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Computer-supported collaborative concept mapping: the effects of different instructional designs on conceptual understanding and knowledge co-construction

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Abstract

Computer-supported collaborative concept mapping (CSCCM) leverages technology and concept mapping to support conceptual understanding, as well as collaborative learning to foster knowledge co-construction. This article investigated the effect of different instructional designs using CSCCM on students' conceptual understanding, and on the type of processes of knowledge co-construction that students engage. Participants (N = 120) were 10th graders enrolled in their physics course, randomly distributed in dyads. They were asked to draw concept maps related to the conservation of energy law, by using CSCCM with different instructional designs (i.e., control, Exp. 1 and Exp. 2). In the control condition, dyads worked collaboratively all the time. In both Exp. 1 and Exp. 2, dyads worked first individually (one week) and then collaboratively (two weeks). However, in Exp. 2, the individual concept map was shared with the peer before collaborating. Conceptual understanding improved significantly for learners in all three experimental conditions, especially in Exp. 2. Statistically significant differences were found in students' knowledge co-construction among the three conditions. Dyads in the control group showed a significantly higher use of quick consensus-building. Dyads in Exp. 1 showed a significantly higher reliance on externalization and elicitation. Dyads in Exp. 2 showed a significantly higher enacting of integration- and conflict-oriented consensus building. Accordingly, an instructional design like Exp. 2 optimizes CSCCM learning outcomes in terms of conceptual understanding and knowledge co-construction.

Keywords: concept mapping, computer-supported collaborative learning, conceptual understanding, knowledge co-construction

1. Introduction

The importance of students' conceptual understanding is increasingly emphasized in policy documents worldwide (Songer & Kali, 2014). Science education should discourage the memorization of inert, disciplinary science facts, and favor instructional activities promoting the use of arguments, data analyses, and the application of acquired knowledge to real-life situations (Mayer, 2002; Songer & Kali, 2014). However, the development of a deep conceptual understanding of science takes effort, time, guidance, and repeated exposures (Brown, Ellery, & Campione, 1998). Therefore, there is a need to support students to achieve a deep conceptual understanding in science, so that they reach the education system goals of meaningful learning and knowledge transfer (Anderman, Sinatra, & Gray, 2012; Gallagher, 2000; Johnstone, 1991; Ploetzner, Lippitsch, Galmbacher, Heuer, & Scherrer, 2009).

Many instructional approaches for addressing students' conceptual learning have been developed (Harrison, Grayson, & Treagust, 1999; Karplus, 1981; Posner, Strike, Hewson, & Gertzog, 1982; Thornton & Sokoloff, 1990; Wiser & Amin, 2001). One such promising approach is to have students generate concept maps (Pérez-Rodríguez, Suero-López, Montanero-

Fernández, Pardo-Fernández, & Montanero-Morán, 2009). By eliciting self-explanations, the task of constructing a concept map can stimulate students' awareness of their own implicit causal models of the physical phenomenon being dealt with (Chi, Slotta, & De Leeuw, 1994). Concept maps are tools known to contribute to students' deeper conceptual understanding, especially when utilized as a tool for knowledge co-construction in collaborative learning (Okebukola, 1990; van Boxtel, van der Linden, & Kanselaar, 2000). Collaborative learning, which has been used in education for several decades, often aims to foster students' meaningful learning, in the sense of appropriating a deeper conceptual understanding by co-constructing knowledge, and not only that the students solve problems together (Baker, 2015; Correia & Infante-Malachias, 2009; Ng & Hanewald, 2009).

The use of concept maps in collaborative learning (i.e., collaborative concept mapping; CCM) can be supported by computers in both face-to-face and not co-located situations. In this sense, computer-support facilitates rearranging, editing and sharing the map, as well as working together and communicating when students are apart. Different instructional designs can be used to implement computer-supported collaborative concept mapping (CSCCM). First, students could be instructed to collaborate directly on CSCCM (Gijlers & de Jong, 2013). Second, an initial individual concept mapping phase could be used as preparation for CSCCM (De Weerd, Tan, & Stoyanov, 2017). Third, instruction could leverage the affordances of CSCCM to support cognitive group awareness (i.e., group members' knowledge of who knows what). Research on computer-supported collaborative learning has indicated that supporting cognitive group awareness in these environments enhances knowledge co-construction (Schreiber & Engelmann, 2010; Stoyanova & Kommers, 2002). However, no research has explored the addition of cognitive group awareness support to the CSCCM capabilities for stimulating conceptual understanding. To the best of our knowledge, the aforementioned instructional designs have not been studied in unison. For example, Stoyanova and Kommers (2002) found that the form in which knowledge is shared during computer-supported collaborative problem solving using concept maps affects the effectiveness of the collaboration. In their design, an individual preparation phase was not considered. De Weerd et al. (2017) found that an individual preparation phase resulted in higher-quality knowledge co-construction, but their design did not include sharing the outcomes of the individual phase to enhance cognitive group awareness.

Accordingly, in this paper, we aim to investigate the effects of the different instructional designs mentioned above, which leverage CSCCM, on students' conceptual understanding and quality of knowledge co-construction. Importantly, we consider factors which might affect students' engagement with CSCCM, such as students' communication skills, self-regulated learning capabilities, and attitudes towards online collaborative learning.

2. Theoretical framework

2.1.Concepts and conceptual understanding

Novak and Cañas (2008) define *concept* as "a perceived regularity in events or objects, or records of events or objects, designated by a label." By considering this definition, science is full of all kinds of concepts and the laws governing them. In the particular case of physics, the majority of students find it an accumulative science filled with concepts, in which if a concept is forgotten or misunderstood, learning other concepts will become difficult (Ornek, Robinson, &

Haugan, 2008). Physics, indeed, encompasses a wealth of interconnected concepts, which many students struggle or fail to integrate and relate to one another consistently (Jones & Mooney, 1981; Koponen & Pehkonen, 2010). For example, one of the most important observations in science is that energy can neither be eliminated from existence nor can it be created from absence; that is, energy is conserved (DiSessa, 2014). This law of energy conservation is essential as it has important applications such as the generation of power by wind or water turbines. Moreover, the learning of many physics' concepts (e.g., work, conservative and non-conservative forces, kinetic energy, gravitational/elastic potential energy, and thermal energy) relies on the understanding of the law of energy conservation. Unfortunately, it has been repeatedly and consistently found that students have misunderstandings about this principle (Tatar & Oktay, 2007). Accordingly, the law of energy conservation and its associated concepts were selected as subject matter for this study on conceptual understanding supported by CSCCM.

Conceptual understanding is arguably the underlying mechanism for meaningful learning, also referred to as deep learning (Jonassen, Strobel, & Gottdenker, 2005; Novak, 2002). Meaningful learning has been described as a student's intention to understand content together with the processes of relating and structuring new ideas to previous knowledge and experience, looking for underlying principles, weighing relevant evidence, and critically evaluating knowledge (Biggs, Kember, & Leung, 2001; Entwistle & McCune, 2004; Lonka & Lindblom-Ylanne, 1996; Loyens, Gijbels, Coertjens, & Côté, 2013). When students gain a deeper conceptual understanding, they learn facts and procedures in a much more useful and profound way that transfers to real-world settings (Sawyer, 2014).

In order to help students to develop their conceptual understanding, it is essential to provide opportunities for them to contrast their own ideas with other alternatives, which might result in conceptual change through cognitive conflict (Limón, 2001; Pea, 1993; Wiser & Amin, 2001). This could be achieved by stimulating knowledge co-construction with peers (Tao & Gunstone, 1999).

2.2.Knowledge co-construction

When learners are working in small groups, they can construct knowledge with the help of their peers through actively taking part in discussions (Roschelle & Teasley, 1995). According to Fischer, Bruhn, Gräsel, and Mandl (2002), collaborative learning should foster the three major processes of knowledge co-construction: 1) externalization of task-relevant knowledge (EX), 2) elicitation of task-relevant knowledge (EL), and 3) consensus building, either quick (QC), integration-oriented (IO) or conflict-oriented (CC). These processes have been described by Weinberger and Fischer (2006) as follows. Externalization refers to students articulating thoughts to the group in an effort to organize and clarify their mental models. Elicitation refers to questioning or seeking a reaction from the learning partner. Quick consensus building refers to accepting the contributions of the learning partners to move on with the task. Integration-oriented consensus building refers to taking over, integrating and applying the perspectives of the learning partners. Finally, conflict-oriented consensus building refers to learners criticizing, modifying or substituting each other's contribution to discourse with the goal of productively resolving the conflict and arriving at a shared understanding.

Consensus building is a challenging step, because it follows an animated divergent thinking session (elicitation) and imposes convergent thinking on the group. The purpose of consensus building is to reach a final product containing the richness of the discussions. The product would merge the participants' contributions into an integrated framework, which is generated by the group. Under non-ideal circumstances, consensus will be achieved through the integration of numerous perspectives into a shared interpretation, where all fragments have an identifiable authorship, and most are from the same participant (Correia, Cicuto, & Aguiar, 2014). Hence, Fisher et al. (2002) consider such a consensus as "illusory". In the socio-cognitive conflict viewpoint, collaborative learners who engage in conflict-oriented consensus building may eventually accommodate their individual cognitive structures (Weinberger & Fischer, 2006). Therefore, among the different processes which take place in knowledge co-construction, conflict-oriented consensus building is considered the one mainly associated with learning (Teasley, 1997). In collaborative learning, the existence of conflicts over the interpretation of a problem can encourage learners to engage in further communication (Dillenbourg, Baker, Blaye, & O'Malley, 1996), and through negotiation, a shared understanding can be constructed (van den Bossche, Gijselaers, Segers, & Kirschner, 2006).

In this regard, it is argued that external representations such as concept maps can be an effective scaffold for the complex process of knowledge co-construction (De Weerd et al., 2017). In fact, research shows that concept maps scaffold knowledge externalization and internalization more effectively than text (Engelmann & Hesse, 2010).

2.3. Concept mapping

Concept maps are tools for organizing and representing knowledge, which consist of nodes representing concepts and labeled lines denoting the relation between pairs of nodes (Novak & Cañas, 2008). Through this graphical representation tool, the organization of concepts in students' memory (i.e., their cognitive structure) can be made visible (Ruiz-Primo & Shavelson, 1996). Learners can use concept maps as a strategy for integrating new knowledge into their prior knowledge, especially when they find it challenging to assimilate the new knowledge (Greene & Azevedo, 2010). By helping to organize knowledge and to structure it, concept mapping not only permits knowledge utilization in new contexts (i.e., knowledge transfer), but also longer-lasting knowledge retention (Novak, 1990). In other words, concept mapping facilitates meaningful learning.

However, despite its benefits, concept mapping is not without its challenges. Concept maps are considered ill-structured tasks since different correct solutions are possible (Jonassen, 1997). In science education, concept maps are regarded as cognitively demanding tasks given the cognitive efforts they require in order to recognize the concepts related to the subject and the relationships among them (Pérez-Rodríguez et al., 2009). Several types of support have been considered to ease the cognitive demands of drawing concept maps (Hatami, Farrokhnia, & Hassanzadeh, 2016; Yin, Vanides, Ruiz-Primo, Ayala, & Shavelson, 2005). For example, instructors can use moderately-directed concept maps by providing students with the key concepts to use, thus predetermining the number of nodes (Chiu, 2003; Gao, Shen, Losh, & Turner, 2007). In addition, the ill-structured nature of concept mapping makes it suitable for

collaborative learning, by sharing the cognitive challenge with other individuals in a manner that reduces this complexity (Kirschner, Sweller, Kirschner, & Zambrano, 2018).

2.4. Collaborative concept mapping

Since concept mapping tasks have no predetermined or fixed answers, CCM elicits knowledge co-construction processes by stimulating socio-cognitive conflict (Wang, Cheng, Chen, Mercer, & Kirschner, 2017). This process enables collaborating students to discover both proximal and semantic relationships between usage of concepts (Reiter-Palmon, Sinha, Gevers, Odobez, & Volpe, 2017). Research has shown that concept maps structure the collaborative discourse and fosters more in-depth and productive interaction (Sizmur & Osborne, 1997; Stoyanova & Kommers, 2002).

However, negative findings have also been reported in the literature of knowledge co-construction during CCM. Van Boxtel and colleagues (2002) found that students' communication seldom reached the explanatory level when reasons for certain propositions were elaborated by the group. In addition to their positive findings, Roth and Roychoudhury (1993) also observed situations where incorrect notions went unchallenged and became ingrained. Along the same line, Chiu (2003) found that while few instances of off-task communication occurred, most of the on-task interactions were devoted to process-oriented exchanges including task collaboration, procedure, and team coordination rather than to interactions that are central to knowledge co-construction such as discussions about concepts, propositions, or relationships. Similar problems were identified in Carter's (1998) study where CCM was used in a college biology laboratory. Analysis of the interaction suggested that most students did not pay close attention to each other's comments and did not capitalize on possible opportunities for knowledge co-construction. Carter also observed that students used memorized but not necessarily accurate answers, had difficulty in forming explicit relationships between concepts, and found the hierarchical nature of the concept maps to be problematic.

These conflicting findings highlight the need to study the effects of CCM within the context in which the activity is carried out. Contextual factors (e.g., the activities learners are engaged in prior to the CCM activity, the kinds of external information and physical tools provided to the learners, and learners' familiarity with concept maps) play an important role in the outcomes of CCM (Gao et al., 2007). For example some research has explored the effects of an individual phase before the collaboration as a way of preparing students for knowledge co-construction using both paper-and-pencil (van Boxtel et al., 2000) and digital or computer-supported (De Weerd et al., 2017) CCM. The results of such individual phase confirm higher quality of knowledge co-construction (i.e., more integrated- and conflict-oriented consensus building statements) and better learning outcomes. The effectiveness of the individual preparation phase might be explained through the possibility it gives for learners to clarify their own cognitive structure and current understanding, before discussing it with others (De Weerd et al., 2017; Gao et al., 2007). In addition, some researchers argue that computer-support can strengthen the benefits of CCM for improving the learning outcomes by providing different functionalities and scaffoldings, as well as removing the frustration felt by students while revising concept maps using paper and pencil (Chang, Sung, & Chen, 2008; Lin, Wong, & Shao, 2012).

2.5. Computer-supported collaborative concept mapping

Although digital concept maps are not necessarily better than their paper-and-pencil counterpart when it comes to learning outcomes (Islim, 2018), CSCCM enable students to reconfigure the map quicker and easier if they rethink concepts and their relationships. Reconfigurations are common since concept mapping is not a straightforward but rather an iterative process. The easier it is for learners to build and edit the map, the less the time consumed by the mechanics of concept mapping, which can then be devoted to the domain-specific conceptual understanding. Computer support may thus facilitate the process of CCM no matter whether the learners are co-located or not. Embedded chat tools can cover the need for communication of not co-located learners and help them to engage in reflection, critical thinking, and task-oriented discussion (Jonassen & Kwon, 2001).

Computer support also makes it easier to share individually created concept maps with peers, which can then enhance cognitive group awareness (Cheng & Chu, 2018; Schreiber & Engelmann, 2010; Stoyanova & Kommers, 2002). Cognitive group awareness refers to students' understanding of which knowledge and expertise their peers have (Wegner, 1987). When learning collaboratively, students actively utilize and combine others' knowledge in order to carry out a joint task (Lewis, 2003). Therefore, collaborative learning will be negatively affected if the prior knowledge differences have not been recognized before carrying out the task (Kirschner et al., 2018). As a result, students' cognitive group awareness is an important facilitator of the knowledge co-construction process, which influences the efficiency and effectiveness of the process (Janssen & Bodemer, 2013) and is a determinant factor for success in collaborative environments (Bodemer & Dehler, 2011). In this regard, Schreiber and Engelmann (Schreiber & Engelmann, 2010) found that using concept maps to visualize collaborators' knowledge structures (see also Engelmann, Dehler, Bodemer, & Buder, 2009; Fischer & Mandl, 2005) can foster cognitive group awareness, which is in turn beneficial for group performance in newly formed ad hoc learning groups.

Despite the affordances and positive results of CSCCM, students' involvement and success in collaborative learning environments are also determined by other factors such as students' communication skills (Barron, 2003), self-regulated learning skills in online learning (Kizilcec, Pérez-Sanagustín, & Maldonado, 2017), and attitudes towards online collaborative learning (Chatterjee & Juvale, 2015).

In sum, previous studies have provided evidence of the potential of CSCCM to support students' deeper conceptual understanding and higher-quality knowledge co-construction (De Weerd et al., 2017; Gijlers & de Jong, 2013; Komis, Avouris, & Fidas, 2002; Leng & Gijlers, 2015; Stoyanova & Kommers, 2002). However, to the best of our knowledge, no study has focused on the effect of using an individual preparation phase on the quality of knowledge co-construction, and of supporting cognitive group awareness by sharing a previously individually created concept map.

Consequently, there is a need to investigate the effectiveness of different instructional designs using concept maps to capitalize on their affordances for deeper conceptual understanding and enhanced knowledge co-construction (Wang et al., 2017). Studies using CCM, whether

computer-supported or not, mostly use tasks fitting in the duration of a lesson (i.e., up to 90 min but most typically less than an hour) (Cheng & Chu, 2018). This relatively short duration is of special interest when it comes to the design of in-class activities. However, it has also been seen as a limitation, since in-depth CCM, including a rich knowledge co-construction process, takes time (Cheng & Chu, 2018; Kim, Yang, & Tsai, 2005). Therefore, this study employs the longer time frame of a week at least, so that time is not a constraint in the process. Considering the gaps identified in the literature previously discussed, we seek to answer the following questions in this research:

Research Question 1: In CSCCM, how an individual preparation phase and cognitive group awareness support affect students' conceptual understanding of physics?

Research Question 2: In CSCCM, how an individual preparation phase and cognitive group awareness support affect the quality of students' knowledge co-construction?

3. Methodology

3.1. Participants

The participants (N = 120) were tenth-graders enrolled in the physics course at an Iranian high school. All the participants were males and their average age was 15 years. The participants signed an informed written consent which they could withdraw at any time during the study. The study was embedded in the coursework, and two extra credits were awarded for participation. The students were randomly divided into dyads, an adequate group size for knowledge co-construction and mutual social support (Stacey, 1999). Typically, CCM studies are conducted with dyads or triads, as they are regarded as suitable for such activities (Kim et al., 2005).

3.2.Materials

3.2.1. CSCCM environment

A CSCCM environment was designed and developed in collaboration with a company using C programming language, Microsoft SQL Server, and JointJS Rappid technologies. The environment was made available online for the duration of the experiment after payment of the corresponding fee to the hosting company. The appearance of the environment is illustrated in the two screenshots of Figure 1, corresponding to the screens of two collaborating students. The students had to log in to use the environment. The environment consists of a top menu with file (e.g., save, print, export PNG, export SVG, delete, close), edit (e.g., undo, redo) and view (e.g., full screen, zoom in, zoom out) options, a left menu with the list of concepts (provided by the teacher) and geometrical shape (e.g., rectangle, ellipse, diamond) selection, a drawing area in the central space, and a right menu with further options for customizing the concept maps such as connection type (i.e., straight line, L shape, U shape), connection style (e.g., straight square corner, rounder square corner, arc), line thickness, line style (e.g., solid, dash), line color, and line starting and ending (e.g., arrowheads).

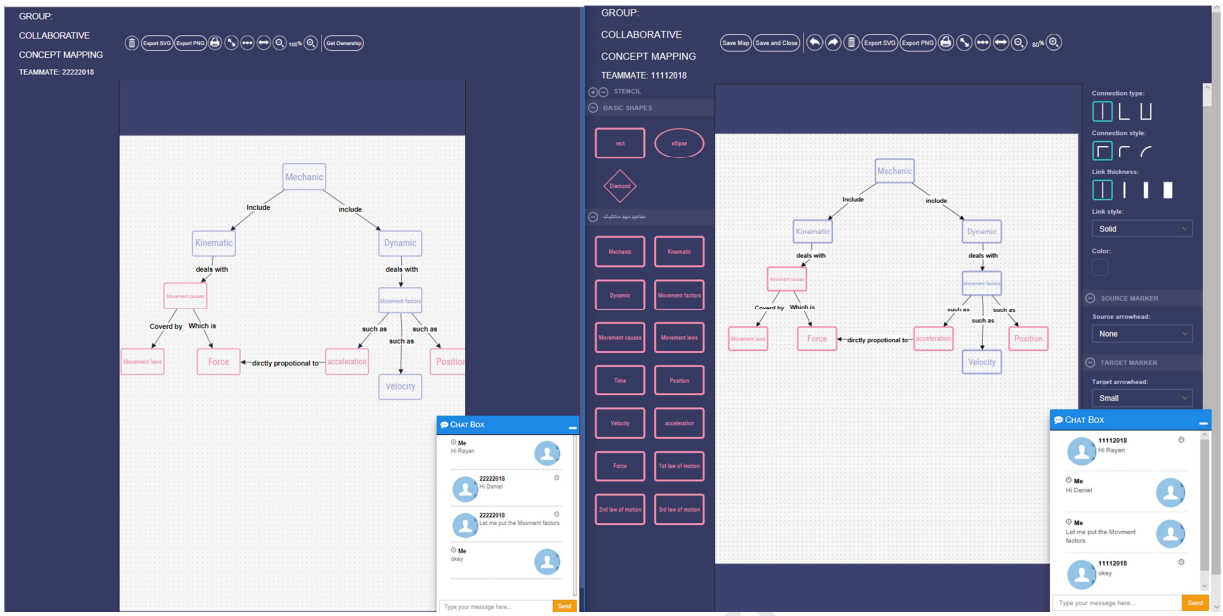


Figure 1: Sample screenshots of two students using the CSCCM environment.

Students enter the CSCCM environment by logging in with their own user and password. The students can access the CSCCM environment via the device of their choice and convenience (e.g., PC, laptop, tablet or smartphone). The teacher introduces the list of concepts relevant to the subject matter in the environment and can keep track of the students' progress in drawing a concept map and message the students. The students can work on the concept maps individually or collaboratively. When two students work collaboratively and simultaneously on the environment, the concept map is visible to both with changes in real time, but only one student at a time has the right to draw, the one who has the "ownership" at that moment. Students can get the right to draw by clicking the "Get ownership" button on the top menu, which sends an ownership request to the collaborating peer. Upon acceptance, the ownership is then transferred to the peer. In this way, they iteratively change the concept map ownership from one to another while drawing together. This way of working is illustrated in Figure 1, where the screenshot on the right corresponds to the student with the ownership. Notice that the drawing tools are available on the right screenshot, as opposed to the left one. In addition, the "Get ownership" button is available rightmost on the top menu of the left screen, as opposed to the right one. This system of alternating ownership emulated a face-to-face scenario where the students would be drawing the concept map on a shared sheet of paper, and both of them can see the progress, but only one student draws on the paper at a time.

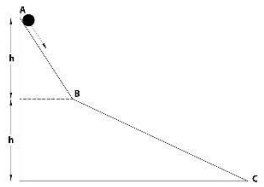
Since an essential feature of collaboration is communication, the environment conveniently includes a chat box and a discussion forum. Through these channels, students can share and exchange their ideas and knowledge on the topic while drawing concept maps together. Although the environment was designed to be intuitive and easy to use, it also contained help in the form of multiple tutorial videos, in case the students, teachers, or users in general needed it.

It is worth mentioning that in CSCCM research, depending on the characteristics and needs of the study, researchers have developed their own concept mapping tools (Cheng & Chu, 2018; Komis et al., 2002), or used commercial software such as Inspiration (De Simone, Schmid, & McEwen, 2001; Stoyanova & Kommers, 2002), or free software such as CmapTools (De Weerd et al., 2017; Schreiber & Engelmann, 2010). There are commonalities and differences between our CSCCM environment and other concept mapping software such as those mentioned. In general, concept mapping programs offer drawing tools including a variety of shapes and connectors, the possibility for customization of the visual appearance of the map, and general file options such as saving, printing, and exporting the concept map. In addition to those, our CSCCM environment is tailored for non-collocated collaboration by offering team members a real-time visualization of the evolution of the map being drawn, and a built-in chat box for students to communicate and discuss when working together on the map. For teachers, the CSCCM environment enabled them to enter a predetermined list of concepts and to follow the progress of the concept maps of all the groups in the class.

3.2.2. Conceptual understanding measurement

To measure the conceptual understanding of students before and after using the CSCCM learning environment, different standard concept inventory tests were examined by two experienced physics teachers. Considering the subject matter of this study, the Energy and Momentum Conceptual Survey (Singh & Rosengrant, 2001) and the Energy Concept Assessment test (Ding, 2007) were chosen for developing the final concept inventory test. The teachers identified the most relevant questions among those in these two tests. A total of 30 questions were selected, 14 questions from the 25 composing the Energy and Momentum Conceptual Survey, and 16 questions from the 33 making up the Energy Concept Assessment test. Examples of the questions are shown in Table 1.

Table 1: Sample questions of final energy concept inventory test.

Q6. Three bicycles approach a hill as described below: (1) Cyclist 1 stops pedaling at the bottom of the hill, and her bicycle coasts up the hill. (2) Cyclist 2 pedals so that her bicycle goes up the hill at a constant speed. (3) Cyclist 3 pedals harder, so that her bicycle accelerates up the hill. Ignoring the retarding effects of friction, select all the cases in which the total mechanical energy of the cyclist and bicycle is conserved. (a) (1) only (b) (2) only (c) (1) and (2) only (d) (2) and (3) only (e) (1), (2) and (3)
Q11. You slide down two consecutive slopes of frictionless ice whose vertical heights h are identical, as shown below. Select all of the following statements that must be true. (1) The change in your kinetic energy is identical for the motion from A to B and from B to C. (2) The work done on you by the gravitational force is smaller for the motion from A to B than from B to C. (3) The work done on you by the gravitational force is greater for the motion from A to B than from B to C.   

(a) (1) only
(b) (2) only
(c) (3) only
(d) (1) and (2) only
(e) (1) and (3) only

To detect any possible overlap in the selected questions, three physics experts were asked to match the test questions with the educational goals of the curriculum in relation to the subject matter. As a result, four questions were identified as redundant and consequently discarded. The reliability of the final test with 26 questions was estimated in a pilot study. The reliability coefficient was sufficiently high for both the pre-test (Cronbach's $\alpha = .73$) and the post-test (Cronbach's $\alpha = .80$). Therefore, it was concluded that the final test can effectively assess the students' conceptual understanding on the subject matter.

3.3. Control measures

As discussed in the theoretical framework, students' knowledge co-construction towards a deeper conceptual understanding is affected by their communication skills, self-regulated learning skills in online learning, and attitude towards online collaborative learning. Therefore, validated instruments were used to control for uneven distribution of these measures in all the experimental conditions, as these factors might impact the results.

3.3.1. Communication skills

The Interpersonal Communication Competence Inventory, developed and validated by Huang & Lin (2018), was used to measure the students' communication skills. The inventory comprises 15 items which are rated on a 5-point Likert scale. In addition to that reported by the authors, the reliability was estimated in a pilot study, obtaining a satisfactory coefficient (Cronbach's $\alpha = .77$).

3.3.2. Self-regulated learning skills in online environments

The Self-Regulated Online Learning Questionnaire, designed and validated by Jansen and colleagues (2017), was used to measure self-regulation skills in online environments. The questionnaire includes 35 items divided into 5 scales (e.g., task definition, goal setting, time management, etc.). The items are rated on a 7-point Likert scale, ranging from ''not at all true for me'' (=1) to ''very true for me'' (=7). The overall questionnaire reliability was estimated in a pilot study to be sufficient (Cronbach's $\alpha = .87$).

3.3.3. Attitudes toward online collaborative learning

The Korkmaz's (2012) online cooperative learning attitude scale was utilized to measure the students' attitudes toward online collaborative learning. The scale is comprised of 17 items rated on a 5-point Likert scale. In addition to the reliability determined by the authors, we estimated the reliability in a pilot study, obtaining a sufficient coefficient (Cronbach's $\alpha = .70$).

3.4. Design and procedure

A pilot study and three participants' training sessions were conducted before the experiment, the latter consisting of three phases. An overview of the procedure is presented in Figure 2.

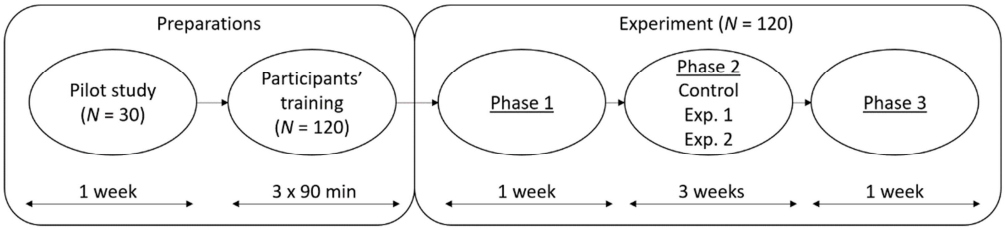


Figure 2: Procedure overview.

Pilot study

In a preparation phase prior to the experiment, a pilot study was conducted with the two-folded aim of testing the functionality of the designed CSCCM environment and estimating the reliability of the questionnaires used. The pilot study was conducted with 30 participants (i.e., 15 dyads) and lasted for a week, which allowed to identify and fix flaws in the environment functionality.

Participants' training

A week before the actual experiment, participants were trained during three 90 min sessions as introduction to the experiment, the procedure, concept map drawing, and the CSCCM environment. This was the only face-to-face part of the experiment, since the task was to be completed in full as a course homework assignment on the online CSCCM environment.

Task and experiment

The task consisted of drawing a moderately-directed concept map with 36 predetermined concepts dealing with energy conservation and related concepts. Two experimental conditions (i.e., Exp. 1 and Exp. 2) and a control group were devised. Both Exp. 1 and Exp. 2 comprised an individual concept mapping phase (one week) and a CCM phase (two weeks). Students were required to start both concept maps (i.e., individual and collaborative) from scratch, although using the same concepts. The difference between the experimental conditions was that in Exp. 1 the individual concept map was never shown to the students' peers, while in Exp. 2, each student was shown the individual concept map of their peer at the beginning of the collaborative phase, in order to support cognitive group awareness. On the other hand, students in the control group were asked not to work individually on the concept map, but collaboratively with their peer all the time (i.e., three weeks). An equal number of dyads (N = 20) was randomly assigned to each of the three conditions (i.e., control, Exp. 1 and Exp. 2). The experiment started once the unit of the subject matter (i.e., energy and energy conservation) had been finalized in the physics course.

Table 2: Overview of the experimental design.

Phase	Condition	Procedure	Duration
1	All three	Introduction, questionnaires, and pre-test	1 week
2	Control	CCM	3 weeks
	Exp. 1	Individual concept mapping	1 week
		CCM without cognitive group awareness support	2 weeks
	Exp. 2	Individual concept mapping	1 week

		CCM with cognitive group awareness support	2 weeks
3	All three	Post- test	1 week

Overall, the experiment lasted for five weeks divided into three main phases: 1) introduction, questionnaires and pre-test (one week), 2) control and treatment (three weeks), and 3) post-test (one week). Table 2 presents the overview of the experimental design. In the first phase, the students continued familiarizing themselves with the general features of the environment by watching videos, reading instructions, and drawing a concept map on a different subject matter for practicing purposes. Additionally, they were required to complete the energy concept inventory pre-test (25 min), and the questionnaires about communication skills (30 min), self-regulated learning skills in online learning environments (30 min), and attitudes towards online collaborative learning (30 min). The pre-test and questionnaires were available and answered online on the CSCCM environment. In the second phase, students worked on the concept map(s) according to the experimental condition their dyad was randomly assigned to. Finally, the students were given one week (third phase) for them to find a suitable time to answer again the concept inventory test (25 min) as a post-test, to measure the effect of the instructional design they were assigned to on their conceptual understanding.

4. Analysis

4.1. Processes of knowledge co-construction

The students' chat logs were segmented into utterances, defined as a distinct and clear message transferred from a student to another or to himself. Altogether, 18071 utterances were obtained during the second phase from the control group (three weeks) and the experimental groups (two weeks corresponding to the CCM). Following Gijlers and de Jong (2013), each utterance was initially classified as either on- or off-task communication, obtaining 15159 and 2912 utterances respectively. Instances of off-task communication (e.g., "do we have math homework?") were excluded from the analysis. Conversely, on-task utterances (i.e., 15159) were further categorized according to Weinberger and Fischer's (Weinberger & Fischer, 2006) processes of knowledge co-construction, as shown in Table 3, by three coders (i.e., the first author and two other physics teachers).

Table 3: Coding schema.

Knowledge co-construction process	Code	Examples of utterances from students' interaction
Externalization	EX	The work of the weight force is related to the gravitational potential.
Elicitation	EL	What is the relation between potential and mechanical energy?
Quick consensus building	QC	Yes!
Integration-oriented consensus building	IO	I agree that the spring force is a constant force.
Conflict-oriented consensus building	CC	I believe that the work of the non-conservative force does not affect the potential energy of the system!

To ensure the reliability of the coding process, the coders received extensive training on applying the coding scheme and they were given the opportunity to practice with sample data and the data from the pilot study. The inter-rater reliability of coding utterances in terms of on-

and off-task communication was sufficient (Cohen's kappa = 0.76). Likewise, the inter-rater reliability for coding utterances as knowledge co-construction processes was also sufficient (Cohen's kappa = 0.79).

4.2. Unit of analysis and statistical tests

The unit of analysis, either at the individual or dyad level, depended on the research question addressed. We used the individual as the unit of analysis to check for the equal distribution of the learners over the three conditions in terms of prior knowledge, communication skills, self-regulated learning skills, and attitudes toward online collaborative learning environments. We also used the individual as the unit of analysis for the RQ1 concerning individual pre- or post-test measures of students' conceptual understanding in each group. To answer RQ2, we used the dyads (group values) as the unit of analysis. The number of utterances categorized by knowledge co-construction processes was aggregated as the sum of those from each individual for each dyad. An analysis of variance for repeated measurements was used to compare individual conceptual understanding between learners in the three conditions. To investigate the differences between the three conditions regarding the quality of the discussions, a multivariate analysis of covariance was performed with the conditions as the independent variables and the number of utterances in the different processes of knowledge co-construction as the dependent variables, while controlling for the difference in the total number of utterances.

5. Results

5.1. Differences in pre-test and control measures

Learners in the three conditions showed no statistically significant differences regarding prior knowledge ($F(2,117) = 0.22$, $p = .80$), communication skills ($F(2, 117) = 0.15$, $p = .77$), self-regulated learning skills in online learning environments ($F(2,117) = 0.10$, $p = .82$), and attitudes towards online collaborative learning environments ($F(2,117) = 1.27$, $p = .51$). These results show that the random assignment of learners to the three conditions led to no significant differences in terms of learners' prior knowledge, background requirements, and individual prerequisites.

5.2. Descriptive information for dependent variables

5.2.1. Conceptual understanding

Figure 3 illustrates the pre- and post-test mean value for each group. Although there was no significant difference among the mean scores of the pre-test, there were statistically significant differences among the mean scores of students in the post-test.

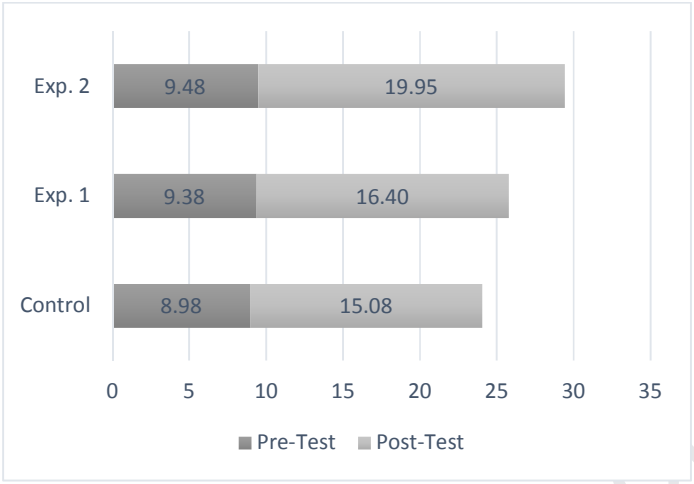


Figure 3: Pre- and post-test mean comparison.

5.2.2. Quality of knowledge co-construction

The descriptive statistics of the number of utterances in the process of knowledge co-construction between students in all three groups is presented in Table4 .

Table4 : Descriptive statistics of coded utterances by dyads.

	Control Group			Exp. 1 Group			Exp. 2 Group		
Code	M	SD	%	M	SD	%	M	SD	%
EX	45.60	13.20	23.58	70.60	10.59	26.67	52.80	10.85	18.66
EL	24.90	6.81	12.87	68.60	20.95	25.53	63.75	16.93	22.53
QC	80.05	11.32	14.40	42.15	8.54	15.92	36.50	7.25	12.90
IO	22.25	10.00	11.50	44.85	8.67	16.94	58.30	10.95	19.43
CC	20.55	7.32	10.62	39.50	9.91	14.92	71.55	14.34	25.29

On average, participants in the control group relied more on quick consensus building, almost two times more than those in Exp. 1 and more than twice when compared to those in Exp. 2. Externalization and elicitation clearly predominated in Exp. 1. Meanwhile, Exp. 2 led the consensus building, whether integration- or conflict-oriented, thus evidencing use of higher quality knowledge co-construction.

5.3. Research question 1

This research question focused on the effects of the individual preparation phase with and without cognitive group awareness support on students' conceptual understanding. An analysis of variance for repeated measurements showed that the average scores of students in the concept inventory test improved significantly ($F(2, 117) = 548.33$, $p < .01$, $\eta^2 = 0.82$) for all groups from the pre-test ($M = 9.25$, $SD = 3.52$) to the post-test ($M = 17.14$, $SD = 4.45$). This indicates that students' conceptual understanding improved significantly in all three experimental conditions. Furthermore, the test showed a statistically significant difference ($F(2, 117) = 15.70$, $p < .01$, $\eta^2 = 0.21$) between the conditions in terms of students' scores in the post-test. The post-hoc Tukey HSD test revealed that the mean score of the post-test for Exp. 2 ($M = 19.95$, $SD = 3.82$)

was significantly higher than the control group (M = 15.07, SD = 3.92) and than Exp. 1 (M = 16.40, SD = 4.18). However, the mean post-test score for Exp. 1 did not differ significantly from the control group.

5.4. Research question 2

The second research question focused on the quality of knowledge co-construction in the different experimental conditions. The multivariate analysis of covariance revealed an overall effect of the conditions on the processes of knowledge co-construction (*Wilks'* λ = 0.11, F(2, 57) = 26.18, $p < .001$, $\eta^2 = 0.66$). A Bonferroni post-hoc test was used to determine the differences between experimental groups in terms of knowledge co-construction, while controlling for differences in the total number of utterances in each condition. The number of quick consensus-building utterances was significantly ($p < .001$) higher for dyads in the control group (M = 80.05, SD = 11.32) than for those in Exp. 1 (M = 42.15, SD = 8.54) and Exp. 2 (M = 36.5, SD = 7.25). The number of externalization (M = 70.60, SD = 10.59) and elicitation (M = 67.60, SD = 8.95) utterances from dyads in Exp. 1 was significantly ($p < .001$) higher than from those in the control group (M_{ex} = 45.60, SD_{ex} = 13.20, M_{el} = 24.9, SD_{el} = 6.81) and Exp. 2 (M_{ex} = 52.8, SD_{ex} = 10.85, M_{el} = 63.75, SD_{el} = 6.93). Finally, the number of integration-oriented consensus building (M = 58.30, SD = 5.95) and conflict-oriented consensus building (M = 71.55, SD = 14.34) utterances for dyads in Exp. 2 was significantly ($p < .02$) higher than those of the control group (M_{IO} = 22.25, SD_{IO} = 10.00, M_{CC} = 20.55, SD_{CC} = 7.32) and Exp. 1 (M_{IO} = 44.85, SD_{IO} = 8.67, M_{CC} = 39.50, SD_{CC} = 9.91).

6. Discussion

The main purpose of this research was to test the effects of different instructional designs leveraging CSCCM on students' conceptual understanding and on the quality of their knowledge co-construction. A pre- and post-test comparison of conceptual understanding, and an evaluation of the quality of knowledge co-construction demonstrated that the differences observed in the three groups of learners arose from the experimental conditions. Important factors such as communication skills, self-regulated learning skills in online learning environments, attitudes towards online collaborative learning environments, and prior knowledge, did not influence the results, as showed the lack of statistically significant differences among the three conditions in terms of these factors, pointing to a successfully randomized sample.

6.1. Conceptual understanding enhanced by CSCCM

Aligned with previous results (Islim, 2018; Komis et al., 2002; Stoyanova & Kommers, 2002) and with the theoretical background of CCM, the findings of this study corroborate the positive effect of CSCCM on students' conceptual understanding. For the two experimental conditions and the control condition, students' conceptual understanding increased by using CSCCM. However, there was no significant difference between students collaborating directly (control condition) and having an individual preparation phase before the collaboration (Exp. 1), unless the product of the individual preparation (i.e., the individual concept map) was shared with the peer at the beginning of the CSCCM (Exp. 2). These results are consistent with those of the

study by Schreiber and Engelmann (2010) using different characteristics than our study in terms of group size (i.e., triads), educational level (i.e., undergraduate), topic (i.e., criminal case), duration of the individual phase (i.e., 10 min), and duration of the collaborative phase (i.e., 45 min). In their study, the groups whose members had access to the individually created concept maps of their peers, outperformed the groups without such option. The same results in such different contexts highlight the role of cognitive group awareness in optimizing the outcomes of CSCCM. As has been previously found, collaborative learning is impaired if group members are not familiar with each other's knowledge (Noroozi, Biemans, Weinberger, Mulder, & Chizari, 2013). Cognitive group awareness is known to be especially critical in newer groups, which often must deal with the problem of not 'knowing who knows what' (Nickerson, 1999). Insufficient cognitive group awareness might result in interpersonal conflicts, misunderstandings and uncertainty about the norms adopted in the group, which are likely to have a negative impact on group performance (Moreland, 1999), as time and effort are expended on issues unrelated to the learning task (Kirschner et al., 2018).

Other studies testing the effect of the individual phase did not measure conceptual understanding but focused instead on processes of knowledge co-construction (De Weerd et al., 2017) and on students' satisfaction with and perceived value of using CSCCM (De Simone et al., 2001).

6.2. Knowledge co-construction in CSCCM

The results of RQ2 clearly show that the instructional design of CSCCM determines the predominant knowledge co-construction processes (i.e., EX, EL, QC, IO, and CC) that students activate. In addition, such processes might explain the degree to which students' conceptual understanding was enhanced through CSCCM depending on the instructional design of the experimental condition they were assigned to.

6.2.1. IO and CC prevailed in Exp. 2 dyads

Participants in Exp. 2 used a significantly higher ($p < .02$) number of utterances related to integration- and conflict-oriented consensus building, which are regarded as the highest quality processes of knowledge co-construction in collaborative learning (Gijlers & de Jong, 2013; Teasley, 1997). Accordingly, their conceptual understanding increased the most. In this experimental condition, the support for cognitive group awareness helped to reduce the amount of utterances in communication dealing with externalization and elicitation of peer knowledge. By making and sharing individual concept maps before collaborating, the students' efforts for grasping the knowledge of their peers was reduced, and they were in a better position for engaging in consensus building, which improves the outcomes of knowledge co-construction. With the advantage of being familiar with the peer knowledge (i.e., cognitive group awareness), students could directly focus the interaction on trying to build consensus from their individual knowledge in the cases where there was agreement (i.e., integration-oriented), as well as in the cases where there was disagreement (i.e., conflict-oriented).

When comparing their maps together, parts of the map in which the dyad coincided led to an integration phase, while parts of the map in which the dyad diverged led to a conflict phase. In

the integration type of interactions, the student is confident about his/her prior knowledge about the concepts under discussion and, in practice, reinforces his/her previous learning. In the conflict type of interactions, the student seeks to convince or be convinced by his/her peer through discussion and negotiation by exchanging arguments. Both interactions lead to an improvement in students' conceptual understanding.

6.2.2. EX and EL prevailed in Exp. 1 dyads

The number of externalization and elicitation utterances was significantly higher ($p < .001$) in Exp. 1. Compared to the control group, students in Exp. 1 have a stronger understanding of their own domain-subject conceptual knowledge, for they completed the individual preparation phase before the collaboration. However, compared to those in Exp. 2, students in Exp. 1 have a weaker cognitive group awareness, as they did not have access to their peer's individual concept map. Although Exp. 1 students were able to successfully share their conceptual understanding with each other in the collaborative phase, they were outperformed by Exp. 2 students. A weaker cognitive group awareness was a disadvantage causing externalization and elicitation to take an important part of their communication and leaving less room for consensus building through negotiation.

6.2.3. QC prevailed in control dyads

Dyads in the control group showed a significantly higher ($p < .001$) use of quick consensus building, so much so that it represented on average the highest use of any knowledge co-construction process across all groups ($M = 80.05$; see Table 4). These students do not have an individual preparation phase to activate their prior knowledge and to recognize the strengths and weaknesses of their own conceptual understanding. Moreover, they were not exposed a priori to their peer's conceptual understanding, which limited their cognitive group awareness. It is then understandable that their knowledge co-construction is characterized by a shallower discussion, as evidenced by their frequent recursion to quick consensus building. Although they had longer time for collaborating, since the week used for individual preparation in Exp. 1 and Exp. 2 was already used for collaboration in the control group, the results show that the extra time did not cover up for the shortcomings of the instructional design they were assigned to.

Quick consensus building can be regarded as harmful to learning, because students try to reach consensus without fully exploring or understanding the contributions of their peers (Chan, 2001). As pointed out by prior research, quick consensus building might occur when students' main interest is not to understand the material but just to complete the tasks (i.e., performance goal orientation, as opposed to learning goal orientation (Pintrich, 2000)), and also when they elude conflicting information to avoid socio-cognitive conflicts with peers (Chinn & Brewer, 1993). In accordance with such contextual and personal characteristics, our results show that dyads in all experimental conditions engaged in quick consensus building to some extent, but significantly more so in the control group. For dyads in the control group, quick consensus building represented 41% of the communication, as compared to 16% and 13% for the Exp. 1 and Exp. 2 groups respectively (see Table 4). These results highlight the role of the instructional design in promoting certain processes of knowledge co-construction, on top of students' goal orientation and propensity to either seek or avoid socio-cognitive conflict.

6.3. Implications

The results of this study have theoretical and practical implications. Theoretically, they add to the mounting evidence of the importance of the type of interactions during collaborative learning for the outcomes of the process (Baker, 2015; Dillenbourg et al., 1996; Webb, 1991). Research has shown that the simple frequency of interaction does not predict students' achievement, but the types of interactions matter (Cohen, 1994). In this paper, interactions understood as processes of knowledge co-construction were shown to influence students' conceptual understanding after the collaboration. In practice, these are actionable results. First, our findings encourage teachers to use CCM in their instruction, especially when facilitated by technology (i.e., CSCCM). In all three instructional designs used, CSCCM enhanced students' conceptual understanding. Second, if teachers would like their students to make the most of CSCCM, an instructional design like Exp. 2 should be used. In other words, the optimal usage of CSCCM in instruction is to start with an individual concept mapping phase, the results of which students should share with their peers to increase cognitive group awareness. This CSCCM instructional design facilitates integration and conflict-oriented consensus building, which are regarded as the highest quality processes of knowledge co-construction in collaborative learning (Gijlers & de Jong, 2013; Teasley, 1997).

6.4. Limitations

In this study, we controlled for factors such as communication skills, self-regulated learning skills in online learning environments, attitudes towards online collaborative learning environments, and prior knowledge. To ensure that confound variables did not affect the results, participants were first randomly assigned to a dyad, and then dyads were randomly assigned to one of the conditions (i.e., control, Exp. 1 or Exp. 2). Random assignment of the participants to the control and treatment groups ensures internal validity (Cook & Campbell, 1979). However, random assignment, which is linked to internal validity, differs from random sampling (i.e., the probability method of selecting the entire sample), which is connected to external validity (Henry, 1990). Like much, if not most, of the naturalistic studies in educational psychology, which sample students from a particular class or school, our study used the nonprobability sampling method of convenience sampling (Battaglia, 2008). In such a sampling approach, cases are selected based on their availability for the study and their easiness to be reached, which poses a risk for the representativeness of the sample to the whole population (Henry, 1990). As a result, caution should be exercised when it comes to the generalization of the results. It is worth remembering also that, although probability sampling ensures greater representativeness of the sample than nonprobability sampling, it still "cannot guarantee representativeness, for at least four reasons" (see Trobia, 2008, p. 784).

6.5. Future work

In this study, short-term individual measurements were employed for explaining the domain-specific conceptual understanding. Accordingly, the measures of short-term individual learning performance may have improved without enhancing deeper processing, which is what promotes long-term retention (Noroozi, Biemans, et al., 2012). Consequently, long-term effects should be measured in future studies.

Due to the characteristics of the school where the study was conducted, the participants were all males. Since gender distribution might play a role in team collaboration and performance (Bear & Woolley, 2011), further research is needed to contrast the results with those of all-female and male-female dyads. Furthermore, collaborative learning in our design occurred in the form of dyadic interactions. A review of the literature indicates that the nature of collaborative learning varies with different group sizes. This is because active participation could go much higher, and it can be a lot easier and faster for dyads than triads or larger groups to establish a shared understanding (Michinov & Michinov, 2009; Noroozi, Weinberger, Biemans, Mulder, & Chizari, 2012). Therefore, it would be interesting to consider this experimental design with different-sized groups for examining the effect of group size in conceptual understanding through knowledge co-construction using CSCCM.

Collaborative learners are hypothesized to have a mutual effect on the learning outcomes of their partners (De Lisi & Golbeck, 1999; Teasley, 1997). Therefore, the type and amount of knowledge transfer in collaborative learning environments are good indicators of performance and learning quality. Concept maps include information about acquisition of propositions, knowledge creation and amount of collaboration among the members of a group (Roth & Roychoudhury, 1993). This collaboration is key to fostering various types of knowledge convergence that could be taken as an outcome of learning in small groups (Weinberger, Stegmann, & Fischer, 2007). Future research should examine the knowledge transfer in the forms of individual-to-group, group-to-individual, and shared knowledge transfer (Noroozi et al., 2013), by considering the individual and collaborative concept maps as representations of the individual's or the group's knowledge respectively.

7. Conclusions

This article investigated the effect of different instructional designs leveraging CSCCM on students' conceptual understanding and on the type of processes of knowledge co-construction that students engage. Importantly, the study was not conducted in a laboratory setting, but in a real educational context as part of a formal, high-school level physics course. In the literature, CCM studies are typically shorter than a lesson time. Our study eliminated time pressure as a factor by allowing the students several weeks for working on their concept maps, as a homework assignment. The results clearly revealed that CSCCM is beneficial for students' conceptual understanding. The best outcomes were obtained by placing an individual preparation phase before the collaboration, where students worked individually on the concept map, and then shared it with their peers to enhance cognitive group awareness. Apart from this practical, evidence-based recommendation, the findings support the strong theoretical connection between instructional design, cognitive group awareness, processes of knowledge co-construction and, ultimately, students' learning outcomes.

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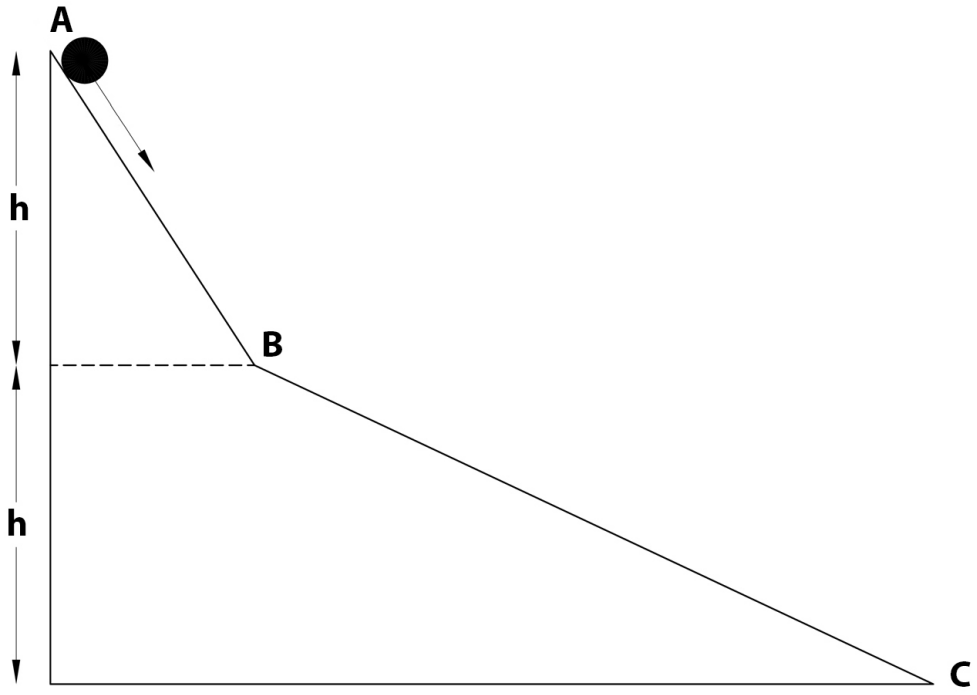

Computer-supported collaborative concept mapping (CSCCM) enhances conceptual learning

Instructional designs of CSCCM condition students' knowledge co-construction process

An individual concept mapping preparation phase enhances CSCCM learning outcomes

Sharing the individual concept map with the peer fosters cognitive group awareness

A shared individual concept map optimizes students' CSCCM learning outcomes