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TOWARDS SUPPORTING INTERACTIVE SKETCH-BASED VISUALIZATIONS

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Abstract. The goal of the information visualization community is to develop interactive visualizations of abstract data to aid in cognition. While most information visualization research approaches this from a data-driven or a task-driven perspective, our objective is to gain a better understanding of how people already use visuals in their everyday thinking processes and to apply this understanding to create new information visualizations. To this end, we have performed three observational studies: one, looking at the lifecycles of sketches and diagrams used by software developers, another looking at the visual constructs on knowledge workers' whiteboards, and a third examining how people might interact with a pen-and-touch based system for data exploration using charts. In this paper we group the findings of these three studies to develop a fuller picture of the ways in which people use sketching for visualization tasks.

INTRODUCTION

Information visualizations are interactive, computer-supported visual representations of abstract data, that is, data with no inherent spatial mapping. Card et al.'s oft-cited definition maintains that the goal of information visualization is to *amplify cognition* by creating interactive visualizations of abstract data (Card, Mackinlay and Shneiderman, 1999). In other words, information visualizations are created to help people think about their data: to find patterns, interpret relationships, explore possibilities, and perhaps most importantly, gain new insights based on the data.

This goal is strongly aligned with the purposes for which people create their own ad-hoc, external visuals, such as sketches, in their everyday thinking processes. People create, re-create, and manipulate their own external visual representations of concepts, ideas, and processes to "extract meaning, draw conclusions, and deepen our understanding of representations and the world more generally" (Kirsh, 2010, p.453). That is, people create visuals to enhance their own cognition about the information or concepts they encounter.

The idea of approaching information visualization from the perspective of visual thinking processes (due to the similarities in the underlying motivation for both) is underexplored; the common approach to creating information visualizations is driven by the underlying data or the tasks to be performed with the visualizations. Our objective is to gain a better understanding of the use of visuals in everyday thinking processes and to apply this broadened understanding to create new information visualizations. Ultimately, such an approach could be useful for creating information visualizations that better integrate into everyday visual thinking processes and through this are able to better support the goal of insight generation.

We have conducted three preliminary studies related to observing everyday visual thinking processes for the purposes of information visualization creation: two observational studies of software developers and knowledge workers, and one study of an initial sketch-based data exploration prototype. In this paper, we synthesize the results of the three studies and comment on the broader themes and implications that emerge from the results.

BACKGROUND

The term *visualization* can have many meanings, but we restrict our usage of the term to conform to the definition given by Card, Mackinlay and Shneiderman (1999, p.6):

> *"The use of computer-supported, interactive, visual representations of data to amplify cognition."*

The goal of such visualizations is to support thinking about the underlying data. This results in visual representations that are dependent upon the structure and content of the data and that also have some degree of interactivity, that is, the potential to be manipulated in order to display different views of the data. It takes considerable up-front work to create a visualization, so often the person who uses the visualization – the data analyst, the knowledge worker, the magazine reader – is not the one who creates it.

The term *information visualization* (InfoVis) refers to a subset of visualizations that represent primarily abstract data (Card, Mackinlay and Shneiderman, 1999). Abstract data is data that does not have an inherent spatial mapping, for instance, textual or financial data (an example of data with an inherent spatial mapping would be geographic data). This means that the creator of an information visualization often has significant freedom with respect to how to spatially arrange the data in the visualization. Heer, Bostock and Ogievetsky (2010) have explained a number of popular techniques for visualizing common types of data in information visualization: time-series data, statistical distributions, maps, hierarchies, and networks.

In contrast to these computer-supported visualizations there are *external visual representations*: ad-hoc, usually analog visual representations of thought, concepts, or data, created to aid in cognition. Examples of such visual representations include sketches jotted on an office whiteboard, mind maps, diagrams of software architecture, or sketches of a software interface. These representations are often casual, not tied to data, and are *static*, that is, they have no capacity for interactivity: to change their view, one must create a new representation or modify the current one by erasing or drawing over it.

Approaches to Information Visualization Design and Evaluation

To date, the most prominent approaches to creating information visualizations have been from data-centric and task-centric perspectives. Earlier work was largely data-centric, characterized by a focus on how to represent various data type structures. As noted by Amar and Stasko (2004), this perspective is characterized by the belief that "good data speak for themselves". The cartographer Jacques Bertin (2011) laid out many of the early foundations for data representation, among them a system of atomic ways in which a mark on a page can vary, called visual variables (these are the *x* dimension, the *y* dimension, size, value, texture, color, orientation, and shape). Edward Tufte's ideas about data display, such as minimizing data ink, integrity in graphics, and the mantra to "above all else show the data" (Tufte, 1983) were also quite influential here, as were studies about the limits of human graphical perception (Cleveland and McGill, 1984). This perspective has led to new representations of data structures such as multi-dimensional scattergraphs and tables, node-and-link diagrams, and trees (Card and Mackinlay, 1997).

The task-centric approach to information visualization goes beyond focusing solely on the way data is represented and calls for consideration of the tasks that will be performed with the data. Several researchers in the information visualization community have argued that it is important for visualizations to bridge the gap between the data representation and the higher-level, analytic task to be performed with the data (Amar and Stasko, 2005), and to be useful in real-world application domains (Plaisant, 2004).

More recently, some researchers have explored a wider range of aspects related to information visualization, reflecting on the role of interaction in a visualization as well as on the broader purpose of InfoVis. North (2006) points out that this “broader purpose of information visualization” is to generate insights. However, he notes, insight is an elusive concept to define and evaluate, which could explain why so many visualizations are still evaluated for how efficiently and accurately they enable one to perform low-level interpretation (as opposed to analysis) tasks. He proposes that a move away from controlled benchmark evaluations to more complex benchmark evaluations, or even open-ended, qualitative evaluations is necessary for a greater understanding of the relationship between visualizations and insight. A similar perspective motivates our work.

The Use of Visuals in Thinking Processes

External cognition, as explained by Card, Mackinlay, and Shneiderman (1999), encompasses any use of the external world to accomplish cognition. One such type of external cognition is visualization, including information visualization; another is *externalization*. Kirsh (2010) defines externalization as the reification of an internal object of thought, and identifies several reasons why externalization might occur:

- To help to offload memory (the most commonly cited purpose of externalization);
- To enable the solution of problems that are beyond the mind's capacity to simulate; and, above all,
- To optimize the cost of completing a task. That is, externalizations can allow tasks to be completed more efficiently, more fully, and in collaboration with others (an externalization is a concrete, visible, so it can be shared or modified by multiple people).

One commonly used type of externalization is sketching. Research into sketching practises is particularly prevalent in fields whose practitioners rely on sketches of physical objects, as in design (Buxton, 2007; Schütze, Sachse and Römer, 2003), architecture (Goldschmidt, 2003), or engineering (Ferguson, 1994). A key finding in this body of research revolves around the importance of the ambiguity inherent in sketches. Sketches may contain rough lines or empty spaces where ideas or details have not been finalized. Seeing these rough, unfinished lines in the context of the sketch can spark new ideas. Tversky, et al. (2003) explain this as a process whereby we re-perceive or reinterpret the ambiguous parts of a sketch to create a new idea; they call this *constructive perception*, and state that this skill can be fostered and applied to various domains. Goldschmidt (2003) calls this process the "backtalk" of sketches, wherein one begins a dialogue by drawing a sketch, and the sketch "talks back" by being a catalyst for ideas.

While sketching is popular in the physical domains described above, knowledge workers working with more abstract concepts often create ad-hoc “thinking” sketches. Whiteboards are a particularly fitting environment for the creation of such sketches. Tang, et al. (2009) and Andrews, Endert and North (2010) have noted that the flexible nature of whiteboards allows for assigning varied meanings to freeform representations. In a study of office workers' whiteboards, Mynatt (1999, p.6) found that the whiteboards were used for thinking, noting:

> *“All manner of incomplete and seemingly vague content was written as participants used their whiteboard as a scratch surface while pondering concepts much larger than their surface representations”*

The three studies we synthesize here have focused on the practises used, visuals created, and tasks performed by knowledge workers.

Information Visualizations Inspired by Human Behavior

In contrast to the conventional data- and task-centric approaches to information visualization creation outlined earlier, some researchers have begun to use observations of people’s behavior with visuals and visualizations to inspire new information visualizations. Van Ham and Rogowitz (2008) asked people to arrange and construct visualizations of graphs to inform automatic graph layout algorithms. Dwyer, et al. (2009) compared human-generated graph layouts against automatic ones and found that the human-generated layouts performed as well as or better than the automatic layouts. Still others have been inspired by people’s sketching behavior in general. NapkinVis (Chao, Munzner and van de Panne, 2010) is a sketch-based tool for creating simple visualizations inspired by the common idea of sketching on the back of a napkin. SketchVis (Browne, et al., 2011) is a pen-based whiteboard system for creating bar and line charts and scatterplots; it was a precursor to the SketchInsight system that is a part of the synthesis in this paper (Walny, et al., 2012).

Kessell and Tversky (2011) have outlined a similar approach for designing static visualizations, which they call the Production-Preference-Performance program. The three phases of this program can be summarized as follows:

- In the *production* phase, people are asked to create visualizations of the information, which reveals how people understand the structure of this information.
- In the *preference* phase, people are shown several alternative visualizations and asked which is the best representation of the information.

- In the *performance* phase, people are asked to perform tasks on one of several visualizations, which reveals how well they are able to interpret the information in the visualizations.

Tversky, et al. (2007) used this model on inherently spatial information – route maps and furniture assembly diagrams – to determine a set of cognitive design principles that could be applied in automatic generation of such visualizations. The program was also applied to information of a more abstract nature, such as tracking objects across space and time (Kessell and Tversky, 2011), and representing abstract categorical and continuous information in a network diagram (Tversky, et al., 2012).

The three studies outlined in this paper follow a similar "human-driven" philosophy: we observe the visual representations people make, their interactions with visuals, and the environment and contexts surrounding the use of the visuals. We analyze the study data in light of our goal of informing new information visualizations that support everyday thinking processes.

THREE STUDIES: A BACKGROUND

What follows is a brief explanation of the three previously-published studies whose results we have synthesized below.

Studying lifecycles of diagrams and sketches (Sketch Lifecycles)

The first study, which we will refer to in the synthesis as the *Sketch Lifecycles* study, centered around collecting the lifecycles of diagrams and sketches that were important to individual software developers. Sketching is a popular practice in software development, both in programming and in prototyping. Cherubini, et al. (2007) found that software developers often use temporary sketches and diagrams and that some of these sketches are revisited or redrawn multiple times over the course of a project, slowly evolving each time. This finding inspired our study, in which we studied why and how such sketches are revisited.

We asked eight researchers who develop software to choose a recent software development project and, in a semi-structured interview, tell us about a sketch or set of sketches that was important to them throughout that project. We performed a qualitative analysis of the interview transcripts using an open-coding approach. This resulted in a characterization of the lifecycles that sketches important to researcher/software developers undergo, transitioning between both media and contexts of use. We visualized ten lifecycles from eight participants as lifecycle diagrams (see Figure 1 for an example).

Participants were characterized according to whether they (a) sketched frequently and were highly invested in their sketching workflow; (b) sketched frequently but had an ad-hoc sketching workflow; and (c) sketched infrequently. We found five types of transitions: (1) *creation* (the externalization of an idea into a sketch or diagram); (2) *iteration* (the modification or re-creation of a sketch or diagram); (3) *copying* (making a direct reproduction of a diagram); (4) *archival* (when a sketch or diagram is no longer actively used); and (5) *discarding* (when a sketch or diagram is discarded, usually deliberately).

This study made it apparent that people are very particular about the way they interact with their sketches and diagrams, whether these are analog or digital. Each lifecycle was unique, even when we collected multiple lifecycles from the same participants. The full results, including all of the lifecycle diagrams and characterizations of the participants, can be found in the proceedings of the 2011 IEEE International Workshop on Visualizing Software for Understanding and Analysis (Walny, et al., 2011a).

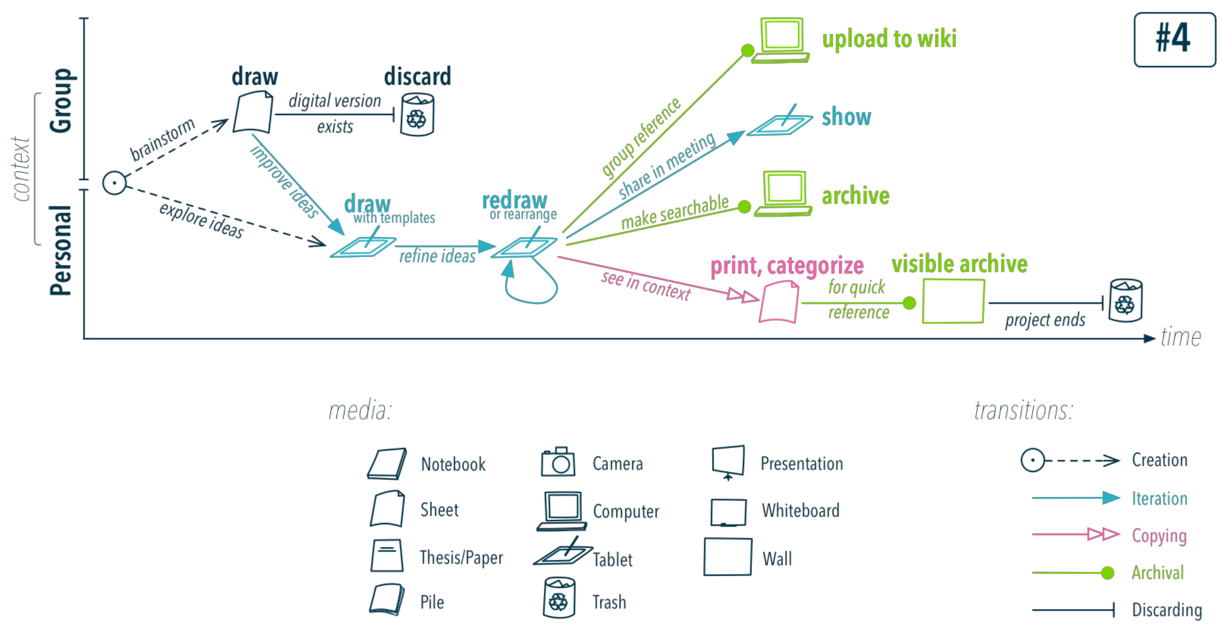

FIGURE 1: A LIFECYCLE VISUALIZATION FROM OUR SKETCH LIFECYCLES STUDY SHOWING THE TYPICAL LIFECYCLE OF SKETCHES DRAWN BY PARTICIPANT 4. THE LEGEND SHOWS THE BREADTH OF MEDIA AND TRANSITIONS WE CATEGORIZED. *FIGURE ADAPTED FROM A PREVIOUSLY PUBLISHED FIGURE (WALNY, ET AL., 2011A).*

Studying visual constructs on whiteboards (Visual Constructs)

Our second study (referred to as the *Visual Constructs* study in the synthesis) focused on snapshots in time of knowledge workers' sketches on whiteboards. We performed a qualitative study in which we collected, unannounced, 82 photographs of whiteboards from 69 knowledge workers' offices at a large research institution and analyzed them from two perspectives: (1) the types visual constructs used and (2) the relationship of words to diagrammatic constructs. In our analysis of visual constructs, we looked at: recognizable information visualization constructs (such as timelines, trees, node-link diagrams, and data charts); spatial organization factors (such as density of coverage on the whiteboard and methods of separation and grouping); layering (palimpsests and erasing); and communicative factors (including emphasis, negation, use of ellipses, and "sketchiness" of lines drawn). In our analysis of the relationship of words to diagrammatic constructs, we extracted a *words-to-diagrams spectrum* (see Figure 2) that showed the various ways in which we saw words and diagrammatic constructs coexisting on the snapshots.

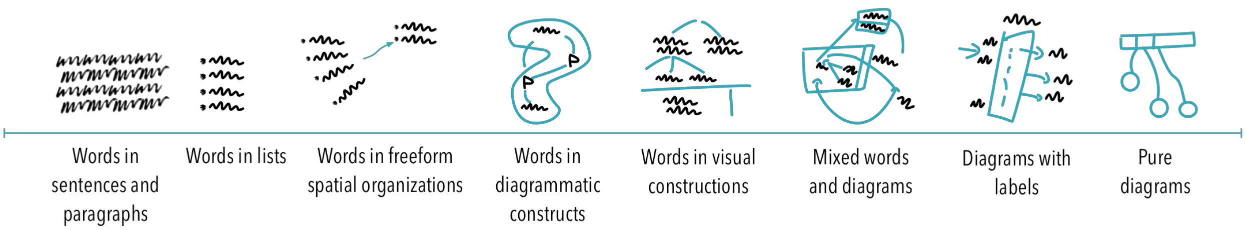

FIGURE 2: THE WORDS-TO-DIAGRAMS SPECTRUM, WITH REPRESENTATIVE EXAMPLES. *FIGURE ADAPTED FROM A PREVIOUSLY PUBLISHED FIGURE (WALNY, ET AL., 2011B).*

We also interviewed ten participants of the study to validate our interpretation of the whiteboard constructs and to gain a deeper sense of the participants' whiteboard usage. We found a myriad of interesting characteristics, including some that are at odds with current information visualization guidelines, such as a large tolerance for clutter and a tendency to view words as primary objects rather than as labels. The full results of this work are available in the IEEE Transactions on Visualization and Computer Graphics (Walny, et al., 2011b).

Understanding pen and touch interaction for chart creation and manipulation on interactive whiteboards (SketchInsight)

Reflecting on the results of the previous two studies, we found that creating information visualizations based on our understanding of visual thinking will likely necessitate stepping away from conventional computer interfaces that involve windows, icons, menus, and pointers (known as WIMP interfaces) and exploring "post-WIMP" interfaces. These post-WIMP interfaces often involve new hardware combinations, for example pen and multi-touch input devices, for which there exist many untested interface design possibilities.

As a preliminary exploration towards designing such interfaces for information visualizations, we ran a study on a prototype chart creation and exploration system for pen and touch whiteboards, called SketchInsight (see Figure 3). We will refer to this in the synthesis as the *SketchInsight* study.

The central question of this study was: *how would people approach interactively sketching information visualizations?* We wanted to know what kinds of pen and touch gestures people would gravitate towards when creating and modifying charts in SketchInsight. To answer this question, we designed the study as a *Wizard of Oz* study: that is, the system was not fully capable of recognizing the pen and touch input. Instead, whenever participants interacted with the system by drawing a stroke on the screen or using some sort of multi-touch gesture on the screen, a hidden experimenter (the "Wizard") rapidly interpreted these interactions and instructed the system on how to respond. This setup allowed the participants to interact with the system however they desired, because the "Wizard", unlike a real software system, could easily interpret a wide variety of interactions in a logical way.

SketchInsight was designed to break away from the WIMP paradigm and follow several design principles intended to provide, to the extent possible, the benefits of using visual thinking tools such as whiteboards or pen and paper. These principles included: specifying what you want to see by drawing it ("what you draw is what you get"); supporting manipulation of objects that is as direct as possible; minimizing explicit mode-switching (e.g. there was no need to switch between a "drawing" and a "moving" mode); and supporting flexibility with good default behaviors.

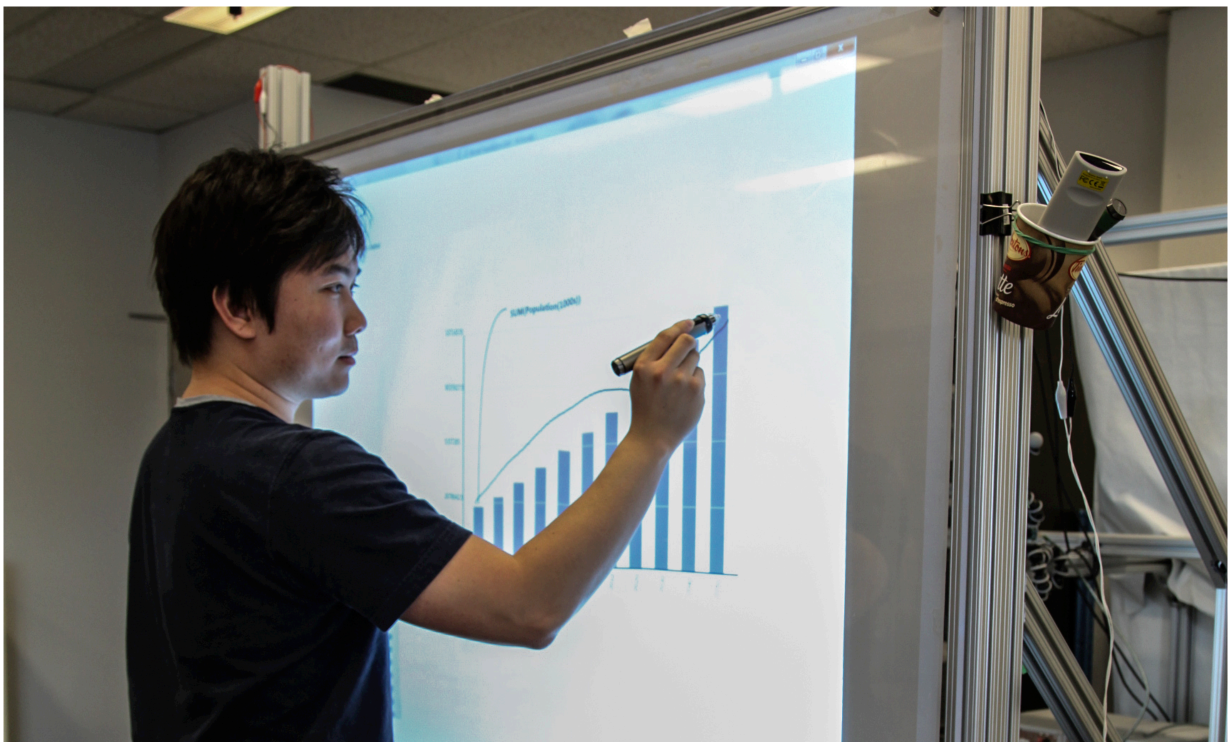

FIGURE 3: TURNING A BAR CHART INTO A LINE CHART USING THE SKETCHINSIGHT SYSTEM.

Highlights of our results include evidence that our participants readily used knowledge about both physical world interactions and knowledge they have already gained about the system to infer how to perform new tasks; indications that our participants had a clear idea of when to use pen interaction vs. when to use multi-touch gestures; and evidence that people tend towards integrated interactions, where interaction with the data and other elements on the screen occurs in proximity to the objects being acted on, rather than on far away menus, buttons, or other controls. The full results of the study can be found in the IEEE Transactions on Visualization and Computer Graphics (Walny, et al., 2012).

SYNTHESIS OF RESULTS

We synthesized the results from the three studies, which we will refer to, respectively, as the *Sketch Lifecycles*, *Visual Constructs*, and *SketchInsight* studies. Our synthesis process was to chart the high-level results of each study, then search for the most prominent emerging themes, particularly those that were evident in the results of two or more studies at once. In a manner akin to affinity diagramming, we categorized individual results into their respective themes (a result could belong to more than one theme). Ultimately, our objective across all three studies is to help inform the design of new interfaces for information visualization that further the information visualization community's goal of supporting individuals' exploration and understanding of information. Thus, we have also reflected on the potential implications of our observations for creating information visualizations. In the following sections, we report on the individual themes and resulting implications.

Variations in Externalization Characteristics

We designed the Sketch Lifecycles and Visual Constructs studies explicitly to allow us to observe externalizations, specifically sketches used to support everyday thinking processes. Consequently, we observed a number of characteristics related to externalization that are rarely considered a factor in information visualization creation. In particular, we saw a richness and variation in the way people externalize that contrasts strongly with the constraints seen in many visualizations, both in terms of the way visual constructs appear and in the support for various contexts of use.

In the Sketch Lifecycles study, we saw externalization occur in the creation and iteration transitions. In the whiteboard study we saw only a snapshot in time of externalizations. Across both studies, the breadth of reasons that we saw for the creation of these sketches were:

- To brainstorm, think, or explore ideas.
- To solve problems, for example to help debug software.
- To plan or organize, for example for writing a paper, doing a project, or performing a literature review.
- As a communicative aid, particularly to explain concepts to others.
- To offload memory, as a record of ideas or useful information.

These reasons for externalization were supported by a variety of processes, mediums, and constructs, and a diversity of people. Some of our participants were highly reflective about their processes. For example, participant 4 in the Sketch Lifecycles study (see Figure 1) was determined to find an optimal digital workflow for his sketching practices; one participant in the whiteboard study was cognizant that the sketches on his whiteboard were much more useful to him personally than the formalized digital versions he had distributed to his team. Others were less interested in their workflows, and simply followed whatever path worked for them.

One strong factor of variation related to the visual constructs we observed. We saw a wide range of spatial organization strategies. Some of these strategies related to space constraints. For instance, we saw various separation and grouping strategies, such as separating lines or boxes, and a significant use of color as a separator. Orientation and layering were often used to fit more information into a small space, but we also talked to people who noted that orientation and spacing had particular meaning to them. For instance, one participant in the Visual Constructs study talked of words “radiating” out of another word, indicating a hierarchy of sorts. He also mentioned that subtle spacing between two constructs indicated a missing element. This subtle spacing was lost in a formalized, digital version of the same diagram later re-created using diagramming software.

We observed variations in other characteristics of visual constructs as well. Some noted that different colors, layers, and distinct personal sketching “styles” helped them to differentiate between sketch authors (for shared sketches from group meetings) as well as to encode temporal information, such as the order in which sketches were drawn.

Social context influenced variation in participants’ workflows, evident in both the sketch lifecycle and whiteboard studies. It had a particular effect on whether analog or digital media were chosen. In the Sketch Lifecycles study, the participant who deliberately set up an optimal digital-based workflow still felt uncomfortable using anything but paper in group or even public settings. Another participant preferred to annotate printed computer-generated graphs in meetings rather than using the digital copy; he later preferred to reference these annotated copies despite his ability to re-generate the original graphs quickly. In the Visual Constructs study, one interviewee explained that he often preferred to use the whiteboard in meetings because it was more forgiving; although a computer simulation would be more precise and still get his point across, it would take longer to set up and made him nervous about making mistakes. Still others seemed to value *immediacy* in group settings, simply wanting to get the “gist” of a chart or hurriedly write something to get a point across. Several participants across both studies took care to formalize sketches they were sharing with others, but placed value on the original hand-drawn versions for themselves. For practical reasons, the change in social context from personal to sharing with a group necessitated a change in the medium used; these changes ranged from processes as simple as taking a digital photo of the sketch to careful formalization using diagramming software.

IMPLICATIONS. Our findings suggest that there is large individual variation in spatial organization strategies, visual construct characteristics, and the contexts in which people use external visual representations. In some cases, the freeform ways in which the visuals are drawn and organized contains information of value for the creator of the sketch, a value that is lost when translated to a digital form using currently available software tools.

Designing any software interface inevitably introduces some constraints in terms of how people will be able to interact with it. It is an exercise in tradeoffs: freedom in one area may mean a reduction in computational power or freedom in another area. However, the considerable variability we have observed suggests that, for our goal of supporting individuals' exploration and understanding of information, it may be useful to explore interfaces that favor greater freedom in the spatial organization of visual constructs and also to support easily switching social contexts.

Immediacy and Effort Optimization

A prominent theme across all three studies was a tendency towards valuing immediacy of the medium and towards effort optimization. We saw several instances in which people gave up many seemingly attractive options, such as color choice, tidiness, the use of real data or underlying computational power in favor of quickly and easily representing their ideas, minimizing interruption to the thought process.

One sign pointing to the importance of immediacy and effort optimization was the set of reasons why people chose to choose their particular (usually analog) tools in the first place. In the Sketch Lifecycles study, analog tools were by far the most preferred in the creation and iteration stages, with digital tools being more used for archival, formalization, or sharing reasons. Although there are many potential reasons behind tool choice, one participant (participant 1) explicitly stated that she used a sketchbook rather than her Tablet PC for the creation stage because she did not have to wait for it to start up. Immediacy was also very important in group settings. Participants in the Visual Constructs study stressed the importance of "getting the point across" as the reason for using the whiteboard over other mediums.

Another sign was in how the tools were used. In the Visual Constructs study we observed many lines with a "sketchy" quality, particularly with data charts, which were drawn mainly to show general trends rather than be faithful to the data. In some diagrams it was clearly evident that if they were part of a larger context, that context was only displayed insomuch as it was needed, a characteristic that aligns with Furnas' concept of "just-sufficient context" (Furnas, 1986).

Those who used digital tools optimized their workflow for speed and effort as well, possibly more so than for the analog tools. For instance, participant 4 from the Sketch Lifecycles study set up an elaborate set of templates so that when he was sketching ideas on his

Tablet PC he already had commonly used constructs ready to arrange as needed. He also used archived all of his sketched using an online service that had the capability to recognize written text in the sketches, so that he could easily retrieve them later using a keyword search. In contrast, several other participants who created diagrams digitally used the simplest tools at their disposal that they already knew how to use, such as standard slideshow presentation software that included basic drawing tools. When it came to saving or discarding diagrams, we saw that many people would only discard something when it became “clutter” and actively got in their way, for instance when a digital version of a paper sketch was saved. Digital versions tended to get saved implicitly because they did not get in the participants’ way on a regular basis – they could be stored and forgotten.

The SketchInsight study participants also demonstrated a tendency towards immediacy and effort minimization. For instance, participants drew axes to initialize creating a chart; for one participant we could clearly see these axes evolve throughout the session from two carefully drawn axes to a lazy “L” shape. Most participants did not write out complete words once they realized that the system included the capability to display autocomplete suggestions for partial written words. They tended to quickly figure out what kinds of interactions the system was capable of and stayed within those bounds rather than experimenting with different possibilities; they also fell back on familiar physical metaphors when deciding when to use pen and when to use touch. We also noticed a tendency towards integrated interactions. People tended to interact with objects very closely to where they were located, which is in contrast to the way many information visualization interfaces look; they often have controls located away from the elements they are to control.

IMPLICATIONS. These findings suggest that information visualizations may more effectively support the thinking process if they strive to reduce the amount of thought interruption involved in using the tool, both when working with a tool and considering the potential switches of social context from personal, to sharing for feedback, to sharing in a formal setting.

Communicative Aids

Thanks to the collaborative nature of whiteboards and the necessity for collaboration in the software development lifecycle, we noted the importance and characteristics of communicating with visuals used during the thinking process.

We saw sketches used in group contexts in order to: brainstorm, think, explore and refine ideas, plan, explain concepts, share ideas to get feedback, annotate feedback, and share formally. Some sketches were archived for group reference, often by taking a digital photo and uploading to a wiki or other shared archive. In one case, this record was of a mutual agreement to be referenced later; in other cases it was simply a record of thoughts or ideas discussed. One interesting observation was some people's reluctance to use digital tools for creating or even modifying sketches in group contexts, whether it was a fear of rudeness (as for participant 4 in the Sketch Lifecycles study) or a fear of making mistakes (one participant in the Visual Constructs study).

The external visual representations we observed contained several visual constructs that were particularly suited towards communication: various forms of emphasis and negation, forms of ellipsis (used to denote missing elements), and sketchiness of lines. The use of emphasis was extensive. We saw the use of size, bolding, circling, color, starring, pointing to with arrows, and underlining, all freeform. We also saw a fair amount of clutter, which is tied to the previously mentioned value placed on “getting the point across” to others. Forgiveness of mistakes was cited as a characteristic of whiteboards that was a useful communicative aid. In several cases, across both the Sketch Lifecycle and Visual Construct studies, we saw instances of formalization, where a hand-drawn sketch would be re-created in digital form and then shared with a wider audience. However, there was a tendency to value the hand-drawn sketch more for later personal reference.

IMPLICATIONS. The visual thinking process is clearly not constrained to the personal domain – often, visual thinking artifacts are shared with others, whether it be during the creation stage or for discussion or feedback of existing artifacts. Sensitivity to differing needs in changing social contexts is important. Further study is needed to understand the differences between visual thinking in personal versus group contexts, but it is clear that certain characteristics are useful in both contexts, such as the freeform nature of the medium and supporting various forms of emphasis. There is also a suggestion that methods that support quicker and easier formalization for sharing contexts could be useful.

Record, Reference, and Distillation

We saw several instances in which people preferred having a history of their thoughts, sometimes coupled with a tendency to distill a series of thoughts into a summary. On the whiteboards we studied, layering was a temporal indicator: newer thoughts were written over older thoughts, which were kept "just in case they were right". Some whiteboards were silted and messy due to the presence of semi-permanent information. In the Sketch Lifecycles study, we saw digital archives, sketchbooks, and piles of paper in chronological order. In both the Sketch Lifecycles and Visual Constructs studies, we observed the occurrence of a "summary sketch", which was representative of the current state of thinking about something and was particularly valued (some participants even explicitly discarded older sketches that had led to the summary sketch because they weren't valued anymore once the summary sketch was complete). Some participants even suggested that the neatness of their summary sketches reflected more developed, organized thought.

IMPLICATIONS. It is not currently a common practice to save previous states of exploration in information visualizations. Our findings suggest that it could be useful to save particular states in chronological order, whether to recall and compare them later, or simply to as a reassuring feature. The ability to summarize the current state of understanding of a visualization, for example through annotations, could also be important.

Abstract Concepts

All of our studies have observed people who work with largely abstract concepts or data, rather than physical entities as in design, architecture, or engineering. This is by design, since information visualizations also deal with abstract data. Accordingly, we saw high importance attached to words; often, they were not merely labels (as they often are treated in visualizations) but actual elements of the diagrams themselves, used in place of pictorial representation. In the Visual Constructs study, we extracted a words-to-diagrams spectrum summarizing the various combinations of words and diagrammatic constructs that we saw (see Figure 2). One participant of the Visual Constructs study speculated that more developed thoughts can be better expressed in paragraphs, whereas diagrams make it easier to represent her thoughts because she can specify relationships using arrows and spatial organization. In the Sketch Lifecycles study, several people placed a high value on annotations they had made (in words) on their sketches, particularly during feedback sessions. And in the SketchInsight study, several people turned to writing commands to the system in words when they could not think of other ways to interact with the system.

IMPLICATIONS. These observations suggest that it is important, particularly when working with abstract concepts, to be able to use words as a primary representation. It may also be effective, when exploring data, to be able to include words directly in a visual representation to summarize current thinking.

CONCLUSION

Coming from the perspective of improving information visualizations, we have synthesized the results of three observational studies that looked at the lifecycles of sketches and diagrams in software development, visual constructs as used on knowledge workers' whiteboards, and initial interactions with a prototype for exploring data on a pen- and touch-enabled digital whiteboard. Several themes have emerged regarding the external visual representations and the contexts and ways in which they are used:

- The large *variation* in the constructs people use in their externalizations, and the contexts in which they are performed.
- The importance of *immediacy* and *effort optimization* of visual thinking tools, which play a role in people's choice of tools at a given moment.
- The prominence of the *communicative* context in relation to the usage of visual representations, and the various requirements for supporting this context.

- The importance placed on having a *history* of the thought process, and of being able to *summarize* one's current state of thought.

- The usefulness of *words* when dealing with abstract concepts with no obvious visual representation.

Creating information visualizations is a complex process that, to date, has been driven by the characteristics of the underlying data, the low-level tasks to be performed with that data, and human perceptual capabilities. Our synthesis of the three studies sheds light on additional aspects relating to the ways in which people already use external visual representations, which could be applied to create information visualizations that better integrate into everyday thinking processes.

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