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Shared Knowledge in Collaborative Problem Solving: Acquisition and Effects

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Abstract

Whenever heterogeneous experts work together, shared knowledge comes into play. In recent years, two important research questions have emerged that we will address in the present paper. First, we analyzed if collaborative problem solving leads to the construction of shared knowledge. The second goal of this study was to demonstrate the assumed positive effect of shared knowledge on collaborative problem solving. Following Newell and Simon's (1972) classic view of problem solving, we distinguish shared knowledge about the initial situation, the goals, and the operators. The kind and amount of prior shared knowledge was varied as an independent variable in four experimental conditions. We showed that participants acquired shared knowledge during the cooperation and that most of this information was correct. Further results indicate that if collaborating partners have knowledge in common, their overall problem solutions are better than if they lack any kind of shared information. However, this effect seems to be mostly due to shared knowledge about initial situation and goals, as this leads to better solutions than shared knowledge about operators.

Introduction

Complex tasks often require the collaboration of experts with heterogeneous background knowledge. If we refer to this kind of collaborative problem solving, the construct of shared knowledge plays a very important role. Two lines of research dealing with the role of shared knowledge can be distinguished. On the one hand, there are studies that address the *acquisition* of shared knowledge in collaborative activities, especially in collaborative learning. On the other hand, many researchers focus on the *effects* of shared knowledge as a prerequisite for effective collaborative problem solving. In the present paper, we will address both issues in a net-based scenario.

Concerning the *acquisition*, it is mostly assumed that collaborative learning leads to the construction of shared knowledge (e.g. Pfister, Wessner, Holmer & Steinmetz, 1999; Roschelle & Teasley, 1995) through interaction and communication (Clark & Brennan, 1991). Although there is evidence for this assumption, this issue is seldom addressed quantitatively. In addition, the possibility of the emergence of false shared knowledge is often neglected. Only a few studies try to quantify the amount of shared knowledge (e.g. Fischer & Mandl, 2000; Jeong & Chi, 2000) and to analyze the way of its emergence (either through individual but similar experience with the learning material or by co-construction). There are several possibilities of co-constructing shared knowledge. One is that two interacting

partners mutually build a piece of shared knowledge that contains novel information, which none of them possessed in full before (e.g. Roschelle & Teasley, 1995). Another possibility, analyzed here, is that one person communicates some of his specific information to his partner, so that the latter learns and understands it, which constitutes shared knowledge between the two. One goal of this article is to analyze and quantify if collaborative problem solving leads to the acquisition of shared knowledge and to determine if it is correct or not. As collaborative problem solving also requires participants to communicate and interact in order to find a solution and, furthermore, in this experiment, to represent it in a common whiteboard, we hypothesize that participants will acquire some sort of shared knowledge.

Concerning its' *effects*, shared knowledge is supposed to be an important variable determining the functioning of groups consisting of members with heterogeneous background knowledge (e.g., expert groups; Hinsz, Tindale & Vollrath, 1997, Smith, 1994). Shared knowledge about the distribution of information within the group is regarded as a major constituent of the group's transactive memory system, which guides information encoding and retrieval on the group level (Wegner, 1987). This shared meta-knowledge augments the group's memory capacity and enables effective retrieval of information held by the group members when needed for problem solving (Moreland, Argote & Krishnan, 1996). Shared mental models comprising shared knowledge about task, team, equipment and situation have been found crucial for effective expert team decision making, problem solving and co-ordination in complex dynamic environments (Cannon-Bowers, Salas & Converse, 1993; Rouse, Cannon-Bowers & Salas, 1992). Furthermore, effective communication requires common ground and shared vocabulary (Clark & Brennan, 1991; Waern, 1992). As shown by this brief summary, the importance of shared knowledge for collaborative activities is widely acknowledged throughout the literature, although the term 'shared knowledge' refers to rather different things. Empirical studies on problem solving that demonstrate the effectiveness of shared knowledge are still rare. In the present paper, we therefore want to develop a taxonomy of shared knowledge that is applicable to problem solving activities in general. Furthermore, we will analyze its facilitating effects in collaborative problem solving and find out whether some components of shared knowledge are more effective than others.

A Taxonomy of Shared Knowledge for Collaborative Problem Solving

In line with Stasser and Titus (1985, 1987) we define *shared* knowledge as the kind of information two or more persons have in common, i.e., possess and understand in essentially the same way. Information available to only one person is called *individual* or *distributed* knowledge. Based on this definition our taxonomy of shared knowledge follows Newell and Simon's (1972) classic view of problem solving. According to Newell and Simon, knowledge about the initial situation, goals and operators is needed to solve a problem. Expanding this view to collaborative problem solving, shared knowledge can be conceptualized as *shared knowledge about the initial situation, the goals and the operators*. This taxonomy provides a more detailed description of shared knowledge and allows for the testing of differential effects of its components. Moreover, it is applicable to any problem without undue commitments concerning specific initial situations, goals and operators.

Analyzing the Effectiveness of Shared Knowledge

Design tasks are a widely used but scarcely investigated example of problem solving (Smith & Browne, 1993; Strube, Garg & Wittstruck, 2002). For our study, we chose the domain of web design with its heavy use of net-based communication between multiple experts as our experimental task: Dyads of subjects adopting the role of an information technology advisor (IT expert) and a representative of a fictitious company (company expert) have to design an online-shop that meets the company's needs. From the perspective of problem solving, the company expert's knowledge is characterized by information about the company's initial situation and goals. The expertise of the IT expert comprises knowledge about operators, i.e., rules to transform the company's goals and constraints into technical solutions.

As hypothesized above, shared knowledge is needed and facilitates collaborative problem solving whenever heterogeneous experts work together. Following this hypothesis and taking into account that individual problem solving requires individual knowledge about initial situation, goals and operators (Newell & Simon, 1972), we assume that collaborative problem solving requires shared knowledge about the initial situation, goals and operators. Therefore, we state the following hypotheses:

1. Shared knowledge, in general, leads to better problem solving performance than a total lack of shared knowledge.
2. Sharing knowledge about all components, the initial situation, goals and operators, is more effective than just sharing knowledge about the initial situation and goals.
3. Shared knowledge about the initial situation, goals and operators is more effective than sharing knowledge about operators alone.

4. Finally, we are interested in the particular difference of shared knowledge about the initial situation and goals as compared to shared knowledge about operators. Information about the initial situation and goals frame the problem and help to decide when a solution is reached. In contrast operators are means to transform one state into another, so we expect that sharing knowledge about the initial situation and goals has different effects than sharing knowledge about operators.

Method

Tasks and Materials

Design Task. Information needed for the design task was provided in two introductory texts, one for the role of the company expert and one for the role of the IT advisor.

After having acquired their task-relevant information (see next section), two participants worked on the design problem, one as the company expert and the other as the IT advisor. They were instructed to discuss solution features of the online-shop in preparation, via chat. Features which were chosen as part of the final solution were to be noted on a common whiteboard.

The introductory text for the company expert comprised 36 knowledge elements, 27 about the company's initial situation (IS) and goals (G), and 9 containing either shared knowledge or irrelevant filler information (depending on the experimental condition). Knowledge about IS and G was considered as a whole because a) this resembles the natural expertise of a company expert, e.g. a manager and b) knowledge elements about IS and G were of the same form, with the only difference that the goals were formulated as a request, e.g. "The company wants their customers to find the desired products quickly and easily". The introductory text for the IT advisor consisted of 27 knowledge elements about operators (O) and 9 shared elements or fillers. The operators had the form of if-then clauses with the 'then' part specifying a technical feature of the solution, and the 'if' part describing constraints to be fulfilled by the company. If the company's initial situation and goals match the 'if' part, the solution feature provided in the 'then' part should be marked as a desirable feature (DF) of the online-shop. If not, the solution feature should be marked as not being part of the online-shop's functionality (No DF). By integrating the 27 knowledge elements about initial situation and goals with the 27 operators, a total of 24 solution features (15 to be part of the shop and 9 to be rejected) were unambiguously determined. The following example should illustrate the task and a filler item (FI) for the company expert:

IS: Products cost between 7 and 180 Euro.

O1: If medium payments (5-1000 Euro) are expected, then the online-shop should provide the opportunity to pay by check or credit card.

O2: If micro payments (0.1-5 Euro) are expected, the online-shop should use systems like e-Cash.

DF: The online-shop should provide the possibility to pay via check and credit card.

No DF: E-Cash should be used for payments.

FI: The well known designer Philippe Starck designed the layout of the stores.

As participants were not true experts in the domain assigned to them, materials had to be simplified as compared to reality. Despite this simplification, the knowledge elements and solution features provided should be correct. Therefore, three experts on matters of the internet rated the correctness of the knowledge elements and the resulting solutions. As a result, several items were changed or eliminated.

Memory Test. To make sure that information provided in the introductory texts was acquired sufficiently, participants performed a memory test, similar to a recognition test. (The difference was that test items were not identical verbatim, but instead in meaning, to items presented during the learning phase.) The following example shows target (T) and distractor (D) for a knowledge element concerning the company's initial situation (IS). Items were presented in random order and should be classified as correct or false.

IS: Online sales should be integrated into the current business practices of the company, as it would be too costly to add additional personnel to process the online shop's orders by hand.

T: Due to personnel and administrative considerations online sales should be integrated into the business practices.

D: Due to personnel and administrative considerations online sales should be separated from the current business practices.

If the criterion of 95 percent correct responses was not reached, text and the subsequent test were presented again. This procedure was repeated until both subjects reached the criterion, or a time limit of 80 minutes was exceeded.

Further Tasks. In addition to the design task, participants had to complete two additional tasks. Prior to the experiment, they answered a questionnaire about relevant aspects of the IT advisor's knowledge. In order to make the experimental manipulation effective, only naive participants were accepted. As a fictitious company was used, there was no need to control for prior knowledge concerning the company. The final task was an unexpected repetition of the memory test already applied after reading the introductory texts. As opposed to the first time, the test now comprised *all* information relevant to the task for both subjects so that the amount of acquired shared knowledge can be determined.

Experimental Design

The kind and amount of prior shared knowledge (SK) was manipulated as an independent variable in four experimental

conditions. In the first condition, no shared knowledge is available prior to collaboration (No SK). The company expert's introductory text only contains the 27 knowledge elements about the initial situation and goals (IS+G), as well as 9 fillers. Accordingly, the IT-expert is provided with 27 operators (O) and 9 fillers. In the second condition, SK (IS+G), knowledge about IS+G is shared. Prior knowledge of the company expert remains unchanged, whereas the 9 fillers of the advisor's prior knowledge are replaced by 9 knowledge elements about initial situation and goals. These 9 elements form the dyad's shared knowledge. Similarly, condition 3 with shared operators is realized, SK (O): Fillers in the company expert's introductory text are replaced by 9 operators, whereas the advisor's prior knowledge stays the same as in the first condition. Condition 4, SK (IS+G+O), provides shared knowledge about both components, starting situation and goals, as well as operators. Like in conditions SK (IS+G) and SK (O), the company expert receives 9 knowledge elements about operators, and the advisor 9 elements about initial situation and goals, in addition to the 27 knowledge elements of their own expertise.

By sharing either 9 IS+G elements or 9 operators in conditions SK (IS+G) and SK (O), 9 solution features can be determined by the advisor (condition IS+G) or by the company expert (condition O) alone, since the shared knowledge elements provide all the information they need in addition to their own expertise. Although each participant is provided with some shared information in condition SK (IS+G+O), the number of solution features that do not require any collaboration remains 9 because the shared knowledge is distributed redundantly. Both partners are able to find the same 9 solution features on their own in condition SK (IS+G+O). In sum, the maximum possible correct solution features is 24 in all conditions.

The variation of shared knowledge as described above focuses on task-relevant shared information such as operators or goals. However, as many of the knowledge elements contained technical terms, providing some of the same knowledge elements to both participants might also have encouraged participants to develop a shared vocabulary around the terms both were exposed to. Furthermore, shared meta-knowledge is another aspect of what is meant by shared knowledge in the present experiment: In conditions SK (IS+G), SK (O) and SK (IS+G+O) participants were told that there is some information they both have in common.

Dependent Variables

Acquisition of Shared Knowledge. The amount of shared knowledge that was acquired during the collaboration was measured by the relative number of items that were recognized in the same way by both cooperation partners in the final recognition test. Initially shared items in the conditions with shared knowledge were excluded as well as all items that had not been discussed during the cooperation

task¹. This measure also allowed to differentiate between correct (items that were recognized correctly by both partners like a ‘hit’) and false shared knowledge (items recognized in the same way by both partners, but falsely like a ‘miss’).

Effects of Shared Knowledge. As an indicator of the effectiveness of shared knowledge, we chose solution quality as our dependent variable. It was measured by the amount of correctly noted solution features, ranging from 0 to 24. All features in the whiteboard were analyzed, only features mentioned more than once were excluded. Solution features were scored as correct if they corresponded to the ideal solution, as determined through the integration of the company expert’s and the IT advisor’s knowledge. Conversely, solution features contradicting the ideal solution were scored as false. Features that were neither correct nor false, were coded as irrelevant, e.g., intrusions or underspecified features.

In order to detect eventual differences in the difficulty of learning the knowledge supplied about IS+G and O, we measured the time required to read the introductory texts and to acquire the information, until the learning criterion was reached.

Subjects and Procedure

64 participants (47 females, 17 males) were randomly assigned to the 4 experimental conditions, as well as to the role of company expert or IT advisor. None of them had task-relevant prior knowledge as controlled by the first questionnaire. After having acquired the information presented in the introductory text according to the learning criterion, participants performed the design task for 50 minutes. This limit seemed to be appropriate as subjects finished their task quite easily within this timeframe. Afterwards, they completed the net-based questionnaire. The only task not expected by the participants was the final memory test. The experiment took between 2.5 and 3 hours all together.

Results

Acquisition of Shared Knowledge

As expected the hypothesis stating that collaborative problem solving leads to the acquisition of shared knowledge could be accepted for correct ($t_{(31)} = 23.25, p < .05$) as well as for false shared knowledge elements ($t_{(31)} = 4.71, p < .05$).

As table 1 shows, about one third of the discussed knowledge elements enter the pool of subject’s shared knowledge. The amount of shared knowledge did not differ significantly between experimental conditions ($F_{(3,56)} < 1$), but participants acquired significantly more correct than false shared items ($F_{(1,56)} = 447.86, p < .05$).

¹ Note that information in the partner’s domain can only be acquired by communication within the dyad.

Table 1: Mean relative number and standard deviations of correct and false shared knowledge (SK).

Condition	Correct SK	False SK
No SK	.37 (.07)	.01 (.02)
SK (IS+G)	.36 (.06)	.02 (.06)
SK (O)	.38 (.12)	.09 (1.0)
SK (IS+G+O)	.33 (.09)	.03 (.04)

Effects of Shared Knowledge

As the 24 solution features were unambiguously determined by combining the company expert’s and the IT advisor’s knowledge, solution features noted on the whiteboards had to be compared to this ideal solution. Because the features that subjects noted were often incorrectly formulated and thus ambiguous, criteria were defined to determine what variations could be accepted as correct. For example, if a solution feature was called ‘eMoney’ instead of ‘eCash’ this was counted in the same way. To control for objectivity, a second rater, blind to the hypotheses of the experiment, assessed all solution features again. 94 percent of all features were rated identically.

Table 2: Mean number and standard deviations of correct, false and irrelevant features.

Condition	Correct features	False features	Irrelevant features
No SK	9.00 (3.46)	1.50 (1.41)	4.50 (3.46)
SK (IS+G)	14.50 (3.16)	.88 (.35)	6.38 (3.85)
SK (O)	11.25 (2.71)	2.00 (1.20)	4.88 (2.85)
SK (IS+G+O)	14.50 (2.39)	1.88 (1.25)	3.75 (3.24)

ANOVA was carried out to compare the quality of the solution in the four experimental conditions. Table 2 shows the means in the 4 experimental conditions (main effect of shared knowledge: $F_{(3,28)} = 6.59, p < .05$). Linear contrasts were carried out to assess overall effectivity of shared knowledge (hypothesis 1), as well as the difference between shared knowledge about initial situation and goals, compared to shared knowledge about operators (hypotheses 4). Hypotheses 2 and 3 were tested by post hoc tests (Scheffé).

The first hypothesis was tested via a linear contrast of condition (No SK), in contrast to the average of conditions SK (IS+G), SK (O) and SK (IS+G+O). As expected, solution quality was poorer when shared knowledge was missing, compared to conditions SK (IS+G), SK (O) and SK (IS+G+O), which had different components of shared

knowledge ($t_{(28)} = 3.65, p < .05$). Concerning the relative effectiveness of shared knowledge about IS+G (hypotheses 4), compared to shared knowledge about O, the former lead to significantly better solutions than the latter ($t_{(28)} = 2.20, p < .05$). Hypothesis 2, stating better results with shared knowledge about IS+G+O, compared to shared knowledge about IS+G alone, was refuted. The same is true for hypothesis 3, stating better results with shared knowledge about IS+G+O, compared to shared knowledge about O alone, although means pointed towards the expected direction. All these analyses were computed for the correct answers.

Only a few false solution features were noted on the whiteboards, without significant differences between experimental conditions ($F_{(3,28)} = 1.60, p > .05$). The number of irrelevant features was also unaffected by the amount of prior shared knowledge ($F_{(3,28)} < 1$).

Subjects needed significantly more time to read and learn information about operators ($M = 2420$ m/sec, $SD = 618$), than those about the initial situation and goals ($M = 2025$ m/sec, $SD = 632$; $F_{(1,56)} = 6.61, p < .05$). There were no differences between the experimental conditions ($F_{(3,56)} < 1$).

Discussion

Concerning knowledge acquisition we assumed that the interaction during the design task would lead to the construction of shared knowledge. As results showed, participants in fact acquired shared knowledge even if the amount was smaller than it could have been. This result can be conceived as a first indicator for the importance of shared knowledge as it was acquired even though participants were not instructed to do so and testing was unexpected. Furthermore, most of this shared knowledge elements were correct, so that they can really help participants to construct a common representation of the task and the solution. In contrast to other studies (Fischer & Mandl, 2000; Jeong & Chi, 2000) we did not have problems in determining how this shared knowledge came about, as participants had no common learning or working material, so that the only way this could have happened is through co-construction. We also could be sure, that this shared knowledge did not exist prior to collaboration as the company expert's information was fictitious and knowledge in the domain of online-shops was controlled for.

Concerning the effectiveness, shared knowledge prior to collaboration leads to better solutions in net-based collaboration than working together without shared knowledge. Overall, solution quality was higher if there was shared knowledge (as in conditions IS+G, O and IS+G+O) than if shared knowledge was lacking, as in condition No SK. Although this general benefit of shared knowledge could be demonstrated, certain kinds of shared knowledge were more helpful in our task than others. Shared knowledge about initial situation and goals seemed to be more effective than shared operators, since the solution quality did not improve when shared operators were added in condition SK (IS+G+O). This result contradicted the hypothesis that sharing information about both components

of shared knowledge, initial situation and goals on the one hand, and operators on the other, is most effective. In the present study, sharing initial situation and goals alone, was as effective as additionally sharing operators. Apparently, sharing operators did not seem to have a facilitating effect on collaborative problem solving. Although the comparison between conditions SK (IS+G+O) and SK (O) lacked statistical significance, means were in line with the assumption that sharing operators is not very effective in a task like our experimental one. This interpretation is strengthened by the results of directly comparing the effectiveness of shared knowledge about the initial situation and goals, with that about the operators. Shared knowledge about IS+G clearly led to better performance than sharing operators.

But how can this effect be explained? First, the structure of the operators is more complex than that of the initial situation and goal elements. While the latter are simple sentences, the operators always combine an 'if' part with a 'then' part. This means that the operators contain technical solution features (in the 'then' part), in addition to information about possible situations and goals of the company (in the 'if' part). Besides their more complex structure, operators contained more information, framed in technical terms, that was new to the participants. Finally, information about the company provides company experts with a more coherent view of the company, whereas operators, in comparison, form a rather loose collection of rules for possible situations. We may assume, therefore, that operators are more difficult to process than knowledge elements about IS+G. This assumption is supported by the higher reading and learning time for operators than for IS+G. As a consequence, understanding and applying operators should be more difficult for the company expert than understanding information about IS+G is for the IT-advisor. From this, it follows quite naturally that sharing knowledge about IS+G should be more effective than sharing knowledge about operators.

Secondly, the structure of the operators has an impact on the ease of integrating information about IS+G into the 'if' part of the operators. As an operator's 'if' part already contains information about possible states of the company's initial situation and goals, it should be easy for the advisor to integrate the shared IS+G information into his or her operators, since it is just an instantiation of what is already provided in the operators' 'if' part. Thus IS+G information, either shared, or newly received during collaboration, does not provide information completely new to the IT advisor. In contrast, if the company expert receives operators, the solution provided in their 'then' part is completely novel information to him, and not just a specification of what he already knows. To deduce the resulting solution feature might therefore be more difficult. In addition, the advisor is able to realize (when he or she receives the shared knowledge elements) that the task-relevant information from the company expert is just a specification of the knowledge already provided by his or her operators. Asking

the right question to gather the information needed should therefore be easier for the advisor than for the company expert. Having shared knowledge about operators does not allow the company expert to infer other possible solution features, since knowledge about the initial situation and goals does not contain underspecified information about possible solution features. So in contrast to the IT advisor, it should be more difficult for the company expert to develop a coherent view of the partner's expertise and thus ask for the appropriate information.

In conclusion, shared knowledge is an effective variable facilitating collaborative problem solving. In the present paper, we show that sharing knowledge about operators is less effective than sharing the initial situation and goals, as the latter is easier to understand and integrate, and additionally, allows making assumptions about the partners' expertise. But shared knowledge is not only a facilitator for collaborative problem solving that can be provided externally or already exists but is also co-constructed during the problem solving process. Of course, it should also be noted that on the basis of the single experiment reported here, it is an open question whether the results hold for other problems and materials as well. Furthermore, the problem reported here is a well-defined one with a clear solution. Concerning ill-defined problems it can be assumed that the positive effect of shared knowledge about IS+G is reduced. In fact, operators will always be more complex, because per definition they consist of an 'if' and a 'then' part. What is said about the ease of integrating the IS+G information compared to integrating operators and inferring the partner's knowledge will also hold true for ill-defined problems. But it is questionable whether these factors will be as helpful *in finding a solution* because in ill-defined problems several solutions are possible. So, having all information to integrate operators and IS+G information does not unambiguously allow to deduce all solution features. Therefore, we assume that sharing knowledge about IS+G is still effective, given the structural differences explained above, but that this effect is less strong.

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