Received: 7 January 2018 | Revised: 14 May 2018 | Accepted: 8 July 2018
DOI: 10.1002/acp.3444

RESEARCH ARTICLE

WILEY

Collaborative learning effects when students have complete or incomplete knowledge

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Summary

Cognitive load theory was used to hypothesize that the effectiveness of collaborative learning is moderated by the completeness of the prerequisite knowledge bases of group members. It was predicted that when group members have gaps in their knowledge base that can be filled by other group members, collaborative is superior to individual learning. In contrast, if group members have no prerequisite knowledge gaps, then collaborative learning is redundant and as a consequence inferior to individual learning. To test these, 58 grade 7 Indonesian students were randomly assigned to work collaboratively or individually on intermediate mathematics problems, with either full knowledge or gaps in their knowledge base. The results indicated that with gaps, collaboration led to superior learning. However, with a more complete knowledge, individual learning was superior to collaborative learning due to redundancy effects. The results suggest that collaboration does not always lead to superior learning compared with individual study.

KEYWORDS

cognitive load theory, collaborative learning, impact of knowledge base

1 | INTRODUCTION

Many studies have shown that collaborative learning in small groups has significant advantages over students who work individually (see Johnson, Maruyama, Johnson, Nelson, & Skon, 1981). Nevertheless, there are situations where individual learning is superior to collaboration. For example, recent evidence has emerged that if worked examples are used to facilitate learning rather than problem solving, individual learning is superior to collaboration (see Kirschner, Paas, & Kirschner, 2009a; Retnowati, Ayres, & Sweller, 2017).

The studies by Kirschner et al. (2009a) and Retnowati et al. (2017) provide fresh insights into collaboration based on cognitive load theory (Kirschner, Sweller, Kirschner, & Zambrano, in press; Sweller, Ayres, & Kalyuga, 2011). In the present study, we continue a cognitive load theory approach, arguing that an incomplete knowledge base is important to create optimum conditions for collaborative learning. Learners benefit most from collaboration when they lack prerequisite knowledge about the content of the information to be learned and can obtain it from other group members. However, if group members already have this information and there are no gaps in the knowledge base, then collaboration may be redundant leading to reduced learning outcomes. We investigated the impact of gaps in the knowledge base on the effectiveness of collaboration using a mathematical problem-solving environment. Before constructing our main argument, we first describe some key findings from the collaborative learning literature.

2 | COLLABORATIVE LEARNING

Although there are many definitions of collaborative learning (see Dillenbourg, 1999), it is commonly considered to be a social context formed by allocating students into small groups to work together during learning. Multiple studies and meta-analyses have found that the various forms of collaborative learning strategies have had significant advantages compared with individual learning (see Johnson et al., 1981), including academic, social, and psychological benefits (Johnson, Johnson, & Smith, 2014). Of importance to the present study is that a number of these studies showing collaborative advantages have used a mathematical learning domain (see Davidson & Kroll, 1991) and featured problem-solving activities (see Van den Bossche, Gijselaers, Segers, & Kirschner, 2006).

Empirical studies and reviews have been conducted to identify the factors that improve collaborative learning (see Cohen, 1994; Schreiber & Valle, 2013; Webb, 2009). It is generally agreed that successful collaborative learning requires active social interactions, group goals, and individual accountability (see Slavin, 1995). Simply grouping students together does not guarantee effective collaboration (Schmidt, Loyens, Van Gog, & Paas, 2007). Common explanations for a collaborative advantage stem from social constructivist theory or social independence theory. It is emphasized that learning occurs through social and collaborative activities where students construct knowledge by interactions with each other and through collective goals (Johnson & Johnson, 1994; Schreiber & Valle, 2013).

2.1 | The transactive memory system

From a cognitive perspective, of great interest is how information is passed from one group member to another. It has been shown that members who are familiar with each other often do better than unfamiliar members due to the development of transactive memory (Hollingshead, 2001). Transactive memory (see Wegner, 1987) occurs when information is shared among group members in a more efficient way according to expertise. Individuals rely on others with more expertise in specific areas to solve problems. It is a shared division of cognitive labor (Hollingshead, 2001) dependent upon knowledge of what each individual in the group knows about each other and how to communicate this information. In a review of transactive memory systems, Noroozi, Teasley, Biemans, Weinberger, and Mulder (2013) suggest that a two-stage process is vital for effective collaborative learning. First, learners gain knowledge of other group members' expertise and establish a transactive memory system by combining this knowledge with their own. Second, learners must engage in transactive discussion which requires building upon, questioning, and elaborating information offered by other group members, as well as the need to sometimes construct opposing arguments to their peers. Acting on the reasoning of others is often referred to as transactivity (Teasley, 1997).

Such arguments emphasize that it is important to establish a transactive memory system and engage in transactive discussions; however, this can be difficult to achieve (Noroozi, Teasley, et al., 2013). A lack of preparation may result in a failure to develop the necessary cognitive tools for transactive memory to function (Wegner, 1987), as well as other factors such as a poor choice of tasks that do not generate the necessary conditions (see Kirschner, Strijbos, Kreijns, & Beers, 2004). Hence, researchers have focused on methods to facilitate the development of transactive memory. At the forefront of such attempts has been computer-supported collaborative learning (CSCL) environments (see Kirschner et al., 2004; Stahl, Koschmann, & Suthers, 2006). Communicating through computers or other vehicles, such as multi-touch interfaces (Schmitt & Weinberger, 2017), does not guarantee success per se and needs to be supported by auxiliary interventions, for example, transactive memory scripts (Noroozi, Biemans, Weinberger, Mulder, & Chizari, 2013; Noroozi, Weinberger, Biemans, Mulder, & Chizari, 2012), argumentation techniques (Noroozi, Kirschner, Biemans, & Mulder, 2018; Noroozi, Teasley, et al., 2013), and knowledge awareness tools (Sangin, Molinari, Nüssli, & Dillenbourg, 2011). Through such additional strategies, researchers have been able to facilitate the development of transactive memory systems in learners in CSCL environments.

3 | COGNITIVE LOAD THEORY

As reported above, much is known about collaborative learning and, in particular, the importance of the transactive memory system. We argue that some fresh insights can be gained into collaborative learning by considering a cognitive load theory approach. Cognitive load theory (Sweller, 2015, 2016a; Sweller et al., 2011) is based on our knowledge of human cognitive architecture and the manner in which that architecture has evolved. The theory assumes that in educational contexts, we teach biologically secondary skills that are culturally important but, unlike primary skills, we have not evolved to acquire automatically (Geary, 2008; Geary & Berch, 2016; Sweller, 2016b). Cognitive load theory is principally concerned with the cognitive processes associated with the acquisition of biologically secondary knowledge. The theory assumes that humans are able to store very large amounts of information in long-term memory (*information store principle*); the bulk of information stored in long-term memory is obtained from other people (*borrowing and reorganizing principle*); when information cannot be obtained from others, it may be obtainable using a generated test procedure during problem solving (*randomness as genesis principle*); novel information is processed by a limited capacity, limited duration working memory prior to being stored in long-term memory (*narrow limits of change principle*); based on signals from the environment, unlimited amounts of information can be transferred from long-term to working memory to generate action appropriate for the environment (*environmental organizing and linking principle*).

Cognitive load theory has identified two major sources of cognitive load that impact on learning: intrinsic and extraneous cognitive load (see Sweller et al., 2011; Sweller, van Merriënboer, & Paas, 1998). Intrinsic cognitive load stems from the to-be-learned materials themselves and is generated by the number of interacting elements contained within the learning tasks (Sweller, 2010). Multiple interacting elements must be processed simultaneously in working memory imposing a heavy working memory load. Extraneous cognitive load is the load generated by instructional designs. Some designs increase the number of interacting elements thus increasing the working memory load. Learning will be facilitated if more resources can be applied to dealing with intrinsic factors (germane resources) and less to extraneous factors (see Sweller et al., 2011). Hence, germane resources are those resources that exclusively deal with schema acquisition (encoding information into long-term memory) and not information concerning the instructional design.

4 | COLLABORATION FROM A COGNITIVE LOAD THEORY PERSPECTIVE

4.1 | Collaboration advantages

According to cognitive load theory, collaborative learning uses the borrowing and reorganizing principle (see Paas & Sweller, 2012).

Learners, when faced with a gap in their knowledge that has not been adequately provided by instruction, can fill that gap from knowledge provided by other members of the group (borrowed) if such group members have that knowledge. Findings from collaborative memory research (Weldon & Bellinger, 1997) suggest a number of ways gaps can be filled such as listening to others recall information (Blumen & Rajaram, 2008), relearn information if necessary (Rajaram & Pereira-Pasari, 2010), and avoid recall errors by receiving feedback from other group members (Barber, Rajaram, & Aron, 2010).

Obtaining information from other group members is also consistent with the collaboration research that shows heterogeneous groupings are more effective than homogeneous groupings (see Johnson & Johnson, 1994; Lou et al., 1996; Zhang, Kalyuga, Lee, & Lei, 2016). In the case of homogeneous groupings, if all members of a group have a similar knowledge base (homogeneous grouping), then borrowing from another group member with superior knowledge is difficult or impossible; whereas if there are differences (heterogeneous grouping), obtaining knowledge from someone else is possible. Heterogeneous grouping is also consistent with the processes involved in transactive collaboration (see Wegner, 1987).

A second advantage of collaboration is that it can help share working memory load by having different members of a group contribute knowledge particular to them but not otherwise available to other members of the group. Recently, collaborative learning has been incorporated into cognitive load theory (Kirschner et al., in press). Kirschner, Paas, and Kirschner (2009a, 2009b) linked collaborative learning to cognitive load theory by proposing that a group of learners have an expanded processing capacity with reduced collective cognitive load compared with individuals. In completing complex tasks, substantial demands can be made on individual working memory. However, through collaboration, the intrinsic cognitive load of a task can be reduced by offloading the cognitive effort across a number of individual working memories. Instead of one working memory dealing with the load, several working memories work together and share the load. As a result, working memory resources can be allocated to learning about relevant information communicated from other group members, which reduces searching for information and lowers extraneous cognitive load. Nevertheless, if tasks are simpler in nature with a lower element interactivity, then individuals can more easily cope with the working memory load generated, and group advantages may be reduced. Evidence to support this argument was found by Kirschner, Paas, and Kirschner (2009a; Kirschner, Paas, Kirschner, & Janssen, 2011) using biology topics and associated transfer tasks.

A third advantage of learning via collaboration is that collaboration is a biologically primary task. Humans have developed over a vast amount of time to collaborate and therefore it is an innate skill that can facilitate the acquisition of biologically secondary knowledge (Paas & Sweller, 2012).

4.2 | Collaboration disadvantages

There are many documented factors that impact poorly on collaborative learning in the general literature. As discussed previously, the development and use of a transactive memory system are essential as well as the promotion of positive interdependence (Johnson & Johnson, 1994), but there are also a number of other well-known phenomena that can easily interfere with collaborative outcomes such as (a) social loafing (Ingham, Levinger, Graves, & Peckham, 1974; Latané, Williams, & Harkins, 1979) where individuals rely on others to do the work, (b) collaborative inhibition where the expected amount of recall of information is reduced through collaboration (Rajaram & Pereira-Pasari, 2010; Weldon & Bellinger, 1997), and (c) a lack of appropriate tasks that do not require a collaborative approach (Kirschner, Paas, & Kirschner, 2011; Zhang, Ayres, & Chan, 2011).

From a cognitive load theory perspective, Kirschner et al. (2009a, in press) theorized that collaboration generates a certain amount of cognitive load through transaction costs. Transaction costs occur when group members must coordinate the various steps in completing the task and the associated communications required between group members, resulting in inefficient processes due to a lack of transactive memory. Transaction costs are therefore a form of extraneous cognitive load, as they are not generated by the tasks themselves (intrinsic cognitive load) but through communication. If transaction costs are high relative to the intrinsic cognitive load generated by the tasks, then learning may become inefficient (Kirschner et al., in press; Kirschner, Paas, & Kirschner, 2011).

Lastly, and the main focus of the present study, under some conditions, collaboration may be redundant, where learners find it unnecessary to collaborate with others in order to learn the required content. In such redundant situations, considerable extraneous cognitive load is created leading to reduced learning (Chandler & Sweller, 1991). Evidence of collaboration being redundant has been found in collaboration-worked examples research. Learners found collaboration redundant when studying worked examples but beneficial when they solved problems (Kirschner, Paas, Kirschner, & Janssen, 2011; Retnowati, Ayres, & Sweller, 2010; Retnowati et al., 2017). Another form of redundancy occurs when a learning strategy is inappropriate due the level of expertise of the learner (known as the *expertise reversal effect*). Strategies that are effective for novices can become ineffective or harmful for learners with greater expertise (Ayres & Sweller, 2013; Kalyuga, Ayres, Chandler, & Sweller, 2003). For example, worked examples that are beneficial for novices may be redundant and have a negative effect for more knowledgeable learners (Ayres & Sweller, 2013; Kalyuga, Chandler, Tuovinen, & Sweller, 2001).

There is additional evidence that expertise can impact on the effectiveness of collaborative learning. Using a computer programming topic with grade 10 students, Zhang et al. (2016) found evidence that heterogeneous collaboration led to higher learning outcomes than individual learning for students with low prior knowledge, but for students with higher prior knowledge, students benefitted more from individual learning than collaboration. This result suggests that for students with expertise in the topic, collaboration was redundant. Similarly, Sangin et al. (2011) argued that different combinations of levels of expertise promote different interactions. When levels of expertise are similar, less elaboration and negotiation is required, compared with situations where a learner can fill a knowledge gap by interacting with another group member.

5 | AIMS AND HYPOTHESES OF THE STUDY

5.1 | Aims

The study had two main aims. The first was to investigate the influence of collaboration on learners with an incomplete knowledge base. To meet this aim, participants with knowledge gaps who learned collaboratively were compared with participants learning individually. The second aim was to investigate the influence of collaboration on learners with a more complete knowledge base. For this aim, participants with fewer knowledge gaps who learned collaboratively were compared with participants learning individually.

5.2 | Hypotheses

The first aim of the study was to investigate the influence of collaboration on learners with an incomplete knowledge base as represented by the collaborative-incomplete or jigsaw group. For the collaborative-incomplete groups, collaboration was necessary to solve the problems because individual group members had prerequisite knowledge gaps (knowledge of only one topic) and therefore collaboration was required to fill these gaps. Individual group members could obtain information from others according to the borrowing and reorganization principle (Paas & Sweller, 2012). In addition, collaboration also provides a collective working memory advantage (Kirschner et al., 2009a). Furthermore, under this condition, learners are likely to be reexposed to essential information (Blumen & Rajaram, 2008) and provided additional retrieval practice by cross-cuing among group members (Congleton & Rajaram, 2011). Hence, these advantages are expected to outweigh the possibility of collaborative inhibition disadvantages. For individual learners with gaps in their knowledge base, it was impossible to obtain information from others or reduce the overall cognitive load. Hence, it was predicted that

> **Hypothesis 1.** *When learners have gaps in their knowledge base (collaborative-incomplete group), collaborative learning is superior to individual learning (individual-incomplete group).*

The second aim of the study was to investigate the influence of redundancy on collaboration caused by a more complete knowledge base of the learner. It follows from Hypothesis 1 that collaboration should be most beneficial under conditions where learners must acquire additional information. However, if that additional information already has been acquired by alternative means such as studying worked examples (see Retnowati et al., 2017), according to cognitive load theory, an exposure to unnecessary, redundant information and processes (such as transactions) can have negative rather than positive effects on learning through increased cognitive load. In contrast, individual learners with no gaps in their knowledge base have the required knowledge base to solve the given tasks. Even though individuals might miss out on some of the potential positive effects of collaborative memory, collaboration was not needed and therefore harmful redundant information effects are avoided. It was therefore predicted that:

> **Hypothesis 2.** *When learners have a complete knowledge base (Collaboration-complete), individual learning is superior to collaborative learning (Individual-complete).*

6 | METHOD

6.1 | Study design features

To meet the first aim of the study, a jigsaw method of collaboration was adopted (see Aronson, 1978). The jigsaw method has been used extensively in collaborative learning research as it promotes positive interdependence (Johnson & Johnson, 1994). In the jigsaw method, each member of the group has specific knowledge about a topic, which they must share with other group members who do not have this knowledge in order to solve the task. Such a design also meets the requirement for transactive processes to be an important influence (Kirschner, Paas, & Kirschner, 2011). In the current study, participants needed prerequisite knowledge about two intermediate-level mathematical topics (area of a triangle and Pythagoras' Theorem) to solve the given tasks. To create a jigsaw group, a subset of participants was initially provided with knowledge about either the first topic only or the second topic only. From this perspective, these participants had gaps in their prerequisite knowledge base. Collaborative groups were formed by combining participants with knowledge of the first topic with participants who had knowledge of the second topic (referred to as a collaborative-incomplete group).

To meet the second aim, a second subset of participants were provided with knowledge of both topics who thus had fewer knowledge gaps. Collaborative groups were formed consisting of participants with a similar knowledge base (the collaborative-complete group), who were compared with similar participants learning individually.

6.1.1 | Study phases

The study design consisted of three phases. Firstly, the knowledge of participants was manipulated individually to provide them with either a complete (both area of a triangle and Pythagoras' Theorem) or incomplete (either area of a triangle or Pythagoras' Theorem) knowledge base. Secondly, the main acquisition phase was conducted where participants learned how to solve problems that required knowledge about both topics either individually or in groups. Finally, all participants were tested individually. Four conditions were created in the second phase consisting of participants who (a) learned individually with knowledge of only one topic (*individual-incomplete* group), (b) learned individually with knowledge of both topics (*individual-complete* group), (c) learned collaboratively with knowledge of only one topic (*collaborative-incomplete* group, or the *jigsaw* group), and learned collaboratively with no knowledge gaps (*collaborative-complete* group). Figure 1 provides a flow diagram of the groupings and learning phases.

6.2 | Participants

Fifty-four students (27 girls and 27 boys), from two Year 7 classrooms in an Indonesian school in Sleman, Yogyakarta, with an average age of 13.7 years (*SD* = 0.76) participated in the study. Students followed the

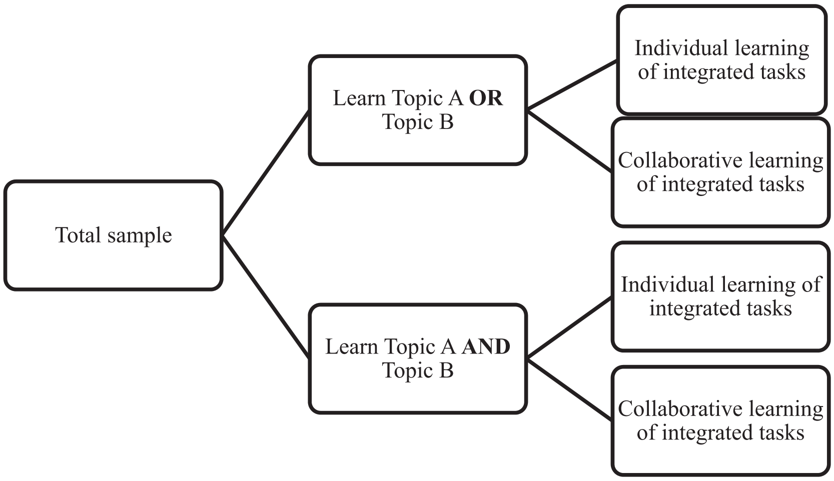


FIGURE 1 Flow diagram indicating groupings and related tasks

Indonesian national curriculum, which requires teachers to use student-centred learning methods including small group work (BNSP, 2006; Depdiknas, 2004; National Ministry of Education, 2006). The participating school indicated that the students had been allocated to the two mathematics classes randomly at the beginning of the school year and were taught by the same teacher. At the beginning of the school year, as part of the school's policy, students were assigned to small learning groups by the mathematics teacher and therefore it was assumed that the participants were used to working collaboratively and may have developed a level of transactive memory (see Wegner, 1987).

Participants were firstly randomly allocated into two groups to acquire the initial prerequisite knowledge: learning one topic only (13 students learning topic A and 14 students learning topic B) or learning both topics (27 students). These initial groups were then randomly assigned into individual or collaborative learning treatments. Eight participants who acquired knowledge of topic A and eight participants who acquired knowledge of topic B were formed into four jigsaw or collaborative-incomplete groups, each consisting of two participants with knowledge about A and two with knowledge about B. Four members per group were chosen because the students were used to working in this size groups, and it was also essential to have an equal number of students with knowledge of the two topics. Sixteen participants who acquired knowledge of both topics were formed into four homogenous groups. The remaining 11 participants with knowledge about either A (5 students) or B (6 students) and 11 participants with knowledge about both topics were designated to solve problems individually.

6.3 | Materials

6.3.1 | Initial base knowledge acquisition

The main tasks in this experiment required participants to find the area of a triangle for which they needed to use Pythagoras' theorem (topic A) to find an unknown side of the triangle and then to apply the formula for the area of a triangle (topic B). For topic A, Pythagoras' Theorem, the learning material consisted of a summary of the theorem and a set of 10 worked examples pairs. Worked examples pairs (study an example solution and solve a similar problem) were used in this phase as they were considered the most effective strategy for novices to learn new information (see Sweller & Cooper, 1985; Trafton & Reiser, 1993). For topic B (see Figure 2a), finding the area of a triangle, the learning material consisted of a summary of the area formula and also a set of 10 worked examples pairs.

Those participants who were required to learn about both topics learned about topic A first, followed by topic B. This learning material consisted of a summary sheet for both topics A and B. The worked example booklet consisted of five pairs of worked examples on topic A and five pairs on topic B. All problem pairs were taken from the sets used for single topics and consisted of exactly half of what was required for participants assigned to learning an individual topic. Hence, all participants in the experiment studied 10 worked example

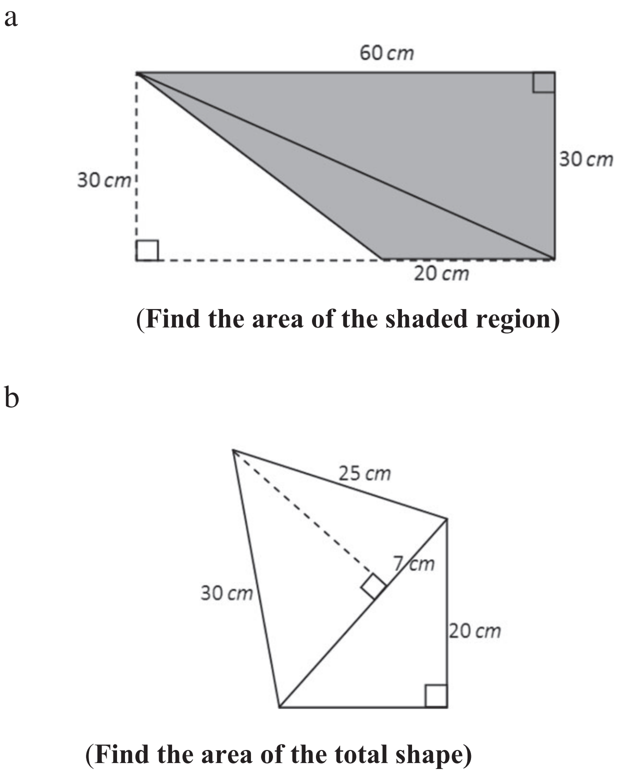


FIGURE 2 (a) An example of a problem from topic B (area of a triangle), (b) An example of a problem combining both topics (area of a triangle and Pythagoras' theorem)

pairs with the same allocated practice time as those who studied one topic. The problems that had to be solved in these pairs were used to assess how well they had learnt the given topics. More detail of the problems used in this phase are given in Appendix A.

6.3.2 | Main learning acquisition phase

The learning material used during this phase required the simultaneous application of knowledge of both topics A and B. Therefore, six triangle area problems requiring knowledge of both topics were constructed and presented in a booklet. Participants were asked to solve these problems. Final answers were provided only without overall solutions. Participants were asked to solve a problem by writing the solution steps in the provided space. Each problem had a combination of triangles (see Figure 2b for an example) and required participants to find the length of unknown sides (using knowledge about topic A) that were relevant to applying the area formula (using knowledge about topic B). Three problems had three-step solutions, and three problems had four-step solutions.

6.3.3 | Test materials

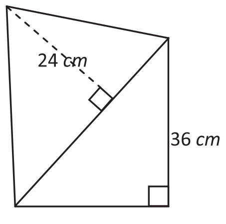
Two tests (similar and transfer) of learning were developed. The similar test (Cronbach's α = 0.78), which consisted of six problems similar to the problems described above in the main learning acquisition phase, required a combination of topics A and B. The transfer test (Cronbach's α = 0.76), which consisted of four problems, used less familiar configurations, additional subgoals, and differently phrased questions (see Figure 3).

6.3.4 | Additional materials

In addition to the learning and testing materials, a table of squares (squares of whole numbers from 1 to 50) was provided. All problems requiring Pythagoras' theorem in the learning and testing materials used Pythagorean triples (e.g., 5, 12, and 13) thus all side lengths consisted of whole numbers and therefore square roots could easily be calculated from the table. This table was provided during learning and testing when the Pythagoras' theorem was used. The purpose was to assist participants' focus on understanding how to apply the theorem rather than the numerical operation.

6.3.5 | Cognitive load measures

To obtain an index of cognitive load during acquisition and testing, a self-rating scale of difficulty was used based on the Paas scale (see Paas, 1992; van Gog & Paas, 2008). To obtain reliable results (see van Gog, Kirschner, Kester, & Paas, 2012), multiple measures were collected by positioning the subjective rating question on every page of the instructional material on the bottom line of the page, as well as the testing materials. The question asked, "How easy or difficult was it to study and solve these problems? Circle your answer on a scale from 1 = *extremely easy* to 9 = *extremely difficult*." The cognitive load ratings collected on each page were added and then averaged to measure the overall participant's cognitive load experienced in the three phases. A Cronbach's α of 0.82 was calculated across the three measures showing a high degree of consistency.



(If the area of the triangle on the left of the diagram is 540 cm², find the area of the triangle on the right of the diagram,)

FIGURE 3 An example of a problem from the transfer test

6.4 | Procedure

A general introduction of the objective of the lesson was given to all participants. It was explained that the learning material would be provided in a written format, and a test would follow directly after the learning phase. Participants were told that calculators were not allowed and that they were required to write their workings in the booklet, and a table of squares would be provided to help calculations.

Following the introduction, participants were presented the initial base knowledge acquisition phase. In this phase, all participants studied individually using the worked example booklet. Participants who were allocated only one topic were instructed to read the provided summary sheet for 7.5 min and then given 30 min to complete the worked examples booklet. Participants studying both topics were allotted 3.75 min to read the summary sheet for topic A and were given 15 min to complete the worked examples booklet (half the time of single topic participants). An identical procedure then was followed for topic B. No feedback was given during and after the phase.

Following this initial base knowledge acquisition phase, participants were separated into two separate classrooms according to their group allocation to begin the main acquisition phase and were briefed accordingly. For individual study, participants were instructed to make an effort to understand the learning material and were not permitted to communicate with other students or the teacher during the study. For collaborative study, participants were told by the teacher to discuss the learning material together by reading the task together, eliciting understanding, helping each other, and making sure every member understood the learning material. They were not permitted to communicate with members of other groups or the teacher during this phase. For both groups, it was also explained how students should complete the cognitive load measures that would appear on each page of their booklet.

Following these briefings, each participant received the summary sheets for both topics and were given 15 min to study them (individually or in their collaborative group). Students could access this summary sheet until the acquisition phase ended. Afterwards, each participant received the designated problem-solving booklet to complete the main learning acquisition phase. Thirty minutes were given for all groups and individuals to complete this booklet. No feedback was provided during or after this phase. Directly following this acquisition phase, the similar and transfer tests were completed individually. All participants were given the maximum time of 20 min to complete each test. No feedback was given.

6.5 | Analysis of test data

Marks for the initial base knowledge acquisition problems were given according to the number of successful steps in the answer. Both topic A and topic B tests had problems requiring a one-step or a two-step solution. A correct calculation for each step was given a score of 1, and an incorrect calculation was given a score of 0. The total score of the problems requiring two solution steps were then scaled to 1 to ensure that every problem had an equal weighting. The minimum score of each test was 0 with a maximum score of 10. The mean scores (and the standard deviations) for the initial base knowledge acquisition tests were 9.81 (0.69), 9.79 (0.58), and 9.94 (0.29) for topic A, topic B, and topic A and B, respectively, indicating that all groups had a high level of mastery of their given topics as maximum possible scores were 10.

Scores for the acquisition, and similar test phases, were also awarded according to the number of successful steps in the answer. For each problem, each successful answer had to show the correct use of Pythagoras' theorem to measure two or more key variables (topic A) and the correct use of the triangle area formula to calculate the area of one or more triangles (topic B). The test problems required either three or four steps for solution. A correct calculation for each step was given a score of 1, and an incorrect calculation was given a score of 0. If the answer was entirely correct, then the problem with three steps had a total score of 3, and the problem with four steps had a total score of 4. The total score for each problem was then scaled to 1 so that every problem had an equal weight of scoring. The minimum score for every test was 0, and the maximum score was 6.

Marks for the transfer test phase were also given according to the number of successful steps in the answer. The marking guidelines were the same as the other phases, with a score of 1 for every correct step and a score of 0 for every incorrect step. The total score of each problem was also scaled to 1. The minimum score for this test was 0, and the maximum score was 4.

Mean scores for each group are recorded in Table 1. Participants in the individual-incomplete group were formed by combining participants instructed in either topic A or topic B. Independent *t* tests conducted on the performance score for these two subgroups groups showed no significance differences, although cell sizes were small.

The performance scores of participants during the acquisition phase were collected and analyzed; however, it should be noted that participants who completed the task in the collaborative groups may have obtained the same answer through consensus among group members, and so each score may represent group rather than individual work. Nevertheless, these scores served as a useful comparison with the unbiased scores obtained with the similar and transfer tests. As can be seen from Table 1, the scoring pattern was identical for each of the three tests. The highest score was achieved by the individual-complete group followed by the collaborative-complete group, followed by the collaborative-incomplete group, and last the individual-incomplete group. This overall stable pattern shows that the acquisition scores were consistent with the other scores and therefore may represent individual scores, as well as indicating no unusual fluctuations due to collaborative memory effects, such as collaborative inhibition moving from phase 1 to phase 2.

6.6 | Cognitive load measures

The means for each collection of the cognitive load measures are shown in Table 2. Again, there was a consistent pattern across the three measures where the lowest rating was recorded by the individual-complete group followed by the collaborative-complete group, followed by the collaborative-incomplete group, and the highest rating by the individual-incomplete group. The pattern observed for these measures are a perfect match for the performance scores. The group with the lowest cognitive loads had the highest test scores, and so on, consistent with predictions made by cognitive load theory (see Sweller et al., 2011). Very large differences in cognitive load were found between the individual-complete group and the individual-incomplete group, suggesting that the latter group experienced great difficulty with the tasks when equipped with only one of the two prerequisite topics.

7 | RESULTS

7.1 | Testing the hypotheses

To test the specified hypotheses and explore other potential differences, a one-way four-group analysis of variance (ANOVA) was

TABLE 1 Means (and standard deviations) for group test results

	Acquisition (0–6)	Similar (0–6)	Transfer (0–4)
Individual-incomplete	1.48 (1.65)	2.50 (1.83)	1.41 (1.16)
Collaborative-incomplete	4.11 (0.56)	4.14 (1.36)	1.53 (1.02)
Collaborative-complete	5.00 (0.58)	4.67 (1.13)	2.07 (1.12)
Individual-complete	5.41 (0.70)	5.57 (0.63)	3.34 (0.71)

TABLE 2 Means (and standard deviations) for group cognitive load ratings

	Acquisition (0–9)	Similar (0–9)	Transfer (0–9)
Individual-incomplete	7.51 (1.56)	6.30 (1.83)	7.20 (1.52)
Collaborative-incomplete	4.67 (1.93)	4.39 (2.12)	6.05 (2.31)
Collaborative-complete	3.80 (1.04)	3.16 (1.23)	4.47 (1.75)
Individual-complete	1.68 (0.74)	1.65 (1.02)	1.98 (0.85)

conducted on each measure collected in the acquisition phase, similar test, and transfer test (see Table 3). Post hoc tests using the Tukey B method followed each significant ANOVA. The results are summarized in Table 3. The ANOVAs (see Table 3) showed significant group differences on each of the three tests, with very low *P* values and very high effect sizes.

7.1.1 | Hypothesis 1: When learners have gaps in their knowledge base, collaborative learning is superior to individual learning

This hypothesis was tested by comparing the collaborative-incomplete group with the individual-incomplete group. For the collaborative-incomplete group, participants studied collaboratively with knowledge of one topic only, whereas for the individual-incomplete group, participants with knowledge of one topic only studied individually. As can be seen from the post hoc results (see Table 4), the collaborative-incomplete group had significantly higher scores on the acquisition and similar tests. The collaborative-incomplete group also had significantly lower cognitive load scores on all three measures. Clearly, there is support for this hypothesis. Participants who lacked knowledge of both topics benefited from learning collaboratively rather than learning individually with reduced cognitive load. Although, the advantage did not extend to the transfer test at a significant level.

7.1.2 | Hypothesis 2: When learners have complete knowledge bases individual learning is superior to collaborative learning

This hypothesis was tested by comparing the individual-complete group with the collaborative-complete group. For the individual-complete group, participants studied individually with knowledge of both topics, whereas for the collaborative-complete group, participants with knowledge of both topics studied collaboratively. The individual-complete group had significantly higher scores on the acquisition and transfer tests, and lower cognitive load measures on all three measures (see Table 4). Although no significant difference was found on the similar test, the significant advantage found on the transfer tests is considered a much stronger indicator of learning and understanding (see Mayer, 2014). Hence, there is also considerable support for the second hypothesis. It is also notable that individuals who had knowledge of both topics significantly outperformed (higher test scores with lower cognitive load) the collaborative-incomplete group on all 6 measures (see Table 4).

TABLE 3 Results of the one-way ANOVAs for performance test and cognitive load measures

Measure	$F(3, 50)$	MSE	P	η_p^2
Learning test	42.8	2.04	<0.001	0.72
Similar test	11.0	1.69	<0.001	0.40
Transfer test	8.57	1.06	<0.001	0.34
Learning CL	31.8	0.43	<0.001	0.66
Similar CL	16.2	2.68	<0.001	0.49
Transfer CL	18.7	3.13	<0.001	0.45

7.1.3 | Other comparisons

The design of the study included two collaborative groups. One contained individuals with incomplete knowledge bases (collaborative-incomplete group) and another containing individuals with complete knowledge bases (collaborative-complete) and therefore it was possible to compare these two groups, although it was not a main aim of the study. Results from the post hoc analyses revealed no significant differences on all measures except the acquisition test scores, where the collaborative-complete group had a significantly higher score. As noted earlier, during the acquisition test, participants could collaborate on their answers and therefore this difference should not be considered a strong indicator of treatment differences. As argued above, it is expected that the collaborative-incomplete group will benefit from collaboration because individuals need information, whereas the group containing individuals with complete knowledge bases (collaborative-complete) may suffer redundancy effects. The results suggest that the positive effects of the former do not outweigh the negative effects of the latter.

As might be expected, it was also observed that participants with access to both topics were superior to participants with knowledge of only one topic. In comparing the individual-incomplete group with the other three groups, it was found that all three groups were superior on five of the six measures (see Table 4). However, only the individual-complete group was significantly superior on the transfer task, indicating the advantage of studying alone with knowledge of both topics.

8 | DISCUSSION

8.1 | Testing the hypotheses

Firstly, it was predicted that when learners have gaps in their knowledge base, collaborative learning is superior to individual learning. This hypothesis was confirmed as learners with gaps in their prerequisite

TABLE 4 Results of post hoc tests for performance scores and cognitive load measures

	Test performances			Cognitive load ratings		
	Learning	Similar	Transfer	Learning	Similar	Transfer
Comparisons with IC	IC > CI IC > II	IC > CI IC > II	IC > CC IC > CI IC > II	IC < CC IC < CI IC < II	IC < CC IC < CI IC < II	IC < CC IC < CI IC < II
Comparisons with CC	CC > CI CC > II	CC > II	ns	CC < II	CC < II	CC < II
Comparisons with CI	CI > II	CI > II	ns	CI < II	CI < II	CI < II

Note. All significant comparisons listed $P < 0.05$. IC: individual-complete; CC: collaboration-complete; CI: collaboration-incomplete; II: individual-incomplete.

knowledge bases had higher learning outcomes, as measured by similar retention tasks, and experienced lower instructional cognitive load, when learning in groups compared to learning individually. The prediction that when learning through problem solving, collaboration is helpful when individuals lack information because it can be "borrowed" from other group members, using the borrowing and reorganization principle (Paas & Sweller, 2012) was supported.

To complete the assigned mathematical tasks, where individual group members had knowledge of only one of the two topics required to complete the tasks, knowledge had to be shared (borrowed) with other group members who had knowledge of the other topic. The results stemming from a jigsaw or collaborative-incomplete grouping design (see Aronson, 1978) suggest that group members did receive information from their peers (borrowing), consistent with the theoretical predictions made. In contrast, individual learners who had gaps in their knowledge base were unable to obtain (borrow) knowledge from others and suffered accordingly.

As collaboration was shown to be superior to individual learning under these conditions, it can be assumed that collaborative learners had developed a transactive memory system and engaged in transactive discussions (Noroozi et al., 2013). Although no special preparation was provided, these participants were used to working together, as part of their regular classes, and this may have been sufficient for them to engage in the required transactive processes, without additional help such as transactive memory scripts (Noroozi et al., 2012). The results also suggest that the choice of tasks was adequate to generate the conditions necessary for effective collaboration to occur (see Kirschner et al., 2004).

It can also be assumed that any potential negative effects of collaboration such as collaborative inhibition (Weldon & Bellinger, 1997) were small compared with the overall positive effects of collaboration. The cognitive load measures indicated that the collaborative learners experienced less cognitive load than individual learners at each phase of the study. Hence, any potential negative transaction costs as described by Kirschner et al. (2009a) may have been small compared with the cognitive load of working individually.

The second hypothesis—when learners have complete basic knowledge bases, individual learning is superior to collaborative learning—was confirmed. Individuals studying alone with complete essential knowledge bases had significantly higher scores on the acquisition and transfer tests, with lower cognitive load than individuals with complete knowledge bases learning collaboratively. This hypothesis was predicted based on the redundancy effect (see Kalyuga & Sweller, 2014). With a complete knowledge base, working collaboratively was redundant as little information, if any, needed to be borrowed from other group members. Requiring learners to use a redundant strategy (collaboration) generates extraneous cognitive load, which in turn interferes with learning (Kalyuga & Sweller, 2014). Presumably, any positive effects of a shared working memory load (Kirschner et al., 2009a) were small compared with the negative effects of redundancy under these conditions.

As indicated above, there are a number of factors that can make collaboration fail such as a lack of a transactive memory system or poor tasks. The positive confirmation of the first hypotheses, where collaboration was effective, suggests that these factors may have had little impact. Sangin et al. (2011) pointed out that when prior knowledge is similar, less elaboration and negotiation are required. Lack of such discussions may have occurred; however, it does not necessarily explain why cognitive load was higher for collaboration compared to individual learning. If anything, a lack of discussion and transactions should have lowered cognitive load. Hence, we suggest that redundancy and its generation of extraneous cognitive load had the most significant impact.

8.2 | Implications

The results of this study suggest that when students have a similar knowledge base, collaboration may be less fruitful than individual learning. Collaboration can be a redundant strategy when learners have similar knowledge bases, or when a worked examples approach is used instead of problem solving as previous shown (Retnowati et al., 2017). Hence, redundancy should be avoided when collaborating just as much as for other learning strategies.

Collaboration seems to be effective if learners who have different knowledge bases are grouped together in a problem-solving environment. However, school students in the same class are unlikely to have been exposed to vastly different learning experiences resulting in different knowledge bases and therefore this situation is unlikely to frequently occur. The learning environment can be manipulated artificially to ensure within-group knowledge gaps, similar to this study, but this may have limited value unless the broader educational aims are to promote collaboration and transactive memory. Providing the emphasis on developing team work and social skills rather than learning subject content, collaboration may have value, even though learning may suffer.

The collaborative learning research outlines a number of ways in which collaboration can be ineffective. It is well known that simply putting students together or using inappropriate tasks does not automatically guarantee an effective learning environment (Slavin, 1995). Our study reinforces the importance of differences in learners' knowledge bases. Asking students with similar knowledge bases to collaborate may be a disadvantage because of redundancy.

8.3 | Limitations

Some caution must be shown in generalizing too much from a single study. In addition, although collaboration took place, we do not know the full extent of the cognitive processes that occurred. For example, we do not know how much transactivity (Schmitt & Weinberger, 2017) there was and how the students reacted to their partners contributions. The collaborating students were grouped using existing school structures, so we can assume that they had developed transactive memory systems (Wegner, 1987), but to what extent they were used is unclear.

Although collaboration was ineffective for students with complete knowledge bases which we attributed to redundancy, we did not obtain evidence that inferior performance was due to redundant processes per se. Hence, there is need for more studies that examine directly the processes that occur under these conditions.

Although the tasks used in this study were appropriate as previously noted, future research could use more open-ended tasks where there is more than one solution (see Cohen, 1994; Laughlin, Zander, Knievel, & Tan, 2003). It would be interesting to see if such tasks lead to richer discussions and more unconventional solutions, with a subsequent greater impact on the effects of collaboration.

Finally, we did not obtain measures of mathematical ability. Future research could obtain measure student's ability in the domain to see if expertise-reversal effects (Kalyuga et al., 2003) were present. It is possible that domain-specific expertise could have moderated the differences found here.

8.4 | Conclusions

This study adopted the relatively novel approach of bringing together concepts and ideas from collaborative research and cognitive load theory. The findings showed collaboration is redundant for learners with similar knowledge bases but beneficial for learners with disparate knowledge bases. From a theoretical perspective, the study suggests that combining cognitive load theory with more general collaborative research may enhance both fields. From an empirical perspective, our results suggest that combining the two fields can generate novel findings with practical implications.

EDUCATIONAL IMPLICATION AND IMPACT STATEMENTS

This study compared students learning mathematics collaboratively or individually. It was found that collaboration during mathematical problem solving was superior to individual learning when learners differed in what they knew and so could provide information to each other but inferior when learners were more similar in what they knew and so did not have useful information to provide to other group members. When students had similar knowledge, they learned better by themselves rather than collaborating.

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How to cite this article: Retnowati E, Ayres P, Sweller J. Collaborative learning effects when students have complete or incomplete knowledge. *Appl Cognit Psychol*. 2018;1–12. https://doi.org/10.1002/acp.3444

APPENDIX A

MATERIALS AND PROCEDURES USED IN THE INITIAL PHASE TO GAIN PREREQUISITE KNOWLEDGE

A.1 | Topic A: Pythagoras' theorem

The summary (i.e., a description of a right-angled triangle and the Pythagoras formula) was written on a single sheet of A4 paper. Ten pairs of worked examples were presented in a booklet designed using problem pairs. Each pair consisted of a worked example and a similar problem to be solved. The worked example provided a problem statement and a step-by-step solution to the problem and was written on the left side of the page. The paired problem to-be-solved was positioned on the right side of the page and consisted of the problem statement only. To provide some feedback and support to participants (see Sweller & Cooper, 1985) final answers for these problems, but not step-by-step solutions, were provided on the same page of the booklet. The relevant instruction was provided directly above each problem and written in the participants' native Indonesian. There were four examples using Pythagoras' theorem to find a single side in a single right-angled triangle (i.e., a one-step solution) and six examples where two sides need to be calculated in more complex triangle configurations (i.e., a two-step solution). Each problem had a slightly modified configuration.

A.2 | Topic B: Finding the area of a triangle

The learning material consisted of a summary of the area formula and a set of worked examples. The summary (i.e., a description of the base and height of a triangle and the area formula) was written on a sheet of A4 paper. Ten pairs of worked examples were presented in a booklet. Five pairs consisted of a single triangle (i.e., one-step solutions) and five pairs had more complex configurations (i.e., multistep solutions). Figure 2a displays an example of the more complex configuration, where participants were asked to identify key lengths (base and height of each triangle in the shaded area) and use them to calculate the area of each triangle using the formula. Each problem had a slightly modified configuration.

A.3 | Learning about both topics

This learning material consisted of a summary sheet for both topics A and B. The worked example booklet consisted of five pairs of worked examples on topic A (two pairs using Pythagoras' theorem to find a single side in a single right-angled triangle, and three pairs where two sides need to be calculated in more complex triangle configurations), and five pairs on topic B (two pairs consisting of a single triangle and three pairs with more complex configurations). All problem pairs were taken from the sets used for single topics and consisted of exactly half of what was required for participants assigned to learning an individual topic.