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Designing learning materials to foster transfer of principles

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Abstract

Education aims to equip learners with knowledge about principles that can be applied across a wide range of situations but often people do not recognize structural similarity between known cases and novel problems. Several approaches for designing learning materials to foster transfer of principles have been proposed including learning a generic instantiation, comparing instantiating concrete cases, and learning multiple representations. However, these approaches have rarely been tested against each other nor have they been examined by a broad range of transfer tasks. We evaluated the transfer potential of the different approaches separately (Experiment 1) and in combination (Experiment 2) by teaching undergraduates the principles of propositional logic. Students were tested on an extensive transfer test one week after learning. The best transfer performance resulted from the simultaneous comparison of a generic instantiation with two concrete cases. We suggest this approach for designing learning materials that introduce new principles.

Keywords: transfer; analogical reasoning; comparison; generic instantiation; learning by multiple representations.

Introduction

Transfer describes the phenomenon “how knowledge acquired in one situation applies (or fails to apply) in other situations” (Singley & Anderson, 1989, p.1). The ability to transfer knowledge is especially important when scientific principles are learned. Science often advances by the discovery of principles that cross-cut and support the cross-fertilization of superficially different domains (Goldstone & Wilensky, 2008). Thus, learning a principle gives students the possibility to understand a broad range of phenomena in different domains. For example, if students learn the principles of propositional logic this should help them to comprehend the output of combinations of logic gates in digital circuits and to evaluate the validity of philosophical arguments. Therefore, it is important that principles learned in educational settings are not restricted to the idiosynchrasies of the learning situation.

Researchers have devised several approaches for designing learning materials that foster transfer of principles. However, the approaches have rarely been tested competitively and the conclusions derived from different lines of research are difficult to compare. Difficulties arise due to differences in conceptualizing and measuring transfer (Barnett & Ceci, 2002). The present research aims at evaluating the different approaches to foster transfer of principles in one research program by teaching participants the principles of propositional logic (i.e. the interpretation of propositions connected by the logic operators negation, conjunction, disjunction, conditional, and biconditional).

Transfer of principles can be conceptualized as analogical reasoning (e.g., Goldstone & Son, 2005). Principles are relational structures that capture the interdependencies between various variables and are highly flexible in meaning. Theories of analogical reasoning essentially explain transfer of a relational structure from a known domain, the source, to a lesser known domain, the target (for an overview see Gentner, 2010). Of course, not all problem solving and knowledge transfer can be reduced to analogical reasoning (see Nokes, 2009, Bransford & Schwarz, 1999). However, to explain the phenomenon of transfer of principles theories of analogical reasoning provide a highly elaborated and parsimonious conceptual base.

Accordingly, educators have to support their students to acquire a knowledge representation of the principle which is a useful and flexible source to solve future (target) problems. Merely teaching by analogy which means basically providing learners with a single concrete source that instantiates the principle and is grounded in everyday experience has been shown to not result in satisfying transfer performance (e.g., Duit, Roth, Komorek, & Wilbers, 2001). Several reasons may account for this failure: inferences strongly depend on the features of the source chosen (e.g., Gentner & Gentner, 1983), learners fail to spontaneously retrieve the required source (e.g., Gick & Holyoak, 1980), or learners retrieve and integrate knowledge in the reasoning process that is irrelevant for the analogy (e.g., Mather, Knight, & McCaffrey, 2005). Given the failure of “classic” analogy, several approaches have been proposed on how to teach new principles.

One approach suggests providing learners with a generic instantiation of the principle, which formalizes or symbolizes a principle without direct reference to concrete objects (e.g., a formula or a sparse graphic representation). Within the framework of analogical reasoning learning a generic instantiation can be considered as learning a single source comparable to learning via analogy. However, a generic instantiation contains (almost) no additional irrelevant information compared to a concrete familiar source. Sloutsky, Kaminski, and Heckler (2005, p. 508) aptly illustrate this: "…when different numerosities are represented by a different number of frogs (as opposed to being represented by a different number of dots), the representation communicates additional, irrelevant information (e.g., shape, color, animacy)". Providing learners with a generic instantiation of a principle first is common in mathematics textbooks and this tendency increases with grade level (Nathan, Long, & Alibali, 2002). Several researchers have demonstrated advantages concerning learning and transfer for generic instantiations over more concrete instantiations of principles (e.g., Kaminski, Sloutsky, & Heckler, 2008; Mevarech & Stern, 1997; Nesher & Sukenik, 1991).

Another approach suggests comparing concrete cases instantiating the principle to promote transfer. The comparison of cases highlights the common relational structure and supports the abstraction and encoding of a general schema while superficial idiosyncratic features of the single cases become less important (e.g., Gentner, 2010). Thus, the source representation is actively abstracted by the learner from multiple concrete cases. Like a given generic instantiation, this "self-constructed" source representation contains less irrelevant information than a single case. Actively comparing cases (in contrast to processing cases sequentially) has been found to increase transfer performance. For example, students who learned the principles of contingent contracts by comparing two case studies formed more contingencies in a face-to-face negotiation exercise than students who interpreted the case studies separately (Gentner, Loewenstein, & Thompson, 2003). The schema abstracted from comparing cases is thus more likely to be retrieved and more flexible than are the concrete representations that are encoded when cases are studied sequentially.

Finally, a third approach suggests providing learners with multiple representations of a principle. Here, learners see different representations of a principle simultaneously such as a formula in combination with a graph or a concrete case. This kind of learning is widely used in multimedia environments (e.g., Ainsworth, 1999). In accordance to this approach, learners actively construct a source representation that integrates the information from the different representations into a coherent structure by aligning the multiple representations (Schnotz & Bannert, 2003). However, this integration process is highly demanding for learners and positive effects on learning and transfer often do not occur (for an overview see Seufert, 2003). Educators are thus advised to explicitly and consistently link examples with corresponding symbols of generic instantiations (e.g. Berthold & Renkl, 2009; Roy & Chi, 2005). The most basic form of learning multiple representations is simultaneously studying a generic instantiation and one concrete case (e.g., Colhoun, Gentner, & Loewenstein, 2008).

For educators it would be highly interesting to know which of these approaches is most effective for fostering transfer. However, providing an answer is difficult because the transfer tasks used to test the different approaches are hardly comparable (Barnett & Ceci, 2002) and the different approaches have not yet been tested against each other within one experimental design.

Overview of Research

In the present research, we evaluated three different approaches to foster transfer separately (Exp 1) and in combination (Exp 2). In both studies, students learned the principles of propositional logic (i.e. the truth functionality of the basic logic operators negation, conjunction, disjunction, conditional, and biconditional). We chose propositional logic because the principles are domain-general and difficult to learn (e.g., Cheng, Holyoak, Nisbett, & Oliver, 1986). Participants in both studies received a booklet that presented a short introduction to propositional logic. They were instructed to write self-explanations for each instance of a principle. This ensured that participants actively processed the materials. More importantly, writing self-explanations supports the integration of different cases (e.g., Gentner, Loewenstein, & Thompson, 2003) and of multiple representations (e.g., Berthold & Renkl, 2009). Immediately after learning, we controlled learning of the materials. One week after learning, participants worked on a transfer test that comprised several transfer tasks to assess the transfer potential of the different learning materials. Thus, both studies consisted of three phases: learning, learning control, and transfer.

Experiment 1

In Experiment 1, four groups of participants learned the principles of propositional logic with different learning materials. Learning materials of three groups were based on the approaches described above: learning generic instantiations of principles (GENERIC), comparing two concrete cases instantiating the principles (COMPARE _CASES), and comparing a generic instantiation with one concrete case (COMPARE_GENERIC_CASE). A fourth group served as baseline (BASELINE). The learners in the BASELINE condition studied the two concrete cases of the COMPARE_CASES approach sequentially without the possibility to compare.

In the *learning phase*, participants of the four intervention groups learned the principles of propositional logic by studying truth tables of the basic operators (see Table 1 for examples). If the learning material was based on generic instantiations of principles (in the GENERIC group), truth tables presented variables for propositions (i.e. p, q) and symbols for the operator (i.e. →). If the learning material was based on concrete cases (in the COMPARE_CASES and BASELINE group), variables and symbols were instantiated with simple sentences. If the learning material was based on multiple representations (in the COMPARE_ GENERIC _CASE group), participants studied a generic instantiation and one of the cases simultaneously.

In the *learning control* test, we tested whether participants learned the principles they were just taught. This test contained tasks based on the same representation used in the learning materials of the respective group. For example, having learned the principles with generic instantiations (e.g., p → q) the tasks contained the identical generic symbols; and having learned the principles instantiated by simple sentences (i.e. cases) the tasks contained the identical sentences. To solve the tasks participants merely had to recall the principles (see Table 1 for examples of the learning control test). Given the intelligible learning material and given that the learning control test was directly adapted to it, no differences were expected across the four intervention groups. To ensure that participants of the four intervention groups benefitted from the learning environment we compared their performance on the learning control test with an additional group without intervention.

One week after learning, the four intervention groups worked on the *transfer test*. This test was identical for all participants. It comprised 20 near and 24 far transfer tasks. Half of the near transfer tasks contained representations which were related to the variables used in the GENERIC learning material. Variables used in the learning material and the learning control test were replaced by different variables (e.g., Proposition_1 for p). The other half of the near transfer tasks contained concrete cases. In these tasks, the simple sentences of the CASE-based learning materials and learning control tests were substituted by other simple sentences (see Table 1 for examples). The far transfer test contained four different kinds of tasks: Wason's selection tasks, conjunction/disjunction fallacy tasks, Venn diagrams, and logic flowcharts. All of these tasks strongly differed from the learning materials, the learning control tests, and the near transfer test with respect to superficial features but could be solved by applying the principles of propositional logic.

For the near transfer tasks we expected the three experimental groups (GENERIC, COMPARE_CASES, COMPARE_GENERIC_CASE) to outperform the BASELINE. Furthermore, we predicted the COMPARE_ GENERIC_CASE group to be superior to the other two experimental groups as they were trained on the two different representations of the principles, whereas the other two groups were only trained on either one. For the far transfer test, we again predicted all experimental groups to outperform the BASELINE. However, given the lack of research comparing the different approaches, we could not make any predictions concerning which of the three experimental groups would perform best.

Method

Participants One-hundred-fourteen undergraduates from the University of Zurich and the ETH Zurich (Switzerland) majoring in a wide range of subjects participated. Additionally 20 undergraduates without any learning intervention were tested on the learning control test. All undergraduates were paid for participation. No participant was familiar with propositional logic. They were randomly assigned to the four groups.

Materials and Procedure In the learning phase, participants worked on the learning materials for one hour. The learning materials consisted of a printed-out booklet in which the principles of propositional logic were introduced. The booklets were identical for all participants with only the presentation of the principles differing between the four intervention groups. After a break of half an hour,

Table 1: Examples of the learning materials, the learning control tasks, and the near transfer tasks used in Experiment 1 and 2

Learning material					
GENERIC			**CASE**		
p	**q**	**p → q**	**Henry is home.**	**Min is on board.**	**If Henry is home, Min is on board.**
true	true	true	true	true	true
true	false	false	true	false	false
false	true	true	false	true	true
false	false	true	false	false	true

Learning control	
GENERIC	**CASE**
You know that the single propositions p and q are both false. Someone claims that p → q. Which truth value can you assign this conditional?	You know that "Henry is home." and "Min is on board." are both false. Someone claims "If Henry is home, Min is on board." Which truth value can you assign this conditional?

Near transfer tasks	
GENERIC related tasks	**CASE related tasks**
You know that the single propositions "Proposition_1" and "Proposition_2" are both false. Someone claims that "Proposition_1 → Proposition_2". Which truth value can you assign this conditional?	You know that "It is raining." and "Peter is going out." are both false. Someone claims "If it is raining, Peter is going out." Which truth value can you assign this conditional?

participants worked on the learning control test for half an hour. One week after learning the participants had one hour to answer the tasks of the transfer test. Learning and transfer were conducted in the same seminar room at the ETH Zurich and participants were tested in groups with up to 15 students.

Results

Learning control All intervention groups strongly outperformed (all *p*s < .01, all *d*s > .8) the participants who did not work on any learning material (their solution rate was 57%). Thus, participants benefited from working on the learning materials (see Table 2). As expected, solution rates between the different intervention groups did not differ significantly ($F(3, 110) = 1.349$, $p = .262$). Given that all participants gained comparably from the different learning materials, we used performance in the learning control test as a covariate for the analyses of the transfer test as our aim was to assess the pure transfer potential rather than the learning efficiency of the learning materials.

Near transfer An ANCOVA revealed a main effect of the learning material, $F(3, 109)=5.372$, $p=.002$, $\eta_p^2=.129$ (see Table 2 for means and standard deviations). The specific comparisons unexpectedly revealed that the COMPARE_ GENERIC_CASE group showed the worst near transfer performance. They were significantly outperformed by the GENERIC ($p=.002$, $d=.63$) and COMPARE_CASES groups ($p=.001$, $d=.69$). Furthermore, they did not perform better than the BASELINE. The GENERIC and COMPARE_ CASES groups significantly outperformed the BASELINE ($p=.027$, $d=.37$; $p=.013$, $d=.43$, respectively, one-sided tests). There was no significant performance difference between GENERIC and COMPARE_CASES groups.

Far Transfer An ANCOVA again revealed a main effect of the learning material, $F(3, 109)=2.692$, $p=.050$, $\eta_p^2=.069$. The specific comparisons (see Table 2 for means and standard deviations) showed a significant advantage for the COMPARE_CASES group over the COMPARE_ GENERIC_CASE group ($p=.005$, $d=.63$). The latter group was again least successful. Only the COMPARE_CASES group slightly outperformed the BASELINE ($p=.056$, $d=.39$, one-sided test).

Discussion

In contrast to our prediction, the COMPARE_GENERIC_ CASE group performed worst in both parts of the transfer test. They did not perform better than the BASELINE and were outperformed by GENERIC and COMPARE_CASES groups. While the GENERIC group performed better than the BASELINE only on the near transfer tasks, the COMPARE_CASES group showed advantages both on near and far transfer tasks. Findings of Experiment 1 thus suggest that comparing two cases which instantiate a principle is most efficient to promote transfer of this principle.

The poor transfer performance of the COMPARE_GENERIC_CASE group might be due to superficial processing of the learning materials. For the COMPARE_CASES group the joint interpretation of two cases is only possible if idiosyncratic features of the single cases are ignored. Thus, they had to actively abstract from the learning materials and encoded a flexible schema that supported transfer. GENERIC-learners might have been encouraged to elaborate the learning materials with prior knowledge, given that no reference to concrete objects was given. In contrast, COMPARE_GENERIC_CASE-learners may have only matched the symbols of the generic instantiation to the idiosyncratic structure of the sentences without abstracting from or elaborating learning materials. Therefore, learning from different representations of principles might induce superficial processing of the materials in which only parts of one representation are mapped onto corresponding parts of another representation. This limits learning gains to tasks which directly match the learning material (i.e. the tasks of the learning control test).

Given the best performance of the COMPARE_CASES group, should teaching new principles be only based on comparison of multiple concrete cases? For everyday (academic) life, it is extremely important for learners to also know a generic instantiation of a principle because this enables them to solve complex problems with a formalized procedure (Koedinger, Alibali, & Nathan, 2008). In Experiment 2, we therefore explored different ways how to

Table 2: Means (percentage of correct answers) and standard deviations of Experiment 1 and 2

	Experiment 1			
	GENERIC (N=28)	**COMPARE_CASES (N=28)**	**COMPARE_GENERIC_CASE (N =30)**	**BASELINE (N=28)**
Learning control	73.5 (12.1)	72.5 (11.7)	67.9 (12.9)	72.8 (10.5)
Near transfer	66.8 (15.7)	67.7 (15.9)	57.5 (13.8)	60.9 (15.9)
Far transfer	55.7 (18.0)	61.5 (18.8)	50.0 (17.8)	54.9 (14.7)
	Experiment 2			
	GENERIC+TWO_CASES (N=27)	**COMPARISON_FIRST (N=27)**	**GENERIC_FIRST (N=27)**	
Learning control	73.6 (14.5)	71.7 (11.5)	75.8 (11.8)	
Near transfer	68.5 (13.4)	63.1 (15.0)	68.1 (17.4)	
Far transfer	63.4 (16.8)	56.7 (18.4)	54.6 (13.2)	

design effective learning materials which contain generic and concrete instantiations of principles.

Experiment 2

In Experiment 2, we combined the two approaches found to have the highest transfer potentials, i.e. learning a generic instantiation and comparing concrete cases, to three kinds of learning materials. The first material presented simultaneously the generic instantiation and two cases (GENERIC+TWO_CASES) for a principle. This learning material is similar to the COMPARE_GENERIC_CASE material of Exp 1, but additionally incorporates a second concrete case. The two additional kinds of learning materials were constructed by sequencing the presentation of generic instantiation and the two cases. In the second group, participants learned the principles of propositional logic first by comparing two cases and then by processing the generic instantiation (COMPARISON_FIRST). In the third group, the generic instantiation was presented first and then the two cases (GENERIC_FIRST). The two additional learning materials were included to serve as an adequate baseline for the GENERIC+TWO_CASES group. We predicted that the simultaneous comparison results in a greater abstraction from the learning material and, accordingly to an advantage for transfer relative to the sequenced materials.

Method

Participants Eighty-one undergraduates from the same population as in Exp 1 participated for payment. No participant was familiar with propositional logic. They were randomly assigned to the different learning conditions.

Materials and Procedure The learning materials were novel combinations of the GENERIC and the COMPARE_CASES learning materials used in Exp 1. To assess learning and transfer we used the same tests as in Exp 1. The procedure was also identical to Exp 1. Note that the complexity of the materials increased from Exp 1 to Exp 2 but we limited the time of learning to one hour in order to keep the studies comparable.

Results and Discussion

No performance differences (see Table 2 for means and standard deviations of all measures of Exp 2) were found in the learning control test ($F(2, 77)=.516$, $p=.599$). Thus, we again used performance in the learning control test as a covariate for the analyses of the transfer test.

Learners of the three groups did not differ in their performance on the near transfer tasks ($F(2, 77)=1.519$, $p=.225$). For the far transfer task, however, we found a marginally significant group effect ($F(2,77)=2.705$, $p=.073$, $\eta_p^2=.066$) which can be traced back to an advantage of the GENERIC+TWO_CASES group over the COMPARISON_FIRST ($p=.093$, $d=.38$) and the GENERIC_FIRST group ($p=.029$, $d=.58$). Thus, the three kinds of learning materials supported near transfer equally well. When it comes to far transfer, however, the group of learners who simultaneously compared generic instantiations and two concrete cases outperformed learners from the other two groups.

General Discussion

The present research evaluated three different approaches for designing learning material which foster transfer of knowledge about principles. Participants learned the principles of propositional logic with different kinds of materials. We assessed the transfer potential by an extensive transfer test comprised of several different transfer tasks. All transfer tasks required the retrieval and the application of knowledge about propositional logic to problems which differed in superficial characteristics from the learning materials but were based on the same relational structures (i.e. the principles of propositional logic).

In Experiment 1, we found that comparing two cases had the highest far transfer potential. Students who learned the generic instantiation did not perform better than the baseline. Surprisingly poor transfer performance resulted from comparing the generic instantiation with one case. Thus, comparing only single instances of different representations as it is usually implemented in multiple-representations-learning-materials seems not to be the best way to support learners in encoding a flexible source to solve future problems. In Experiment 2, we thus combined learning a generic instantiation with comparing two cases in different ways. The most successful combination was the simultaneous comparison of the generic instantiation with two cases (GENERIC+TWO_CASES). In contrast to the most successful learning material in Experiment 1, COMPARE_CASES, the GENERIC+TWO_CASES group did not only abstract and encode a generalizable schema but additionally learned a generic instantiation within the same amount of time. Comparing cases and a generic instantiation can thus be considered an effective way to support transfer of principles across domains and the acquisition of a representation that is needed for the formalized solution of complex problems.

To our knowledge the present study was the first to evaluate different approaches of how to foster transfer of knowledge about principles within one research program by using a broad range of transfer tasks. The findings have practical importance. The learning of principles is particularly common in mathematics and science instruction. Principles often cross-cut domains and thus, knowing principles and being able to flexibly transfer these principles can help students to understand diverse phenomena. Providing learners with a generic instantiation and two concrete instantiations (i.e. cases) of the principle simultaneously might be a promising way to design introductory learning materials to foster the transfer of knowledge about principles.

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