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REVIEW ARTICLE

A Cognitive Load Approach to Collaborative Learning: United Brains for Complex Tasks

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Abstract This article presents a review of research comparing the effectiveness of individual learning environments with collaborative learning environments. In reviewing the literature, it was determined that there is no clear and unequivocal picture of how, when, and why the effectiveness of these two approaches to learning differ, a result which may be due to differing complexities of the learning tasks used in the research and the concomitant load imposed on the learner's cognitive system. Based upon cognitive load theory, it is argued that learning by an individual becomes less effective and efficient than learning by a group of individuals as task complexity increases. Dividing the processing of information across individuals is useful when the cognitive load is high because it allows information to be divided across a larger reservoir of cognitive capacity. Although such division requires that information be recombined and that processing be coordinated, under high load conditions, these costs are minimal compared to the gain achieved by this division of labor. In contrast, under low load conditions, an individual can adequately carry out the required processing activities, and the costs of recombination and coordination are relatively more substantial. Implications of these ideas for research and practice of collaborative learning are discussed.

Keywords Collaborative learning · Cognitive load · Task complexity · Brain science

Contemporary learning paradigms argue for the facilitation of lifelong learning in collaborative as opposed to individual environments. This is based upon the premise that the collaboration process will include discussion, argumentation, and reflection upon the task at hand, thus leading to deeper processing of the information and richer and more

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meaningful learning. These environments can be either traditional collaborative ones, such as in face-to-face problem-based learning, or computer-mediated environments, which can be synchronous or asynchronous and/or distributed or nondistributed. Although different educational, social, and economic arguments have been advanced to explain the potential of collaborative learning and justify its use, it is argued that the basic rationale for choosing collaborative learning as the preferred educational approach should be its relative effectiveness and efficiency for learning in comparison with more traditional educational approaches in which learning takes place as an individual activity.

This article presents a review of the available research on collaborative learning (i.e., learning in a group in which knowledge and/or information may be divided across individuals, but where the group as a whole carries out the task) to show that it is not possible to draw unequivocal conclusions about the superiority of collaborative learning above individual learning. The mixed results found are discussed in the context of the way research in this field is typically conducted, and the theoretical framework of cognitive load is used to identify factors that determine if and how collaborative learning can be effective and/or efficient for learning, especially in comparison to individual learning. Group learning is considered to be more effective if the learning outcomes of the n members of a group are higher than the sum of the learning outcomes of n comparable individual learners and more efficient if those learning outcomes are obtained with the investment of less mental effort.

Collaborative Learning Research

Collaborative learning environments take on a great variety of forms. They can, for example, differ in size, composition, pursued goal, supporting tools, synchronicity, common knowledge distribution, division of tasks, and so forth. However, independent of this, they all ask for a certain mutual and shared effort of the members of the group. Teasley and Roschelle (1993) investigating the construction of shared meanings in model-building activities showed the importance of individuals making a conscious and continued effort to solve a problem together. Just putting two or more individuals in the same room and assigning them the same task is not a guarantee for true collaboration. For collaboration, group members must actively communicate and interact with each other with the intention of establishing a common focus and achieving a common goal (Akkerman *et al.* 2007; Beers *et al.* 2006). To achieve this, valuable knowledge and information held by each group member must actively be shared (i.e., retrieving and explicating information), discussed (i.e., processing the information), and remembered (i.e., personalizing and storing the information). Although the processes occurring during group discussions such as negotiating of meaning including verbalizing explanations, justifications, and reflections (Beers *et al.* 2007; Kirschner *et al.* 2008), giving mutual support (Van Boxtel *et al.* 2000), and developing arguments about complex problems or propositions (Munneke *et al.* 2007) are very important and often the subject of the research conducted, collaborative learning models should primarily be based on the premise that actual *learning* is best achieved—in terms of effectiveness, efficiency, or both—interactively rather than individually.

However, it is hard to find unequivocal support for this premise in the research because empirical evidence of actual learning in terms of knowledge increase is, on the one hand, not straight forward and, on the other hand, reveals mixed results. There is, for example, research showing the benefits of working in collaboration rather than in more traditional individual learning environments. With regard to the positive effects, students working collaboratively have been found to become more actively engaged in the learning process, to retain the information being learned for a longer period of time (e.g., Morgan *et al.* 2000), to have their higher-order skills fostered more (e.g., Sloffer *et al.* 1999), and are enabled to engage in activities valuable to the processes of learning such as self-directed learning, negotiating meaning, verbalizing explanations, justifications and reflections, and giving each other mutual support (e.g., Van Boxtel *et al.* 2000). These results are primarily found in highly structured and/or highly scripted learning environments in which learning processes were bound to strict rules (Dillenbourg 2002). But even when this was the case, beneficial effects on learning were not always found (Beers 2005; De Westelinck *et al.* 2005; Mäkitalo *et al.* 2005; Van Bruggen *et al.* 2002; Van Drie *et al.* 2005). Along with the positive findings, however, there is also a body of research showing mixed and negative findings regarding both the learning process itself (Gregor and Cuskelly 1994; Hallet and Cummings 1997; Heath 1998; Mason 1991) and group forming and their dynamics (Hiltz 1998; Hobaugh 1997; Hughes and Hewson 1998; Taha and Caldwell 1993). Groups appear to fall prey to information processing limitations such as underutilizing base-rate information (Tindale 1993), committing additional resources to failing projects (i.e., the sunk cost effect—Smith *et al.* 1998), ineffectively sharing information known only by individual group members (i.e., hidden profile paradigm), production blocking (Diehl and Stroebe 1987), and social loafing (Latané *et al.* 1979). It has become clear that simply placing learners in a group and assigning them a task does not guarantee that they will work together (Hiltz 1998; Hobaugh 1997; Hughes and Hewson 1998; Taha and Caldwell 1993), engage in effective collaborative learning processes (Gregor and Cuskelly 1994; Hallet and Cummings 1997; Heath 1998; Mason 1991), or lead to positive learning outcomes (Beers 2005; De Westelinck *et al.* 2005; Mäkitalo *et al.* 2005; Van Bruggen *et al.* 2002; Van Drie *et al.* 2005).

This inconclusiveness and the associated problem of identifying the factors that determine the effectiveness and efficiency of collaborative learning might be attributable to four characteristics of the way research in this field has typically been designed and conducted. The first characteristic is that learning potentials and claims are often only indirectly tested by measuring performance, group processes, or both in the learning phase (e.g., number of contributions, moves, types of contributions, etc.), instead of measuring them directly by appropriate measures of actual learning outcomes in a test phase specifically designed for testing learning and/or transfer (Kester and Paas 2005). While problems in the learning phase might be successfully solved and group processes successfully stimulated, this does not necessarily mean that learners have effectively or efficiently learned (Kirschner *et al.* 2006; Sweller *et al.* 2007). In addition, because of indirect testing, the measures used are often a determination of the quality of the group product or group processes rather than of the learning of the individual group members. The quality of group processes or products does not necessarily reflect the quality of learning of the individual group members, as the group product might, for example, be the result of the input of the most knowledgeable or diligent group member. The importance of collaborative learning and the superiority of groups above individuals could be best understood when assumptions of learning effectiveness are not primarily based on measurements of performance and/or group processes during the learning phase but also on appropriate tests of learning outcomes and transfer.

The second characteristic is the dominant research focus on naturalistic studies in real-life contexts. Kirschner *et al.* (2004) argue that most systematic design process models center on designing effective conditions for the attainment of individual learning outcomes

(Van Merriënboer *et al.* 2003) and attempt to control instructional variables to create a learning environment that supports the acquisition of a specific skill (i.e., student A will acquire skill B through learning method C). This control of the instructional variables is complicated by the use of collaborative groups. In such groups, a multitude of individual and group-level variables affect the collaborative learning process making it practically impossible to both predefine the conditions of learning or instruction for a group setting such that interaction processes and competency development are controlled and predict the processes that the group will carry out. Kirschner *et al.* (2004) refer to this as a shift from causal to probabilistic instructional designs. This approach leads to a complex pattern of interactions between cognitive, motivational, and social factors that are difficult to both predict and interpret. To be able to disentangle the contributions of each of these factors to the learning processes and outcomes of group-based learning, the different factors need to be studied within tightly constrained experimental environments, one at a time, keeping all other aspects constant.

Thirdly, computer supported collaborative learning research often focuses on surface level characteristics and/or variables (e.g., synchronicity or asynchronicity, "optimal" group size, whether the task was a case, a problem, or a project). For example, a group that could be considered "small" for carrying out one type of task might be too "large" to efficiently and/or effectively carry out a different task. This surface level approach cannot answer fundamental questions such as: Was collaboration really necessary? Did learners design (i.e., the goal being divergent and creative) or prove or diagnose something (i.e., the goal being convergent and specific)? Who determined the goal, how to reach it, and what is correct? Or under what circumstances do groups *learn* most effectively and efficiently? For research to provide a better understanding of the factors that determine if, and how, collaborative learning is effective/efficient, more fundamental aspects of the collaboration process need to be studied, such as the nature/characteristics of the task that is to be carried out and the nature/characteristics of the individual learners in a group (Kirschner 2002).

The final characteristic of collaborative learning research that might be responsible for the inconclusive results is its focus on group performance instead of on the contribution of each group member. There are a substantial number of studies suggesting that collaborative learning improves students' achievements compared to working alone (Hartwick *et al.* 1982; Johnson and Johnson 1989). This suggestion is based on empirical data showing that collaborating groups outperform the "average" individual working alone on a wide range of recall assignments in which groups and individuals are asked to recall as many facts of an event, story, or film, or recall as many nonsense words as possible (Brown 2000; Hartwick *et al.* 1982; Kerr *et al.* 1996; Kerr and Tindale 2004; Levine and Moreland 1998; Lorge and Solomon 1961; Stasser and Dietz-Uhler 2001; Vollrath *et al.* 1989; Stasser *et al.* 1989). The better performance and the assumption that in real-life situations more recalled items could provide a better basis to make a decision or solve a problem would therefore make collaborating groups superior to individuals working alone. Superiority is attributed to a group interaction process in which specific information held by one member of the group is shared with and distributed among the other group members through a process of communication and coordination. However, only focusing on a group product instead of on the individual group member contributions can be considered to be a misinterpretation of the data.

Research taking a closer look at this presumed superiority argues (Laughlin *et al.* 2002, 2003, 2006) that group performance should be compared to an expected performance of a nominal group (i.e., a fictitious group formed by pooling the nonredundant performances of individuals working alone) instead of to the individual performance. The performance of the nominal group is then used as a reference point for comparing the performance of the actual collaborating groups. This approach is similar to Lorge and Solomon's (1955) pooling of abilities model. The performance of the group can be at the level of what such pooling would predict, above this level or below. The first possibility holds that the collaboration or interaction process does not make individual group member performance more effective. The latter two levels hold that collaboration either facilitates or inhibits performance of the individual group member. Facilitation, in this respect, means that the collaboration process causes the group performance to be better than the simple sum of the individual performances. Working in a group is then more efficient/effective (Laughlin *et al.* 2002, 2006). Inhibition implies the opposite in which collaboration is detrimental to the performance of the individual group member (Kerr and Brunn 1981; Latané *et al.* 1979; Weldon and Bellinger 1997). Although groups as a whole perform better than the individual who is working alone, they do not perform optimally. Working together causes a process loss (Steiner 1972) due to poor coordination, which is considered to be a performance-limiting factor. Studies, which have taken a critical look at the possible superiority of groups by comparing group performance with the expected performance of nominal groups, have shown that group recollection is either at or below the level that such pooling would predict (Hinsz 1990; Hoppe 1962; Meudell *et al.* 1992; Perlmutter and De Montmollin 1952; Stephenson *et al.* 1983; Weldon and Bellinger 1997). Collaboration appears to inhibit individual group member recall, and therefore, the superiority of learning in collaborating groups has not been proven. This misrepresentation shows that including the data of individual group members would be much more informative and straightforward than just basing conclusions on group performance.

Summing up, the way collaborative learning research is conducted and the inconclusive results obtained make it impossible to draw sound conclusions as to the relative effectiveness and efficiency of collaborative learning environments compared to individual learning environments. To counter this, research should base its claims on direct measurements of learning in a test phase, should study one important or fundamental aspect of the learning environment at a time, and should focus on performance of the group members rather than on the group as a whole.

Kirschner *et al.* (2008) have argued that to better design, analyze, and understand effective instructional procedures for individual and group learning, the structures that constitute human cognitive architecture need to be taken into account. A theoretical framework which states that any instructional procedure that ignores these structures is not likely to be effective is cognitive load theory (CLT; Paas *et al.* 2003a, 2004; Sweller *et al.* 1998; Van Merriënboer and Sweller 2005). By applying CLT to collaborative learning environments, one can argue that if individuals are to work together and learn effectively and/or efficiently in groups, the architecture of their cognitive system and the characteristics of the task to be carried out must be understood, accommodated, and aligned. This theoretical framework could provide a better understanding of the factors that determine if, when, and how collaborative learning will be effective and efficient for learning, especially when compared to an environment where individuals learn independently.

Cognitive Load Theory

Cognitive load theory is based on the cognitive architecture of individual learners. CLT is concerned with the learning of complex cognitive tasks, in which learners are often overwhelmed by the number of interactive information elements that need to be processed simultaneously before meaningful learning can commence. CLT distinguishes between three types of cognitive load (Sweller *et al.* 1998). The load is considered to be "intrinsic" if it is imposed by the number of information elements in a task and the interactivity between those elements. The more elements there are within a task and the more interaction there is between them, the higher the intrinsic cognitive load. When the load is imposed by the manner in which the information is presented to learners and by the learning activities required of them, it is called either "extraneous" or "germane" cognitive load. Extraneous load is imposed by information and activities that do not directly contribute to learning, while germane load is caused by information and activities that foster learning processes. Intrinsic, extraneous, and germane cognitive load are considered additive in that, taken together, the total load cannot exceed the memory resources available to the learner if learning is to occur (see Paas *et al.* 2003b).

The relations between the three forms of cognitive load are asymmetric. Intrinsic load provides a "base" load that is irreducible other than by constructing additional schemas and automating previously acquired schemas—in other words, by an increase in expertise or by deconstructing the task so that less elements interact (see Ayres 2006; Pollock *et al.* 2002). Any available working memory (WM) capacity remaining after resources have been allocated to deal with intrinsic load can be allocated to deal with the extraneous and germane load. These can work in tandem in that, for example, a reduction in extraneous load by using a more effective instructional design can free capacity for an increase in germane load. If learning is improved by an instructional design that reduces extraneous cognitive load, that improvement may have occurred because the additional WM capacity freed up by the reduction of extraneous cognitive load has now been allocated to germane cognitive load. Also, as a consequence of the acquisition of new cognitive schemas, intrinsic load is reduced. A reduction in intrinsic load reduces the total cognitive load, thus freeing up WM capacity for information processing. The freed up WM capacity allows the learner to use the newly learned material (i.e., the newly acquired cognitive schemas) in acquiring more advanced schemas. A new cycle, thus, commences, and over many cycles, very advanced knowledge and skills may be acquired.

Instructional control of this (too) high cognitive load has become the focus of CLT. In the past two decades, cognitive load research has generated a substantial knowledge base on the design of instruction for individual learners. However, previous research on group-based learning has made clear that there is no one-to-one mapping of instructional design guidelines for individual learning onto group-based learning (Kreijns *et al.* 2003). As the instructional design for group-based learning environments might differ from those of individual learning environments, it is important to reconsider the cognitive load perspective to determine the conditions under which group-based learning environments may or may not be effective.

The Group as Information Processing System

When groups of collaborating learners are considered as information processing systems in which the information within the task and the associated intrinsic cognitive load can be divided across multiple collaborating working memories, it can be argued that because of a combination of the expanded processing capacity and the distribution advantage, the more complex the task is, the more efficient it will become for individuals to cooperate with other individuals in a fashion that reduces this load. This distribution advantage for complex tasks has been shown at a more basic level in the domain of cognitive brain research. Research there has shown that the capacity of the brain was increased by dividing the processing of complex tasks between the two hemispheres of the brain (i.e., interhemispheric processing), instead of using one hemisphere (Maertens and Pollmann 2005). By presenting stimuli to either the left visual field (i.e., processed by the right hemisphere), the right visual field (i.e., processed by the left hemisphere), or both (i.e., processed by both hemispheres), Banich and colleagues (Banich and Belger 1990; Belger and Banich 1992; Banich *et al.* 1994) have shown that processing within one hemisphere becomes less efficient than processing between the two hemispheres as task complexity increases. Thus, dividing processing across the hemispheres is useful when processing load is high because it allows information to be divided across a larger expanse of neural space. Although such division requires that information be recombined and that processing be coordinated, under high load conditions, these costs are minimal compared to the gain afforded by a division of labor. In contrast, under low load conditions, a single hemisphere can adequately handle the processing requirements and the division of information does not add a significant amount of computational power and, thus, the costs caused by interhemispheric coordination are relatively more substantial. In the context of CLT and collaborative learning, this interhemispheric interaction effect could be explained in terms of a need for more working memory capacity when complex tasks need to be learned. If a task is of such a high complexity that two hemispheres (i.e., one individual) are not enough to process and relate all the interactive information elements, more processing capacity is needed. Therefore, it could be argued that assigning high complexity tasks to groups of learners allows information to be divided across a larger reservoir of cognitive capacity and might result in more effective and efficient learning than assigning them to an individual learner.

It is, therefore, hypothesized that the more complex the learning task (i.e., the higher the intrinsic cognitive load), the more efficient and effective it will be for individuals to collaborate with other individuals in a manner that reduces this load. By contrast, less complex tasks that can easily be solved by a single individual will lead to less efficient learning in groups than in individuals alone, because the required group communication and coordination process (i.e., transaction costs) impose an additional cognitive load upon the group members, regardless of whether this communication and coordination is beneficial to learning or not (Kirschner *et al.* 2008). Group communication is a process in which members of a group share and discuss the learning task, the relevant information elements, and the task solution as well as communication intended to reach common ground. Group coordination is a process that manages the interdependencies between group members so that every group member knows exactly which activities other members are carrying out or will carry out, in order to effectively determine what one's own activities at the moment and in the future should entail (see Malone and Crowston 1990). Group coordination has to occur at both the group level (e.g., allocating resources among and defining workflow across the group members—Ellis *et al.* 1991) and the task level (e.g., a shared text editor use requires that group members to know exactly where others are typing at any given moment—Dourish and Bellotti 1992; Gutwin 1997). According to CLT, these communication and coordination activities may either impose extraneous cognitive load with simple tasks because communication and coordination processes are not necessary for or interfere with learning or a germane load with more complex tasks because communication and coordination processes are necessary for carrying out the learning task and, thus, for effective learning.

The CLT-based claim that individual learning will be more effective for simple cognitive tasks is supported by research on recall tasks (e.g., Vollrath *et al.* 1989; Stasser *et al.* 1989). Evidence for the claim that collaborative learning will be more effective in complex cognitive tasks has been found when more complex problem-solving tasks were used as a learning measure instead of recall tasks. When learners had to work with the information elements relevant for carrying out the task, relate them to each other and by doing so come up with a solution to a problem, groups not only outperformed individuals but also the nominal group (Andersson and Rönnberg 1995; Kirschner *et al.* 2008; Kramer 1999; Laughlin *et al.* 2002, 2006; Ohtsubo 2005). Under these conditions, participating in a group facilitated the performance of the individual group member. The complexity of a task seems to be an important factor in determining whether collaboration is beneficial or not.

Conclusion and Discussion

This article identified four possible causes for the mixed results of research on the effectiveness and efficiency of collaborative learning as compared to learning individually. The first is that learning is often only indirectly tested by measuring individual/group performance and/or group processes in the learning phase instead of through the use of appropriate measures of actual learning and/or transfer outcomes in a separate test phase. Van Gog and Paas (2008; see also Paas and Van Merriënboer 1993) have argued that performance in a learning phase does not have to be predictive for what has been learned. Learning can only be reliably determined by measuring performance in a test phase. A second possible cause is that the dominant research focus of most collaborative learning research is the use of naturalistic studies in real-life contexts. This research, due to its probabilistic nature, involves complex patterns of interactions between cognitive, motivational, and social factors that are both difficult to predict and interpret. Thirdly, the majority of research tends to focus on surface level characteristics and variables of the learning environments used (e.g., group size, communication modes), which preclude the answering of fundamental questions regarding effective and efficient collaborative learning. An example of a nonsurface level variable is task complexity. Finally, regardless of whether performance is adequately tested (see the first cause), most research focuses on group performance instead of on the contribution of each group member. This focus, when compared to individual performance, might lead to a misinterpretation of the data, in the sense that groups can be incorrectly considered superior. To this end, when comparing performance, group performance of collaborative groups should be compared with group performance of nominal groups.

The article then took a cognitive load approach to collaborative learning which was considered to provide the opportunity to restudy and reinterpret learning in groups. Cognitive load theory with its differentiation between intrinsic, extraneous, and germane cognitive load allows for a better understanding of the nonsurface level aspects of collaborative learning such as task complexity (i.e., intrinsic load caused by the number of elements in a learning task and the interaction between those elements) and communication and coordination activities in collaborating groups (e.g., transaction costs that can cause either extraneous or germane cognitive load, depending on the situation).

The article also argued for studying new and different perspectives from other scientific disciplines as a way of understanding collaborative learning compared to individual learning. As an example, cognitive brain research on interhemispheric interaction was used as a source of inspiration for a cognitive load perspective on collaborative leaning. This perspective, in which groups are considered as information processing systems consisting of multiple collaborating working memories, can be used to generate new hypotheses and study the effectiveness and efficiency of collaborative learning. It is expected that groups have an advantage above individual learners—as is the case in the research on information processing between two hemispheres or within one hemisphere—because this would allow for distributing cognitive effort among group members. From this point of view, the complexity of the task was identified as an important factor for determining whether collaborative learning will or will not be effective and/or efficient as compared to individual learning. Taken together, it was hypothesized that the more complex the learning task is (i.e., the higher the intrinsic cognitive load), the more efficient and effective it will be for individuals to collaborate with other individuals in a manner that reduces this load. The review of previous studies along with the empirical results of studies by the authors themselves testing this hypothesis are promising, in the sense that studies using simple recall tasks revealed that individuals seem to be more effective while groups seem to exhibit more effective learning when more complex problem solving tasks were used.

With regard to possible implications for educational practice, it is important to know why and when collaborative learning will be superior to individual learning. This review suggests that the complexity of the task (i.e., the intrinsic cognitive load) should be a determining factor when deciding whether to employ a learning model or environment which is based upon an individual or a collaborative learning paradigm. The higher the complexity of the learning tasks, the more likely it is that collaborative learning will lead to better learning outcomes—either in terms of effectiveness, efficiency, or both—than individual learning. This means that if an institution chooses collaborative learning as an educational model, then the educational designers (most often the teachers) need to guarantee that the learning tasks given to the groups (e.g., problems, projects, etc.) are complex in nature and thus cannot be easily carried out by an individual. This also suggests that practitioners should not make an exclusive choice for individual or collaborative learning but rather that they vary the approach depending on the complexity of the tasks to be learned.

In conclusion, although the cognitive load perspective appears to provide both an interesting and a fruitful supplement to the prevailing social and motivational perspectives of collaborative learning, it should be noted that ultimately, the complex interactions between cognitive, motivational, and social factors need to be investigated. For now, the presented cognitive load perspective can broaden the horizon of researchers investigating collaborative learning and contribute both to the identification of those cognitive nonsurface level variables affecting collaborative learning and to the instructional design of effective and efficient collaborative learning.

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