KNOWLEDGE CONVERGENCE IN COMPUTER-SUPPORTED COLLABORATIVE LEARNING: THE ROLE OF EXTERNAL REPRESENTATION TOOLS

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Knowledge Convergence in Computer-Supported Collaborative Learning: The Role of External Representation Tools

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Abstract

This study investigates how two types of graphical representation tools influence the way in which learners use knowledge resources in two different collaboration conditions. In addition, the study explores the extent to which learners share knowledge with respect to individual outcomes under these different conditions. The study also analyzes the relationship between the use of knowledge resources and different types of knowledge. The type of external representation (content-specific vs. content-independent) and the collaboration condition (videoconferencing vs. face-to-face) were varied. Sixty-four (64) university students participated in the study. Results showed that learning partners converged strongly with respect to their use of resources during the collaboration process. Convergence with respect to outcomes was rather low, but relatively higher for application-oriented knowledge than for factual knowledge. With content-specific external representation, learners used more appropriate knowledge resources without sharing more knowledge after collaboration. Learners in the computer-mediated collaboration used a wider range of resources. Moreover, in exploratory qualitative and quantitative analyses, the study found evidence for a relation between aspects of the collaborative process and knowledge convergence.

Keywords: Cooperative learning, collaborative learning, graphical representation, shared knowledge, shared external representation, videoconferencing, visualization, knowledge convergence

Knowledge Convergence in Computer-Supported Collaborative Learning: The Role of External Representation Tools

A question which is central for both research and for the practical application of computer-supported collaborative learning is, how spatially distributed learners manage to converge with respect to their knowledge. In this paper, we will focus on a theoretical aspect which seems both highly relevant for the field and which has so far been neglected by empirical research: the aspect of knowledge convergence. According to Roschelle (1996), convergence, not conflict, is the crucial aspect of collaborative learning: two or more learners whose activities have an impact on those of their partners, which in turn have an impact on their own activities. Salomon and Perkins (1998) spoke of "Spirals of Reciprocity" to characterize these collaborative interdependencies. The psychology of knowledge acquisition has dealt mostly with the individual. Even when analyzing collaborative learning processes, attention has been focused on how individuals represent their knowledge and how they solve problems. What the learning partners actually do and how they represent their knowledge and solve problems has played a subordinate role up to this point (Jeong & Chi, 1999). Even less is known about how convergence is affected by specific characteristics of different collaboration conditions. We believe that a more elaborated concept of knowledge convergence could advance research on computer-supported collaborative learning.

In our analysis of collaborative learning, we will consider two main aspects of *knowledge convergence*: process convergence and outcome convergence (Fischer, 2002). (1) *Process convergence*: An important issue in literature on collaborative learning is how learners influence the learning of their partners (e.g., Tudge, 1989). An important concept here is transactivity in discourse (Teasley, 1997), i.e., how "participants acknowledged, built, and elaborated on other's ideas" (Hogan, Nastasi & Pressley, 2000, p.426). Recent approaches in social psychology emphasize the interdependence of cognitive responses within dyads or groups (e.g., Nye & Brower, 1996). Interdependence means that "each individual's cognitive responses are influenced by the interaction in which he or she is a participant" (Ickes & Gonzalez, 1996, p.297). *Convergence* (or divergence) of the cognitive responses can be determined as the most basic aspect of this interdependence. Convergence means that the reciprocal influence of the collaborators leads to an increased similarity of the cognitive responses within the group (Ickes & Gonzales, 1996).

In collaborative learning environments, convergence with respect to several types of cognitive responses in the learning process could be addressed. If two or more learning partners collaborate, they use both shared and unshared knowledge resources. An important question is how two or more group members use the knowledge available to them (from their prior knowledge and from learning material) to collaboratively construct new knowledge through discussion. From studies in collaborative decision-making and problem-solving, we know that groups often tend to neglect unshared resources, i.e., knowledge and information that only one person or a small percentage of group members have access to (e.g., Buder, Hesse, & Schwan, 1998; Stasser & Stewart, 1992). Instead, the group members discuss the knowledge resources and information that they are all aware of. So far, few empirical studies have investigated the role of this biased information-sampling phenomenon with respect to learning. The studies of Roschelle and Teasley (Roschelle, 1996; Roschelle & Teasley, 1995) showed that learning partners mutually impact the learning process, even in short term collaborative activities. By presupposing that a range of different resources are available in collaborative learning environments (e.g., prior knowledge, new conceptual knowledge, contextual information), we assume that dyads or groups develop a specific profile of resource use in a given context, i.e., they converge with respect to their resource use. Different tasks may require collaborators to converge to varying degrees. Whereas some tasks typically require learners to find and to sustain a shared focus of attention (e.g., collaborative problem-solving), other tasks may allow collaborators to diverge and specialize. In this way, learners may only use a small number of joint resources (Klimoski & Mohammed, 1994). So far, there is only some initial research on the question regarding how and to what degree a joint focus of attention on resource use is actually established in collaborative learning groups. The Roschelle (1996) study indicates that a collaborative style of what to include in the "joint problem space" develops over time. Barron (2000) showed that a major aspect is how the use of resources is coordinated within a group (e.g., Barron, 2000). The explicit coordination of the learning partners on how to proceed with the task, as well as when to include specific resources is often seen as a crucial factor for promoting learning and cognitive development (e.g., Rogoff, 1991).

(2) *Outcome convergence: Types of shared knowledge.* If group members learn together, they can construct shared cognitive representations. It may be of interest to examine to what extent the learning partners construct similar knowledge representations. A number of studies show that team members converge in similar knowledge representations during collaboration (see Klimoski & Mohammed, 1994). Such a dynamically developed shared knowledge base can increase team efficiency in work settings (e.g., Cannon-Bowers & Salas, 1998; Orr, 1990). At least some degree of shared knowledge seems to be necessary for teams to work effectively. Although different types of teams might require different degrees of shared knowledge to function appropriately, the extremes (all knowledge in common vs. no shared knowledge at all) can be detrimental to team efficiency (see Klimoski & Mohammed, 1994). Recently, theoretical approaches on learning communities (e.g., Bielaczyk & Collins, 1999; Scardamalia & Bereiter, 1996) have explicitly

emphasized the importance of shared knowledge. Members of collaborative learning communities search, collect, and share resources which could be relevant to a particular topic of interest. Some degree of shared knowledge can improve collaborative learning in small groups as well as in other kinds of collaborations (e.g., Nicolopoulou & Cole, 1993). However, the pioneering study of Jeong and Chi (1999) showed that only a relatively small portion of the knowledge, which a dyad constructs during collaboration, is actually represented by both of the learners. Moreover, it is not guaranteed that shared representation will lead to a similar application of knowledge (Renkl, Mandl, & Gruber, 1996). Therefore, we also consider *shared application-oriented knowledge* to be an important outcome. One main question is, to what extent former learning partners are similar in their ability to apply the knowledge to new contexts.

The relationship between process convergence/divergence and outcome.

Approaches employed in the learning sciences and in educational psychology often seem to imply that convergence-related processes and outcomes are desirable as such, especially in cases where learners converge on a high level. However, studies on group decision-making show that converging cognitive processes during collaboration do not necessarily lead to better individual outcomes or result in more similar outcomes (see Brodbeck, 1999). For instance, an individual who adapts his/her thinking to fall in line with another group member might abandon his or her own more effective strategies in tackling a problem. In cases where a group has to utilize as many of the available knowledge resources as possible, it might even be beneficial for the group outcome if the individuals diverge during the collaborative process (Schultz-Hardt, Jochims & Frey, 2002). So far, there is limited empirical evidence on these relationships in the context of collaborative learning. In addition, there is only limited empirical evidence that sharing knowledge is actually beneficial for individual learning outcomes (Jeong & Chi, 1999).

Computer-supported collaborative learning

Computer-mediated communication through videoconferencing. Thus far, collaboration conditions using internet-based communication technologies have hardly been investigated systematically with respect to knowledge convergence. Sassenberg, Boos, Laabs and Wahring (1998) showed the phenomenon of biased information sampling (the tendency to neglect unshared knowledge resources in group decision making, see above) for synchronous text-based collaboration. However, in that study, the effect was of comparable size in the computer-mediated scenario and in a face-to-face setting. It is unclear to what extent the conditions of videoconferencing impact the use of knowledge resources and the construction of shared and unshared knowledge. Until now, there have been few systematic studies on this topic. The learning partners may mutually influence which knowledge resources are used in a joint problem space through non-verbal and paralinguistic signals. Although non- verbal and paralinguistic signals can partially be transported through audio and video connections, differences do exist between face-to-face communication and videoconferencing (Fussel & Benimoff, 1995; O'Connaill & Whittaker, 1997). For example, the lack of eye contact and gaze awareness as well as the limited ability to make deictic gestures in a videoconference might increase the difficulty of maintaining joint focus during collaboration. Overlapping turns and unwanted interruptions can often occur under these conditions. Collaborators frequently react to these problems with longer turns and a higher number of verbally explicit attempts to coordinate their activities (Sellen, 1992). Depending on technical aspects of the environment (e.g., delay, quality of audio transmission), it might be more or less easy to keep a joint focus of attention. Therefore, an increased process divergence can be expected in videoconferencing environments, as collaborators have more difficulties referring to the same concepts or objects.

With respect to outcomes, on the other hand, most empirical studies on problem-solving and decision-making found few substantial differences between videoconferencing and face-to-face conditions. In spite of different process characteristics, individuals in a group typically reach qualitatively similar solutions in videoconferencing and in face-to-face settings (see Finn, Sellen & Wilbur, 1997).

Knowledge convergence and shared external representation.

Researchers in the field of cooperative learning often emphasize the importance of instructional support. A number of different approaches have been developed and tested in empirical studies (see Cohen, 1994; Slavin, 1996). With regards to computer-supported collaboration, visualization by shared graphical representation tools play an increasingly important role (e.g., Roschelle & Pea, 1999). One major dimension of shared graphical representations is the degree of content specificity. Prototypical examples of *representation tools* are the highly popular shared whiteboards (mostly simple graphic editor software). They are intended to support interaction between distant collaborators by providing them with the opportunity to collaboratively visualize graphical elements as well as written notes (Dillenbourg & Traum, 1997). However, the subject area (e.g., medical diagnosis, botanical classification), as well as the task type (e.g., discussion, decision making, learning) do not influence the design of these tools. Alternately, in *content-specific graphical representations*, the degrees of freedom of the external representation are constrained by content and task-relevant structures. For example, so-called visual languages are designed to support discourse by providing collaborators with a set of symbols for task-specific categories (Lakin, 1990; Suthers, 2001). The CardBoard system, for instance, is a core component of a web-based learning environment that provides learners with a visual language for a scientific discussion (Gassner & Hoppe, 2000). Learners can visualize their contributions using categories such as clarifying questions, inference, rejection, pro and contra arguments, or association. Thus far, there have been no empirical investigations comparing the effects of content-specific shared representation vs. content-independent shared representation with respect to process and outcome convergence in face-to-face and computer-mediated collaborative learning scenarios. Analogous to the *representational guidance* concept (Suthers, 2001; Suthers & Hundhausen, 2001) a simple *representational convergence assumption* could be formulated to state that the provision of a shared representation tool would facilitate process convergence with respect to a more similar use of knowledge resources. With respect to outcomes, external representation tools should foster the construction of shared knowledge. Both effects could be seen as independent of the content specificity of the representation tool. However, due to the conceptual structure of the *content-specific* external representation, content specificity would increase the convergence to instructionally desirable points in the conceptual space.

Research questions and hypotheses of the study

Based on the information presented above, the study examines knowledge convergence with respect to processes and outcomes under different collaborative conditions. The following four research questions and resulting expectations have been formulated:

(1) *To what extent is there a tendency for collaborative learners to converge with respect to processes and outcomes*? Our expectations were as follows: Independent ofthe content specificity of the representation tool and of the collaboration condition, the dyadic interaction should increase knowledge convergence to a substantial degree. More specifically, we assume (a) a general tendency towards process convergence. Therefore

collaboration in a group of learners should increase the level of similarity in resource use. (b) Collaboration in a group of learners should increase the level of shared factual knowledge. (c) Collaboration in a group of learners should increase the level of shared application-oriented knowledge.

(2) *What are the effects of the content specificity of the shared representation tool and of the collaboration condition on process convergence*? Our expectations where as follows:
(a) Content specificity of the shared representation facilitates the convergence of resource use, and should foster convergence towards the conceptual resources it represents. (b) In a videoconferencing condition, convergence in resource use should be less than in a face-to-face condition, independent of the content specificity of the shared representation. (c) The effects of content specific shared representation tool on process convergence should be moderated by the collaboration condition.

(3) What are the *effects of content specificity of the shared representation tool and of the collaboration condition on outcome convergence?* The according expectations where:
(a) Content specificity of the shared representation tool should facilitate both the convergence of factual knowledge and the convergence of application-oriented knowledge. (b) The videoconferencing condition should not differ from a face-to-face condition with respect to either the convergence of factual knowledge or the convergence of application-oriented knowledge. (c) The effects of the content specificity of the shared representation on outcome convergence should be independent of the collaboration condition.

(4) *How are the aspects of knowledge convergence interrelated?* We assumed that (a) more successful learners share more knowledge than less successful learners. (b) Furthermore,

we assumed that there are discourse patterns, which facilitate the construction of shared knowledge. As we did not find theoretical models or empirical studies to warrant specific assumptions, we formulated the following exploratory research question: Which discourse patterns facilitate outcome convergence?

Method

Overall analytical approach. To investigate our research questions, we analyzed the interactions and learning of pairs of university students of educational science[i] as they evaluated a set of cases about teachers managing a collaborative learning situation. These pairs collaborated under 4 different collaborative learning conditions – using video-conferencing or working face-to-face while using content-specific or content-independent representations. Students first worked individually and read a theory text about collaborative learning, and then evaluated and made recommendations about a specific collaborative learning situation described in the case. We collected information about their prior factual and application-oriented knowledge of collaborative learning, recorded audio of their discourse and final evaluations, and tested their factual and application-oriented knowledge after their collaborations. These data were aggregated and used to determine process as well as outcome convergence. We used nominal dyad analyses to further determine the percentage of knowledge convergence, which could be attributed to actual dyadic interaction. In addition to the quantitative analyses of the effects of the collaboration conditions, we used qualitative single case analyses to gain more insight into the complex interaction patterns potentially related to knowledge sharing.

Sample and design. Sixty-four students of educational science1 from the University of Munich volunteered for this study. The participants were separated into dyads and each dyad was randomly assigned to one of the four experimental conditions in a 2x2-factorial design. Participants did not know each other beyond their usual contact in the courses (i.e., we made sure that friends were not assigned to the same dyad). We did not try to homogenize the dyad composition with respect to gender, age or prior knowledge. However, as more than 70% of the participants were female, there were more female student dyads than male student dyads. We varied the content specificity of the graphical representation tool (content-independent vs. content-specific) and the collaboration condition (face-to-face vs. videoconferencing). Time-on-task was held constant in all four conditions (three hours).

Learning environment. Students in all conditions had to work on complex cases in the domain of education. During the collaboration phase, students were asked to apply theoretical concepts from a theory text included in the learning environment in order to analyze the cases. (1) Theory text. Students were provided with a three-page description of an integrated theoretical framework for the conditions of successful small group learning according to Slavin (1993) and Cohen (1994). First, the text argues that it is important to distinguish "collaboration-supporting practice tasks" from "natural group tasks" using a specific set of criteria. Collaboration-supporting practice tasks are tasks that can potentially be solved by individual learners as well as by a group of learners. Therefore, the motivation to work together and help each other has to be fostered by setting up a specific reward structure. Among the central concepts introduced are "group rewards", "criteria-oriented vs. social norm -oriented", and "identification of individual contribution". "Natural group tasks" are introduced as typically revolving around "ill-defined problems" that are characterized by "no single or standard solution procedure" and potentially more than one right solution, and that includes a high degree of "resource interdependence" of the learners. (2) Cases. In these cases, fictitious teachers describe a plan for an instructional session and ask the participants (in their role as university students of education) for an evaluation of the plan from a theoretical perspective. In one of the cases, for example, a young teacher from a vocational training school reports a detailed plan for a lesson including small group learning (see Appendix). Case information provided points to a natural group task. However, a reward structure is in place, which is more appropriate for a collaboration-supporting practice task, potentially undermining intrinsic motivation of the students. All the cases include strengths and weaknesses (i.e. appropriate and inappropriate task features when analyzed with respect to the integrated theoretical framework for the conditions of successful small group learning).

Experimental Task. While working collaboratively on a case, students were provided with a collaborative, synchronous visualization tool to represent their solution graphically. The students' task was to prepare an (spoken) evaluation of each of the cases together using the graphical tool to represent the most important case information and the most relevant theoretical concepts. Students were told prior to the analysis that they would have to provide the spoken evaluation after 25 minutes of collaboration on each of the cases. The representation tool would support the evaluation and they would be able to keep the visual representation that they constructed during this spoken evaluation.

Collaboration conditions. All dyads collaborated in synchronous computer-supported learning environments with synchronous shared external representation tools displayed on a 20" monitor.

In the videoconferencing condition we used a desktop videoconferencing system and application sharing technologies to support the collaborative and synchronous use of the representation tools. Realization of audio and video transmission: Commercially available desktop videoconferencing environments still had large picture-sound delays (from 0.3 to 1 sec) at the time this investigation took place. Moreover, the audio transmission in these systems often was of an inconsistent quality. As it was not the goal to investigate interaction problems due to technical deficits that should vanish in a few years, we decided to set up an audiovisual communication without noticeable delay between sound and picture. More importantly, we ensured the use of a perfectly clear audio component without any degradation in quality over time. In our experimental setting, we directly wired a camera and a microphone positioned on the monitor in one room to the computer in the other room so that resource consuming compression and decompression could be reduced to a certain degree. As we used neighboring lab rooms, the wires could connect the hardware components directly through the separating wall. We used a standard active loudspeaker system for the audio display. The audio component allowed for synchronous sending and receiving enabling learning partners to speak at the same time. We used two identical Connectix QuickCams as video cameras. The video signal was further processed by Apple QuickTime Conferencing software. The video picture was located near the upper right corner of the screen directly under the camera to ensure a certain degree of eye contact. Picture size was less than one sixth of the full screen size. The shared external representation tools were realized by a data conferencing component (Timbuktu Pro) that allowed screen sharing in real-time via TCP/IP. This ensured both learners to be able to access the shared external representation tool simultaneously. The system worked reliably throughout the study.

In the face-to-face condition, learners collaborated in physical co-presence (i.e., sitting side-by-side in one room) with reference to one 20" computer screen. Each learner had a keyboard and a mouse of his or her own.

FIGURE 1 The content-independent shared representation tool. The toolbar provides access to different functionalities of a simple graphics and text editor. No specific prior structure concerning the content andthe task is represented in the tool.

C*ontent specificity of the shared external representation.*

Dyads in the *content-specific representation tool condition* were provided with the CoStructure-Tool, a computer-based graphical mapping tool that includes boxes for case information and boxes for theoretical concepts, into which text can be typed directly (Fig. 1). Different types of lines representing positive and negative relations can be used to connect the boxes. Moreover, the screen of the CoStructure-Tool is divided into an empirical and a theoretical level. Both learners in each dyad were provided with a keyboard and a mouse and could access the different objects on the screen simultaneously. Learners in the *content-independent shared representation condition* worked on a computer tool, which included the functionality of a simple graphic editor (Fig. 2). The learners could type and edit text, draw lines, circles and rectangles, change the colors of these items, and drag the items across the screen. All these functions were accessible via a tool bar. In contrast to the content-specific representation tool, this structure did not involve different conceptual levels, concept cards with their semantic labels, or different types of connection lines. Thus, when compared to the content-specific representation, the content-independent representation provided students with greater degrees of freedom to express their thoughts. We used this condition as a control for possible alternative functions of the external representation, e.g., as an external extension of the limited working memory.

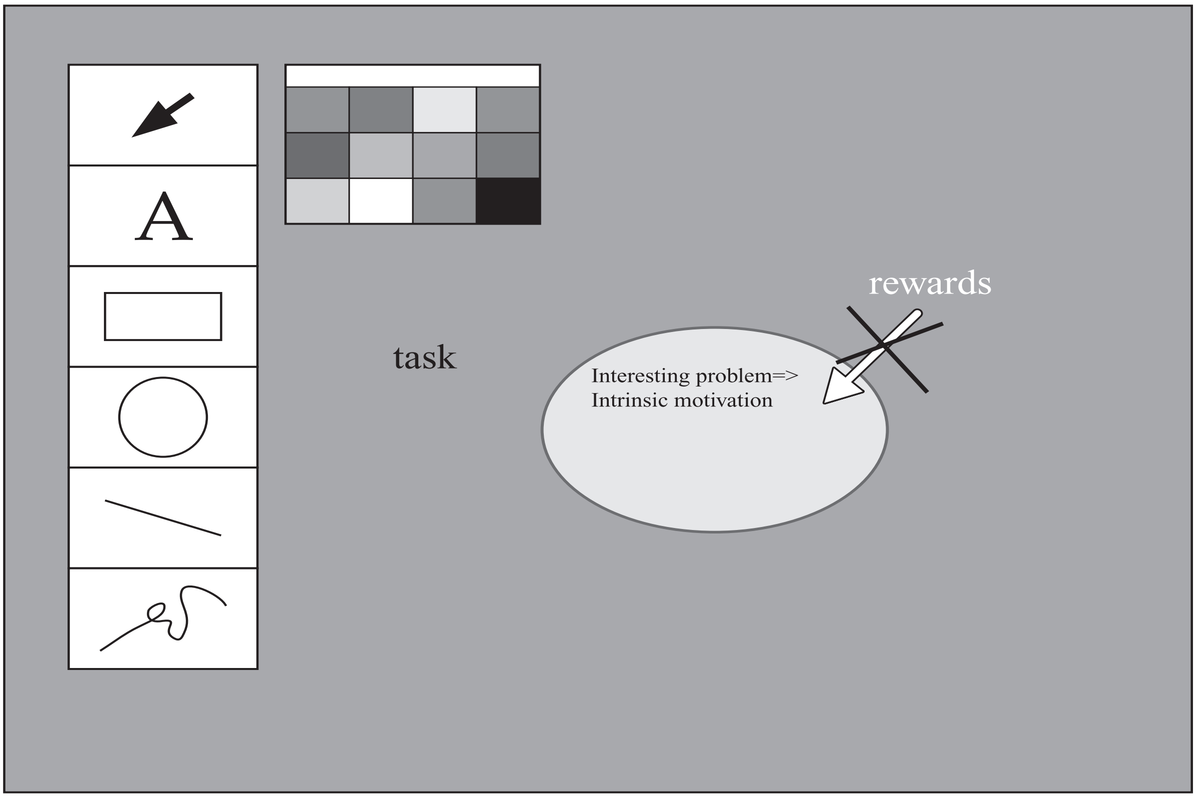


FIGURE 2 The content-specific shared representation tool with two different conceptual levels (theoretical and empirical), concept cards for the representation of concepts and case information on these levels, and two different relation types (symbolized by the lines).

Procedure. Students were given a questionnaire on demographic aspects and prior experience with the technologies employed in the studies (5 min), as well as a pre-test including a content-specific factual knowledge test (10min), and a case task to measure application-oriented knowledge (15 min). Students were then made familiar with the learning environment, especially with the use of the shared representation tools (25 min). Next, learners read the theory text and worked together on three cases (95 min). The collaboration was followed by an individual post-test of factual and application-oriented knowledge (that paralleled the individual pre- tests). Finally, learners completed a questionnaire on controlled variables (e.g. motivation).

Instruments, variables and data types

(1) Process convergence. As data sources to assess process convergence within the dyads, we used tape recordings of discourses and of (oral) final evaluations. To reduce the volume of data, we decided to analyze the discourse of only one of the three cases, which the learners worked on collaboratively (see Appendix for the selected case). We separated the transcripts of audio taped discourse protocols into 8026 speech act segments. We used a coding scheme for the analysis of collaborative knowledge construction developed earlier (Bruhn, Gräsel, Fischer & Mandl, 1998). From this more comprehensive coding scheme we only used the "content" dimension - to determine the kind of resources the learners used in discourse. There were 6 categories of resource use and explicit coordination used. As indicator of (a) new conceptual resources, we determined the number of segments that refer to concepts in the theory text. Example: "I thought that in natural group tasks there should be no additional group rewards". (b) To assess the use of contextual resources, we counted the number of segments that explicitly refer to case information in the given case description texts. Example: "Did you understand what the teacher wants to do with this video thing?" (c) For relations between new conceptual and contextual information we counted segments that explicitly linked a theoretical concept within the theory text to case information. Example: "This video tape is a kind of group reward, isn't it?" (d) As indicators of prior knowledge resources we counted segments that included explicit

reference to a theoretical concept NOT included in the theory text. Example: "In the Graesel seminar on Tuesday someone introduced this Self-Determination Theory." (e) We assessed the relations between prior knowledge resources and conceptual resources by determining the number of segments explicitly linking theoretical concepts which were not in the theory text to case information given in the case description texts. Example: "These media assignments run counter to self-directed learning in my view." (f) Moreover, we measured the explicit coordination of resource use as the number of segments, including verbally explicit attempts to regulate or sequence the use of the six resource types described above.

The analyses with this coding scheme are the basis for the measures of convergence in resource use (see paragraphs below) and for the single case studies in connection with research question 4 (see point (3) of this section).

Measures of convergence in resource use applied in the study. To assess convergence in resource use we determined (a) profiles of resource on the basis of the six resource-use categories described above (e.g., contextual resources, new conceptual resources) and (b) an overall coefficient of convergence in resource use. The six variables were z-standardized. (c) Moreover, we measured representational convergence.(a) In a single case approach, the individual frequencies were used to visually represent the similarity/dissimilarity between the profiles of resource use of learner A and learner B in dyadic diagrams. These were used to illustrate the results regarding research question 1. Narrow lines for learner A and learner B indicate a basic similarity in resource use. The profiles of resource use are similar if both learners refer with similar frequency to the resource use categories (e.g. to new contextual resources). (b) In a second step, we calculated an overall coefficient of convergence/divergence in resource use. The score is a dissimilarity measure based on Euclidean distances. The variables included in the calculation were the (z-standardized) individual frequencies on the six categories of resource use (see Cook, Salas, Cannon-Bowers and Stout, 2000 for a comprehensive discussion of different dissimilarity measures). This score is easily computed with the distance procedures in statistics software packages. We used the six variables of resource use (in rows), the two learners of the dyads (in columns), and squared Euclidean distances as the measure. A low score indicates convergence in resource use between dyad members, whereas a higher score can be seen as an indicator of divergence.

(c) Measurement of representational convergence towards the conceptual structure represented by the external representation tool. The frequency of use of new conceptual resources in discourse was used as an indicator to assess the extent to which learning partners converged with respect to resources represented by the tool. New conceptual resources and their categorization are the predominant components of content-specific representation. Therefore, more frequent use of new conceptual resources can be regarded as evidence of representational convergence towards the conceptual structure of the representation tool.

(2) *Measurement of outcome convergence*. Two different kinds of knowledge tests were used to measure factual knowledge and application-oriented knowledge. The factual knowledge test consisted of two open questions focusing on the concepts of the theory text. The open questions were "When is small group learning successful?" and "When is small group learning NOT successful?" No further prompting was used. The answers were divided into proposition-like segments and coded with respect to a comprehensive content analysis scheme consisting of central concepts of the theory text. We defined (a) *shared*

factual knowledge as the number of concepts and the relations between these concepts, which both former dyad members appropriately described in their (individual) factual knowledge test. (b) *Unshared factual knowledge*, in contrast, was determined by the number of concepts and the relations between these concepts which only one of the two former dyad members described appropriately in the test. Similar operational definitions of shared factual knowledge were previously used by Jeong and Chi (1999).

Beyond factual knowledge tests, we used a *case task to assess application-oriented knowledge*. For the prior knowledge test and post-test, different cases were used. The cases were similar to the collaborative cases (see Appendix for an example) in that they reported an instructional problem of a teacher who is planning a group-learning situation. They also included the idea that this plan should be evaluated from a theoretical perspective. The cases were also similar to those used during collaboration with respect to writing style and degree of difficulty. The individual oral evaluations were transcribed, segmented into proposition-like parts and coded with respect to the number of appropriately applied concepts of the theory text. Similar to the approach used for factual knowledge, we defined (a) *shared application-oriented knowledge* as the number of new conceptual resources and the relations between new conceptual resources and contextual resources, which both former dyad members appropriately used in their (individual) case analysis. (b) *Unshared application-oriented knowledge*, in contrast, is defined as the number of new conceptual resources and the relations between new conceptual resources and contextual resources, which only one former dyad member appropriately used in his or her (individual) case analysis.

The reliability coefficients for the variables ranged from Cronbach's alpha = .78 (shared application-oriented knowledge) to Cronbach's alpha = .87 (for shared factual knowledge).

(3) Analysis of *discourse patterns* (research question 4). To analyze the relationship between the profiles of resource use and outcome convergence, three dyads with the highest degree of outcome convergence (i.e., high shared factual *and* high shared application-oriented knowledge in the post-test) and three dyads with a low degree of outcome convergence (i.e., low shared factual *and* low shared application-oriented knowledge in the post-test) were selected post-hoc and compared with respect to their resource use.

In addition, we conducted qualitative single case studies on more complex discourse patterns. The procedure consisted of (a) formulating one or more interaction-related hypotheses that were able to explain the discourse patterns of one specific dyad to some degree, (b) test and possibly refute the hypotheses in a consensus-oriented inquiry in the transcript with a second investigator and (c) test, refine, and possibly refute the hypotheses in other dyads. Although this method is of a highly interpretive nature, it seems to be an appropriate approach to the analysis of longer and more complex discourse sequences, for which traditional quantitative analyses are of little help. It can be regarded as a means to generate hypotheses for further research.

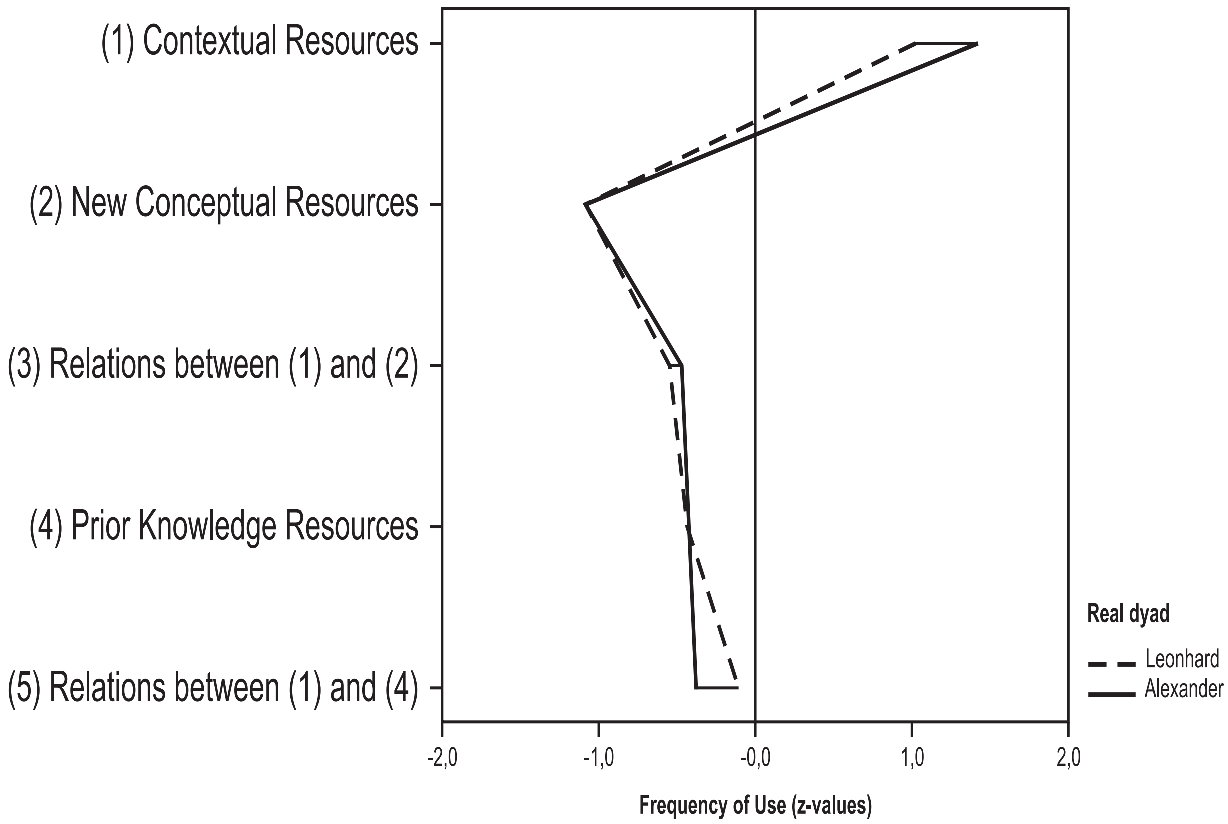
Nominal dyad analyses. Nominal dyads are used as a baseline for a number of dyadic variables (Jeong and Chi, 1999). Two learners of the same experimental condition who have not worked together were randomly assigned to nominal dyads post-hoc. Nominal dyad analyses aim at identifying parts of the variance beyond those explained by the experimentally varied conditions, which can be attributed to the specific interaction within dyads. Therefore, nominal dyad analyses systematically compare nominal dyads to real dyads (i.e., two learners who actually worked together during the collaboration phase). As all other conditions remained the same, actual interaction during the collaboration phase was the only difference between real and nominal dyads.

Note that this definition of nominal groups differs from those typically used in social psychology (see Brodbeck, 1999). In social psychology, nominal groups are composed of individuals who actually worked individually on an experimental task. In our case, all individuals worked in dyads during the experiment but were assigned to another dyad post-hoc.

Learning prerequisites and controlled variables. Among the most important learning prerequisites, we measured prior knowledge with the two knowledge tests described above (factual and application-oriented knowledge). We also examined the learner's experience with visual learning strategies (two items in the questionnaire at the end of the experiment) and their experience with computer and network technology (two items in the questionnaire at the beginning). After the experiment, we administered a 9-item motivation scale.

In the different analyses, we used the dyad or the individual as the unit of analysis. We used univariate, ANOVAs with two between-subject factors to analyze the effects of the conditions as well as their interaction on the dependent variables; t tests were used for the comparison of real dyads to nominal dyads and the post-hoc comparison between successful and less successful learners. An alpha level of .05 was used for all statistical tests.

Profiles of Resource Use in Real Dyads



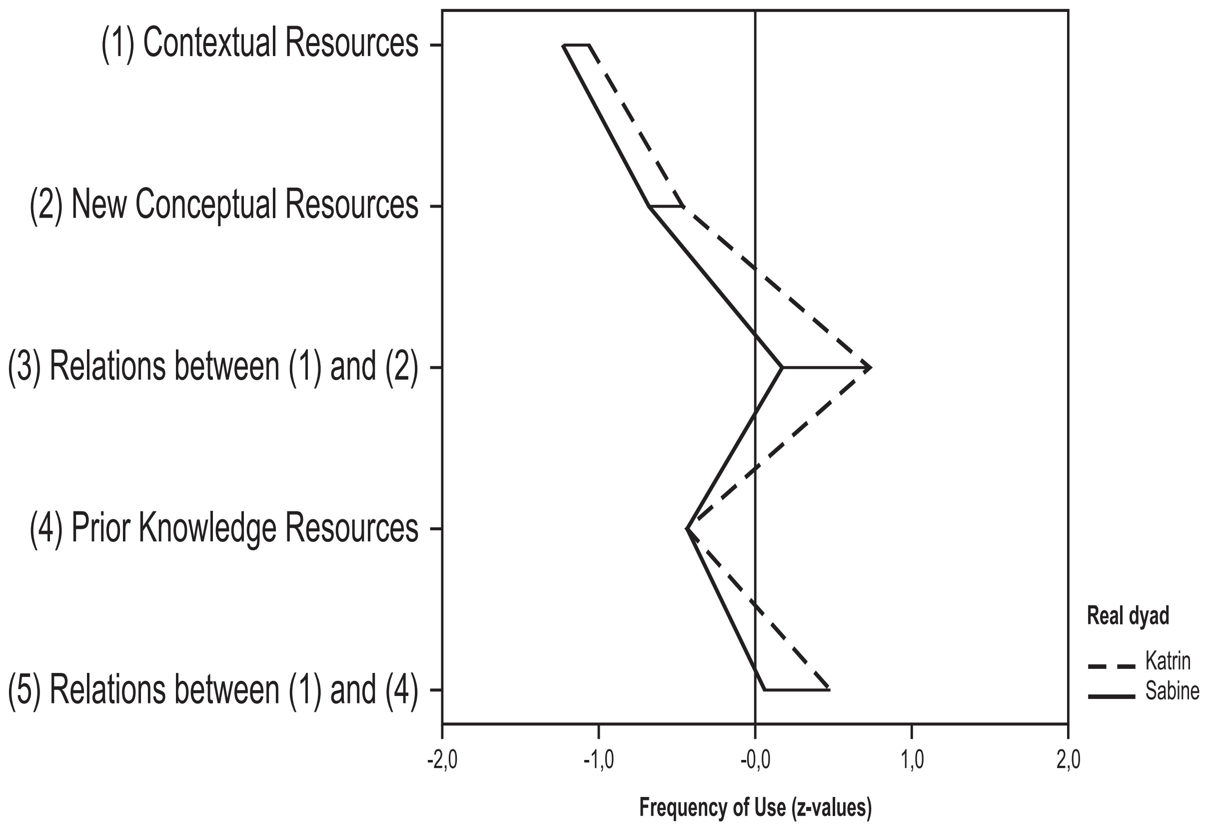


FIGURE 3 Profiles of resource use for real dyads. The line represents the individual values on the z-standardized variables of resource use. The closeness of both lines indicates high similarity in the profiles of resource use in a specific dyad.

Results

Learning prerequisites and controlled variables

Concerning learning prerequisites we found that the experimental groups did not differ systematically with respect to prior knowledge (which was relatively low in all of the four groups). Similarly, randomization was successful with respect to the controlled variables. We found no substantial differences concerning the experience with visual learning strategies, or with computer and network technologies. In the questionnaire at the end of the experiment, we found no differences with respect to learning motivation.

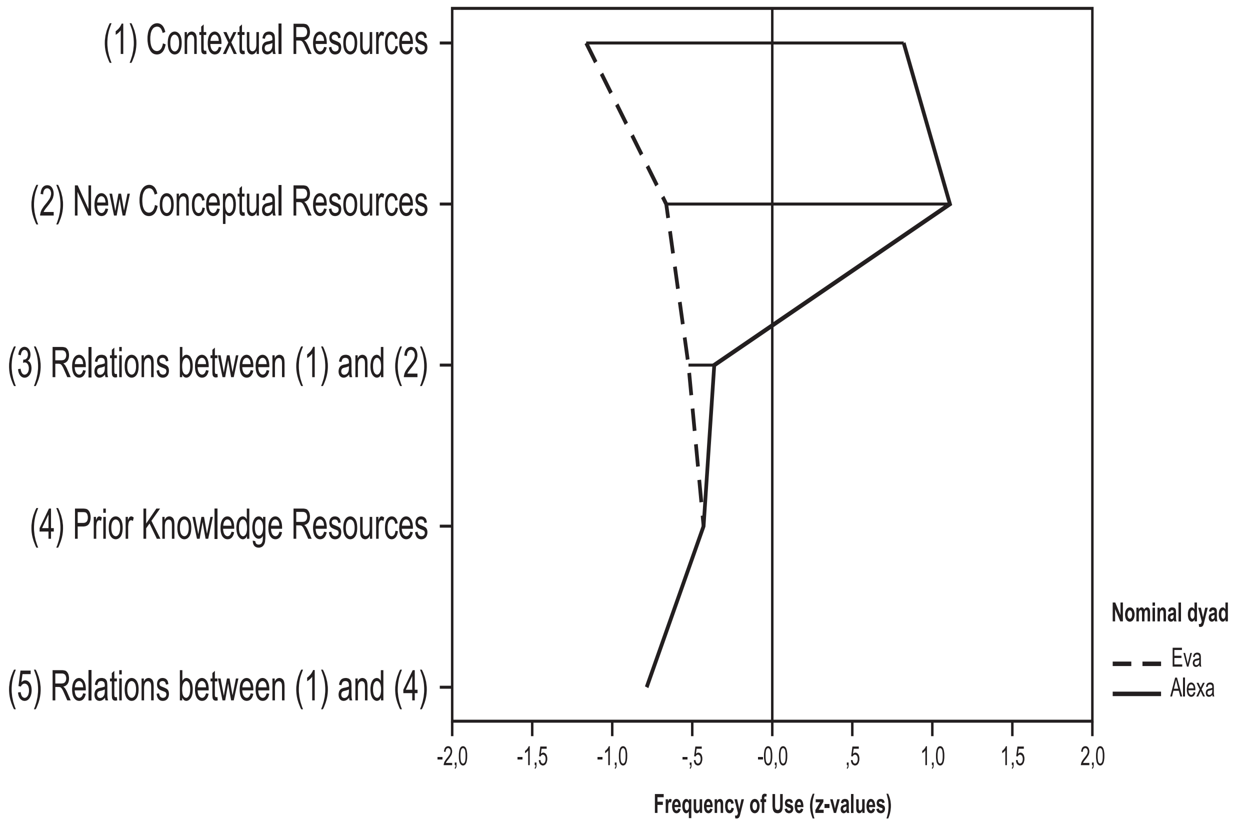
Research question 1: Convergence tendency

(1) *To what extent is there a tendency of collaborative learners to converge with respect to processes and outcomes*? Independent of content specificity of the representation tool and of the collaboration condition, the dyadic interaction should increase knowledge convergence to a substantial degree. (a) First, we hypothesized a general tendency towards *process convergence*. This should be indicated by increased *similarity in resource use within* a group of learners. A comparison of real dyads with nominal dyads with respect to the divergence measure should help in answering this question. Figure 3 shows two typical profiles of resource use of real dyads, whereas figure 4 represents profiles of resource use of nominal dyads. Most real dyads showed such similarities in their profiles. This impression could be quantitatively validated. In 59 of the 64 cases the divergence in resource use was smaller for the real dyads than for their nominal controls. Partners from real dyads used resources in a substantially more similar way than learners randomly paired in nominal dyads within one experimental condition, $t(63) = 10.22$, $p < .01$ (one-tailed). (b)

Second, we assumed that collaboration in a group of learners would increase shared factual knowledge (measured by the individual factual knowledge test after the collaborative learning phase). This step in the analysis also aims to rule out the possibility that the shared knowledge we measured was caused by similarities in experimental conditions alone, e.g., the learning material. Therefore, we again compared real dyads to nominal dyads, this time focusing on shared and unshared knowledge (Tab. 1). Results, however, showed that real dyads did not differ from nominal dyads with respect to the representation of shared and unshared factual knowledge, $t(31) < 1$, *ns* (one-tailed). (c) Thirdly, we tested the hypothesis that collaboration in a group of learners should increase *shared application-oriented knowledge* (as measured by the case-based knowledge application test). Results of the *t* test indicate that more application-oriented knowledge is shared after the collaboration phase in real dyads than in nominal dyads (see Tab. 1), $t(31) = 1.96$, $p < .05$ (one-tailed), $d = 0.34$. Real dyads do not differ from nominal dyads concerning unshared application-oriented knowledge, i.e., in the number of concepts that only one of the dyad members applied correctly in the individual case-based knowledge test after the collaboration phase, $t(31) = -0.87$, *ns* (one-tailed).

In summary, the results support the general hypothesis that collaborators tend to converge in both process and outcomes. However, the tendency is stronger with respect to the process than outcomes. In fact, only a small proportion of knowledge (less than 20 %) is actually shared in all of the conditions we employed in our experiment. The tendency to share application-oriented knowledge is higher than the tendency to share factual knowledge.

Profiles of Resource Use in Nominal Dyads



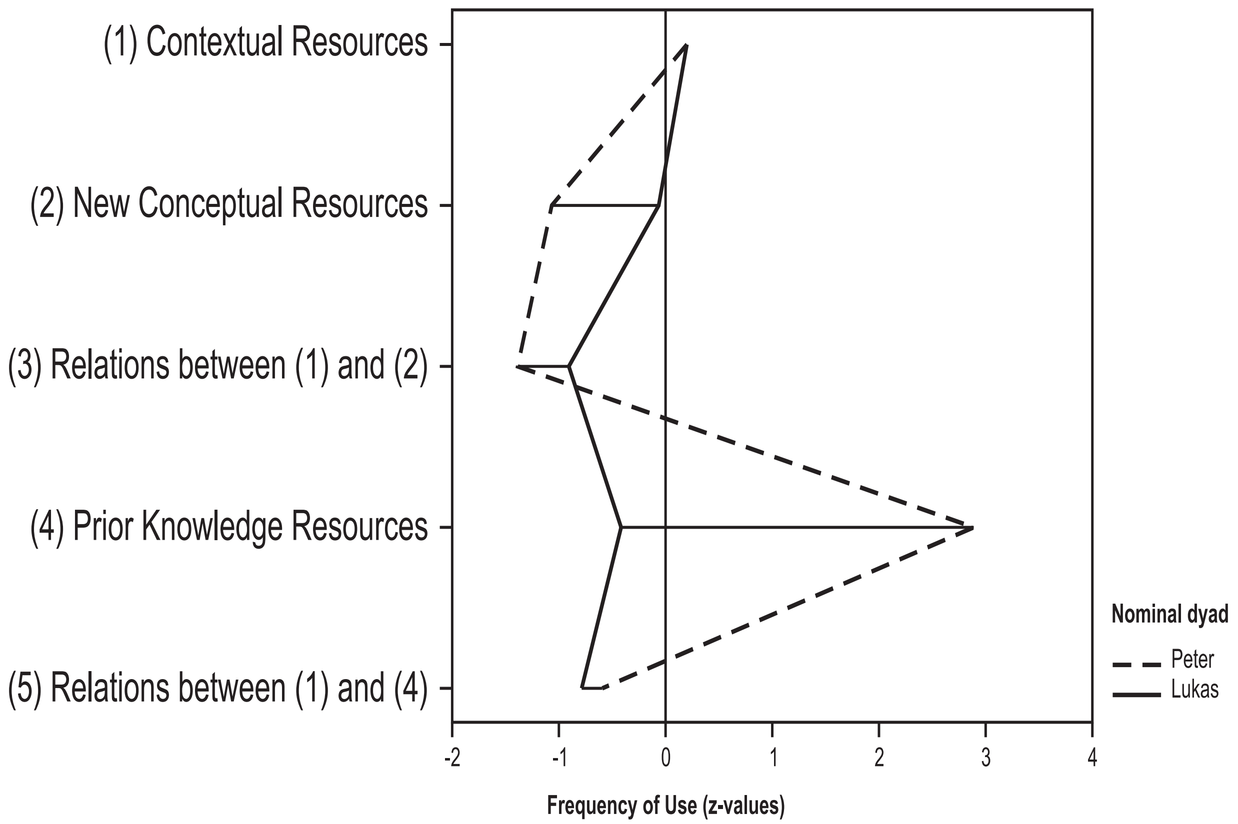


FIGURE 4 Profiles of resource use for nominal dyads. The line represents the individual values on the z-standardized variables of resource use. The closeness of both lines indicates a high similarity in the profiles of resource use in one specific dyad. In contrast to the real dyads in Figure 3, learners of nominal dyads (i.e., learners who did not learn together but were grouped randomly post hoc) are typically less similar in regard to their profiles of resource use.

TABLE 1
Learning Outcome (Factual and Application-Oriented Knowledge) in Real and Nominal Dyads

	Learning Outcome			
	M		*SD*	
Type of Dyad	*Shared*	*Unshared*	*Shared*	*Unshared*
Factual knowledge				
Nominal	2.97	12.81	2.53	7.35
Real	3.13	12.84	2.85	7.63
Application-oriented knowledge				
Nominal	0.47	4.00	0.62	3.19
Real	0.75	3.44	1.05	2.80

Effects of the conditions on process convergence (research question 2)

(2) *Effects of content specificity of the shared representation and of the collaboration condition on process convergence.*

(a) First, we tested if the content specificity of the shared representation would have a positive effect on the convergence of resource use (representational convergence assumption). To test the first part of the hypothesis, we compared the overall coefficient of convergence/divergence in resource use between conditions (Tab. 2). As expected, the content-specific representation tool led to a narrower scope of the dyads' resource use profiles, $F(1,60) = 9.79$, $p < .01$; $\eta 2 = 0.14$.

Moreover, we assumed that a content-specific representation should facilitate the convergence to the use of those conceptual resources that it represents (i.e., the instructionally desirable concepts). The results support this assumption. The use of *new conceptual resources* (i.e., the theoretical concepts provided by the theory text in the learning environment) was affected by the type of tool: dyads learning with the content-specific representation tool used and elaborated substantially more new conceptual resources than dyads with the content-independent representation tool (see Tab. 3), $F(1,28) = 8.35$, $p < .01$; $\eta 2 = 0.23$.

TABLE 2
Convergence and Divergence Concerning the Profiles of Resource Use in the Four Experimental Conditions

	M		*SD*	
Content Specificity of External Representation	*Videoconferencing*	*Face to Face*	*Videoconferencing*	*Face to Face*
Content specific	2.72	2.44	0.89	0.86
Content independent	4.00	3.05	1.17	1.72

In summary, with the content-specific representation, learners converged on a narrower scope of resources. Their focus was on those resources, which were made salient by the conceptual structure of the shared representation tool.

(b) With respect to the collaboration condition, we assumed that the overall convergence in resource *use should be lower in videoconferencing than in a face-to-face condition. This effect should be independent of the content specificity* of the shared representation. Again, we used the coefficient of convergence/divergence of resource use as an indicator (Tab. 2). Results show that the collaboration condition independently explained a substantial part of the variance. The videoconferencing condition led to a wider scope of resource use profiles, $F(1,60) = 4.08$, $p < .05$; $\eta 2 = 0.06$. This effect was independent of the content specificity of the shared representation tool (i.e., no significant interaction between collaboration condition X content specificity of the external representation).

TABLE 3
The Use of Different Kinds of Knowledge Resources in the Experimental Conditions

	Knowledge Resources			
	M		*SD*	
Content Specificity of External Representation	*Videoconferencing*	*Face to Face*	*Videoconferencing*	*Face to Face*
Contextual resources				
Content specific	47.50	61.75	29.03	43.37
Content independent	46.50	59.63	28.53	42.91
New conceptual resources				
Content specific	9.12	17.62	7.41	6.35
Content independent	7.63	3.75	11.01	3.20
Relations between contextual resources and new conceptual resources				
Content specific	36.13	42.25	19.33	22.70
Content independent	29.75	26.25	29.79	23.90
Prior knowledge resources				
Content specific	1.13	0.38	2.47	1.06
Content independent	3.63	1.63	5.26	4.60
Relations between contextual resources and prior knowledge resources				
Content specific	14.63	6.63	11.33	10.32
Content independent	11.50	9.25	16.96	12.02

Results further showed that computer mediation by videoconferencing reduced the facilitating effect of the content-specific representation on the conceptual structure that it represented (new conceptual resources in Tab. 3). There was a significant interaction effect of collaboration condition X content specificity of the representation, $F(1,28) = 5.41$, $p < .05$; $\eta 2 = 0.16$.

In summary, the results support the assumption that computer mediation can lead to a wider scope of resource use, independent of the content specificity of the representation tool. Interestingly enough, we found that the representational convergence (i.e., the more frequent use of resources made salient by the representation by both of the learning partners) was reduced by the videoconferencing condition.

(3) Effects of content specificity of the shared representation tool and the collaboration condition on outcome convergence.

(a) First, we assumed that the content specificity of the shared representation tool facilitates both the convergence of factual knowledge and the convergence of application-oriented knowledge. To assess outcome convergence, we analyzed two aspects of both factual knowledge and application-oriented knowledge: *shared* knowledge and *unshared* knowledge (Tab. 4). However, with respect to shared factual knowledge, no substantial differences between the two types of representation could be found, F (1,28) = 0.13; *ns*. The same is true for unshared factual knowledge, F(1,28) = 1.24, *ns*.

TABLE 4
Learning Outcome in the Experimental Conditions

	Learning Outcome			
	M		*SD*	
Content Specificity of External Representation	*Shared*	*Unshared*	*Shared*	*Unshared*
Factual knowledge				
Content specific				
Videoconferencing	2.63	15.75	2.13	6.86
Face to face	3.25	14.38	3.37	7.21
Content independent				
Videoconferencing	3.75	11.75	3.45	8.48
Face to face	2.88	10.88	2.70	7.95
Application-oriented knowledge				
Content specific				
Videoconferencing	0.88	3.25	1.36	1.75
Face to face	0.88	2.50	1.13	2.39
Content independent				
Videoconferencing	0.63	3.13	1.06	3.18
Face to face	0.63	4.88	0.74	3.52

With respect to application-oriented knowledge, the content specificity did not substantially influence outcome convergence concerning either shared ($F(1,28) = 0.42$, *ns*), or unshared ($F(1,28) = 1.29$, *ns*) application-oriented knowledge.

Contrary to our assumptions, the content specificity of the tool had no effect on the similarity of the outcomes of former learning partners.

(b) Results further revealed that videoconferencing in fact does not differ from a face-to-face condition with respect to either convergence of factual knowledge or convergence of application-oriented knowledge (see Tab. 4). Face-to-face dyads do not differ from videoconferencing dyads with respect to shared factual knowledge, $F(1,28) = 0.01$; *ns.* The same is true for unshared factual knowledge, $F(1,28) = 0.43$, *ns.* Moreover, face-to-face dyads do not differ from videoconferencing dyads with respect to shared application-oriented knowledge, $F(1,28) = 0.00$, *ns.* Here, too, the same is true for unshared application-oriented knowledge, $F(1,28) = 0.26$, *ns.*

In accordance with our assumptions, the findings suggest that the construction of shared knowledge is neither hindered nor facilitated by the conditions of the synchronous computer-mediated collaboration in a videoconferencing environment when compared to a face-to-face condition.

(c) Finally, we assumed that the effects of content specificity of the shared representation on outcome convergence are independent of the collaboration condition. Results support these assumptions (see Tab. 4). There are *no interaction effects* of content specificity X collaboration condition with respect to both factual and application-oriented knowledge: Shared factual knowledge, $F(1,28) = 0.51$; *ns*; unshared factual knowledge, $F(1,28) = 0.12$, *ns*; shared application-oriented knowledge, $F(1,28) = 0.00$, *ns*; unshared application-oriented knowledge, $F(1,28) = 1.60$, *ns*.

In accordance with our assumption, the two tool types do not lead to different degrees of outcome convergence in a videoconference when compared to a face-to-face setting.

(4) *The interrelation of aspects of knowledge convergence*

(a) On the basis of the literature on cognitive convergence, we assumed that successful individual learners converge more strongly with respect to their individual outcomes than less successful learners. The question here is the extent to which shared knowledge is valid for individual learning outcomes. To answer this question, we compared learners who were more successful in the application-oriented knowledge test to learners who were less successful. This comparison was made using median split on the basis of *z*-standardized values to separate the two groups of learners according to the degree of knowledge they shared. Results of the comparison by *t* test show that more successful learners shared more concepts with their learning partners ($z = 0.41$) than the less successful learners, $z = -0.41$; t $(30) = 2.51$, $p < .05$ (one-tailed). The more successful learners did not, however, acquire significantly more unshared knowledge ($z= 0.22$) than the less successful learners, ($z=-0.22$), t $(30) = 1.26$; *ns* (one-tailed). Unshared knowledge refers to concepts that only one of the two former learning partners applied in the individual application-oriented knowledge test.

Although the absolute amount of shared knowledge in the data is rather low and the comparison is not experimental but post-hoc, our findings can be cautiously interpreted as supporting the assumption that outcome convergence has a positive relation to individual knowledge acquisition.

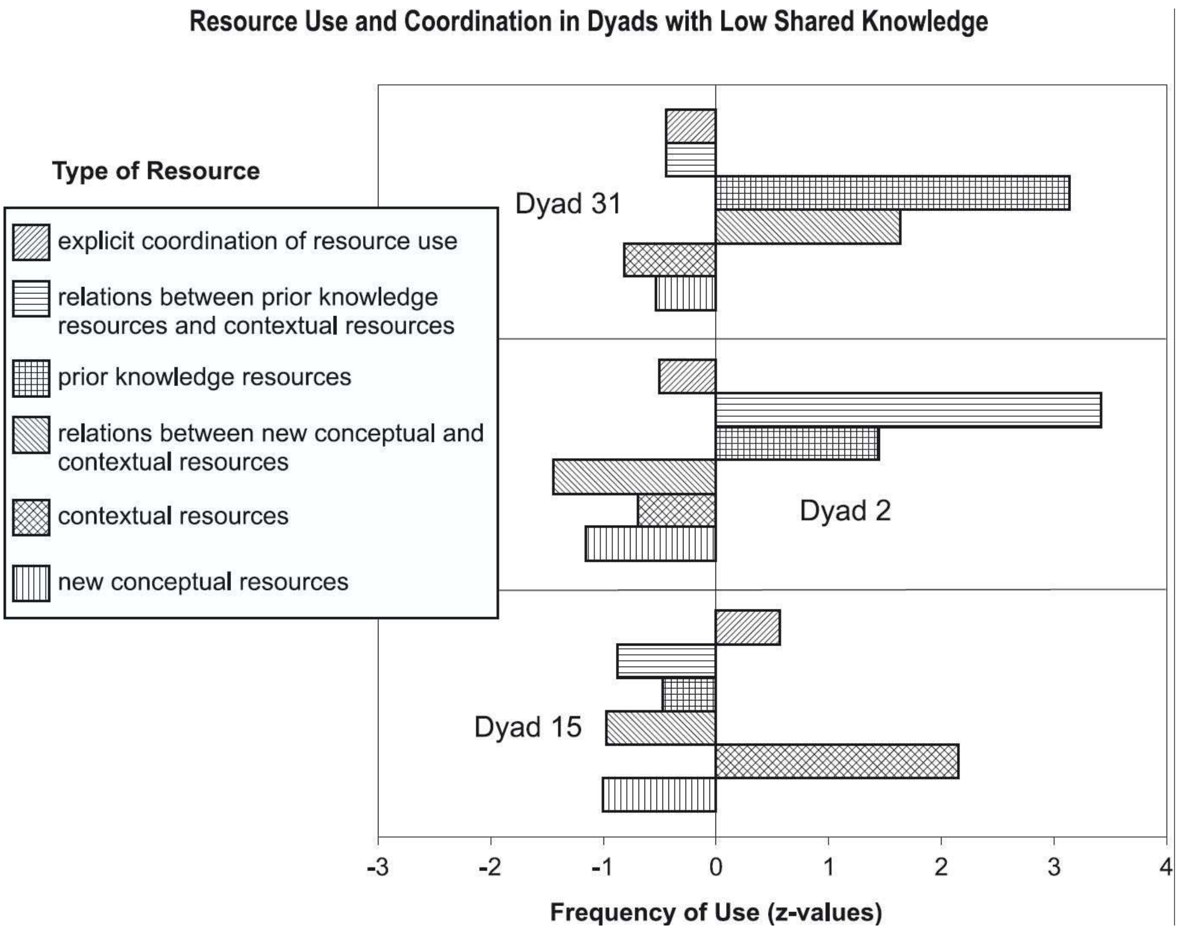


FIGURE 5 Profiles of resource use and coordination in dyads with little or no shared knowledge (Dyads 31, 2, and 15). The bars represent the individual values on the z-standardized variables of resource use and its coordination.

(b) Which discourse patterns facilitate outcome convergence? To address this explorative research question, we analyzed the relationship between the use of knowledge resources and shared knowledge with respect to the outcomes. Using the variables of shared factual and shared application-oriented knowledge as criteria, we selected six dyads: three Dyads with little or no shared knowledge and three dyads with a high degree of shared knowledge. Figure 5 shows the resource use profiles for the three dyads with little shared knowledge. Dyads without shared knowledge (after collaboration) often show a high degree of contextual resources use (i.e., case information, e.g., dyad 31 in Fig. 5). Conceptual resources - whether from prior knowledge or new concepts from the theory text - are rarely used. Other "low shared knowledge" dyads use conceptual resources more frequently. For example, dyad 2 seems to fully rely on prior knowledge resources, which were partially inadequate for identifying a solution to the problem. Single case studies of discourse sequences reveal that those dyads often use the time available to exchange monologues on the basis of their prior knowledge and own experiences. As in the following case of Peter and Niko, those discussions are characterized by long turns and low mutual reference.

1. Peter: Then they changed through, so, the basic groups, there was always one person nominated to build a project group. So there was one person from the project group within each basic group.
2. Niko: Mhm.
3. Peter: And I think, it works here in a similar way. First of all, somebody has, thus, you have a whole course, this course is divided in four different basic groups, mhm, work groups, that's it, and, thus, he is in the work group violence and mass media. And then, and then it's said that this groups include single experts, so that everybody does something for the central theme violence and he chooses one of those four. And the others, the other three groups also have central themes. They may have slightly different central themes and one should have expert opinions of the four things, print media, video games, TV and video, which can be performed in front of the group. However, I think that's quite useful. Because you don't have to do everything by yourself, you can divide the work: You take care of this part, this part and this part and you discuss it first, so that your group has the same level, and then you can carry it forward into the whole group. So that way everybody is able to bring in his own aspect and the group aspects. However, I think

that's quite cool, because you are able to get a lot of information without working too hard.

4. Niko: Mhm. What I wanted to say: There it is said: Each group member gets one example. One is italicized. That means, mhm, every group member gets a different example, so that they have four different examples in all. And in my opinion group work is only useful if the group works on the same task and has the same basis.

5. Peter: You have got the same basis, the basis is violence and mass media in the group.

6. Niko: Yes, but the same basis does not refer to violence and mass media, but it refers to the case example. Because if you have got four different case examples, than you aren't able to speak the same language. And if everybody has got their own example, then collaborative working isn't necessary, mhm, not possible, because everybody has to explain to the others what kind of example they have which results in never ending discussions, and that's why every group member should get the same example of violence in the media. And at first the groups members work individually on it. And, mhm, if now for example, it is written here: The group members have to accumulate and discuss their observations and then present three to four thesis about the effect of showing violence in the media they had worked on. Then four members would speak about four different things. And they wouldn't reach a common point. Because each situation, each violence situation, each situation, described situation is different. And that's why I don't think that's possible, because if you have different levels, different levels e.g. of violence, a group with four different levels, then in my opinion a group discussion is not possible

> anymore, because first of all you have to explain to the others, one has to explain to the other three group members which is his scene and than the other three also have to explain their scene. And that's work, look here, because in my opinion it is only useful if every group has the same example, so that they all have the same knowledge, or rather information level. And then they are able to talk about it and insert the different aspects. But if every body has a unique example it is more or less only meta-communication. That's talking about different things

Learners of dyad 15 discuss conceptual resources from their prior knowledge and apply relevant theoretical concepts more frequently. In contrast to "high shared knowledge" dyads, the learning partners do not elaborate on their theoretical concepts and do not place emphasis on task coordination. Results of case studies suggest that the lack of explicit task coordination may be related to low degrees of shared knowledge. Typically, with this lack of explicit coordination, one learner assumes the role of the guide, but his or her task strategy (the "secret master plan") remains largely implicit.

"High shared knowledge" dyads generally elaborate more frequently on appropriate theoretical concepts and often coordinate their activities more explicitly (dyads 19, 6, 26 in Fig. 6). In contrast to dyads 6 and 26 who show high degrees of shared factual knowledge representation, learning partners of dyad 19 constructed a high degree of shared application-oriented knowledge. During their collaboration they elaborated more frequently on conceptual resources and applied them more frequently to the case information. Moreover, they coordinated their learning activities even more explicitly than the dyads with shared factual knowledge only (dyads 6 and 26).

Beyond these quantitative profiles, the qualitative single case studies revealed more complex discourse patterns. Some of them can be related to shared knowledge in the outcomes. The following excerpt of a dialogue exemplifies such a pattern, in which no clear roles are assigned and learners work on their task with a joint focus of attention, transactively responding to their learning partner's contribution in a manner of flexible co-construction.

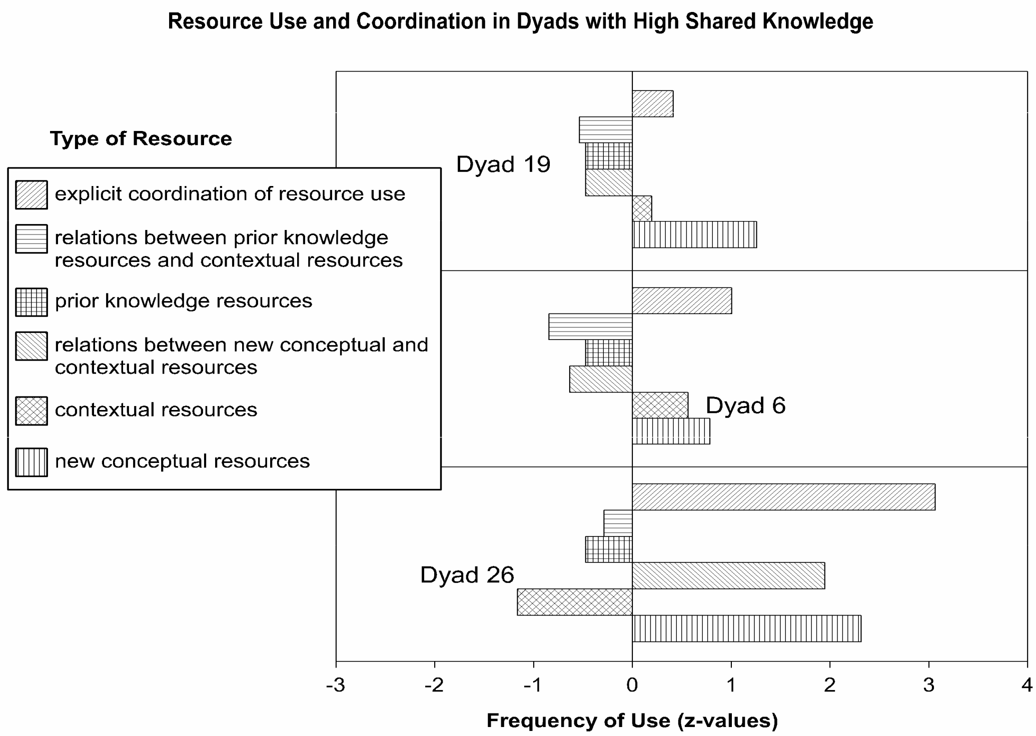


FIGURE 6 Profiles of resource use for dyads with a higher degree of shared knowledge (Dyads 19, 6, and 26). The bars represent the individual values on the z-standardized variables of resource use and its coordination.

1. Anna: Good. And what the bonus is at the end is irrelevant. In my opinion it’s interesting, that the…this teacher … is very intrinsically motivated.

2. Annett: Yes, he says that at the top of the text.

3. Anna: Yes, there he says: We were really lucky, actually we wanted to…

4. Annett: Mhm.

5. Anna: …get the theme, then here..mhm,

6. Annett: Anyway, that the boys care more about it and so on…

7. Anna: Exactly. Now I am asking myself: Why does he also want to have the extrinsic motivation? I mean, why does he need it?

8. Annett: I think, I understood the text to mean, that he is afraid, that.. well, not really afraid, but that he is worried about, that maybe, there isn't so much interest or, that he would like to make sure, that the people enjoy taking part.

9. Anna: That's what I don't understand. Because he says: "Actually everybody wanted that topic…, nearly everybody. And I think, that we were very lucky." And he speaks for the whole group. Hm, if we look at your diagram now, then we don't have a collaboration-supporting practice task.

10. Annett: That's quite right, actually. That's actually a natural group task.

11. Anna: Exactly. Natural group task…, mhm, that means, we should write it down right now.

12. Annett: But I think, that the reward does not have much attraction, that's more a small thing along the way. Because they are going to exchange it in the group, the videos, I suppose, -- thus, I…

13. Annett: You are making that assumption.

14. Anna: Yes.

15. Annett: However, that's not said in the text. <laughs> That's not said in the text and that's a …, <clears her throat> well, … in my opinion it's a

problem, because it is ultimately the same theme, that mhm, …. which we had before, only that the topic is not that one teacher is the best, but that one teacher's presentation or…, ….report…or, mhm, what is it called?

16. Anna: One group.
17. Annett: No,… One, there are always four teachers, four teachers work on one media area.
18. Anna: Yes, the group gets a reward. The best group and not the best teacher or presentation.
19. Annett: That's right, the group gets the reward… mhm, the question is, what you do, if you get a bad topic? I mean, ok, this….this reward can be attractive, because, yes, you are right, that's not bad, not bad because.. because the themes are not equally interesting.

Throughout discussion phases, these two participants contribute quantitatively and qualitatively to a similar degree. The turns are relatively short and the follow-up turns are mostly transactive in the sense of building on what the other contributed before. It is interesting to note, however, that this kind of co-construction is not always good from the instructor's point of view. In the dialogue example, Anna and Annett are converging on a meaning of "reward" that is not compatible with the theory they were asked to apply. This does not mean that their interpretation does not make sense from other theoretical perspectives or when considered in light of their own experiences. However, in their convergence to a common interpretation of the concept, they diverged from the "scientific meaning" provided to them in the learning environment.

We found a "scaffolding" pattern of discourse in only one dyad that was heterogeneous with respect to prior knowledge: the more knowledgeable peer supervises the activities of the learning partner and occasionally provides support by executing parts of the task. The following two sequences are excerpts of the dialogue in this dyad. Sandra assumes the role of the guide obviously trying to support Katrin in performing the analysis, thereby typing and handling the external representation tool most of the time. The second sequence also includes a section, where Sandra intervened when Katrin seemingly misapplied the theoretical concepts to the case (turns 16-26).

1. Katrin: Mhm. Yes, than all the stuff is fulfilled, isn't it?
2. Sandra: Yes, now we have to go over it.
3. Katrin: Yes, sure.
4. Sandra: So.
5. Katrin: So, the problem is ill defined.
6. Sandra: Yes.
7. Katrin: Because no one..
8. Sandra: Yes, the problem is not very precise.
9. Katrin: There is not going to be one answer, right?
10. Sandra: No, no answer pattern, or something like that. There is nothing like that.

…

1. Katrin: Hm. (pause). No, that may have negative… but I don't think its wrong here.
2. Sandra: Why?

3. Katrin: Yes, because it is, I mean it is written there, that they are very happy, that they received this topic because they are interested in it and they are teachers themselves.
4. Sandra: Yes sure, but…
5. Katrin: Look, that's only a small intrinsic…, that's a kind of…
6. Sandra: Yes, sure, but it has to be theoretical.
7. Katrin: Sweetie.
8. Sandra: That's the whole theory of the natural group task, what you have to do there…
9. Katrin: No, there it says just "may"
10. Sandra: Hm?
11. Katrin: That it may have negative consequences.
12. Sandra: Yes, but, it says nothing there, for example that the extrinsic motivation, for example in the form of different kind of group rewards should be used. It says there, that you should refrain from doing it….
13. Katrin: Yes, you could write that ..mhn…, …mhn..
14. Sandra: (pause) Every group should get a video, because….
15. Katrin: Yes, somehow, the topic is interesting for everyone. Now this cool word comes again. <Katrin types> is in-teres-ting for everyone, ok, but, how should we, but in this case…

The case studies, however, also reveal additional patterns, which can be related to a small degree of shared knowledge. For example, a number of dyads divided the labor inappropriately: Each partner assumes a different role; however, this role assignment is sometimes inadequate for the construction of shared knowledge, and the roles never change. Some of the dyads implicitly assigned the roles of a "thinker" and a "painter", i.e.

one learner analyzed the case whilst the other visualized the results of the analysis using the external representation tool.

1. Susan: Thus, here we can… Do you want to write?
2. Petra: Mhm, you tell me what to write. Where do I have to put it?
3. Susan: Mhm, up there.
4. Petra: Up there?
5. Susan: Mhm.
6. Petra: OK.
7. Susan: Thus, here it is about a natural group task….
8. Petra: Should I write it on top of it? As headline? Natural group task?
9. Susan: Yes.
10. Petra: Or are we going to do that at the end?
11. Susan: No, no, at the beginning, ok.
12. Petra: <mumbles> Thus, group task <types>

These participants came to good solutions for the case problems, which they worked on together. However, one of the partners will typically be better able to individually apply the new knowledge afterwards, if roles are not changed.

Discussion

The results of the study indicate a general tendency for the collaborators to converge with respect to process and outcomes. Nearly all of our dyads strongly converged to commonly focus their attention on specific types of resources. However, in all of our experimental conditions, the largest amount of the knowledge acquired during this highly convergent process was not shared, but unshared knowledge. The results show that the relation of shared knowledge to unshared knowledge is less then 1 to 5. This corresponds to the proportion found in earlier investigations (Jeong & Chi, 1999). A higher degree of shared knowledge could have been expected considering that the learners were supposed to reach a consensus regarding a problem solution. In the Jeong and Chi study, the construction of shared knowledge was not a task explicitly assigned to the learners. An interesting question for future research is, how the amount of shared knowledge could be systematically affected by explicitly stating the goal of knowledge sharing. Moreover, we only used one specific measure of shared knowledge based on the application of concepts to cases by individuals. Maybe a measure based on recognition rather than generation would have yielded a higher degree of shared knowledge. Also, we did not employ more team-oriented transfer measures. So, instead of only measuring individual knowledge, it could be interesting for future studies to also investigate how dyads with low and high knowledge convergence perform on subsequent tasks together. This would be the appropriate research model for team-oriented approaches (e.g., aircraft teams, Cannon-Bowers & Salas, 1998).

With respect to process convergence, we only used one of several possible interaction measures. This measure is based on similarities in how often the different knowledge resources available to the students were used. In a computer-supported collaboration task, this might be regarded as a basic indicator of a joint focus of attention. However, other measures, such as the transactivity of discourse (Teasley, 1997) or the use of the learning partner as an informational resource (Dillenbourg, Baker, Blaye & O'Malley, 1995) could open up a different perspective. It is plausible to assume that there are convergent and divergent processes which occur at the same time but which relate to different dimensions of the interaction. For example, whereas some computer-supported collaboration tasks might afford a joint focus of attention with respect to knowledge resources, they might at the same time support the assignment of different roles that are connected with diverging types of activities (e.g., explainer and critic).

Furthermore, the findings clearly show that, in contrast to process convergence, the extent of shared factual knowledge can hardly be explained by intra-dyadic variance. This means that the specific interaction in the dyads is not responsible for the fact that learning partners have similar factual knowledge at the end of their collaboration. The other learning conditions (e.g., the theory text, the case) are better predictors. In contrast, shared application-oriented knowledge is clearly affected by dyadic interaction. Here, former learning partners are more similar than randomly grouped partners. This pattern of findings might indicate that collaborative learning specifically fosters processes of higher order that relate more to application-oriented knowledge and transfer than to factual knowledge (Gabbert, Johnson & Johnson, 1986; Nastasi & Clements, 1992; Salomon & Perkins, 1998).

The results of single case analyses are considered preliminary and tentative indicators of how discourse may be related to shared knowledge. At least two hypotheses for further empirical work can be formulated by analyzing the identified profiles and strategies. *First*, explicit task coordination is a good predictor of outcome similarity, especially concerning application-oriented knowledge. If the pursued task strategy remained implicit, none of the analyzed individual cases would transfer considerable amounts of shared knowledge. The important role of the explicitness of the task strategy is emphasized by theoretical and empirical work (Collins, Brown & Holum, 1991; Rogoff, 1991). Barron (2000) recently provided a further differentiation of the concept of coordination. In two detailed qualitative case studies of mathematical problem-solving in a group of successful and a group of unsuccessful learners, Barron found that unsuccessful learners had problems with three aspects of coordination: the mutuality of interaction, the extent to which a joint focus of attention could be established in the group, and with respect to the level of shared task alignment. Outside the field of education, several approaches highlight the important role of explicit coordination in constructing a shared situation model or a team mental model (e.g., Klimoski & Mohammed, 1994). An instructional consequence would be to find ways to increase the explicitness of the different aspects of task coordination.

Second, learners who share less knowledge with their learning partners often dedicate less effort to discussing the appropriate conceptual resources. Instead, some dyads focus on the contextual resources provided by the case information. In these dyads, an inadequate distribution of labor with inappropriate but stable role assignments was observed. Yet, learners in these dyads do not necessarily learn less than learners of dyads with a large amount of shared knowledge. They may even come to appropriate collaborative solutions. However, it is typically only one of the partners who is able to later perform the task on his or her own.

Conditions of knowledge convergence. Results correspond with earlier work on videoconferencing, which showed that possible differences concerning the process rarely result in different outcomes (Finn et al., 1997; Fischer & Mandl, 2003). Videoconferencing enlarged the bandwidth of resource usage profiles compared to the face-to-face setting. Taking this bandwidth as an indicator of a joint focus in collaborative knowledge construction, the condition of the audio-visual network seems to facilitate a higher diversity of focuses throughout the process. These process differences do not reappear in the outcomes; the collaboration condition hardly influenced the acquisition of shared and unshared knowledge. It has not been determined whether differences with respect to the joint process focus would result in different effects with task types other than the one used here. For example, it would be interesting to investigate the effects of videoconferencing on resource use in an information sampling or hidden profile paradigm (Stasser & Stewart, 1992). Studies in that context consistently showed that when making decisions, groups tend to rely on informational resources, which all or mostly all members are already familiar with (i.e. too narrow a bandwidth of resources).

Literature indicates that videoconferencing effects are often due to disturbances in the interaction caused by technical transmission deficiencies like an audio-video delay (see Bruhn, 2000). From this perspective, the results might be seen as an indication that the audio-video conditions realized did not hamper collaborative knowledge construction. This could be due to the high audio quality and the lack of delay between audio and video transmission. The quality of the video itself might not alone be a decisive factor because of thefact that the participant's attention centered around the shared external representation tool.

It is often assumed that external representation and visualization could improve communication between learning partners. Indeed, effects of visualization on the discourse could also be shown for our learning environments with respect to resource use. More appropriate resources are used when learners are supported with the content-specific representation tool. In analogy to the *representational guidance* effect found by Suthers (2001), we might call this the *representational convergence effect*. However, the differences regarding resource use did not result in a higher amount of shared knowledge. In comparison to the study by Jeong and Chi (1999), which employed a similar quantitative methodology, visualization hardly caused an increase in the percentage of shared knowledge. In this earlier study, neither visualization nor any other instructional support of the collaboration was involved. Comparison values from studies on the effect of other interventions on shared knowledge are not yet available (as for example for reciprocal teaching, group jigsaw). Therefore, no general statements on the effectiveness of the two types of external representation can be made. On the whole, doubts about exclusively positive effects of visualization on collaboration seem to be justified on the background of our single case studies. The example of the inadequate division of labor clearly illustrates that dysfunctional effects of shared external representation tools on collaborative knowledge construction are possible.

In summary, the findings of this study add evidence to support the hypothesis that, for better or worse, learning partners converge strongly with respect to process in collaborative learning environments. The emergence of shared knowledge as a learning outcome, however, is rather the exception than the rule. With videoconferencing, the degree of shared knowledge is relatively low. However, it is not any higher for the face-to-face condition. Specific visualization tools, often thought of as support for knowledge sharing, might change processes and even individual outcomes (e.g., Fischer, Bruhn, Gräsel, & Mandl, 2002). However, they do not facilitate the construction of shared factual or application-oriented knowledge.

More research is needed on the role of knowledge convergence in collaborative knowledge construction. We would expect differences in functionality of knowledge convergence for different task types (e.g., decision-making vs. problem-solving). Important insights may also come from studies on the interaction of different types of knowledge in the process of collaborative problem solving (e.g., Plötzner, Fehse, Kneser, & Spada, 1999).

Furthermore, the effects of other types of instructional support for collaborative knowledge construction (e.g., Palincsar & Brown, 1984; Slavin, 1996) on knowledge convergence should be analyzed.

Moreover, more effective support for groups with respect to an appropriate degree of knowledge convergence needs to be developed. The analyses of discourse patterns suggest that important aspects of the process, which are related to the emergence of shared knowledge are not affected by external representation tools (the role assignment and distribution of labor, as well as the explicitness of task coordination). A promising instructional support would therefore include some kind of collaboration script including the assignment and the change of adequate roles (e.g., O'Donnell, 1996) as well as prompts or scaffolds (Reiser, Tabak, Sandoval, Smith, Steinmuller & Leone, 2001) to facilitate a more explicit task strategy. It is possible that a combination of shared graphical representation with a coordinating collaboration script as *scripted graphical representation* could provide the instructional support needed to facilitate knowledge convergence on an appropriate level.

In our view, knowledge convergence should be considered more thoroughly in theoretical approaches to collaborative learning. In addition to questions of homogeneity/heterogeneity of learning prerequisites (e.g., Plötzner et al., 1995), theoretical models should include statements about the mechanisms of cognitive convergence and the role that shared knowledge plays in collaborative knowledge construction. Theoretical approaches as well as empirical studies may consider aspects of knowledge convergence including the convergence/divergence with respect to resource use, the construction of shared and unshared factual knowledge, and the construction of shared and unshared application-oriented knowledge. Aspects of this framework can also be used to evaluate collaborative learning environments in practice.

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Appendix: Learning Case

You are approached by a friend, who has just begun teaching at a vocational school: "I think I told you already, that I am taking part in a training called 'School and Mass Media – Development and Problems'. I'd like to have your expert opinion. Let me tell you about it: The seminar takes two weekends. The Professor, Dr. Wannenmacher is an educationalist who works for ZDF. We've already had a preliminary discussion, where we discussed topics and formed study groups. These groups are responsible for presenting certain topics at the seminar. The teachers at the seminar are almost all as young as I am. Seems as if only younger teachers are interested in the problems of this world. My group's topic is "Active Violence and Mass Media", which is really exciting. We were lucky to get this topic because all the groups wanted to have it. Our job is to present the topic. Our presentation is on the first Saturday and we will be given 2 hours to present. The only requirement besides of the time restriction is that we have to build small groups of teachers. These groups are supposed to work on different aspects of the topic.

So here's what we have planned: We want to organize the groups according to media branches; printed media, video games, television, videos. Each media group will be made up of four teachers and each teacher will be given one example of violence in his/her media group, which he/she is supposed to work on. The group members are then supposed to gather and discuss their observations. In the end, they should choose three or four theses and prepare them for presentation during the seminar, using examples to illustrate what they conclude. We want to have Mr. Wannenmacher evaluate the groups' efforts in the plenum. Good groups will get an extra bonus. We already talked to Mr. Wannenmacher about this. As I said, he works for ZDF and has already done a documentary on violence and media. He’s agreed to donate videos of his documentary as rewards. We think this will appeal to the teachers, since they could use the video in their classrooms. What do you think, isn’t our group project great?

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Footnote

[1]Educational science (Erziehungswissenschaft) is a 9 semester master curriculum with focuses on learning and instruction, technology-enhanced learning, further education and professional development. Moreover, the curriculum includes methods-related training with a focus on qualitative and quantitative research methods.

Table 1

*Learning Outcome (Factual and Application-Oriented Knowledge) in Real and Nominal Dyad*s.

	Learning outcome			
	Mean		Standard deviation	
Type of dyad	Shared	Unshared	Shared	Unshared
	Factual knowledge			
Nominal dyads	2.97	12.81	2.53	7.35
Real dyads	3.13	12.84	2.85	7.63
	Application-oriented knowledge			
Nominal dyads	0.47	4.00	0.62	3.19
Real dyads	0.75	3.44	1.05	2.80

Table 2

Convergence/Divergence Concerning the Profiles of Resource Use in the Four Experimental Conditions.

Content specificity of external representation	Mean		Standard deviation	
	Videoconferencing	Face-to-face	Videoconferencing	Face-to-face
Content-specific	2.72	2.44	0.89	0.86
Content-independent	4.00	3.05	1.17	1.72

Note. Smaller mean values indicate convergence.

Table 3

The Use of the Different Kinds of Knowledge Resources in the Experimental Conditions

Content specificity of external representation	Knowledge resources			
	Mean		Standard deviation	
	Videoconferencing	Face-to-face	Videoconferencing	Face-to-face
	Contextual resources			
Content-specific	47.50	61.75	29.03	43.37
Content-independent	46.50	59.63	28.53	42.91
	New conceptual resources			
Content-specific	9.12	17.62	7.41	6.35
Content-independent	7.63	3.75	11.01	3.20
	Relations between contextual resoures and new conceptual resources			
Content-specific	36.13	42.25	19.33	22.70
Content-independent	29.75	26.25	29.79	23.90
	Prior knowledge resources			
Content-specific	1.13	0.38	2.47	1.06
Content-independent	3.63	1.63	5.26	4.60
	Relations between contextual resources and prior knowledge resources			
Content-specific	14.63	6.63	11.33	10.32
Content-independent	11.50	9.25	16.96	12.02

Table 4

Learning Outcome in the Experimental Conditions

Content specificity of external representation	Learning outcome			
	Mean		Standard deviation	
	Shared	Unshared	Shared	Unshared
	Factual knowledge			
Content-specific				
Videoconferencing	2.63	15.75	2.13	6.86
Face-to-face	3.25	14.38	3.37	7.21
Content-independent				
Videoconferencing	3.75	11.75	3.45	8.48
Face-to-face	2.88	10.88	2.70	7.95
	Application-oriented knowledge			
Content-specific				
Videoconferencing	0.88	3.25	1.36	1.75
Face-to-face	0.88	2.50	1.13	2.39
Content-independent				
Videoconferencing	0.63	3.13	1.06	3.18
Face-to-face	0.63	4.88	0.74	3.52

Figure Captions:

Figure 1. The content-independent shared representation tool. The toolbar provides access to different functionalities of a simple graphics and text editor. No specific prior structure concerning the content and the task is represented in the tool.

Figure 2. The content-specific shared representation tool with two different conceptual levels (theoretical and empirical), concept cards for the representation of concepts and case information on these levels and two different relation types (symbolized by the lines).

Figure 3. Profiles of resource use for real dyads. The line represents the individual values on the z-standardized variables of resource use. The closeness of both lines indicates high similarity in the profiles of resource use in a specific dyad.

Figure 4. Profiles of resource use for nominal dyads. The line represents the individual values on the z-standardized variables of resource use. The closeness of both lines indicates a high similarity in the profiles of resource use in one specific dyad. In contrast to the real dyads in Fig. 3, learners of nominal dyads (i.e., learners who did not learn together but were grouped randomly post-hoc) are typically less similar in regard to their profiles of resource use.

Figure 5. Profiles of resource use and coordination in dyads with little or no shared knowledge (dyads 31, 2, 15). The bars represent the individual values on the z-standardized variables of resource use and its coordination.

Figure 6. Profiles of resource use for dyads with a higher degree of shared knowledge (dyads 19, 6, 26). The bars represent the individual values on the z-standardized variables of resource use and its coordination.