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Representational Scaffolding During Scientific Inquiry: Interpretive and Expressive use of Inscriptions in Classroom Learning

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Abstract

External representations (inscriptions) such as tables, visualizations, graphs and diagrams have been widely studied to determine their cognitive effects. However, a research-based pedagogy for their classroom use is yet to be offered. The two independent studies presented here are conceived from the same standpoint: the cognitive effects of inscriptions are influenced by the mode of their use (interpretive or expressive). The results of these studies indicate that the interpretive and expressive use of different external representations during scientific inquiry influenced students' (1) understanding the logic of designing experiments and their (2) ability to coordinate experimental data with theories. Representational scaffolding with collaboratively shared evidential-consistency maps helped students overcome traditional "inquiry traps" such as confirmation bias. These results show that representational scaffolding can provide an effective pedagogy for cognitively-based instructional interventions to teach scientific inquiry skills.

Introduction

Representing knowledge with inscriptions such as pictures, diagrams and maps is a pivotal aspect of scientific practice. These external representations can be tools to think with for the clarification of ideas while designing experiments, analyzing data, and formulating theories. They can also be tools to talk with, aiding communication between a community of scientist-peers. Increasingly, everyday decisions are based on information presented with external representations found in textbooks, newspapers and even on breakfast cereal boxes. Today it is considered part of basic education to be able to understand and communicate with external representations. Arguably, external representations are at the center of both scientific and everyday reasoning. Thus a study of how one learns to make sense of and reason with representations has great significance.

For the purpose of research on learning, external representations should be differentiated from the internal products of one's thinking, often also described with the terminology "representations" (Kotovsky & Simon, 1990). I use the word "inscriptions" (Latour & Woolgar, 1979; Lehrer & Schauble, 1998) interchangeably with "external representations" and with both I refer to artifacts of thinking existing outside of one's head. My primary aim with this article is to describe the potential use of these external representations of thinking to scaffold learning. First, I describe the theoretical grounding of my overall approach to the understanding and use of inscriptions in classroom

learning. Next, I detail two studies, which describe the effects of inscriptions on two crucial aspects of scientific inquiry: (a) the logical process of setting up informative (unconfounded) experiments and (b) the reasoning associated with making sense of empirical observations by building evidential-consistency relationships between experimental data and theories. Finally, I describe the implications of these results for learning and teaching scientific inquiry skills and outline future research to further develop a cognitively-based pedagogy built on representational scaffolding.

Theoretical grounding

My analysis of the educational benefit of various forms of external representations starts with a framework outlining the cognitive value of inscriptions. Developed by Collins and Ferguson (1993), this framework states that each form of external representation carries with it a methodology or heuristic for its use. External representations function through two mechanisms. They can (a) narrow the space of information search by localizing the most important message into perceptually salient, jointly displayed chunks (Larkin & Simon, 1987). They can also (b) provide a way for previously obscured information to become available (to "emerge") during the development and interpretation of inscriptions (Koedinger, 1992). That is, external representations scaffold activity by making certain aspects of inquiry salient (Stenning & Oberlander, 1995) and by constraining the user to certain activities (Suthers, 1999). With such mechanisms external representations provide representational scaffolding during classroom learning.

For example, students provided with the table shown in Figure 1a can clearly see that the most important variables to consider when determining what makes balls roll farther down ramps are the steepness of the ramp, the length of run, the surface of the ramp and the type of ball. No other variable is deemed important by the developer of this table, thus students' thinking is constrained to these essentials. One salient piece of information from this table is that all four of these variables should be considered for each apparatus of a simultaneous comparison (for both ramp A and ramp B).

Another salient component of experimental design emerges when students fill this table out. If students neglect to pay attention to any of the variables on one of the ramps the missing information becomes salient – as indicated by

the empty cells in Figure 1b. Thus, representational scaffolding can provide an innovative instructional methodology to teach students how to design informative (un-confounded) experiments.

VARIABLES	RAMP A	RAMP B
Surface		
Steepness		
Length of run		
Type of ball		

Figure 1a. Representational scaffolding by constraining students' thinking to the focal elements of experimentation.

VARIABLES	RAMP A	RAMP B
Surface	Smooth	Rough
Steepness	High	High
Length of run	Long	
Type of ball	Golf	

Figure 1b. Representational scaffolding by the salience of empty cells drawing students' attention to variables that may have been ignored during experimental testing.

With few exceptions (Lehrer & Schauble,1998) however, the full potential of the use of inscriptions in classroom science learning environments has not been examined.

There are two modes of using inscriptions: interpretive and expressive. These two modes are inherently combined during the development and the use of external representations in scientific practice. In classroom environments, however, students usually use inscriptions interpretively: they are given a teacher-developed external representation to make sense of by observing parts or by completing, "filling it out" – as shown in Figure 1. Expressive use of inscriptions entails the active generation of a form of external representation with the aim of communicating an idea. While students' active generation and manipulation of their own knowledge is considered important under the currently dominant constructivist pedagogy, inscriptions are rarely used expressively by students during classroom learning.

The study of inscription use in classroom learning environments is best approached by the examination of students' difficulties with each of these modes of using inscriptions. The first study described here shows how students used inscriptions both interpretively and expressively while designing and conducting scientific experiments and recording data results. The second study describes the effects of a software tool that eases students' way into working with external representations. Both of these studies illustrate the value of learning with inscriptions and indicate which student difficulties should be considered

in the further refinement of an instructional methodology that is built on representational scaffolding.

Representational scaffolding during scientific experimentation

Subjects and Procedures

Two classrooms of 28, 4th grade students experimented in small groups of 3-4 to determine what makes balls roll farther down on ramps. The instructional goal was to teach valid experimentation skills, specifically the control of variables strategy or CVS. The task of each student group was to design experiments with a pair of physical ramps and record their experiments in laboratory notebooks. The outcome of the research-based methodology to teach valid experimentation skills from this study was detailed in Toth, Klahr & Chen (in press). The present paper focuses on the effects of using inscriptions during scientific inquiry in the classroom. Two slightly different procedures were employed by the classroom teacher, each allowing a focused view at either the interpretive or the expressive use of inscriptions.

During the first week of instruction student groups learned how to create controlled comparisons with pairs of ramps and filled out a teacher-specified table of dependent and independent variables to indicate their experimental setup. This table representation was similar to that in Figure 1, with the exception that the two possible values for each of the four variables were already provided in the cells of this table. The students' role was simply to circle the variable value of their choice to map their ramp setup onto the table. Prior to experimentation, students were specifically taught how to conduct this mapping activity. This interpretive use of inscriptions was intended to help students as well as the teacher keep track of the experimental designs used over time. The researcher's classroom observation notes recorded student's activities and their difficulties.

During the second week of the study - after two weeks of spring break – the students applied the previously learned skill of designing controlled experiments to learn more about ramps. This time they designed experiments using one ramp at a time. They were asked to record each of their experiments into any external representations of their choice (expressive use). Data sources included videotapes of classroom experimentation, laboratory notebooks recorded by students and the researchers' observation notes. Students' expressive use of inscriptions was scored using a modified version of a quantitative coding scheme suggested by Kosslyn (1989). The scoring included attention to how the inscription communicated the logical design of experiments and the clarity of reasoning inherent in it.

Results and Discussion

Interpretive use of inscriptions Classroom observations of the interpretive use of inscriptions (first week) indicated that

as soon as students looked at the teacher-developed table and tried to fill it out, they wanted to go back to the physical ramps and make changes to the setup of the variables. They indicated that they wished to set their tests up "better" or "differently." While this intent of the students created a slight problem for the experimenters – who at the time were interested in documenting students' developing knowledge of experimentation strictly adhering to a prior protocol developed during laboratory studies (Chen & Klahr, 1999) – this observation soon led to the realization that the interpretive use of the pre-developed table representation may have helped students abstract the overall structure of the experiment and thus aided their understanding of the design of un-confounded experiments. I hypothesize that as students filled out their teacher-defined table an important characteristic of scientific inquiry may have become salient to them: the criteria that all important variables of an experimental setup should be considered during experimental design. As outlined above (Figure 1) this table constrained students' thinking to the most important variables, but also made student errors in designing informative (controlled) experiments salient to them. If one of the variables was not attended, this omission became obvious ("emerged") during the work with the representation. Similarly, if two variables were changed instead of one between experiments (a confounded experiment was created) this oversight was made perceptually salient. Thus information previously not available to students became obvious through the representational scaffolding provided by the use of this inscription.

After a week of focused experimentation and instruction, students learned the strategy of creating controlled experiments from which they could tell with certainty the effect of any focal variable under investigation (Toth, Klahr & Chen, in press). Having learned to overcome systemic error with the use of the control of variables strategy (CVS) during experimentation, students were presented with a new challenge: to record their experiments with inscriptions of their own choice (expressive use) while they continued applying CVS to learn more about variables associated with ramps. The subsequent analysis of the student-developed inscriptions from this second week of study revealed various student difficulties.

Expressive use of inscriptions Two characteristics of the expressive use of inscription were noticeably difficult for students: (1) using the common techniques of developing inscriptions (using labels and data correctly in a coordinated way) and (2) reasoning scientifically with inscriptions. Various problems resulting from the lack of experience with a common representational technique were identified. Common problems included missing labels, missing data content and insufficient alignment of data with labels.

Students' laboratory notebooks fell into three specific patterns in terms of reasoning scientifically about

experiments through inscriptions: (a) showing incorrect CVS only, (b) showing a combination of correct and incorrect CVS over time, (c) indicating a possible search for interaction of variables without clear CVS design

These effects were found even after students were documented to have learned the control of variables strategy (Toth, Klahr and Chen, in press). That is the effect found here can be attributed to either students' inability to use external representations or the lack of transfer of the CVS strategy to situations slightly changed from the condition of learning.

Overall it appears that the interpretive use of a well-selected external representation (Figure 1) can positively influence student's understanding of skills associated with scientific inquiry. This effect is due to the representational scaffolding inherent in any form of inscription. This characteristic makes certain inscriptions especially fitting for a learning task while not appropriate for others. In this example, a table representation appears to be fitting for the interpretive task of abstracting and combining the logical components of scientific experimentation. However, the expressive use of inscriptions is more problematic as it should consider the structure of the domain, the goal of the activity as well as the cognitive state of the interpreter. It is hypothesized that innovative pedagogies such as collaborative reflection and discussion conducted through external representations may help students learn the skills of developing effective inscriptions.

The next study describes a software tool called Belvedere (Suthers et al., 1997) that eases students' way into working with external representations. It also details the effects of representational scaffolding by different forms of representations and suggests a reflective methodology to support the use of inscriptions in classroom learning environments.

Representational scaffolding while coordinating data with theories

Subjects and Procedures

Four classrooms of 9th grade students (N = 73) participated in a 2X2 research design in which the effects of two different external representations (evidence mapping vs. prose writing) was studied. As part of their science class—taught by their regular science teacher—the students participated in problem-based-learning. They were presented with a set of scientific challenges to which no known solutions existed at the time. Their task was to explore web-based information sources – a set of researcher developed¹, hypertext materials – and to find a solution to a scientific challenge such as mass extinctions, the evolution of marine iguanas or the sudden appearance of a mysterious

¹ The materials used in this study were developed primarily by Arlene Weiner with assistance from the author.

disease. Evidence mapping entailed using a shared, whiteboarding software tool, BELVEDERE, to diagram evidential consistency relationships between hypotheses and data. BELVEDERE's main menu provided epistemological categories that included object-shapes for hypotheses (rounded rectangle shapes in Figure 2), data (rectangle shapes in Figure 2) and links to indicate consistency ("for" links), inconsistency ("against" links) and conjunction ("and" links) between data and hypotheses (Figure 2).

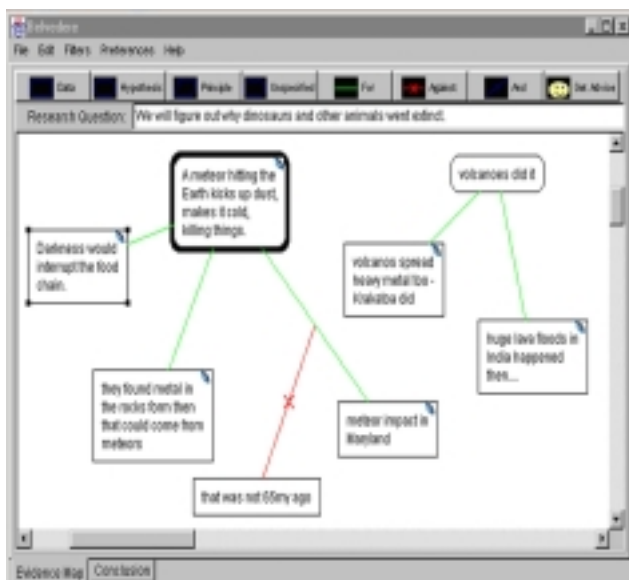


Figure 2. Example evidence map created with the BELVEDERE software tool.

The diagramming activity started with exploring the web-based materials for information and continued with recording ideas using the software tool. In order to make this record with the mapping tool students needed to categorize the currently considered information as data or hypothesis, select from the appropriate shape from the menu pallet and copy the information being considered into the selected object-shape. Similarly students could choose links from the menu to indicate evidential consistency relationships between data and hypotheses (Figure 2.)

Students not using the software tool for mapping used prose writing to record their thinking during inquiry. Prose writing consisted of using a word-processor to write a prose-based account of exploring the web-based materials and solving the challenge problem. Students were instructed to record the main aspects of their inquiry: both data and hypotheses and detail how they decided on a conclusion. In addition, one of the classrooms in each condition (mapping and prose) was given a method of explicitly reflecting on the process of their inquiry by using a paper-based handout of specific inquiry criteria detailing optimal performance during inquiry. These so-called “reflective assessment rubrics” were used from the beginning of inquiry for

reflection as well as during final assessment of performance. Students who did not use the explicit reflection were only implicitly prompted about the criteria by which their work will be evaluated. It was expected that this implicit prompting would result from the structure of the challenge materials and the nature of the inquiry activity.

Thus each of the four classrooms was randomly assigned to one of the following treatments: Map&Reflect, Map-NoReflect, Prose&Reflect, Prose-NoReflect (Figure 3).

Treatment	Materials	Representation	Reflection
Map & Reflect	Hyper-Media	Mapping	Reflection
Map - NoReflect	Hyper-Media	Mapping	No-Reflection
Prose & Reflect	Hyper-Media	Prose	Reflection
Prose - NoReflect	Hyper-Media	Prose	No-Reflection

Figure 3. Elements of experimental design for study two.

The effects of representational scaffolding on students' inquiry skills was analyzed from students' inquiry artifacts - the products of their work (maps or prose). Though students conducted many units of problem-based-learning, the results discussed here are from the first unit only. This unit was chosen with the expectation that the use of inscriptions in the early stages of inquiry would provide intricate details of representational scaffolding inherent in these inscriptions. It was expected that this software tool will ease students' into reasoning about data and hypotheses with inscriptions, as it scaffolds the development of evidence-map representations with pre-defined categories that can be flexibly used to allow students' to actively generate and manipulate their own scientific knowledge.

As an indicator of students' effectiveness during inquiry three scores were analyzed: (1) the number of information units (hypotheses and data) recorded and correctly categorized, the (2) number of inferences recorded (indicating correct relationships between data and hypotheses) and the (3) the quality of final conclusions drawn by students in each condition.

Results and Discussion

Groups in the prose writing condition recorded about the same number of hypotheses and data as groups in the evidence mapping condition. However, analysis of the amount of information that was correctly categorized by students revealed that the mapping groups categorized significantly more of their recorded information as hypothesis and data compared to the prose writing groups. Since in either condition (mapping or prose) the percentage of incorrectly categorized information units was minimal

(<10%) it is reasonable to argue that it was the effect of the mapping representation that scaffolded students' categorization efforts. That is, the evidential consistency mapping, with its pre-defined epistemological categories, prompted students to consider the meaning of these categories and to organize the outcome of their investigations based on these categories. Unlike the mapping activity, the prose writing was a familiar mode of communication for students. However, the prose representation did not make the categories of scientific inquiry perceptually salient throughout students' investigation, resulting in the lower number of information pieces categorized by the prose writing groups. There was no significant effect of the type of reflection on either the number of information units recorded nor on the categorization of these records.

Interesting representational scaffolding effects were found during the analysis of the inferences recorded by student groups in the different conditions. The mapping groups recorded significantly higher number of inferences describing relationships between data and hypotheses compared to the prose writing groups (Figure 4).

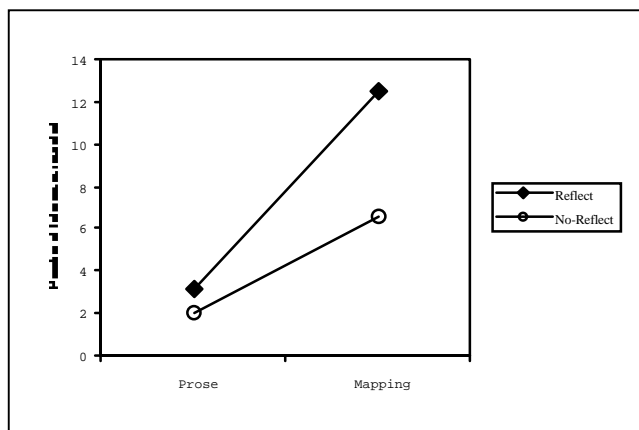


Figure 4. The effects of representational scaffolding and explicit reflection on the number of inferences between data and hypotheses recorded by students

The use of explicit reflection also significantly influenced student's ability to express inferences indicating the relationship of their data and hypotheses. The Map&Reflect groups performed significantly higher than any other group, including the Map-NoReflect group on this measure.

Analysis of the types of inferences (consistency, inconsistency and conjunction) revealed that the difference between the Map&Reflect groups compared to the Map-NoReflect groups was in the frequency of inconsistency ("against") relationships recorded (Figure 5). This is a crucial finding that indicates the value of both mapping and explicit reflection and their combined effect helping students overcome confirmation bias during the evaluation of scientific hypotheses based on empirical data.

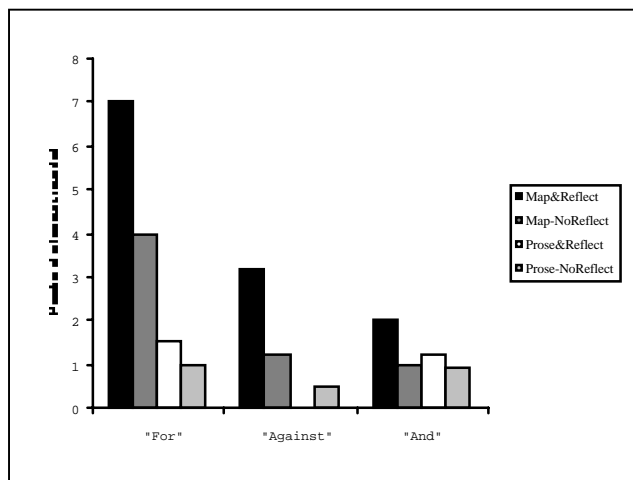


Figure 5. Sub-scores of information evaluation by groups in the four treatment condition.

Furthermore, when students' final reasoning with prose conclusions were analyzed there were no significant differences between prose and mapping groups in the quality of the final conclusions. Since these conclusions were written in prose by students in both conditions (mapping or prose), this finding indicates the lack of efficiency in transferring the inquiry skills learned by the mapping groups from the mapping activity to prose writing. Further instructional interventions are necessary to ensure a more effective transfer.

Overall it appears that the evidence mapping provide better scaffolds for students during scientific inquiry when the goal of activity is to categorize information and evaluate scientific hypotheses based on evidence. Explicit reflection on the specific criteria of scientific inquiry was found to support the evidence mapping activity, but not traditional prose writing.

Conclusion and Educational Significance

External representations of thinking can play a pivotal role in the learning of scientific inquiry skills. The studies presented here detailed the effects of inscriptions during two important processes of scientific inquiry: (1) designing and conducting experiments and (2) coordinating experimental evidence with domain theories. The classroom studies described here yielded evidence for two methods of using inscriptions: interpretive and expressive. Interpretive use of a teacher-developed table representations was found to scaffold students' progress of inquiry by making the variables of an experiment salient and by perceptually constraining the students' attention to abstract the characteristics of correct experimentation. However, during the expressive use of inscriptions students were found to have difficulty with using the common techniques of

developing inscriptions and with indicating their reasoning during experimentation. While the lack of transfer of CVS skills has been clearly documented since this study (Toth & Klahr, 2000) further instructional interventions and studies can reveal how a reflective pedagogy based on representational scaffolding may help with this transfer difficulty. The results of study two indicate that such methodology may be very effective.

While evaluating experimental data against theories, the representational scaffolding effect provided by evidential consistency mapping (compared to prose writing) was confirmed. Evidence mapping was found to be a successful instructional methodology to teach how to categorize and label scientific information and to teach students how to evaluate hypotheses based on empirical data. The findings also suggested that reflective assessment (by the use of the explicit criteria for maximum performance in rubrics format) was an effective instructional manipulation to support the scaffolding effect of external representations.

In collaborative classroom learning environments there has been a need for a methodology that combines cognitive effectiveness with the social circumstances of collaborative learning. The effects of collaborative reflection over shared representations seem to be promising and should be further refined. One such study is currently under way by the author to explore how the social circumstances of the anticipated peer-interpretation of inscriptions influence students' expressive use. Further research should also consider the use of software tools in the shared activity of expressively and collaboratively using various forms of inscriptions.

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