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Abstract

So far, information visualizations, i.e., graphical representations of huge amounts of abstract data which do not have a natural visual representation, have mainly been used to support *information-retrieval tasks*. In this paper we investigate whether information visualizations are also suitable to foster tasks that focus on *knowledge acquisition or learning.* In addition, we address the issue of how information visualizations have to be designed to be efficient learning tools. We conducted an experimental study which provided evidence that information visualizations can foster knowledge acquisition and that 2D-information visualizations are better suited for knowledge acquisition than 3D-ones. In addition, we found slight performance improvements due to using color to code information.

Technological innovation allows storing fast growing quantities of information. Accordingly, it has become increasingly important to develop efficient methods to structure large and complex information sets. Recently, there have been several attempts to tackle this challenge by using information visualizations, i.e., graphical representations of large amounts of abstract data which do not have a natural visual representation (Wiss, Carr, & Jonsson, 1998). For instance, information visualizations have been used to display abstract data like document collections or text-based information contents in the WWW. So far, information visualizations have mainly been investigated with regard to technical issues and in the context of information-retrieval tasks – where they proved to be very useful to improve users' ability to use information. However, it is not clear whether information visualizations can also foster knowledge acquisition or learning. Additionally, little is known about the cognitive processes involved in, and maybe supported by the use of information visualizations as learning tools. Therefore, the aim of our empirical study was to investigate to what extent multidimensional information visualizations are superior compared to a non-spatial representation when the task is to memorize a data set and to

acquire an understanding of the relationships embedded within this set. Moreover, we were interested in the design of information visualizations for learning. Particularly, we investigated experimentally whether information visualizations should be two-dimensional or whether a third spatial dimension may be helpful for knowledge acquisition. Finally, the question is addressed whether knowledge acquisition with spatial information visualizations can be further enhanced by using color coding to represent attributes of data.

Figure 1 shows a simplified sketch of the type of spatial information visualization used in the empirical study presented in this paper. In this sketch, three attributes of four information units A, B, C, and D are represented by means of three spatial dimensions.
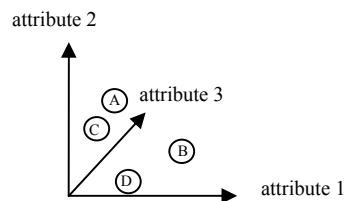

Figure 1: Simplified sketch of a 3D-information visualization.

Information units pool those parts of data sets that belong together. The units can be described by their values on numerous different attributes. Typically, only a subset of these attributes can be represented spatially. Thus, other attributes of the information units may be represented textually or by other codes (e.g., color coding).

What is the Pedagogical Potential of Information Visualizations?

There are different cognitive theories arguing that information visualizations may be efficient tools to enhance the acquisition of knowledge on large and abstract data sets,

whereby knowledge acquisition refers to understanding and memorizing abstract data and their interrelations.

- Firstly, *theories of computational effectiveness* pay specific attention to the inferences learners have to make in order to understand a task or a domain. The argument here is that some representational codes facilitate some inferential (learning) processes better than others. In their seminal work, Larkin and Simon (1987) found for example that search processes in physics are performed much easier with diagrammatic representations than with textual ones. This idea that different representations with the same "content" can still offer different processing opportunities is called "computational effectiveness" (Larkin & Simon, 1987). Following this idea, spatial information visualizations may allow learners to draw inferences very easily on how different information units are related to each other with regard to those attributes that are represented spatially. In this respect, information visualizations are rather similar to concept maps because both of them allow arranging information units spatially in a specific way. Concept maps are 2D-diagrams that illustrate relationships between concepts in a domain by representing these concepts as nodes. These nodes are connected by labeled lines in order to represent their interrelations. It could already be shown that concept maps foster processes of knowledge acquisition (Tergan, 2003), as these representations provide learners with a better understanding of the structures underlying a domain without imposing high cognitive demands on them to extract this information. Due to the aforementioned similarities between information visualizations and concept maps, these processing advantages should also hold for information visualizations.

- Secondly, the *cognitive theory of multimedia learning* (Mayer, 2001) is based on a dual-channel assumption which proposes that textual information is processed and encoded in a verbal system, whereas pictures or graphics are predominantly processed in a pictorial system. The theory assumes that a well-designed combination of text and graphics leads to better memory retention than the use of only one representation. The reason for this is that using the capacity of both memory systems should lead to more information being processed than using only one of the systems. In addition, dual coding might contribute to the construction of a stronger mental model, if the information of both processing systems has to be integrated actively. In addition, research on spatial cognition differentiates between a what-system and a where-system for visual cognition (Landau & Jackendoff, 1993). The where-system is used to process the location of objects, whereas the what-system is dedicated to identify features of an object itself. Memory studies revealed that the where-system operates more effectively with respect to speed and accuracy than the what-system (e.g., Amorim, Trumbore, & Chogyen, 2000). Representing attributes of information units by means of two or three spatial dimensions (instead of a purely textual representation or color coding) might accordingly improve the processing of these attributes by deploying a more efficient processing system.

- Thirdly, following the *cognitive load theory* (Sweller, van Merriënboer, & Paas, 1998), instructional procedures should be designed to prevent cognitive overload. More specifically, the amount of cognitive processing not directly relevant to learning - and thus causing extraneous cognitive load - should be reduced. The necessity of avoiding high levels of extraneous load is especially relevant when the contents to be learned are complex in relation to learners' level of prior knowledge. In this case, the representation of the learning contents imposes a considerable amount of intrinsic cognitive load so that substantial extraneous load can lead to overload in that no more capacity for processes of understanding is left. Cognitive processes directly relevant to understanding and learning are causing germane cognitive load. There are thus two reasons why information visualizations might be particularly appropriate to facilitate learners' acquisition of complex data structures that consist of highly interrelated information units. Firstly, distributing different attributes of information units across different memory and processing systems might provide additional processing resources that can be used to increase germane cognitive load. Secondly, providing learners with a spatial representation of some attributes of information units might reduce extraneous cognitive load by reducing search processes as well as making it easier to draw inferences on how different information units are related to each other with regard to these attributes.

According to these theoretical considerations it can be hypothesized that information visualizations might have a substantial pedagogical potential because they allow to deploy cognitive resources available for learning in a way that is more appropriate than it is with conventional representations of large sets of information units (e.g., spreadsheets).

How to Design Information Visualizations for Knowledge Acquisition?

Beyond the general claim that information visualizations are tools that might foster the acquisition of knowledge on large and abstract data sets, we are also interested in the issue of designing profitable visualizations. Particularly, the study reported in this paper addresses how dimensionality of information visualizations and color coding of attributes might affect learning.

2D- versus 3D-information visualizations?

Although, there are a few empirical studies investigating the dimensionality of information representation in general, nearly none of these studies is related to information visualization or even learning with information visualization. Furthermore, these findings seem to be rather inconsistent and depending heavily on the concrete tasks accomplished with the information representation. For instance, Park and Woldstad (2000) found that 2D-displays are superior to 3D-displays for performing telerobotic tasks. Contrarily, the study of Risden, Czerwinski, Munzer, and Cook (2000) compared 2D- and 3D-browsers with regard to the ease of information retrieval and concluded that 3D-visualizations are preferable. However, only a small number of studies demonstrated the superiority of 3D-representations. In sum, the existing evidence is by no means

sufficient to decide whether information visualizations should be 2D or 3D in the context of learning tasks.

From a more theoretical point of view, one might assume that representing three attributes of information units spatially should be superior to representing only two attributes in a spatial format because of the abovementioned advantages of spatial representations in general (i.e., distribution of information across processing systems, superiority of the where-system, computational effectiveness). However, 3D-information representations might at the same time impose additional extraneous cognitive load onto learners due to the fact that they are usually associated with an increased interactivity and with additional orientation demands. For instance, 3D-visualizations usually have to be equipped with the option to look at information units from different viewpoints (e.g., by rotating the visualization) to counteract the problem that information units might be concealed by other units. As a result, this interactivity may impose additional cognitive processing demands because learners must control the interaction with the environment and maintain orientation.

We studied the role of the dimensionality of information visualizations empirically to decide whether the advantages or the disadvantages of introducing a third spatial dimension prevail in knowledge acquisition.

Should information visualizations for knowledge acquisition be color-coded or not?

The issue whether it might be helpful to enhance information visualizations by color coding of particular attributes of information units seems to be less ambiguous than the role of dimensionality. As color is a basic element of visual perception (Treisman, 1987), color coding can be expected to make information more salient. Therefore, color coding should provide learners with a better understanding of the structures underlying a domain. It has been shown that coloring objects increases learners' ability to retrieve object information from memory. As the color of objects is stored in long term memory together with other object information (e.g., Hanna & Remington, 1996), color information provides an additional cue for memory retrieval. It can thus be hypothesized that color-coded information visualizations should be superior to those without color coding. However, it remains an open question whether color coding and dimensionality will interact when they are combined with each other. On the one hand, combining spatial representation and color coding results in multiple memory traces which should enhance learning; on the other hand, encoding the same attribute of an information unit by means of two different representational codes might make it necessary to map two representational systems onto each other. This might involve the processing of redundant information which in turn can result in additional extraneous cognitive load and learning impairments. Therefore, it is unclear and subject to experimental investigation whether introducing a double coding of particular attributes of information units will support or hinder knowledge acquisition.

Experiment

In this experiment we first investigated whether information visualizations are more suited to foster knowledge acquisition than text-based information representations. Secondly, we analyzed whether dimensionality and color coding of information visualizations influence learning.

Method

Participants Subjects were 100 students (56 female, 44 male) of the University of Tuebingen, Germany. Average age was 24 years.

Materials and procedure This work is associated with the European project "Mummy" of the Computer Graphics Center in Darmstadt (Germany), which focuses on mobile knowledge management using multimedia-rich portals for context-aware information processing, e.g., at construction sites. Therefore, our experimental environment was designed to provide architects with an overview on the details of their construction projects. Each project is described by values on six different project attributes, namely "rate of return", "construction costs per sqm", "number of problems", "construction progress", "size of construction site", and "construction volume".

With regard to the procedure, first the participants received a booklet for measuring different control variables like retentiveness in a paper-pencil test. Afterwards, they received an introduction to the experimental environment and its usage. To ensure that all participants saw the same information, the exploration of the environment during the subsequent practice phase was standardized. In the learning phase subjects were given 50 minutes to accomplish five tasks. In the context of these tasks they had to find 14 of the 42 information units and had to learn the data contained in these information units. Consecutively, subjects received another booklet containing 35 test tasks. In this test phase the learning materials were no longer available. There were no time limits during testing. Finally, participants had to fill out a questionnaire asking for difficulties regarding the use of the learning materials, the strategies used as well as assessing the cognitive load experienced during learning.

Design and dependent measures As an experimental baseline, the information on the construction projects was represented by means of a spreadsheet which listed 42 construction projects (i.e., information units) alphabetically (Figure 2). The first column in Figure 2 represented the name of the construction projects, whereas the other columns contained the values of these projects with regard to the six aforementioned attributes. The last column listed further project information beyond these attributes.

Figure 2: Excel spreadsheet representation (baseline).

To reduce complexity, the range of possible attribute values was restricted to four (i.e., very small, small, big, and very big). Due to the spreadsheet size it was impossible to see the data of all projects without scrolling. A pilot study showed that using this spreadsheet to memorize the abstract data set and to recognize relations between information units was a very difficult task for the subjects.

In order to implement our experimental manipulation, we represented the same data set by means of information visualizations that were either 2D or 3D and that were either monochrome or used color to represent one of the attributes. All of the manipulations (i.e., dimensionality and color coding) referred to the same specific attribute ("construction progress") and the way it was represented. In the 2D-information visualizations both "size of construction site" and "construction volume" were visualized spatially, i.e., they were represented by the axis of the 2D-information space (Figure 3). Information units were arranged in this information space according to their values on these two attributes. In Figure 3 the information units are represented by squares (labeled by their project name). The value of the attribute "construction progress" was represented by a digit attached to the project label. This digit was visible in all four information visualizations.
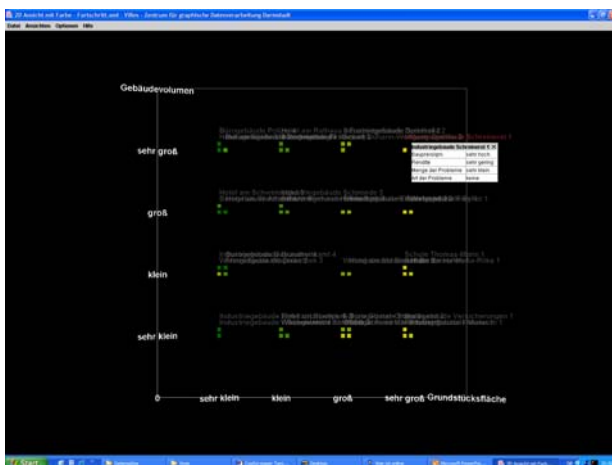

Figure 3: Two-dimensional color-coded information visualization with opened pop-up window.

The remaining project attributes ("rate of return", "construction costs per sqm", and "number of problems") as well as the further project information could be accessed through pop-up windows by clicking on the information units. In Figure 3, one pop-up window is opened. The pop-up windows could be moved with the mouse by learners in case the window concealed information of interest. To facilitate orientation, the project label of the viewed information unit changed its color from white to red and position lines from the information unit to the axes appeared while contacting the unit with the mouse pointer (position lines, see Figure 4).
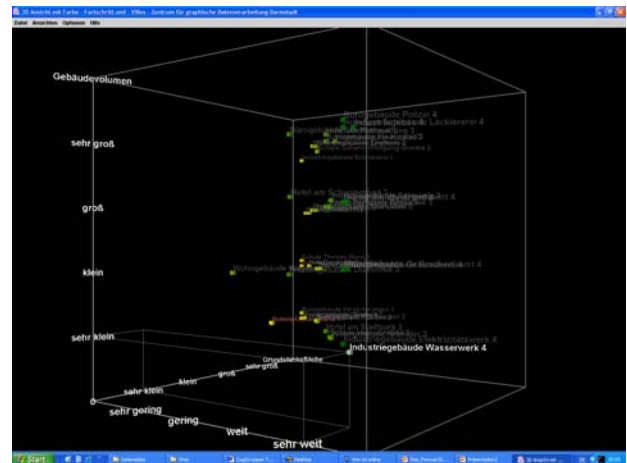

Figure 4: Three-dimensional color-coded information visualization with position lines.

In the 3D-information visualizations a third axis was included to visualize the attribute "construction progress" spatially (Figure 4). To ensure that all information units would be visible in the 3D-information visualizations, the users were allowed to rotate the vertical axis by moving the visualization with the mouse button pressed. To avoid "lost in navigation phenomena", users could push a home-button to attain the start perspective again at anytime.

The colored conditions differ from the monochrome information visualizations depending whether "construction progress" was additionally represented by means of color coding. In the monochrome conditions the information units were always presented in blue against a black background. However, in the colored conditions the information units were displayed in colors ranging from light yellow to dark green – indicating the values of "construction progress".

To sum up, the information visualization conditions differed in the representation format for the attribute "construction progress". In all information visualization conditions the values on this attribute were represented symbolically as a digit. In addition, in 3D-information visualizations the values on "construction progress" were visualized on the third axis. In 2D-conditions there was no spatial representation of this attribute. Furthermore, in polychrome information visualizations the values on the attribute "construction progress" were represented by means of the color of the information units. In monochrome conditions no color was used to visualize this attribute.

Dimensionality and color coding were both varied between subjects resulting in a 2x2-design (plus the baseline spreadsheet condition). Subjects were randomly assigned to the spreadsheet or to one of the four information visualization conditions.

With regard to the dependent measures, as a first dependent variable we measured *performance* with regard to the different knowledge tasks. Overall performance was calculated as the sum of both correct answers and partial correct answers. For 10 of the 35 tasks, partial credits were assigned to score subjects' answers. In the remaining tasks one point was assigned for each correct answer. For each task a maximum of one point was possible resulting in a maximum overall score of 35 points. *Relational performance* referred to tasks that asked for comparative judgments with regard to attribute values, whereas *item-specific performance* focused on specific attribute values. Both measures consisted of 15 tasks each. Five further tasks assessed *structural performance* which was concerned with the recognition of correlational structures within the data set. Furthermore, in each case four tasks were used to assess where-performance, what-performance, and varied-performance. *Where-performance* assessed knowledge on the attributes that were visualized spatially in all information visualizations, whereas tasks on *what-performance* registered knowledge on information always presented as text. Finally, *varied-performance* was concerned with knowledge on "construction progress", i.e., on the attribute whose representation was varied across conditions.

As a second dependent variable we measured learners' confidence with regard to the correctness of their answers. Learners rated each answer to a task with regard to whether they felt low, middle, or high confidence that their answer had been correct. In the *overall confidence* measure these ratings were summed across all tasks, whereby higher rating indicated higher confidence. This overall measure was subdivided into *confidence for correct answers* displaying a participant's belief in that a correct answer was correct. *Confidence for wrong answers* indicated a participant's conviction that a false answer was correct. Because there were 35 items for which every subject had to rate his or her confidence and because ratings ranged from one to three a maximum of 105 points was possible for each of the confidence scores.

As a third dependent variable, we assessed learners' subjective cognitive load by asking them how much *effort* they had to invest into learning and how *difficult* it had been to remember the contents. The effort and the difficulty ratings were given on a five-point scale, ranging from very low to very high.

Results and Discussion

The analysis of the data is divided into two parts: First, we compared the baseline spreadsheet condition to the overall means of all information visualization conditions in order to answer the question whether information visualizations in general are helpful for acquiring knowledge on large data sets compared to a purely text-based representation. In the second analysis, we assessed the effects of dimensionality and color coding by comparing the four information visualization conditions in an ANCOVA (dimensionality x color coding with retentiveness as a covariate, see below).

Do information visualizations foster learning? In a first step, we tested whether subjects achieved higher performance with information visualizations than with a spreadsheet, i.e., here we did not further differentiate between the different kinds of information visualizations. A two-tailed t-test for independent samples showed in fact a higher overall performance for information visualizations (M=20.80) compared to the spreadsheet (M=17.88; $t(98)=2.18$; $p<.05$). However, which kinds of information visualizations produced this effect? To answer this question, each of the four different kinds of information visualizations was compared to the spreadsheet separately (Table 1). Whereas the 2D-conditions were both superior to the baseline (without color coding: $t(38)=2.20$; $p<.05$; with color coding: $t(38)=3.53$; $p<.001$), there were no differences between the 3D-conditions and the spreadsheet condition (without color coding: $t(38)=0.34$; $p=.74$; with color coding: $t(38)=1.28$; $p=.21$).

Table 1: Means for performance, confidence, and cognitive load ratings for the information visualization conditions.

		Information visualizations			
		two-dimensional		three-dimensional-	
		monochrome	with color	monochrome	with color
Performance	**overall performance (35 tasks)**	**21.80**	**23.38**	**18.43**	**19.60**
	relational performance (15 tasks)	9.55	10.15	8.10	8.75
	item-specific performance (15 tasks)	10.35	10.98	8.88	9.10
	structural performance (5 tasks)	2.40	2.85	1.95	2.05
	where- performance (4 tasks)	3.05	3.10	2.70	2.40
	what- performance (4 tasks)	1.60	2.25	1.85	1.80
	varied-performance (4 tasks)	2.40	2.50	1.60	1.75
Confidence	**overall confidence (max. 105 points)**	**72.46**	**75.63**	**67.25**	**64.60**
	confidence correct answers (max. 105 points)	47.48	51.66	35.80	35.65
	confidence wrong answers (max. 105 points)	23.08	21.97	29.45	27.05
Cognitive load	**effort** (max. 5 points)	**3.65**	**3.60**	**4.15**	**3.95**
	difficulty (max. 5 points)	**3.40**	**3.35**	**3.75**	**3.75**

Which representation format of information visualizations is the most suitable for knowledge acquisition? In all analyses of variances reported here, we used retentiveness as a covariate because it was strongly associated with the dependent variables. In a first step we analyzed subjects' overall performance by an univariate ANCOVA (dimensionality x color coding).

Subjects who were presented with a 2D-information visualization outperformed subjects in the 3D-conditions ($F(1,75) = 15.16$; $p<.001$). Additionally, we obtained a marginally significant main effect for color coding in favor of "with color coding" ($F(1,75) = 2.87$; $p<.10$). There was no significant interaction between the two factors. The superiority of the 2D-information visualizations was not only confirmed for overall performance but also for the detailed performance measures - with one exception. There was no significant difference for the what-performance, but this was not astonishing because the information necessary to answer the respective tasks was represented the same way across all conditions. There were no main effects for color coding in the detailed performance measures.

Concerning the overall confidence learners felt regarding the correctness of their answers, we found that subjects learning with 2D-information visualizations were more certain that their answers were correct than subjects in the 3D-conditions ($F(1,75)=8.71$; $p<.01$). Further analysis revealed that learners in the 2D-conditions were not only more convinced that the correct answers they had given were correct ($F(1,75)=18.16$; $p<.001$). Moreover, they also felt more uncertain that their false answer might be correct ($F(1,76)=5.33$; $p<.05$). This pattern of results suggests that subjects in the 2D-conditions had a more accurate assessment of what they really knew. There were no main effects for color coding nor was there an interaction with respect to the overall confidence variable.

With regard to the cognitive load ratings registered after the test phase we found that subjects using 3D-information visualizations indicated that they had to invest more effort into learning than did those in the 2D-conditions ($F(1,76)=4.51$; $p<.05$). In addition, they also evaluated learning as being more difficult than subjects in the 2D-conditions ($F(1,76)=3.30$; $p<.10$). There were no main effects for color coding nor were there interaction effects.

Summary and Conclusions

In our experiment we provided evidence for the suitability of information visualizations for knowledge acquisition. Moreover, we demonstrated that in general 2D-information visualizations are more suitable to foster knowledge acquisition than 3D-ones. This could be due to the fact that learners had to invest more effort and experienced more difficulties during learning in the latter conditions. The question of whether these demands resulted from the necessity to rotate the 3D-information visualization will be addressed in further studies. With regard to the influence of color coding, there were only slight performance increases when information was displayed in color.

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