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Using lag-sequential analysis for understanding interaction sequences in visualizations

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ABSTRACT

The investigation of how users make sense of the data provided by information systems is very important for human computer interaction. In this context, understanding the interaction processes of users plays an important role. The analysis of interaction sequences, for example, can provide a deeper understanding about how users solve problems. In this paper we present an analysis of sequences of interactions within a visualization system and compare the results to previous research. We used log file analysis and thinking aloud as methods. There is some indication based on log file analysis that there are interaction patterns which can be generalized. Thinking aloud indicates that some cognitive processes occur together with a higher probability than others.

1. Introduction

Understanding the sequential structure of interaction with software artifacts can contribute to a deeper understanding of how humans make use of technology and adapt to different situations (see, e.g., Sanderson and Fisher, 1994; Olson et al., 1994). In this regard sequential analysis methods provide a means to determine whether and how events unfolding in time are related to each other (cf. McComas et al., 2009). On the one hand, such information can help to detect usability issues. For example, if there is a recommended sequence of activities to achieve a goal then it would be interesting to identify deviations from this procedure. Such deviations might be indicators of usability problems. On the other hand, the analysis of interaction sequences can provide more information about how users solve problems with software. Nevertheless, the processes of insight generation are still not very well understood. Pike et al. (2009) therefore argue that sequences of interaction steps should be mapped to cognitive events. Such a mapping could clarify processes of insight generation which is relevant to know for designing user-centered and problem driven systems. However, we still do not know very much about what the users' activities mean and how they are related to their cognitive processes, although, for example, the theory of distributed cognition (Hollan et al., 2000) can help to clarify issues in this context. Many research methods such as interviews or questionnaires, or measurement of time and error are not appropriate for the investigation of interaction sequences because they cannot represent the chronology of the users' activities (Pohl, 2012). The methods which are most appropriate to capture interaction sequences are observation, log files, thinking aloud, and eye-tracking (cf. Pohl, 2012).

Because of the emphasis on analytical activities such aspects are, for instance, highly relevant for visualizations. A user-centered design can ensure the utility and usability of such systems to support users to understand the structure of as well as the interconnections between the data. Furthermore, it has been argued that the interaction with visualization systems can be conceptualized as problem solving activity (Green et al., 2008) and hence the analysis of interaction processes is considered an important topic in the information visualization community (cf. Pike et al., 2009). Therefore, theories of reasoning might be a valuable source for the development of visualizations.

The goal of this paper is to contribute to the clarification of some of the issues pointed out above. In particular our contributions are:

- We aim to advance the understanding of users' interaction patterns with visualizations systems. To this end, we present a study which draws upon theories of graph comprehension and

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distributed cognition and which utilizes data gathered via log files and thinking aloud to identify common patterns of behavior within a visualization system for exploring contingency tables. Results of the study are also related to results from previous studies to find out whether it is possible to generalize the results of this research.

- We propose the use of transitional probabilities and lag-sequential analysis (LSA) (Bakeman and Gottman, 1997) – a statistical technique well suited for analyzing event-based sequential data and which is commonly used in behavioral sciences – for analyzing the interaction streams gathered through log files and thinking aloud.

Although we focus on visualizations in this paper we think that – due to the emphasis on reasoning processes – this research is also relevant for human computer interaction (HCI) in general. Designing systems so that users can fluidly interact with them is important for all complex information processing tasks, not only for the usage of visualizations. Interacting with, for instance, the web or with spreadsheet systems may also constitute a complex task which encompasses sequences of various interactions. These systems can only be useful when the right interaction processes are supported by the system and when these interactions are easy to use and well designed.

2. Related work

There are several theories of human reasoning which may be relevant for the explanation of the interaction of users with visualization systems (for an overview see, e.g., Pohl et al., 2012a). We found two of these approaches especially relevant for our empirical research: graph comprehension and distributed cognition. In general, graph comprehension theories are more concerned with cognitive processes going on inside people's minds, whereas distributed cognition emphasizes the interaction of the users with artifacts and the influence that the design of an artifact has on the solutions reached. As a consequence, different methodologies are used for investigations in the context of these two approaches.

Graph comprehension: Graph comprehension is a set of theories which try to describe and explain how people make sense of graphs (Friel et al., 2001). In this context, the term graph is defined as a graphical representation of data, as, for example, in bar charts or line charts. This definition differs from the definition of graphs in graph theory which describes graphs as consisting of nodes (vertices) and links (edges). The term as defined in graph comprehension is much wider in scope than in graph theory. Graph comprehension theory describes how inferences are drawn from simple diagrams. It is typically based on perceptual principles and focuses on less complex graphs like line plots and bar charts, but in recent years more complex visualizations have also been investigated. An important aspect of graph comprehension is that viewers develop a mental model based on several cycles of examining the graphs in which important variables and relations between these variables are identified. In the context of the theory of graph comprehension a considerable amount of research has been conducted to identify characteristics of this process. One major aspect of this research has been to clarify whether viewers only get a superficial impression of the meaning of a graph or if they get a deeper understanding which enables them to go beyond the data and predict developments based on the information from the graph (Tversky, 2005). Friel et al. (2001), for example, reviewed several models on graph comprehension and, based on that, distinguish between three different levels of graph comprehension: (1) reading the data (i.e., extracting data and locating data points), (2) reading between the data (i.e., finding connections between data), and (3) going beyond the data (i.e., making inferences).

Ratwani et al. (2008) also investigated the main issue of distinguishing between activities which aim at reading of data and, on the other hand, making inferences. They conducted a thinking aloud study and analyzed the protocols with the following coding scheme: extraction of quantitative and qualitative data; searching for specific objects; making inferences; making comparisons between components of the graph. Transition probability matrices of activities were utilized to analyze the data. These matrices indicate the probability with which one activity of a certain category follows another activity. Subjects had to solve two types of tasks: (a) tasks with the goal to extract single values and (b) integration tasks (basically inferences and comparisons). They assumed that solving the extraction tasks would be straightforward, while the integration tasks would contain repeated cycles of the same sequence of activities because going beyond the data is necessary in this context. They found evidence for this assumption. This study by Ratwani et al. (2008) influenced the thinking aloud study described in this paper.

Trafton et al. (2000) also conducted a thinking aloud study to analyze a graph comprehension task. They distinguished between the categories goal (talking about the goal of the task), extracting quantitative and qualitative values, inference, and brief writing. Based on this approach, Trickett and Trafton (2006) developed a more comprehensive model of graph comprehension. They argue that in many cases users are not able to directly extract information from a graphical representation. In such situations, users adopt spatial transformation as a strategy to get insights into the data. These spatial transformations are mental operations, in contrast to physical operations, for example, on a computer screen. Trickett and Trafton (2006) argue, based on their empirical research, that they found significantly more spatial transformations than physical transformations. This implies that even if an interactive visualization is available, people will still conduct spatial transformations in their minds in many cases.

Distributed cognition: One of the main reasons why distributed cognition might explain the interaction of users with software artifacts is the fact that distributed cognition takes the artifact itself into account (Hollan et al., 2000; Hutchins, 1995; Kirsh and Maglio, 1994). The interaction between the user and the artifact plays an important role in the context of this theory. Cognitive processes are shaped by the design of the artifacts. Liu et al. (2008) describe how distributed cognition could be applied as a theoretical foundation for the explanation of the interaction with visualizations. They argue that the form of the representation may evoke different solution strategies because of different affordances of the representations. Kirsh (2010) notes that the utility of external representations is not only due to the fact that they lighten the cognitive load of human memory. He describes seven additional advantages external representations might have. Andrews and North (2012) point out that distributed cognition emphasizes the importance of observing the interaction processes of the users with visualization systems. These interaction processes allow researchers to make inferences on the nature of the underlying cognitive processes as interaction and cognitive processes are tightly linked.

Interaction provenance: The analysis of users' interactions with a system has also become prominent in the field of analytical provenance (cf. Dou et al., 2009; Groth and Streefkerk, 2006; Gotz and Zhou, 2009; Sun et al., 2013; Walker et al., 2013; Xu et al., 2015) which focuses *on understanding a user's reasoning process through the study of their interactions with a visualization* (North et al., 2011). In this context several evaluation studies (e.g., Dou et al., 2009; Gotz and Zhou, 2009; Lipford et al., 2010) were