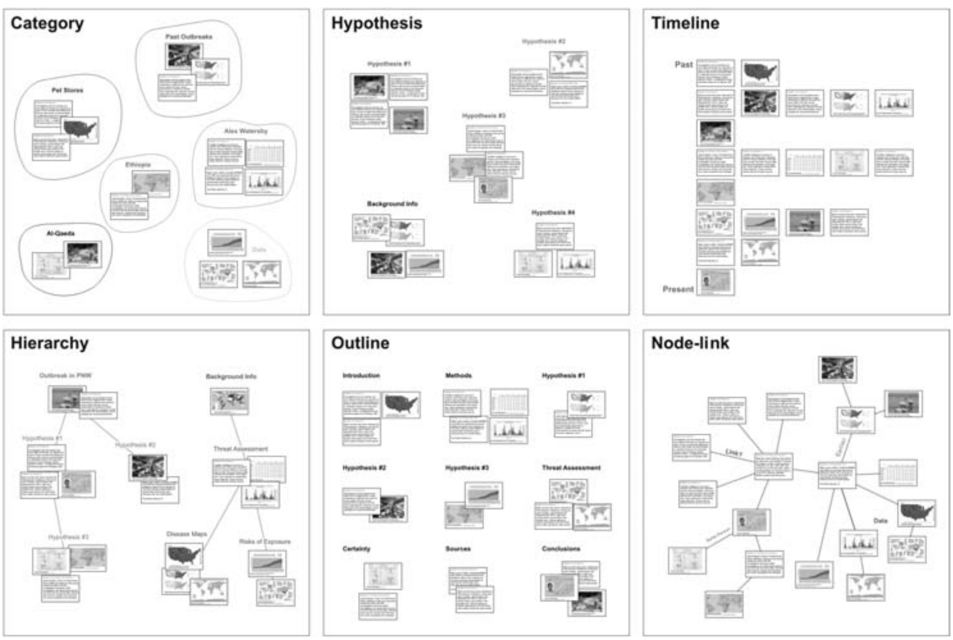

Figure 7. Synthesis organizational metaphors gathered from experiment evidence.

5.1.2. Hypothesis

Users should be allowed to select a group of artifacts and indicate that they are part of one or more hypotheses. In synthesis experiments, participants placed artifacts in close proximity and provided annotations on the workspace or on tags to indicate different hypothesis groups. Synthesis support tools should help users quickly identify groups of artifacts as pieces of a hypothesis, and should reveal linkages between hypotheses based on time of occurrence, keyword/category similarity, or other measures.

5.1.3. Time line

Synthesis support tools should enable users to sort and align artifacts to a time line. Because many experiment participants chose to apply time line organizations to only a portion of their workspace, time line organization should be applicable to subsets of items as desired. Organization by time may be more applicable in global terms when considering the problem of keeping track of multiple collections of artifacts – as participants described in interviews at PNNL.

5.1.4. Hierarchy

New tools should allow users to develop hierarchical organizations of their information. Hierarchies may be applied to results within a particular project, as well as the projects themselves when they are considered part of a knowledge base. Information structured in a hierarchy can be denoted by the placement of artifacts in a tree structure, including headings and subheadings indicated by annotation on the workspace or on movable tags.

5.1.5. Node link

Synthesis support tools should support the use of node-link organization to evaluate social networks in collections of artifacts. Synthesis tools should allow users to develop node-link organizations with subsets of information, as no participants in synthesis experiments applied this strategy to the entire workspace. Node-link organizations tended to emerge in the later stages of analysis as participants moved through multiple organizations of the information to evaluate and enhance their hypotheses.

5.1.6. Report outline

New synthesis support tools should allow users to organize objects according to report headings and outlines common to their domain. While experimental evidence does not show this type of organization, a report outline structure was frequently mentioned during interviews in a synthesis needs assessment study conducted in parallel with the experiments reported here (Robinson 2009) as an important strategy for organizing analytical results. In those interviews, analysts stated that reports are a primary resource for recalling prior work, so providing tools to view artifact collections from this perspective may support analytical recall.

5.2. Synthesis support tools

Basic organizational capabilities must be coupled with the appropriate set of corresponding tools to support effective and efficient individual and collaborative synthesis. The following sections provide guidelines for tools that group, annotate, zoom, tag, collapse, link, sort, and search artifacts.

5.2.1. Group

Synthesis software should support the development of artifact groups by allowing artifacts to be moved around the workspace at will, and by providing users the ability to select multiple artifacts and assign a group tag or region to identify their association. To support multiple types of grouping, tools are required to help users create additional views of individual or multiple groups to reflect multiple perspectives, such as time, category, or hypothesis.

5.2.2. Annotate

New synthesis support tools should allow users to annotate workspaces and artifacts at will. Annotations in both textual and graphical formats should be supported, as experiment participants frequently mixed together both types. Pen- and/or touch-enabled interfaces are promising avenues for supporting easy annotation in synthesis toolkits. Sketch maps, time lines, and other graphics appeared in several synthesis experiment results – things that are impractical for users to create in software without using a stylus.

5.2.3. Zoom

Synthesis support tools should provide zooming capability for users to closely examine one or multiple items at a time. Experiment evidence shows that users frequently wanted to examine artifacts in a particular group when they attempted to examine multiple artifacts at a time. Zooming tools should support this kind of 'regional' zooming as well as individual artifact zooming.

5.2.4. Tag

It is important for new synthesis support tools to enable artifact tagging to indicate keywords, time, certainty, membership in a hypothesis, and other information. Experimental evidence suggests that tagging happens to individual artifacts as well as groups of artifacts, so tagging tools should be agnostic to either case. Tags should be implemented in a way that allows them to be moved around the workspace to indicate rankings or to adapt to evolving methods of artifact organization.

5.2.5. Collapse and expand

New synthesis support tools should provide users with the ability to minimize groups of artifacts into stacks. Stacks should be expandable on the fly as users return to groups that they may have minimized to tidy the workspace or to indicate that they had examined those artifacts. Users should be able to use images, tags, or other conspicuous means to identify their stacks.

5.2.6. Link

Users should be able to indicate linkages between artifacts and artifact groups using line and arrow graphics in future synthesis support tools. Links may be used to indicate any kind of association between artifacts, including time, social connections, and hypothesis membership. Users should be able to annotate links to indicate these types of relationships as they see fit.

5.2.7. Sort

Synthesis support tools should allow users to quickly sort collections of artifacts by time, artifact type, category, or other attributes as needed. Sorting should be applicable globally as well as locally to specific groups of artifacts.

5.2.8. Search

Users of synthesis support tools should be able to query artifacts to identify matches to keywords, categories, temporal references, and other attributes. Search results should simply identify and highlight matches and allow users to regroup artifacts as they see fit.

5.3. General design guidelines

Results from experiments and interviews (Robinson 2009) reveal several overarching design guidelines that contextualize the development of new synthesis support tools such as those highlighted in Section 2.Flexibility, support for mixed metaphors, and tools to manage contextual information are three key design foci for future synthesis tools.

5.3.1. Flexibility

As demonstrated by the creative use of analog tools in synthesis experiments, synthesis support tools will need to allow users to draw from a palette of common tools and organizational metaphors that are designed with flexibility and creativity in mind. The goal should be to create synthesis interfaces that afford all the flexibility of real materials – yet enable advanced digital capabilities to quickly search, sort, duplicate, and reconfigure the workspace.

5.3.2. Mixed metaphors

The workspaces created in synthesis experiments show that new tools for synthesis support must allow the use of multiple organizational methods, including in combination within a single workspace. An obvious advantage that software synthesis tools could provide over real materials as evaluated in this study is that software tools should be able to easily support the creation of multiple workspaces with the same information. This would allow users to develop multiple synthesized collections, perhaps to systematically evaluate information from various perspectives.

5.3.4. Managing contextual information

Experiment results and interview responses indicate that synthesis support tools should allow artifacts to be designated as background, contextual, or unknown information. The shoebox (Pirolli and Card 2005) metaphor can be employed here as a dedicated portion of the interface reserved for storing artifacts that are not yet in immediate use on the workspace. It could be the starting point for many real-world synthesis activities, as users delve into a collection of analytical artifacts and add meaning to them on the workspace. A shoebox should allow users to quickly sort and search artifacts – an action that participants initiated in synthesis experiments.

6. Conclusions

Our research provides an initial examination of part of the geovisualization research process that has until now had little attention. The results of our experiments show that synthesis conducted in the individual realm is an intricate and varied activity. A realistic geographic problem was used in the design of the experiment materials, including artifacts that feature a variety of spatial references, and a range of hypotheses that each feature spatial components. Supporting synthesis will require flexible tools that allow for diverse approaches and creativity.

Problem domains that we wish to support with geovisualization tools will require dedicated tools to help users synthesize collections of analytical results into meaningful information for decision makers. This research provides a set of software design guidelines based on experimental evidence gathered from analysts and experts. These guidelines can be employed immediately to shape new synthesis support tools intended for individual use. Our work also provides an experimental methodology for studying synthesis that can be used for additional research.

Implementing synthesis tools using the guidelines presented here will provide the opportunity to conduct important follow-up studies to explore how well they support synthesis when it is conducted in the digital realm. Experiments using large maps in place of blank sheets of paper, and user-created artifact collections would provide additional valuable context for understanding synthesis. Other future studies could focus on methods for representing analytical results as artifacts, synthesis in collaborative, as opposed to individual settings (building on Isenberg *et al.* 2008, Robinson 2008), and synthesis in long-term tasks with larger artifact sets. Q4

The problem domains that geovisualization tools seek to support are quite challenging, and relevant data may include a wide array of media formats. Visually enabled analytical tools will likely become key mechanisms through which analysts tackle these problems (Thomas and Cook 2005, Andrienko *et al.* 2007). However, such tools are only beneficial if they are coupled with equally sophisticated means for collecting, organizing, and adding meaning to the results they generate. Our improved understanding of synthesis and the future research it suggests can help meet the challenges posed by a future world certain to be full of diverse data sets and daunting analytical problems.

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