Encouraging the Active Integration of Information During Learning with Multiple and Interactive Representations

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Abstract: Computer-based learning environments commonly comprise various linguistic as well as static and dynamic pictorial representations, frequently combined with the possibility to modify them interactively. While multiple and interactive external representations have the potential to improve learning in specific ways, they also place specific demands on learners. For instance, learners have to process and relate different representations, to control and evaluate their interactions with these representations, and to construct a coherent mental representation. In many cases, learners are not able to meet these demands and suffer from cognitive overload. Taking advantage of cognitive load theory, we try to improve learning with multiple and interactive representations by reducing extraneous cognitive load and by increasing germane cognitive load which is supposed to be related to learning processes. To accomplish this, we encourage learners to actively integrate different representations and to interact with them in a structured and reflective way. We implemented these measures into the statistics learning environment VISUALSTAT and evaluated them experimentally. An analysis of variance revealed (1) that the active integration of different representations improved learning significantly, and (2) that the structured interaction with different representations increased verbal comprehension.

Introduction

External representations such as texts, formulas, static and dynamic visualizations are commonly embedded in computer-based learning environments in order to improve learning in various ways. Frequently, the different representations are presented simultaneously and provided with the opportunity to modify them interactively.

Many empirical studies, however, have shown that learners very often do not take advantage of the potentials of multiple representations (e.g., Ainsworth, Bibby & Wood, 1998). In contrast, the presentation of multiple, dynamic, and interactive representations might even impede learning (e.g., Ainsworth, 1999).

One reason for these findings may lie in the high demands multiple representations place on the learners' cognitive capabilities. For instance, the learners might have to process large amounts of information, to direct their attention simultaneously to different representations and to relate different representations to each other in order to construct a coherent mental representation (cf. Lowe, 1998).

In the following, starting from various potentials, requirements, and problems of learning with multiple and interactive representations, we will describe the design of two kinds of support measures to facilitate learning with multiple and interactive representations. We will base our considerations on cognitive load theory (Sweller, 1994), on the theory of structure mapping (Gentner, 1983) as well as on research on discovery learning with simulations (e.g., de Jong & van Joolingen, 1998; van Joolingen & de Jong, 1997). Finally, a study is delineated that evaluates the support measures experimentally.

Potentials, Requirements, and Problems of Learning with Multiple and Interactive Representations

The use of multiple representations in computer-based learning environments offers various possibilities to instructional design. For instance, multiple representations can complement each other, resulting in a more complete representation of an application domain than a single source of information does (e.g., Ainsworth, 1999). They may also realize different conceptual perspectives on an application domain, which may lead to the construction of multiple mental representations, which can flexibly be used during problem solving (e.g., Spiro & Jehng, 1990). Furthermore, if multiple representations are equipped with dynamic and interactive components, they can be modified dynamically, and the effects of these modifications on other representations can be observed simultaneously. This allows dynamic processes and abstract concepts to be illustrated as well as students to be engaged in active and constructive learning processes.

During the last ten years, however, psychological as well as educational research demonstrated that learning with multiple, dynamic and interactive representations in computer-based learning environments is not only associated with specific potentials but also with specific requirements. For instance, each representation may rely on notations that are not familiar to the students. Furthermore, in many cases students are not able to identify visual and spatial structures in pictorial representations which would allow them to understand an application domain (e.g., Lowe, 1998). In other cases, students do not interpret the perceived visual and spatial structures conceptually (e.g., Weidenmann, 1994). Very often, such a lack of visual literacy is accompanied with illusions of understanding (e.g., Salomon, 1994).

The need to process multiple representations places additional demands on the learners. For example, learners may have to direct their attention simultaneously to different representations and – especially if multiple representations are combined with dynamic components – to process large amounts of information. Very often, these demands overburden the students' cognitive capabilities resulting in only little learning (e.g., Sweller, 1993, 1994).

With regard to interactive representations, research on discovery learning has shown that students often do not interact in a systematic and goal-oriented way with these representations. In particular, many students fail to state, test, and evaluate hypotheses systematically (van Joolingen & de Jong, 1991, 1997).

One of the most severe problems of learning with multiple representations, however, may be the finding that students frequently do not systematically relate different representations to each other (e.g., Ainsworth, Bibby & Wood, 1996; Anzai, 1991; Kozma, Russell, Jones, Marx & Davis, 1996; Lowe, 1999; Peeck, 1993). As a consequence, these students fail to integrate the information into coherent mental representations. Very often, their mental representations of an application domain remain fragmentary and disjointed. During problem solving, for instance, these students might switch back and forth between different mental representations of a posed problem without being able to determine which representation contributes in which ways to the problem's solution (e.g., Anzai, 1991).

Although multiple, dynamic, and interactive representations have the potential to deepen the learners' understanding, their mental coordination and integration does not take place on its own.

Facilitating Learning with Multiple and Interactive Representations

Cognitive Load Theory

Cognitive load theory provides guidelines to assist in the presentation of information in such a way that helps learners to optimize their intellectual performance. Based on the assumptions of (1) an effectively unlimited long-term memory and (2) a limited working memory (e.g., Baddeley, 1986), cognitive load theory aims at designing instructions that do not overburden the learners' cognitive capabilities. Three sources of cognitive load are distinguished: (1) intrinsic cognitive load which is affected by the complexity of the application domain as well as by the learners' pre-knowledge, (2) extraneous cognitive load which corresponds to the effort required to process poorly designed instructions, and (3) germane cognitive load which is supposed to be directly related to learning processes. For a long time, research on cognitive load theory focused on instructional design intended to decrease extraneous cognitive load. Only recently, various studies have been conducted which focus on the increase of germane cognitive load. These studies aim at further improving instructions by making learners take advantage of otherwise unused working memory capacity during learning (Kirschner, 2002; Sweller, 1988; van Merriënboer, Schuurman, de Croock & Paas, 2002).

Supporting Learning with Multiple Representations

John Sweller and his colleagues have demonstrated that extraneous cognitive load can be reduced in a number of ways (e.g., Sweller, Chandler, Tierney & Cooper, 1990). With regard to multiple representations, they demonstrated in a series of experiments that the physical integration of textual and graphical information can prevent learners from splitting their attention between the two kinds of representations. The presentation of the information in an integrated format resulted in much better learning than the presentation in a separated format (e.g., Chandler & Sweller, 1991, 1992; Tarmizi & Sweller, 1988).

While the integrated presentation of information can reduce extraneous cognitive load, it does not directly support learners in constructing meaningful knowledge. Learners may remain rather passive, still unable to mentally process and integrate the represented information in an adequate way. According to the theories of Mayer (1997, 2001) as well as Schnotz and Bannert (1999), however, the integration of linguistic and pictorial information into coherent mental representations is essential for successful learning with multiple representations.

Schnotz, Picard and Hron (1993) proposed the concept of structure-mapping (Gentner, 1983) to describe the process of relating graphic representations and mental models. According to Gentner's model, which originally was developed in order to describe the processes involved in drawing analogies, an analogy is constructed by (partially) mapping the mental structure which represents a familiar domain onto the mental structure which represents a unfamiliar domain. Gentner and Markman (1997) demonstrated how structure-mapping can be used to model how similarities among objects are established. In our research, we take advantage of the concept of structure-mapping in order to support the mental integration of different sources of information by encouraging learners to externally relate different representations to each other and – as a consequence – to mentally integrate them as well.

In many cases, different sources of information in computer-based learning environments delineate structures which are (partially) related to each other. Because students rarely identify relevant structures and establish relations between them, we take advantage of the model of structure-mapping in order to guide the implementation of support measures into a learning environment. These support measures interactively and systematically (1) encourage the identification of structures relevant to an application domain and (2) support the construction of relations between the identified structures by (partially) mapping one structure onto the other.

In earlier research, it has been demonstrated that students who actively relate different sources of information to each other construct more complete and more coherent mental representations of the application domain than students who do not (e.g., White, 1993). To know the relations between different sources of information also allows learners to flexibly switch between them on the one hand and to integratively make use of them on the other hand during problem solving, for example (e.g., Anzai, 1991). Structure-mapping provides one means to guide the construction of such relations.

We propose the design of learning with multiple representations in such a way that extraneous cognitive load is decreased and germane load is increased. We attempt to accomplish this by presenting different external representations to the learners in a separated format and then encouraging the learners to interactively map components of familiar representations step by step to components of unfamiliar representations.

Supporting Learning with Interactive Representations

Learning with interactive representations is in various ways similar to learning with complex computer simulations. In both, learners have to infer the characteristics of an underlying conceptual model by changing input variables and by observing the resulting changes in values of output variables (de Jong & van Joolingen, 1998; Reigeluth & Schwartz, 1989). However, learners often do not interact in a goal-oriented way with these representations and frequently fail to state, test, and evaluate hypotheses systematically.

To overcome the problems of learning with interactive simulations, it was repeatedly suggested to support learners by structuring the processes of discovery learning (e.g., Spada, Reimann & Häusler, 1983; van Joolingen & de Jong, 1991). For instance, learners can be encouraged to (1) identify parameters of the underlying model, (2) generate hypotheses about relationships between parameters, (3) test the hypotheses by designing experiments, predicting the outcomes, performing the experiments, and interpreting the results and (4) evaluate the results in the light of the hypotheses formulated. However, it has been demonstrated that successful learning with interactive simulations requires further support. Particularly, generating and testing hypotheses seem to be very demanding tasks. De Jong and his colleagues proposed several measures to support learners in carrying out these tasks. For instance, they suggested to present the conceptual model underlying the simulation step by step, to reduce the hypothesis space as well as the experiment space, and to provide learners with various types of assignments or questions (e.g., Njoo & de Jong, 1993; Swaak, van Joolingen & de Jong, 1998).

Linking these suggestions to cognitive load theory, on the one hand, germane cognitive load might be increased by encouraging learners to test hypotheses in an active, structured, and reflective way. On the other hand, extraneous cognitive load might be decreased by providing learners with informative examples of data and – while they are supposed to formulate hypotheses – by guiding their attention to relevant aspects of the simulation.

Research Questions and Hypotheses

Is it possible to improve learning with multiple and interactive representations by reducing extraneous cognitive load and encouraging germane cognitive load? Taking into account the above considerations, this question comprises the following aspects:

1. Can learning with multiple representations be improved when
    - learners actively relate different representations to each other (increase of germane cognitive load) and
    - produce step by step an integration of these representations (decrease of extraneous cognitive load)?
2. Can learning with interactive representations be improved when
    - learners test hypotheses in a structured and reflective way (increase of germane cognitive load) and
    - are provided with informative examples of data and their attention is guided to specific aspects of the representations (decrease of extraneous cognitive load)?

With respect to question 1, we assumed that learners who actively relate and integrate different representations outperform learners who received the same representations in a separated or in an already integrated format.

With respect to question 2, we predicted that learners who test hypotheses in a structured and reflective way and whose attention is guided to selected aspects of a representation outperform learners who interact with the representations in a self-guided way.

Method

Participants and Design

Our hypotheses were tested in a 3 x 2 factorial design with the factors (1) integration of information (presentation of non-integrated information, presentation of integrated information, active integration of information) and (2) structuring of interactions (free exploration, structured testing of hypotheses).

Overall, 84 social science students of the universities of Freiburg and Tübingen were randomly assigned to the six experimental conditions. They were paid for their participation. Because the application domain was statistics, all participants had attended statistics courses at most one year before the experiment took place.

Procedure and Materials

The application domain was made up of various statistics concepts such as the principle of least squares and the partition of the sum of squares in the one-way analysis of variance.

The instructional material consisted of (1) a printed text, (2) dynamic and interactive visualizations, and (3) static illustrations with verbal, algebraical, and graphical components. The visualizations were taken from the interactive learning environment VISUALSTAT[1] (Plötzner, Bodemer & Feuerlein, 2001).

[1] www.psychologie.uni-freiburg.de/visualstat/

The learning time was the same under all conditions. The procedure comprised six different phases.

Phase 1: Reactivation of pre-knowledge. At the beginning of the experiment, all participants refreshed their knowledge about statistics by means of an instructional text (30 minutes).

Phase 2: Pre-test. Subsequent to the instructional text, the participants took a multiple choice test. It was made up of four different types of questions: (1) pre-knowledge questions, (2) recall questions, (3) verbal comprehension questions and (4) visual comprehension questions. The recall questions were related to information which was explicitly given in the instructional text. Answering the verbal and visual comprehension questions required reasoning and transfer. The visual comprehension questions required visualizations to be interpreted. The pre-test included 3 questions of each type.

Phase 3: Introduction to the visualizations. Afterwards, the participants received a general introduction to the different visualizations (5 minutes).

Phase 4: Relating different representations. Before the learners started to interact with the visualizations, they were provided with static variants of the dynamic and interactive visualizations complemented with verbal and algebraic components from the instructional text (10 minutes).

- In the condition *non-integrated information*, the visualizations, the algebraic, and the verbal components were presented separately (see Fig. 1). The relation between components of the different representations was established by corresponding numbers.
- In the condition *integrated information*, the information was presented in an integrated format (see Fig. 1).
- In the condition *active integration of information*, the learners were asked to relate the algebraic and verbal components to the corresponding components of the visualizations by drag and drop (see Fig. 1). By doing so, the learners constructed step by step an integrated format of the different representations. They could check the correctness of their mappings after having integrated all components and, if desired, view the correct solution.

Presentation of non-integrated information | Presentation of integrated information | Active integration of information

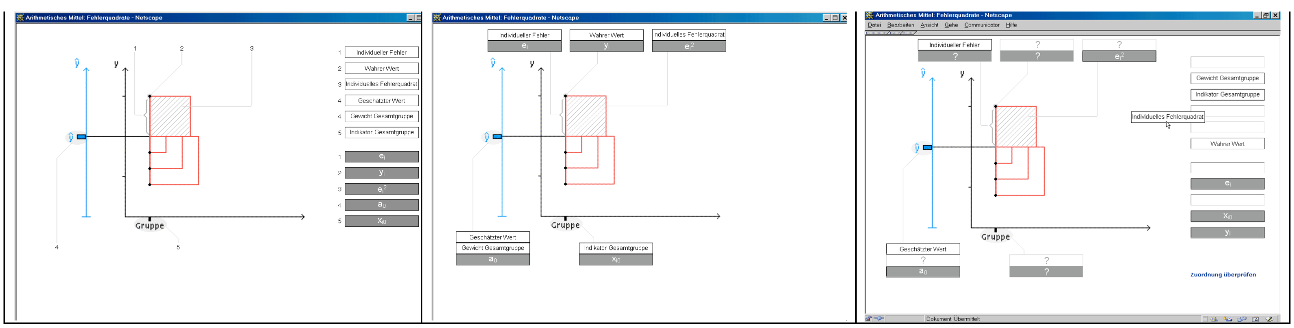

Figure 1. Variation of the factor integration of information.

Phase 5: Interacting with the visualizations. Next, all participants interacted with the dynamic visualizations (45 minutes). In this phase, information on various statistical concepts was presented simultaneously (see Fig. 2). The features of the visualizations and the amount of guidance differed according to the experimental condition.

- In the condition *free exploration*, learners could modify the visualizations in a self-guided way by entering data and by moving a slide control.
- In the condition *structured testing of hypotheses*, learners were provided with informative examples of data and were asked to focus their attention on only one visualization at a time. In addition, the learners were encouraged to formulate and test hypotheses about the effects of moving the slide control.

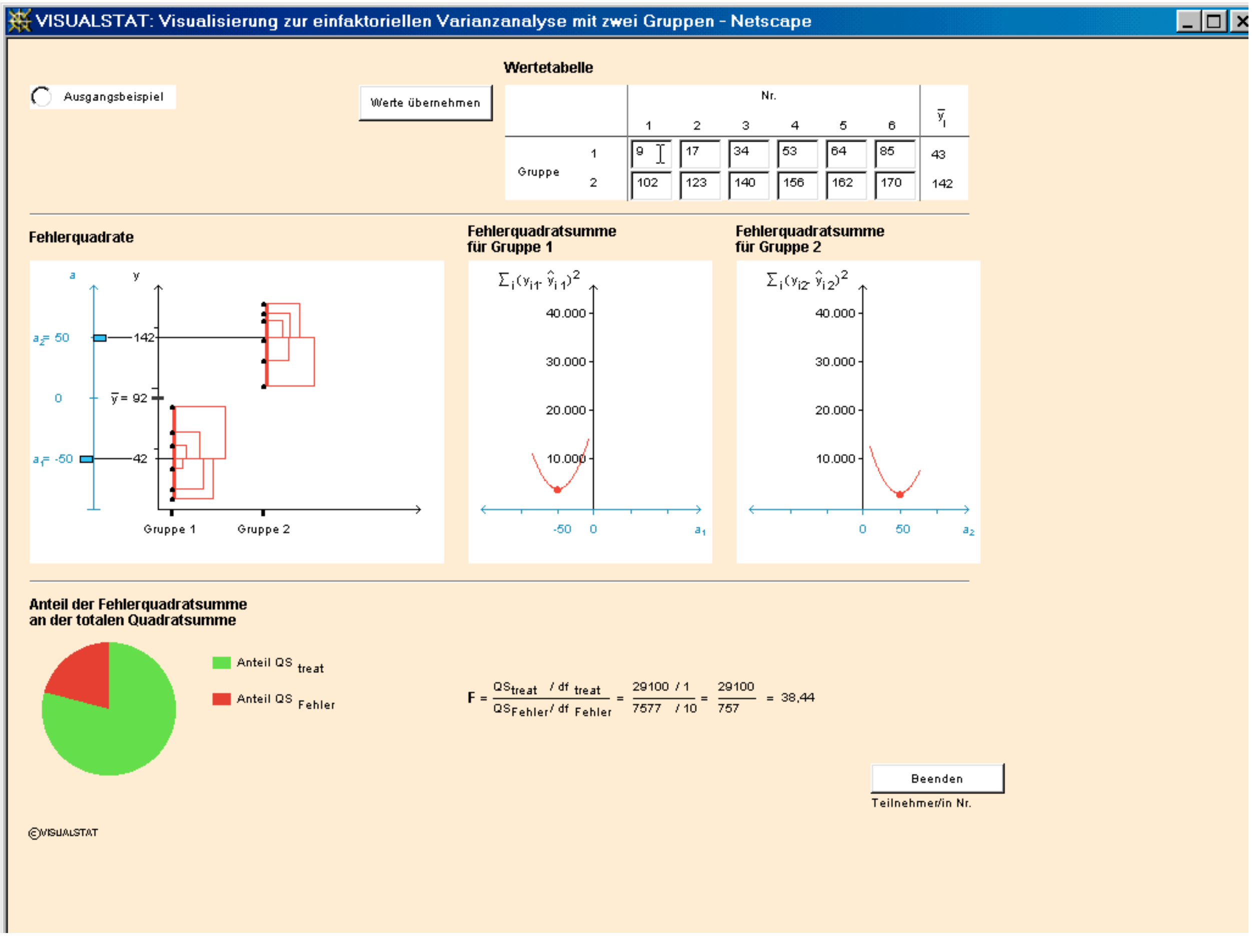

Figure 2. Dynamic and interactive visualizations of various concepts underlying the one-way analysis of variance.

Phase 6: Post-test. Finally, the participants took another version of the test described above. The post-test consisted of 8 recall questions, 12 verbal comprehension questions, and 12 visual comprehension questions.

Results

In the pre-test, there were no statistically significant differences between the groups. Therefore, in the following, only the results of the post-test are presented. To make them comparable, the test scores were transformed to percentages of correct answers above chance level.

Results across all Types of Questions

Concerning all 32 questions of the post-test, a two-way analysis of variance revealed a highly significant effect of the factor *integration of information* ($F(2, 78) = 10.36$; $p < .001$). On average, learners who actively integrated different representations outperformed learners who were provided with separated or already integrated representations. There was no statistically significant effect of the factor *structuring of interactions* ($F(1, 78) = 1.46$; $p = .230$) even though on average the learners who did not actively integrate information performed better in the stuctured condition than in the free exploration condition. Learners who actively integrated information were not able to take additional advantage of the structured testing of hypotheses and performed nearly on the same level as with free exploration. There also was no significant interaction between the two factors ($F(2, 78) = 0.68$; $p = .509$).

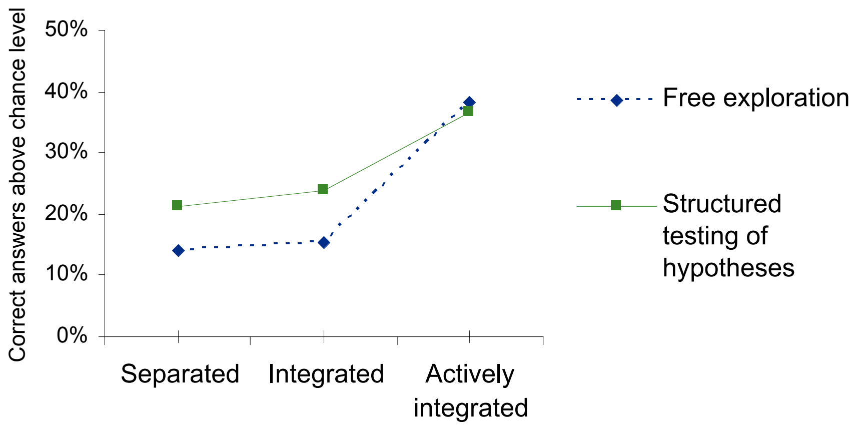

Figure 3. Results across all types of questions.

Recall

With regard to the recall questions, we found the same effects as in the overall analysis. On average, the active integration groups performed better than the groups with separated or already integrated information ($F(2, 78) = 3.58$; $p < .05$). There was no statistically significant effect for the factor *structuring of interactions* ($F(1, 78) = 0.35$; $p = .558$) and for the interaction between the two factors ($F(2, 78) = 0.59$; $p = .558$).

Verbal Comprehension

Concerning the verbal comprehension questions, in addition to a significant effect of the factor *integration of information* in the predicted way ($F(2, 78) = 13.73$; $p < .001$) the analysis of variance revealed a significant effect of the factor *structuring of interactions* ($F(1, 78) = 4.80$; $p < .05$). On average, structured testing of hypotheses lead to more learning than free exploration. Again, we found no significant interaction effect ($F(2, 78) = 0.15$; $p = .863$).

Visual Comprehension

The effect of the factor *integration of information* was also significant with respect to visual comprehension ($F(2, 78) = 4.24$; $p < .05$). There was no significant effect of the factor *structuring of interactions* ($F(1, 78) = 1.15$; $p = .286$) and of the interaction between the two factors ($F(2, 78) = 1.18$; $p = .314$).

Discussion

Multiple and interactive representations have the potential to improve computer-based learning in various ways, but they can also be very demanding for learners. For instance, students frequently do not systematically relate different sources of information to each other and therefore fail to integrate the information into coherent mental representations. With respect to interactive representations, students frequently do not interact systematically with them and have difficulties to state, test, and evaluate hypotheses in a goal-directed way. In addition, learning with multiple, dynamic, and interactive representations often demands large amounts of the learners' cognitive capacities.

In this paper, we made use of cognitive load theory (Sweller, 1994) to design two kinds of support measures to facilitate learning with multiple and interactive representations. We designed learning with multiple and interactive representations in such a way that extraneous cognitive load is decreased and germane load is increased.

With respect to learning with multiple representations, we took advantage of the theory of structure mapping (Gentner, 1983; Gentner & Markman, 1997) to encourage learners to interactively map components of familiar representations step by step onto components of unfamiliar representations.

With respect to learning with interactive representations, we based our considerations on research on discovery learning with simulations (e.g., de Jong & van Joolingen, 1998; van Joolingen & de Jong, 1997). We encouraged learners to test hypotheses in an active, structured, and reflective way and provided them with informative examples of data.

We evaluated the support measures experimentally. With respect to the integration of different sources of information, Sweller et al. (1990) demonstrated that an instructional format consisting of a single, integrated source lead to better learning results than a conventional instructional format consisting of multiple sources of textual information and diagrams. In the tendency, we found the same result. In addition, we showed that on average, learners who actively integrated different representations even performed significantly better than learners who were provided with already integrated representations.

With respect to the structuring of interactions, we found that learners who previously were not encouraged to integrate different representations could benefit from the support of learning with the dynamic and interactive representations. They had a better comprehension of the domain than the learners who interacted with the representations in a self-guided way.

Unexpectedly, the support of the process of hypothesis testing could not further improve the learning outcomes of students who actively integrated different sources of information. Perhaps learners could not take advantage of its potentials because the assignments how to structure the testing of hypotheses imposed additional extraneous load onto the learners. This load might be reducible by training the learners over a longer time to formulate and test hypotheses systematically.

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