Learning from Complex Cognitive Tasks: Comparing Groups to Individuals

Femke Kirschner, Educational Technology Expertise Center / Open University of the Netherlands,
Fred Paas, Educational Technology Expertise Center / Open University of the Netherlands and
Institute of Psychology / Erasmus University Rotterdam
Paul A. Kirschner, Educational Technology Expertise Center / Open University of the Netherlands and
Research Centre Learning in Interaction / Utrecht University
Email: femke.kirschner@ou.nl, fred.paas@ou.nl, paul.kirschner@ou.nl

Abstract: The effects of individual versus group learning (in triads) on efficiency of retention and transfer test performance in the domain of biology (heredity) among 70 high-school students were investigated. Applying cognitive load theory, the limitations of the working memory capacity at the individual level were considered an important reason to assign complex learning tasks to groups rather than to individuals. It was hypothesized that groups will have more processing capacity available for relating the information elements to each other and by doing so for constructing higher quality cognitive schemata than individuals if the high cognitive load imposed by complex learning tasks could be shared among group members. In contrast, it was expected that individuals who learn from carrying out the same complex tasks would need all available processing capacity for remembering the interrelated information elements, and, consequently, would not be able to allocate resources to working with them. This interaction hypothesis was confirmed by the data on efficiency of retention and transfer test performance; there was a favorable relationship between mental effort and retention test performance for the individual learners as opposed to a favorable relationship between transfer test performance and mental effort for the students who learned in groups.

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Collaborative learning models are based on the premise that certain types of learning are best achieved interactively rather than through a one-way transmission process (Johnston, James, Lye, & McDonald, 2000; Littleton & Häkkinen, 1999; Slavin, 1983, 1995; Veerman, 2000; Veerman & Veldhuis-Diermanse, 2001; Weigel, 2002). Although collaborative learning is emerging as a promising educational approach, research on its effects on learning has been highly inconclusive (Kester & Paas, 2005). We believe that these inconclusive results have, among other things, been caused by a lack of attention to the structures constituting human cognitive architecture (Sweller, Van Merriënboer, & Paas, 1998) when designing collaborative learning environments.

Research stressing the potential of collaborative learning shows that collaborative learning environments can stimulate and/or enable learners to engage in activities that are valuable for learning. It is important to note that these positive results were found in studies that implemented 'extra' measures to ensure that participants engage in effective collaboration, primarily using highly constrained and scripted collaborative learning environments (Dillenbourg, 2002).

It has become clear that placing learners in a group and assigning them a task does not guarantee that they will work together, engage in effective collaborative learning processes, and show positive learning outcomes (Soller, 2001). However a controlled collaborative learning environment is also not a guarantee for success (Beers, 2005; De Westelinck, De Craene, & Kirschner, 2005). Results of these recall studies suggest that the collaboration process is detrimental for group-member performance even though the environment was constrained and communication and coordination were bound to rules and kept to a minimum (Weldon & Bellinger, 1997).

Different results were found when the tasks used were problem-solving tasks instead of recall tasks. When learners had to work with the information elements, relate them to each other, and by doing so find the solution to a problem (Laughlin, Hatch, Silver, & Boh, 2006). This time, participating in a group facilitated the performance of the individual group member. The type of the task seems to be an important factor in determining whether collaboration is beneficial or not.

The research in which individuals and groups are compared regarding their recall or problem-solving performance implies that individual learning is superior to group learning for relatively simple recall tasks, and that group learning is superior to individual learning for relatively complex problem-solving tasks. A possible explanation for this can be found in cognitive load theory (CLT: Paas, Renkl, & Sweller, 2003, 2004). CLT is mainly concerned with individual learning from complex cognitive tasks. It assumes that individuals cannot process an unlimited number of information elements in their working memory (WM). Applying the principles of CLT, this study considers groups as information processing systems consisting of multiple (limited) WMs which can create a collective working space. From this theoretical point of view, multiple collaborating WMs always provide more processing capacity, but whether this capacity can be used effectively depends on the type of task. It can be argued that a group has more effectively available processing capacity than an individual information processing system for tasks in which the relevant information needs to be shared among working memories for learning to commence. In a group, the cognitive load imposed by a task can be shared among group members, and by doing so free-up WM capacity at the individual level that can be used to deal with more complex problems and construct higher quality cognitive schemata compared to an individual working alone. Therefore, the limitations of the WM-capacity at the individual level can be argued to be an important reason to assign complex learning tasks to groups rather than to individuals.

However, creating a collective working space is only possible if the relevant knowledge held by each individual group member is communicated and coordinated within the group (Salas, Simms, & Burke, 2005). Structure and control of knowledge communication and coordination are very important for collaborative learning environments to be effective. The beneficial effect of being able to share the cognitive load within a group could be annulled by the costs of communication and coordination between the group members, the so called cognitive and social transaction costs. This concept of transaction costs is more and more used in the field of learning and especially collaborative or cooperative learning (i.e., learning in groups) (Ciborra & Olson, 1988; Yamane, 1996). Within a collaborative or cooperative learning environment these transaction costs are "the costs of setting up, enforcing, and maintaining the reciprocal obligations, or contracts, that keep the members of a team together [and]…represent the "overhead" of the team…linked to the resources (time, skills, etc.) employed to allow a work team to produce more than the sum of its parts" (Ciborra & Olson, p. 95). In our situation, they refer to the specific cognitive load that has to be taken into account when learners are communicating with other learners and coordinating both the carrying out of the task and the communication between each other.

When communicating and exchanging information learners are forced to come up with and agree upon a common solution by combining and integrating their individual ideas into a shared and collective one. Because CLT has exclusively focused on individual learners performing an individual task, the cognitive load associated with initiating and maintaining communication and coordination - the transaction costs - have not received specific attention. However, collaborative learning environments can only be effectively designed if those costs are taken into account. The transaction costs can be argued as imposing intrinsic, germane, or extraneous cognitive load on learners. Intrinsic load is imposed when communication and coordination are inherent to a collaborative learning situation and/or environment, one cannot exist without the other. Germane load is imposed when the transaction costs are effective for learning because they foster shared understanding, trust, mutual performance monitoring, common ground, argumentation, coordination, and positive cognitive conflicts (Leitão, 2000) which have been shown to facilitate the learning process. Extraneous load is imposed when the transaction costs are ineffective for learning because it fosters errors, conflicts, unnecessary duplication, etc. (Bernard & Lundgren-Cayrol, 2001). Especially the extraneous or ineffective cognitive load should be minimized for collaborative learning to be effective. If these costs are not controlled and minimized, the freed-up WM-capacity at the individual level could be used for non-essential or non-learning related communication instead of constructing high quality cognitive schemata. The advantage of being able to share the cognitive load that a complex task causes could be annulled by too high transaction costs.

Taking both the complexity of the task and the transaction costs into account, a prerequisite for group-based learning being more effective than individual learning would be that the demands involved in carrying out the task alone exceed the sum of the cognitive resources that a single individual can supply and the resources needed to deal with the ineffective social transaction costs of communication and coordination of the knowledge between the group members. In this study, it is hypothesized that when performing complex tasks group members will be able to collaborate with one another in a fashion that reduces the high intrinsic cognitive load and therefore will be able to develop higher quality schemata than learners working individually. Higher quality schemata would allow those working in groups to attain higher performance on transfer tasks with less investment of mental effort than individual learners. By contrast, it was expected that those learning from carrying out the same complex tasks individually would need all of their processing capacity for remembering the interrelated information elements, and consequently, would not be able to allocate resources to working with and applying them. This would allow those working individually to attain higher performance on retention tasks with less investment of mental effort than group members. Group members will be able to solve a problem by collaboratively combining the information elements that are distributed across the multiple working memories in the group. Consequently, there will be no need for group members to remember all information elements.

Method

Participants

Participants where 70 fourth year Dutch high school students (38 boys and 32 girls) with an average age of 15.4 years (SD = 0.7) who participated in the experiment as part of a biology course.

Materials

All materials used in this experiment were in a domain of biology concerned with heredity, specifically the transfer of both genotypic and phenotypic biological characteristics from parents to their offspring through genes which carry biological information (e.g., eye color in humans, fur length in dogs, leaf shape in plants). In this domain, a general introduction and an instruction on how to solve inheritance problems, three problem solving tasks, and six transfer tasks were designed. Tasks (i.e., learning and test), introduction and instruction were all paper based. A computer was used solely for time management.

The introduction

The general introduction and instruction on solving heredity problems discussed the relevant heredity characteristics, the basic terminology, the rules and theory underlying heredity, and the combination of this general instruction in a worked out example of how to solve heredity problems. The worked out example combined terminology, characteristics, rules, and theory.

Learning tasks

Learners were required to use the information and worked out example presented in the introduction to carry out three similar problem-solving tasks. These problem-solving tasks required learners to combine a number of necessary information elements to give a correct answer to two questions concerning the proportion of possible genotypes of the offspring. Each piece of information was relevant but insufficient by itself for solving the problem, but when combined with the other information the problem could be solved. While learners in the individual condition received all information elements necessary for performing the task, these information elements were distributed in the group in such a way that every triadic group member only received one third of the information elements necessary for performing the task.

Test tasks

Three retention tasks and three transfer tasks were designed to determine how much was learnt. The first three tasks consisted of problems that were almost identical to the learning tasks that the learners received during the learning phase. The other three tasks consisted of problems that differed structurally from the training tasks.

Instruction

All learners received two non-content related instructions, one immediately before the learning tasks, and one before the transfer tasks. These instructions included the procedure, rules, and use of computer, pen, and paper when working on the learning or transfer tasks. For all learners in all conditions, the rules on using pen and paper while solving the problem were the same, namely that its use was prohibited. It was important that all information elements were held in working memory and could not be offloaded onto the booklet. For learners in the group condition, it was stressed that working together was necessary for solving the problem.

The instruction preceding the transfer tasks was the same for all participants and almost identical to the instructions in the individual condition during the learning phase. Only this time, they had to use pen and paper to write down exactly what they were doing.

Computer

The computer was solely used for time registration and time management. *Cognitive-load measurement.* After each task in the learning and test phase, the participants were required to indicate how much effort they had invested in answering the questions by rating this on a 9-point cognitive-load rating scale (Paas, 1992), ranging from ‘very very low effort’ to ‘very very high effort’.

Performance measurement

Solving a problem meant answering questions related to the genotypes, phenotypes, and proportion of both in a certain family. A participant received one point for giving a correct answer to each of the questions. In the transfer test the minimum score for a task was 0 points and the maximum 4 points. The maximum retention test score was 12 points. The minimum score for the transfer tasks was 0 points and the maximum score was 2 or 3 points depending on the number of questions in a task. The maximum transfer test score was 7 points. For the statistical analysis, the performance scores on retention and transfer were transformed into proportions.

Efficiency measurement

Performance efficiency was calculated for the retention and transfer tests using Paas and van Merriënboer's (1993; see Van Gog & Paas, 2008) computational approach by standardizing each of the participants' scores for retention-test and transfer-test performance, and mental effort invested in the retention and transfer tests respectively. For this purpose, the grand mean was subtracted from each score and the result was divided by the overall standard deviation, which yielded *z*-scores for effort (*R)* and performance (*P)*. Finally, a performance efficiency score, *E*, was computed for each participant using the formula: $E = [(P - R)/2^{1/2}]$. High efficiency was indicated by a relatively high test performance in combination with a relatively low mental-effort rating. In contrast, low efficiency was indicated by a relatively low test performance in combination with a relatively high mental-effort rating.

Design and Procedure

Participants were randomly assigned to the individual or group learning condition in such a way that 16 participants worked individually on the three learning tasks and 54 participants worked in 3-person groups (i.e., triads). All participants had to individually study a general introduction to heredity concepts and problems. They received this introduction on paper and had to hand it in after 20 minutes. The participants were then randomly assigned to the individual or group condition to work on the first learning task which took 10 minutes. After the task, each learner had to rate the amount of invested mental effort on a 9-point rating scale (Paas, 1992). Next, they worked on the second learning task for which they had 12 minutes. After this task, they had to again rate the amount of mental effort invested. Finally, they worked on the third learning task, also for 12 minutes, and rated the amount of invested mental effort. After this learning phase, participants in the group condition were set apart and all (i.e., individuals and groups) had 1 hour to individually solve three retention problems requiring them to individually apply the newly learned principles in familiar situations, and three transfer problems requiring them to use the principles in new, unfamiliar situations. During the test phase, the amount of invested mental effort was measured after each transfer task using the same cognitive load scale used in the learning phase.

Results

Learning phase

Table 1 shows the means and standard deviations of the dependent variables of the learning phase as a function of instructional learning condition. A significance level of .05 was used for all analyses. An independent sample t-test (one-tailed) revealed that group members invested significantly less mental effort than participants who learned individually. An independent sample t-test (one-tailed) revealed that group members performed significantly better on the training tasks than the participants who learned individually. There was no significant difference between group members and individuals on the amount of time they invested in solving the problem. The time spent to reach a final answer was the same for group members and individuals.

Test phase

A 2 (learning condition: individual vs. group) x 2 (type of test performance: retention vs. transfer) mixed design ANOVA was used to analyze the test phase data. For all analyses, the first factor, learning condition, was a between-subjects factor, and type of test performance was a within-subjects factor. Means and standard deviations per condition for the dependent variables retention test performance, transfer test performance, mental effort, retention test performance efficiency, transfer test performance efficiency, and time are provided in Table 1. A significance level of .05 was used for all analysis. The ANOVA revealed no main effects of learning condition and type of test performance, but revealed a significant interaction between learning condition and type of test performance, indicating that participants who had learned individually exhibited more efficient retention performance, participants who had learned in a group exhibited more efficient transfer performance. With regard to mental effort, an ANOVA revealed a significant effect of transfer, indicating that retention problems caused a lower mental effort than transfer problems. There was no main effect of learning condition and no learning condition x type of test performance interaction. The main effect for learning condition and type of test performance were not significant. The learning condition x type of test performance interaction was almost significant, suggesting that participants who learned individually performed better on retention problems, while participants who learned in a group performed better on transfer problems. The ANOVA performed on the time on task neither revealed significant main effects nor an interaction.

Table 1: Means and Standard Deviations of the Dependent Variables in the Training and Test Phase: Performance (0-1),, Mental Effort (1-9), Retention Efficiency (based on z-scores of Mental Effort and Performance), Transfer Efficiency (based on z-scores of Mental Effort and Performance), and Time (sec.)

		Type of task	Individual		Group	
			M	*SD*	*M*	*SD*
Learning phase	Performance [a]	Learning tasks	.70*	.29	.94*	.12
	Mental Effort	Learning tasks	4.48*	1.31	3.65*	0.98
	Time	Learning tasks	297.58	110.54	306.30	113.40
Test phase	Performance	Retention tasks	.95	.08	.84	.14
		Transfer tasks	.47	.26	.54	.20
	Mental Effort	Retention tasks	3.96	1.62	3.60	1.16
		Transfer tasks	5.17	1.41	4.86	1.28
	Efficiency	Retention tasks	.18	1.22	-.17	.97
		Transfer tasks	-.23	1.33	.26	.94
	Time	Retention tasks	252.73	75.58	260.02	27.41
		Transfer tasks	242.02	66.73	248.94	39.72

[a] Performance is the proportion of correct answers on the learning tasks.

* $p<.05$

Discussion

In this study, it was hypothesized that group members would be able to collaborate with each other in a way that the cognitive load imposed by a complex task would be reduced. Due to this reduction, group members were expected to develop higher quality schemata than individual learners carrying out the same task. Consequently, it was predicted that group members would have to invest less mental effort to apply acquired knowledge and skills to tasks that differ from the ones trained, as indicated by more efficient transfer performance. In contrast, it was expected that learners carrying out the same complex tasks individually would not have the advantage of the collective workspace and thus would have less WM-capacity left to work with the interrelated information elements. This means that they were expected to be able to only focus on what is initially necessary to work with the elements (i.e., remembering them) and consequently would have to invest less mental effort remembering the information elements, as indicated by more efficient performance on a retention task.

This interaction hypothesis was confirmed. While those learning individually performed more efficiently on a retention task in the test phase than learners who had learned in a group, group learners performed more efficiently on transfer tasks than did individual learners. In other words, by making use of each others processing capacity through sharing the cognitive load imposed by the task, it was possible for group members to more deeply process the information elements and work with them by relating them to each other, and construct higher quality schemata in their long term memory. For individual learners who could only rely on their own WM and, thus, had to process all of the information elements themselves, the experienced mental effort in the learning phase was significantly higher than that of the group members. The limited processing capacity of the individual combined with the complexity of the learning tasks meant that it was only possible for them to focus on remembering the information elements instead of relating them to each other so as to construct higher quality schemata. The conclusion here is clear, namely that collaborative learning can have a positive effect on deep learning of complex cognitive tasks.

A second conclusion, based on the significantly lower metal effort scores of the group members during the learning phase and their more efficient performance on the transfer tasks during the test phase, is that the transaction costs caused by communication and coordination in the groups were not excessively high. For groups, excessive transaction costs could annul the benefit of the possibility of groups to divide the cognitive load among its members.

It should be noted that the learning conditions in this study can be considered rather artificial, for example, as a result of the very strict division of information and roles within groups and the fact that learners were not allowed to use pen and paper. In that sense, it is not clear to what extent the present results can be generalized to a real classroom setting. We acknowledge that, ultimately, the research on group-based learning requires an interrelated perspective integrating cognitive, motivational, and social aspects. However, to be able to disentangle the contributions of each of these factors to the learning processes and outcomes of group-based learning, they need to be studied within tightly constrained experimental environments, one at a time, keeping all other aspects constant.

Although we have shown that learning-task complexity is an important factor that helps determine the effectiveness of group learning, it should be clear that it is not merely complexity of the tasks that determines if group learning, other than individual learning, is favorable in a certain context. Recent research has identified a number of other task characteristics relevant when considering group learning as a good option.

In this study, the type of communication and coordination activities and communication that took place within the groups was not recorded or analyzed. Therefore, we do not know what topics were discussed, whether the discussions that were carried out were mostly content related, whether social talk was part of those discussions and, if so, to what extent, whether learners actually engaged in discussions at all, or whether every group member participated in the communication and coordination equally or whether there were roles or patterns of communication. We concentrated here on the transaction costs that would be detrimental for learning and therefore cause extraneous cognitive load. It could, however, also be possible that the communication among the group members was such that it fostered learning instead of hampered it and by doing so caused germane cognitive load (which is, in contrast to extraneous load, effective for learning). Carrying out such an analysis would add a useful and interesting new dimension to this study and would be interesting to analyze in further studies.

Another interesting topic for further research is determining how to measure a group's cognitive load. In this study, group load was considered to be the average of the individual mental-effort scores. However, group cognitive load could also be defined as the sum of the individual scores, it could be possible to ask the group as a whole to score their group mental effort on the 9-point rating scale that is also used for individuals, or it might even be the case that it could be better to use two rating scales, one that measures the mental effort a group member experiences while solving a problem (the rating scale used in this experiment; Paas, 1992), and another that measures how much effort it took the group member to be a member of the group as a whole.

Finally, further research could be carried out to determine at which level of task complexity it becomes more effective and/or efficient to assign learning tasks to groups rather than to individuals. In such research, the optimal trade-off between task complexity, learner characteristics (e.g., expertise, age) and group characteristics (i.e., group size, group homogeneity with respect to learner characteristics) for the effectiveness of collaborative learning environments could be determined. We often see in both research and education that learners involved in collaborative learning or problem solving are required to send a minimal number of emails to each other or to add a minimal number of messages to a discussion board when working collaboratively via computer mediated communication (i.e., computer-supported collaborative learning). These requirements could be due to the fact that the learning tasks that the learners must carry out or the problems that the learners collaboratively must solve are not sufficiently complex to warrant the requested or required collaboration.

In summary, this study showed that group learning is superior to individual learning of a complex cognitive task if the transaction costs are kept to a minimum and if performance is measured on transfer problems. In contrast, individual learning is superior to group learning if performance is measured on retention problems.

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