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Operationalizing collaborative problem-solving skills: A framework for assessment and development in the digital age

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ABSTRACT. This article delves into the operationalization of collaborative problem-solving (CPS) skills, focusing on the essential aspects required to effectively apply CPS in the modern digital age. The article emphasizes the growing significance of CPS skills as technology-based work and the automation of routine tasks demand proficiency in addressing non-routine, complex challenges. To enable successful CPS, a new set of skills including information literacy, divergent thinking, and problem-solving, both individually and collaboratively, are explored. The article investigates the strategies and approaches employed by individuals and teams when engaging in collaborative problem solving, with an emphasis on knowledge sharing and skill pooling. The study highlights the criticality of CPS as an invaluable skill set, enabling individuals to effectively collaborate and overcome intricate problems. Moreover, as contemporary work environments increasingly rely on successful group problem solving, the significance of operationalizing CPS is expected to continue growing in the future.

Keywords: collaborative problem solving, problem solving, PISA, literacy, Human-to-Human, Human-to-Agent, Twenty-first Century Skills.

The twenty-first century is dominated by collaborative settings and teamwork in both the academic and professional industries. This is why work environments have started to depend highly on successful problem solving in a

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group context. Although collaboration has been a highly researched topic as part of several psychology spheres until today, collaborative problem solving as a construct is still relatively new.

1. What is Collaborative Problem Solving and why is it important?

1.1. Definitions

Collaborative Problem Solving has been described as the ability to "effectively engage in a process whereby two or more agents attempt to solve a problem by sharing the understanding and effort required to come to a solution and pooling their knowledge, skills and efforts to reach that solution" (Krkovic et al. 2017, p. 13, cf. OECD 2013).

Given that problem solving means having a specific situation to analyze and resolve, there are two different processing types, depending on the nature of the problem: static (simple) and interactive (complex) problem solving. A situation becomes a problem whenever the path from the starting point towards the goal is ambiguous and a solution can only be reached by using non-routine activities. This requires from the solver a specific cognitive process, as the solution is not obvious. (Krkovic et al., 2017)

1.2. Related concepts CPS and Problem solving

The following concepts emerge as related to both collaborative problem solving and problem solving:

Assessment: Several articles cited in this review discuss the assessment of collaborative problem solving, including the use of computer-based assessments and the potential for computer agents to replace humans in the assessment process. The articles also touch on the importance of developing standardized assessments for collaborative problem solving.

Education: The changing role of education and schools is discussed, with a focus on how these changes impact the development of problem-solving skills in students.

Perspective-taking: the role of individual perspective-taking within a group in collaborative problem solving.

Competency Model: A generalized competency model of collaborative problem solving which highlights the importance of various competencies in successful collaborative problem solving.

PISA Framework: The Organisation for Economic Co-operation and Development (OECD) developed a framework for measuring collaborative problem solving as part of the Programme for International Student Assessment (PISA).

Shifts in Assessment: the shifts in the assessment of problem solving, which have moved from traditional paper-based tests to computer-based assessments and assessments of collaborative problem solving.

In their case study Bull et al. (2018) explore the use of Minecraft as a virtual world for collaborative problem-solving activities. They discuss how the interactive and immersive nature of Minecraft can facilitate the development of problem-solving skills in students.

Overall, collaborative problem solving and problem solving are closely related concepts, and there is a growing interest in developing assessments and frameworks to measure both. Additionally, we emphasize that education is important in developing these skills, as is the need for perspective-taking and a generalized competency model to guide the development of collaborative problem-solving skills.

1.2.1. Static Problem Solving vs. Complex Problem-Solving Tasks

In static problem solving, the difficult part in reaching a solution is finding the best way to handle the process, as both the problem's initial state and goal are clearly defined from the start. Krkovic et al. (2017) exemplifies this with the task of putting together a piece of furniture without having instructions. The problem solver has all the necessary parts, tools and knowledge of what the furniture should look like when put together, the only missing part being putting the pieces together where to start, what the best order of actions is, which parts fit together, and which tools to use for which parts.

In contrast, complex problem solving implies dealing with inaccurate problems with unclear starting and ending points. The problem solver needs to do an extra effort in order to gain more knowledge before or while managing the situation. Same authors give the example of repairing a car with highly interdependent parts. Here, the problem solver needs to explore several possible reasons that could account for why the car is not running, make changes to its parts, monitor how these changes influence the functioning of other parts and the general functioning of the vehicle. On the basis of the information gathered, the solver will make subsequent repairs and reevaluate the progress. The focus of the investigation may shift as a result of the problem solver's interaction with the car or the interdependency of the parts of the vehicle.

Hence, it can be concluded that complex problem solving implies two distinct dimensions: acquiring the necessary knowledge, all while interacting with a dynamic setting and possible changes in the process and applying that knowledge by always having the end goal in mind. Added to the equation, collaboration in both static and complex problem solving refers to two or more people working together, trying to solve a problem and reach a unified solution by sharing knowledge and skills.

Greiff et al. (2014) have focused on the assessment of collaborative problem-solving skills in technology-rich environments and address the challenges involved in assessing these skills, providing recommendations for designing effective assessments that capture the complexities of collaborative problem solving.

In terms of capacities and skills involved in collaborative problem solving, Griffin and colleagues conceptualize it as consisting of five broad strands, the capacity of an individual to: recognize the perspective of other persons in a group; participate as a member of the group by contributing their knowledge, experience and expertise in a constructive way; recognize the need for contributions and how to manage them; identify structure and procedure involved in resolving a problem; and, as a member of the collaborative group, build and develop knowledge and understanding (Griffin et al., 2012).

Csapó & co's 2018 literature review examines the role of education in the development of problem-solving skills, discussing various educational approaches and strategies that can enhance problem-solving abilities in students, emphasizing the importance of fostering these skills from an early age.

1.3. Importance

Collaborative problem solving is an important skill for individuals to possess as it allows them to work effectively with others to solve complex problems. The articles cited hereby highlight the importance of collaborative problem solving in a variety of contexts, including education and assessment.

One article by Sun et al. (2018) presents a generalized competency model of collaborative problem solving that highlights the importance of various competencies, including communication, coordination, and shared understanding. The authors argue that these competencies are essential for successful collaborative problem solving.

The OECD also recognizes the importance of collaborative problem solving and has developed a framework for measuring this skill as part of the PISA assessment (Organisation for Economic Co-operation and Development, 2017). The framework emphasizes the importance of interpersonal and intercultural skills, as well as cognitive skills, in collaborative problem solving.

Hayashi (2017) provides further evidence of the importance of collaborative problem solving in a study that investigated the role of individual perspective-taking within a group. The study found that individuals who were able to take on the perspectives of others were more effective in solving complex problems collaboratively.

Overall, these articles highlight the importance of collaborative problem solving in a variety of contexts and emphasize the need for individuals to possess the competencies necessary to effectively work with others to solve complex problems. Collaborative problem solving has become increasingly important in today's globalized and interconnected world, where individuals must work with others from diverse backgrounds and perspectives to tackle complex challenges.

2. Operationalization of CPS

2.1. What Skills Does CPS Include?

Many changes took place in daily life during the past decades, especially since the advancement and modernization of technologies lead to a technology-based society. Many of the tasks that used to be repetitive and manually labored in the past are now automated and done by robots instead of people. Human employment is nowadays more common in non-routine, complex tasks that require a new set of skills, more digital-friendly but also from a cognitive complexity perspective. Examples of such skills, better known as twenty-first century skills, are information literacy, divergent thinking ("thinking out of the box"), and problem solving (on both an individual and a collaborative level) (Krkovic et al., 2017).

Not only is this transition happening in the economic environment, but also in schools and educational systems. Instructional methods have been stressing the importance of developing and using complex problem-solving skills especially through self-exploratory tasks such as laboratory experiments or programming tasks. All these radical shifts require people to look differently at daily problems, by approaching them more flexibly and dynamically. The more complex the problem gets, the more likely it is for managers and employees to solve it in a collaborative way. This is also valid for schoolwork or even in personal or family settings.

As much as collaboration involves multiple actors, each one of them brings in an individual contribution and a particular set of skills in order to reach a successful problem-solving process. In 2012, PISA identified four processes that make up individual problem solving (OECD, 2017):

- gathering information related to the problem
- representing the problem and the various relationships in the problem with tables, graphs, symbols or words
- devising a strategy to solve the problem and carrying out this strategy
- ensuring that the strategy has been followed and reacting to feedback obtained during the course of solving the problem

These four processes are still relevant to the problem-solving aspects of the PISA 2015 collaborative problem-solving assessment. In addition, there are three competencies specific to collaborative problem solving:

- establishing and maintaining shared understanding (finding out what other team members know and ensuring that team members share the same vision of the problem)
- taking appropriate action to solve the problem (determining what collaborative actions need to be performed – for example, who does what? – and then executing these actions)
- establishing and maintaining team organization (following one's own role in the problem-solving strategy and checking that others also follow their assigned role)

Individuals' cognitive abilities and social skills are thought to be best expressed while interacting with each other in a group. Sun and colleagues (2018) consider therefore CPS as a process that hinges on individuals' and group's ability to establish a common ground concerning the nature of the problem, develop a solution plan, monitor progress along the way, and accommodate multiple perspectives while respectfully managing disagreements.

As much as cultivating students' and workers' collaborative problem-solving skills is essential nowadays, there are some significant challenges in operationalizing CPS mainly because it contains hard to measure aspects as behavioral and collaborative ones. The main challenge, as presented by Krkovic and colleagues (2017) is to include all the relevant sub skills and at the same time maintain the important psychometric criteria such as objectivity, reliability, validity, and scalability. Frequent concerns that arise in the operationalization of CPS are presented in the same paper and include the following:

- Could the frequency of collaborative acts be used as an indicator of the quality of collaborative work? In particular, how many collaborative acts does it take to make the collaboration more efficient and effective?

- Are there specific styles of collaboration that rely on personality traits that need to be considered in the operationalization?
- Can judgments of collaboration on an individual level be made when, in reality, the person will always need to deal with different team members and may act differently according to the situation?

Over the years, there has been a shift from experimental research to empirical studies which lead to different approaches to operationalizing the individual problem-solving construct, all of them being based on computer-supported scenarios. There are two types of scenarios – realistic and formal – depending on the applied tools' structure and semantic cover, also known as "cover story".

2.2. Realistic Scenarios

This type of scenario was the first one ever to appear in research on individual complex problem solving, starting with the Lohhausen system. In this scenario, the problem solver acts as a mayor of a fictional village where he possesses all the decision-making power, as long as the community stays satisfied with its living conditions. Realistic scenarios such as this one are structured by deliberately chosen relations between variables in the system (i.e., ad hoc systems), which are commonly based on one face-valid task.

One of the most important benefits of these scenarios is their face validity, because they are commonly semantically rich and therefore able to simulate the complexity of the real world. As any other study and system, this one is not exempt from limitations either, especially regarding their psychometric properties – low objectivity due to unclear achievement criteria or questionable reliability. Some researchers even suggest that the complexity of these scenarios does not adequately represent the complexity of the real world (Krkovic et al., 2017).

2.3. Formal Scenarios

These scenarios appeared as a response to the realistic scenarios' limitations and are based on a priori set structural equations, which are characterized by multiple short tasks. The development of formal-based scenarios had a strong impact on including complex problem solving in LSAs, since the new approach offered better psychometrical properties of the tasks, as necessary in a large-scale context.

In particular, formal systems are usually based on multiple items that have a specific underlying structure, the goal of which is to enable more reliable and valid assessment. Since Funke (1985, 1999) first introduced the use of formal systems in task development, a number of individual complex problem-solving scenarios have been based on them, for instance Multiflux, Genetics Lab, MicroDYN and MicroFIN.

The formal-based scenarios differ according to the structure of the system they are based on. Consequently, the formal systems can be categorized as two different types: linear structural equation (LSE) systems and finite state automata (FSA). While LSE systems tend to be rather homogeneous in their structure, the FSA systems are heterogeneously structured. This, in turn, determines how broadly aspects of complex problem solving may be captured, depending on the instrument used. Introducing the LSE and FSA conducted a considerable development of the psychometric qualities of complex problem-solving simulations (Krkovic et al., 2017).

In the case of Linear Structural Equation (LSE) Systems, the problem simulation consists of various input and output variables, where the problem solver can only manipulate the inputs. Not only does one output variable change based on the test taker's decisions, but also based on a function of time or as a side effect from another changed output variable. Advantages of such systems include the fact that they can be structured as a multiple-item test; they allow for a wide range of difficulties; and it will take participants a shorter amount of time to complete the tasks.

As for the Finite State Automata (FSA), these systems include various nonlinear features without following any pattern. Although it is still a matter of input and output variables influencing each other, in this case the problem solver needs to explore the perfect interaction of the input variables, in order to achieve the desired results. Therefore, a variable has an influence on the outcome from only a specific value onwards, which could require from the test taker more complex problem-solving skills.

2.4. Human-to-Human versus Human-to-Agent Settings

Assessing collaborative problem solving is commonly realized through two distinct types of interactions: human-to-human (H-H) and human-to-agent (H-A). Although both settings present advantages, there are also some limitations attached to each one which have been debated in the literature for a while now. Over time, researchers have investigated how much these two settings differ and in which conditions is the students' performance higher when completing the assessments.

While human-to-human is considered to be a more natural and face-valid approach, the human-to-agent approach allows creating a more standardized assessment setting. One empirical study example from an incipient research phase on the subject is the one implemented by Rosen (2015) in which 179 students aged 14 from the United States, Singapore and Israel were asked to complete CPS tasks in both settings, having identical methods and resources. One major difference identified, which also makes the H-A approach more attractive is its possibility to provide more opportunities for students to demonstrate their CPS skills. While interactions with human partners could be limited to a particular amount of possibilities, the H-A mode allows programming a much wider range.

Another meaningful finding was that interacting with a computer agent involves significantly higher levels of shared understanding, progress monitoring, and feedback and thus, a higher performance. However, the two models seem to be similar enough in terms of motivation and ability to solve the problem of the students involved. Eventually, the author considers that models can be as equally effective as long as they are adapted to particular educational purposes. In the case of highly trained teachers in subjects such as communication and collaboration, using H-H settings is recommended as it could be a more powerful tool in students' learning process. On the contrary, when students do not have a higher CPS level, technology can fill the gaps with its computer agents-based assessments and bring an improvement to the individual evaluation process.

As much as human-to-human interactions may seem more personalized, flexible and enriching, human-to-agent settings can equally adopt flexible strategies that permit a large space of alternative conversations, context-sensitive rules and change-adaptive processes. Even nowadays, people communicate with each other more through virtual tools rather than face-to-face, so H-A settings are becoming pretty indispensable. Computer agents can be programmed depending on multiple factors starting from concrete, non-human specific ones to behavioral and social aspects that can be controlled.

This concern of whether or not H-A interactions are an accurate approximation of H-H interactions was also approached by OECD (2017) in a study which concluded the following:

- There were no practically relevant differences between students' responses to the two versions of the collaborative problem-solving tasks
- Teachers' opinions of their students' collaboration skills correlated well with their students' performance in the computer-based collaborative problem solving assessment

- Some students performed several collaborative problem-solving tasks in an H-A format before performing a couple of tasks face-to-face with another person through unrestricted interaction. Their performance with the computer agent was a moderately good predictor of their performance with the human partner.

Given that this study was done as well with the purpose of identifying the effectiveness of PISA computer-based assessment, it concludes that human-to-agent settings can still describe students' ability to collaborate with other humans.

There is no doubt that there are differences between the way students collaborate with other human beings and with computer agents. In other words, agents could actually replace humans as collaboration partners in CPS assessments. This was also one of the reasons why, three years later, Herborn and colleagues (2018) conducted a study to validate the PISA 2015 CPS assessment mentioned above by investigating the effects of replacing computer agents with real students in classroom tests, therefore by using a human-to-human setting.

The authors obtained the otherwise confidential PISA 2015 CPS tasks, reformatted and redesigned them, used an identical interface and the predefined chat design, and had students communicate with one another by selecting from a fixed set of chat options. This H-H condition was indeed constrained by these chat options, but less constrained than the H-A condition. In total, 386 students from 9^{th} and 10^{th} Grade in Germany and Luxembourg participated to this research. All of them were informed about which types of partners they were collaborating with, in order to emphasize a likely effect of the collaboration partners' nature on the main test takers.

Eventually, while the results did not suggest any performance accuracy differences, behavioral actions such as clicking, dragging and dropping, or moving elements of the tasks, registered some differences compared to the PISA 2015 assessment in H-A format. Specifically, students collaborating with classmates interacted slightly more frequently during the tasks than those collaborating with only the computer agents, thus more time was spent on solving the tasks in the H-H format. However, as these differences were small enough and did not affect actual performance, they do not seem to limit the comparability of H-A and H-H tasks.

This study also showed how human-to-human settings allow for more natural communication and external effects (e.g., group composition or the collaboration partner's CPS proficiency) on the main test-taker's performance. Clearly, computer agents will not replace actual humans in collaborations anytime soon, but they are certainly increasingly integrated in educational settings and workplace environments.

3. Main CPS Assessment Tools

Everything that we know up to now about collaborative problem solving is due to multiple research, studies and experimental assessments completed over time. This chapter aims to summarize several examples of the assessment tools used in testing and measuring collaborative problem solving.

3.1. Assessment and Teaching of Twenty-first Century Skills (ATC21S) Project

This project was the first large-scale assessment of CPS targeting students between 11-15 years old. It relied on human-to-human, computer-supported collaboration where students were randomly matched to work together in various problem situations. The assessment closely followed two main categories of skills: social and cognitive.

The main social skills include participation, perspective taking and social regulation (negotiation, self-evaluation and taking group responsibility). Cognitive skills include planning, systematically executing solutions and monitoring progress, learning and knowledge building. Thus, team members needed to identify the problem structure and procedures, collect and assess information required to build solutions, and engage in strategic problem solving (Sun et al., 2018). Despite all problems being different in content, all of them required from students to use these skills and collaborate with each other in order to find the solution.

Krkovic et al. (2017) illustrates the structure of ATC21S through the balance beam task, shown in Fig. 1. Here, two participants work on a typical problem-solving task – bringing the scale into balance by using different weights. To do so, participants need to collaborate by exchanging tools back and forth, communicating their ideas, and discussing plans. Thus, the task collects information about students' collaborative skills and how they apply these skills in complex problem-solving contexts.

The project provides students and teachers with an instant report, thus further strengthening its formative purpose. The ATC21S project pioneered the use of real collaboration in the assessment of collaborative problem solving in large-scale settings and is therefore the most advanced project yet developed for exploiting the qualitative information that comes from the interactions of collaborating dyads.

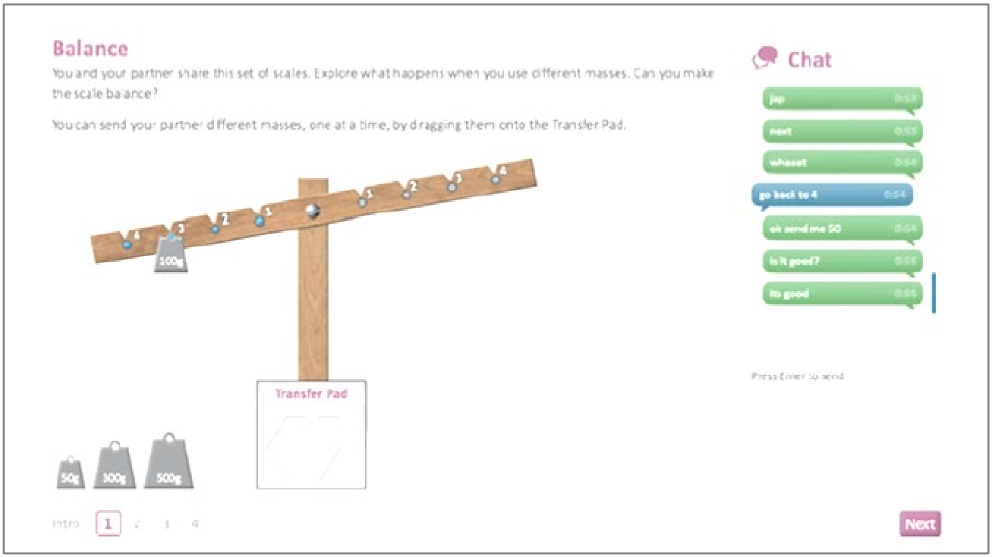

Fig. 1. ATC21S task example: The balance beam task (Krkovic et al., 2017)

3.2. Rosen and Foltz (2014) Study – Comparison between H-H and H-A

Rosen and Foltz (2014) opted to measure the concept through one H-A evaluation test and an H-H one, together with a quantitative measuring instrument. The latter involves assessing the motivation of individuals to work in the given task. It consists of four items, and the answer consists of a four-point Likert scale (1 = strongly disagree, 4 = strongly agree). Its items have been taken from the literature and include: "I felt interested in the task"; "The task was fun"; "The task was attractive"; "I continued to work on this task out of curiosity" (Rosen, 2009; Rosen and Beck-Hill, 2012). The fidelity of the instrument, also referred to as internal consistency, was 0.85.

The computerized task of measuring collaborative problem solving skills (CPS) involves collaborating with another partner, either a virtual agent (avatar) or a classmate. This involves finding the best conditions for an animal in a zoo, with the aim of extending its life expectancy. Life expectancy is constantly displayed during the task. The student had the freedom to choose different foods, living habitats and additional options. All this time, both partners could see choices by making and communicating via chat. In this chat, 4-5 response options could be selected, which change depending on the context of the tasks. By approaching this of the predefined choice of messages, the authors were able to monitor and measure collaboration and communication skills (e.g., Hsieh and O'Neil, 2002).

These predefined communication messages with each other, along with CPS process measurements, were automatically recorded based on the type of message used for each situation. Specifically, each message was coded a priori as representing each of the CPS abilities. At the beginning of the task, the student and partner were encouraged by the researchers to discuss the best approach to achieving the best conditions for the animal, and at the end of the task, each individual was asked to provide feedback about the partner's performance.

The level of difficulty of the task was relatively low and served as a platform for the overall assessment of CPS skills. This was due to the centrality of the collaboration dimension in CPS. At the same time, due to the exploratory nature of the study, the participants were not limited either in the number of trials or in terms of time - both necessary to find the optimal solution for the situation. However, the task was designed in such a way that at least two attempts to solve the problem and at least one act of communication with the partner were needed to complete the assessment task.

In the case of H-A setting, the agent (Mike) had the responses scheduled with different characteristics relevant to different CPS situations (e.g. to agree or disagree with the participant, either to contribute to or to confuse the problem, etc.). This approach gave each student similar optimal chances to show their CPS skills.

As for results evaluation, the problem-solving dimension was assessed by one point for each year of the animal's life expectancy achieved. The score for the shared understanding dimension consisted of a limited number of initial questions asked by the participant at the beginning in a pre-defined appropriate; the answers to the partner's starting questions were also monitored. The score for monitoring progress was calculated based on the communication initiated by the student before the final registration of the chosen variables.

At the same time, for this dimension, the student's statements based on the displayed life expectancy results were also taken into account. The feedback dimension was evaluated by two teachers, independently, from US schools. They evaluated the students' written answers on a Likert scale from 1-4. The inter-evaluator fidelity on this dimension was 92%. Grammar errors were not taken into account, only what related to CPS.

3.3. Collaborative Science Assessment Prototype (CSAP)

The Collaborative Science Assessment Prototype (CSAP) project was developed to measure, according to its title, the field of science. It consists of six practical challenges based on the literature (Hao et al., 2017).

Five evaluation tools were administered:

1. A standalone test for general science knowledge consisting of 37 multiple-choice items adapted from the Scientific Literacy Measurement (SLiM) instrument (Rundgren, Rundgren, Tseng, Lin, & Chang, 2012).
2. A personality survey, Ten Item Personality Measure (TIPI) (Gosling, Rentfrow, & Swann, 2003).
3. A demographic survey adapted from the National Assessment of Educational Progress (NAEP, 2013).
4. Two versions of a web-based science simulation task on volcanoes:
   a. Collaborative version (a.k.a. Tetralogue): Two participants collaborate to interact with two virtual agents in the simulation to complete a science task on volcanoes.
   b. Single-user version (a.k.a. Trialogue): A single participant interacts with two virtual agents in the simulation to complete a science task on volcanoes.
5. A post-collaboration satisfaction survey.

The Trialogue simulation was developed to measure students' scientific exploration skills, using multiple choice answers, constructed responses (CRs) and conversational items. The task requires three people working together to solve it. In this simulation, students interact with two virtual agents, one of whom plays the role of co-elderly student, respectively mentor of the student. The goal is to complete a scientific task about volcanoes.

The individual task was used by researchers with two objectives in mind: on the one hand it served as a control option to verify the effect of collaboration, and on the other hand the authors used the answers provided by participants as baseline for item properties (e.g. correct item ratio). The collaboration version included the option to communicate through a chat for the two participants and another chat, which allowed the team to communicate with agents, thus the title of Tetralogue.

Moreover, the authors designed a four-step response procedure in the collaborative version of the simulation task, by which it captures each team member's science inquiry skills before and after the collaboration. The procedure for responding to a question in the simulation is as follows:

1. Each participant is prompted to respond to the item individually before any collaboration.
2. Each participant is prompted to discuss the item with her partner.
3. Each participant is prompted to revise her initial response if she wants.
4. A representative is randomly chosen to submit a team answer.

In this way, the responses before collaboration capture each individual member's science inquiry skills specific to the task, while the changes in responses after the collaboration reflect how effective the collaboration was and it allows to probe directly which CPS sub-skills may be more important for better collaboration outcomes.

3.4. Collaborative Problem Solving in PISA 2015

According to Ramalingam (2017), although PISA assesses mainly reading, mathematics and science abilities, from time to time it includes evaluations that go beyond this spectrum, such as problem solving (in 2003, 2012 and 2015). Acquiring high levels of problem-solving skills is the foundation for future learning, for effective participation in society and for the proper conduct of personal activities. It basically involves the application of learned knowledge to new situations.

The first attempt to assess collaborative problem solving in PISA was in 2012 on the grounds that it comprises essential skills for a successful hiring after school where teamwork is indispensable. Although this did not succeed due to significant challenges of that time, experts and literature made possible the addition of CPS tasks in PISA in year 2015. Here, 52 educational systems participated in this cross-cultural and national evaluation.

A number of existing models and frameworks were reviewed in order to conceptualize the key processes involved in CPS. The conceptualizations of collaborative skills differ in the details across the models, but there are a number of correspondences and some convergence. Eventually, three core competencies were adopted in the PISA 2015 CPS framework, namely: establishing and maintaining shared understanding, taking appropriate action to solve the problem, establishing and maintaining team organization (OECD, 2017).

As students develop collaborative problem-solving skills, the complexity of the problems they can solve increases, which is directly impacted by the clarity of the tasks' objective, the number of people involved in the same workgroup or even their motivation, engagement and openness to collaboration.

A single score summarizes students' overall proficiency in CPS. To illustrate what the score means, PISA has adopted an approach to reporting survey outcomes that involves the development of learning metrics, which are dimensions of educational progression. Four levels of proficiency are identified and described in Table 7 in an overall reporting scale for CPS to enable comparisons of student performance between and within participating countries and economies (OECD, 2017).

Table 7. Proficiency scale descriptions for CPS

Level	What students can typically do
4	At Level 4, students can successfully carry out complicated problem-solving tasks with high collaboration complexity. They are able to solve problems situated in complex problem spaces with multiple constraints, keeping relevant background information in mind. These students maintain an awareness of group dynamics and take actions to ensure that team members act in accordance with their agreed-upon roles. At the same time, they are able to monitor progress towards a solution to the given problem and identify obstacles to be overcome or gaps to be bridged. Level 4 students take initiative and perform actions or make requests to overcome obstacles and resolve disagreements and conflicts. They can balance the collaboration and problem-solving aspects of a presented task, identify efficient pathways to a problem solution, and take actions to solve the presented problem.
3	At Level 3, students can complete tasks with either complex problem-solving requirements or complex collaboration demands. These students can perform multi-step tasks that require the integration of multiple pieces of information, often in complex and dynamic problem spaces. They orchestrate roles within the team and identify information needed by particular team members to solve the problem. Level 3 students can recognise information needed to solve a problem, request it from the appropriate team member, and identify when the provided information is incorrect. When conflicts arise, they can help team members negotiate a solution.
2	At Level 2, students can contribute to a collaborative effort within a problem space of medium difficulty. They can help solve a problem by communicating with team members about the actions to be performed. They can volunteer information not specifically requested by another team member. Level 2 students understand that not all team members have the same information and are able to consider different perspectives. They can help the team establish a shared understanding of the steps required to solve a problem. These students can request additional information required to solve a given problem and solicit agreement or confirmation from team members about the approach to be taken. Students near the top of Level 2 can take the initiative to suggest a logical next step, or propose a new approach, to solve a problem.
1	At Level 1, students can complete tasks with low problem complexity and limited collaboration complexity. They can provide requested information and take actions to enact plans when prompted. Level 1 students can confirm actions or proposals made by others. They tend to focus on their individual role within the group. With support from team members, and working within a simple problem space, these students can contribute to a problem solution.

Table 8. Matrix of CPS skills for PISA 2015 (OECD, 2013)

	(1) Establishing and maintaining shared understanding	(2) Taking appropriate action to solve the problem	(3) Establishing and maintaining team organization
(A) Exploring and understanding	(A1) Discovering perspectives and abilities of team members	(A2) Discovering the type of collaborative interaction to solve the problem, along with goals	(A3) Understanding roles to solve problem
(B) Representing and Formulating	(B1) Building a shared representation and negotiating the meaning of the problem (common ground)	(B2) Identifying and describing tasks to be completed	(B3) Describe roles and team organization (communication protocol/rules of engagement)
(C) Planning and executing	(C1) Communicating with team members about the actions to be/being performed	(C2) Enacting plans	(C3) Following rules of engagement, (e.g. prompting other team members to perform their tasks.)
(D) Monitoring and reflecting	(D1) Monitoring and repairing the shared understanding	(D2) Monitoring results of actions and evaluating success in solving the problem	(D3) Monitoring, providing feedback and adapting the team organization and roles

4. CPS Assessment by using AI tools

Collaborative problem-solving assessment can be done using AI tools in several ways. One approach is to use machine learning algorithms to analyze data collected from collaborative problem-solving tasks. For example, Herborn et al. (2018) used machine learning techniques to analyze data from the PISA 2015 collaborative problem-solving assessment and found that computer-based agents were able to accurately assess students' collaborative problem-solving skills.

Another approach is to use natural language processing (NLP) techniques to analyze students' interactions during collaborative problem-solving tasks. Rosen and Foltz (2014) used NLP to analyze chat logs from a collaborative problem-solving task and found that their automated system was able to accurately assess students' collaborative problem-solving skills.

Furthermore, AI tools can be used to provide real-time feedback to students during collaborative problem-solving tasks. For example, Hao et al. (2017) developed an AI-based system that provides real-time feedback to students during a collaborative problem-solving task, which has the potential to enhance their problem-solving skills.

In summary, AI tools can be used to assess and provide feedback on collaborative problem-solving skills using techniques such as machine learning and natural language processing. Such tools have the potential to enhance the assessment and development of collaborative problem-solving skills, particularly in the context of online and distance learning.

5. Conclusions

Collaborative problem solving is a critical construct that encompasses the joint efforts of multiple agents in resolving problems through the sharing of knowledge, understanding, and collaborative endeavors. It encompasses two distinct problem-solving types: static (simple) and interactive (complex), with the latter involving intricate tasks characterized by ambiguous initial states and goals. Complex problem solving necessitates the acquisition of additional knowledge while engaging with dynamic environments, all while keeping the ultimate objective in mind.

The modern digital age underscores the increasing significance of collaborative problem-solving skills, as traditional routine tasks become automated, making room for non-routine and complex challenges that demand a fresh skill set. Consequently, there is a burgeoning interest in developing assessments and frameworks to effectively measure and enhance collaborative problem-solving skills. Education plays a pivotal role in cultivating these skills, emphasizing the need for perspective-taking and a generalized competency model that can guide their development.

However, the operationalization of collaborative problem-solving skills presents challenges, primarily related to the measurement of behavioral and collaborative aspects while ensuring compliance with rigorous psychometric standards, including objectivity, reliability, validity, and scalability. To address this, researchers have explored different approaches to operationalizing individual problem-solving constructs using computer-supported scenarios. These approaches encompass realistic scenarios, which simulate real-world complexities through carefully crafted relationships between system variables, and formal scenarios, characterized by a priori structural equations and multiple short tasks that offer enhanced psychometric properties.

Assessment tools have been developed to evaluate collaborative problem-solving skills. Notably, the Assessment and Teaching of Twenty-first Century Skills (ATC21S) project is a large-scale assessment targeting students aged 11-15. It employs human-to-human, computer-supported collaboration to assess the social and cognitive dimensions crucial to collaborative problem solving. Additionally, Rosen and Foltz's (2014) study compares collaborative problem solving through human-agent and human-human evaluations, monitoring communication and collaboration skills via predefined messages and process measurements.

Collaborative problem solving assumes paramount importance in the modern era, where effective problem resolution in group contexts is increasingly sought after. Its development and assessment remain pivotal to individuals' abilities to navigate complex challenges alongside their peers. Future research should delve into exploring the untapped potential of collaborative problem solving, identifying effective instructional strategies, and unraveling its implications across diverse domains. This academic pursuit will facilitate the advancement of knowledge in collaborative problem-solving skills and contribute to the growth and success of individuals and teams in various professional settings.

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