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The effects of online simulation-based collaborative problem-solving on students' problem-solving, communication and collaboration attitudes

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Abstract
Despite national curricula and instructional reforms calling for collaborative problem-solving skills (CPS), however, there is an absence of a theory-laden model showing how to effectively construct CPS for science learning. We therefore developed and validated a simulation-based CPS model that exploits its constructs, sequences, and causal relationships, and evaluating its effectiveness on students' problem-solving. Over the span of a two-week physics science course, 57 ninth-grade students were recruited from two intact middle school classes to engage in this online simulation-based collaborative problem-solving (CPS) program. This program consisted of nine electrochemistry problem-solving lessons spread across four class sessions, each lasting 45 min. Results indicated that the simulation-based CPS model was validated and proven to contribute to effective problem-solving by linking PS solution proposing, peer communication, implementing PS solutions with simulation, and providing evidence-based explanations. The simulation-based CPS model successfully improved the performance of both high- and low-achieving students. With the support and presence of high-achievers, low-achievers' collaboration attitude was boosted, which lead them to achieve similar learning success.

Keywords Computer simulation · Collaborative problem-solving · Peer communication · Collaboration attitudes · High-vs. low-achievers

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1 Introduction

Collaborative problem-solving (CPS) has become increasingly recognized as a powerful tool for helping students solve complex scientific problems collaboratively, thus national curriculums and instructional reforms across many nations (Binkley et al., 2012; Darling-Hammond & McLaughlin, 2011) have incorporated CPS skills. OECD defines CPS as an individual's ability to share and integrate their existing knowledge and perspectives with others when solving problems together (OECD, 2013). Collaborative learning offers students the opportunity to construct a shared understanding of knowledge and meaning-making of the content (Fischer et al., 2013). Understanding chemistry concepts can be challenging because they require understanding three representational levels, macroscopic, microscopic, and symbolic (Johnstone, 1993). Electrochemistry is one of the most complex topics in the study of chemistry (Supasorn et al., 2014). The primary reason that electrochemistry is considered one of the difficult topics both at the high school and undergraduate levels is that most processes involve the microscopic level (molecular level) that cannot be observed directly (Rahayu et al., 2022), or involve the complex nature and too many concepts (Akram et al., 2014). Individuals may find it challenging to grasp microscopic concepts and solve complex problems on their own. The inclusion of CPS skills in educational and professional settings has the potential to equip individuals with the necessary skills and tools to tackle complex problems and thrive in the twenty-first century (Griffin & Care, 2014). Low academic achievement may hinder students' school learning and future careers (Al-Zoubi & Younes, 2015). Cook et al. (2008) reported that students' academic achievement and prior knowledge are critical for predicting their knowledge construction and comprehension. Other studies suggested that low-achieving students can be as proficient at problem-solving skills as high-achieving students with appropriate instruction (Ben-David & Zohar, 2009; Grimberg & Hand, 2009). While science instruction and curriculum reforms have been widespread, a theory-laden model on how to build an effective simulation-based CPS for science learning is still lacking. The purpose of this study is therefore to develop and validate a simulation-based CPS model and investigate its effectiveness in promoting students' learning of science and minimizing the achievement gap between low- and high-achievers.

2 Theoretical frameworks

Studies of CPS have found that it improves student problem-solving competency (Malik et al., 2019), engagement (Unal & Cakir, 2021) and content knowledge (Harskamp & Ding, 2007). Garrison (1991) decomposed the problem-solving process into problem identification, problem description, problem exploration, applicability, and integration. In some studies, the PS process is divided into problem representation, solutions search, and solutions implementation

(Bransford & Schwartz, 1999; Newell & Simon, 1972), or meeting the problem, analyzing problems and issues, discovering, and reporting, and presenting and evaluating solutions (Chua et al., 2016). Another study delineated physics problem-solving as identifying known conceptions, providing possible solutions, evaluating solutions, implementing solutions, and providing evidence-based explanations (Cheng et al., 2017). Considering that the literatures above share the PS components of proposing problem solutions, implementing solutions, and providing evidence-based explanations, we incorporate them into our CPS model.

Collaborative learning improves the acquisition and retention of knowledge and helps students solve problems (García-Valcárcel et al., 2014). Science is a process in which scientific knowledge is socially constructed, and in which discursive activity is central to the science process (Driver et al., 2000). Duran (2014) noted that communication helps obtain information or new ideas that can help understand a problem better and working together to develop effective solutions to complex problems. Dialogues and the discussions of ideas encourage students' thinking and learning (Faranda & Clarke, 2004). CPS provides students with a communication platform to reconstruct their knowledge and thinking, filling gaps in their understanding and formulating strategies that can collaboratively tackle complex issues (Fawcett & Garton, 2005). Studies of group work found that a critical relationship existed between providing explanations and achievement (Howe & Tolmie, 2003; Veenman & Spaans, 2005). Moreover, explaining to others can enhance learning since the explainer can reorganize and clarify the material, recognize misconceptions, fill in the gaps in their understanding, internalize and acquire new strategies and knowledge, and develop new perspectives and understanding (Saxe et al., 2002). The groups failed to make progress or seemed to be functioning ineffectively when no group member could answer the question, exhibited problems communicating, and worked without allowing true dialogue (Johnson & Johnson, 2009). Communication is a key component of collaboration, which enables students to solve problems together.

Computer simulation has been recognized as a promising tool for supporting CPS activities during scientific learning (Andrews-Todd & Forsyth, 2020; Ceberio et al., 2016). The simulation can provide opportunities for students to test the invisible and abstract phenomena in the real world and integrate multiple perspectives from their team members, which ultimately aids their understanding of scientific concepts (Akpınar, 2014; Lu & Lin, 2017). Simulations can reveal invisible, abstract, and microscopic phenomena that are difficult to view in the real world (Chou et al., 2022; Sinensis et al., 2019), and thus help students construct knowledge by observing concrete simulated phenomena (Saab et al., 2012). Simulations offer a unique opportunity to engage students in interactive, hands-on learning experiences that can support their learning of science (Rutten et al., 2012). Providing learners with simulations can help them gain a deeper understanding of complex concepts and microscopic phenomena.

3 Hypotheses development and research model for simulation-based CPS

As identified in the literature, communicating with one's partner, proposing solutions to a problem, implementing those solutions with simulation, and developing evidence-based explanations are essential for CPS. However, their constructs, sequences, and causal relationships remain unclear. Based on the theoretical frameworks above, we have proposed the constructs and causal relationships among these elements that govern our research hypothesis in Fig. 1. We hypothesize that including communication among group members may lead to the development of PS solutions, which further influence the implementation PS solutions with simulations and evidence-based explanations, and thereby contributing to their problem-solving performance. The following hypotheses were proposed to validate its effectiveness using the partial least squares structural equation model (PLS-SEM).

H1. Communication dialogues between students have a significant positive effect on their PS solution generation.
H2. PS solutions proposed by students have a significant positive effect on their implementation of PS solutions with simulations.
H3. PS solutions proposed by students have a significant positive effect on their ability to make evidence-based explanations of the results.
H4. Implementing PS solutions with simulation has a significant effect on their ability to provide evidence-based explanations.
H5. Evidence-based explanations provided by students have a significant impact on their problem-solving performance.

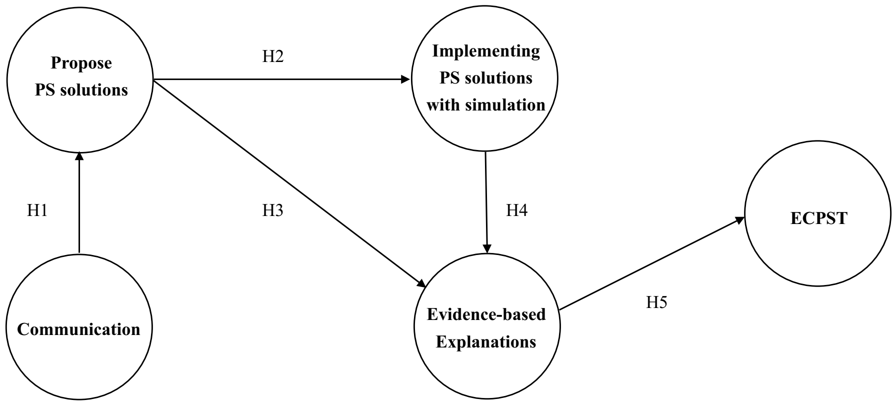

Fig. 1 Proposed model construct for simulation-based CPS learning

4 Research questions

This study aims to determine whether our validated simulation-based CPS model can enhance students' electrochemistry problem-solving abilities and benefit students of varying achievement levels through online collaboration. Therefore, the following four research questions are proposed as guidelines: (1) whether high- and low-achievers would significantly improve their performance on the electrochemical problem-solving test (ECPST) after learning;(2) whether high- and low-achievers would significantly improve their performance in proposing problem-solving (PS) solutions after peer communication; (3) whether high- and low-achievers would engage in a different amount of supportive dialogues, including giving support, requesting support, and reminding; and (4) whether high- and low-achievers differ in their attitudes toward collaborations after completing the online electrochemistry CPS learning.

5 Method

5.1 Subjects and procedures

Over the span of a two-week physics science course, a total of 57 ninth grade students from a middle school two intact classes were recruited to participate in this online simulation-based collaborative problem-solving (CPS) program. To prove and validate the effectiveness of this simulation-base CPS program, thus we designed an entire electrochemistry unit with nine electrochemistry problem-solving lessons spread across four class sessions, each lasting 45 min. The nine electrochemistry problem-solving lessons comprised five on galvanic cells and four on electrolytic cells (Fig. 2). Each simulation-based CPS lesson was designed with four components: communication with partners, proposing PS solutions, implementing PS solutions with simulations, and making evidence-based reasoning. During four class sessions over two weeks, high- and low-achievers were anonymously paired

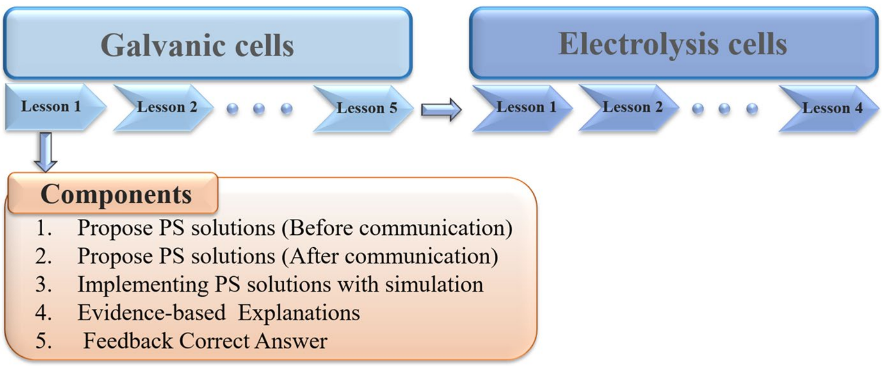

Fig. 2 The design of online simulation-based CPS learning

up heterogeneously without knowing the identities of their partners. It is to ensure that social status does not negatively impact the ability to engage in communication dialogues, problem-solving, and collaborations.

Students were classified into high- and low-achievers based on their school science achievements. We used median school science achievement scores, with a threshold of 80 points, to classify students into high and low achievers. Students with school science achievement scores ≥ 80 points were classified as high achievers, and those with scores < 80 points were classified as low achievers. Heterogeneous groups were formed, each comprising one high- and one low-achiever. One week before and after online electrochemical collaborative problem-solving (CPS) program, all students were administered the electrochemical problem-solving test (ECPST). During the online learning, students' online problem-solving processes were collected and recorded in MySQL database, including their problem-solving (PS) solutions, implementation PS solutions with simulations, evidence-based explanations, and communication dialogues.

5.2 The development of online electrochemistry collaborative problem-solving (CPS) learning activities

The electrochemistry CPS project was developed based on the national standards for 9th grade chemistry curriculum. A panel of three scientists designed the electrochemistry problem-solving content, including a science education professor, a Ph.D. candidate in science education with three years of middle school science teaching experience, and an experienced middle school science teacher. To create the online electrochemistry CPS program, Unity 3D technologies were used to develop simulations and experiments, the photon network was used to build multi-person collaborations, and a MySQL database was utilized to collect data.

Nine problem-solving lessons were designed: five on the topic of galvanic cells and four on the topic of electrolytic cells. Each CPS lesson required the students to communicate with their partners, propose PS solutions, implement PS solutions with simulation, and provide evidence-based explanations (Fig. 2). The five lessons on galvanic cells covered identifying electrode pairs to generate electric currents, finding electrolyte solutions to produce electric currents, finding salt bridge solutions to generate a current, identifying the electronic flow between electrodes, and identifying the movement of ions in the electrolyte solutions. The four lessons on electrolysis cells covered identifying electrolyte solutions, identifying how the electronic flow affects the anode and cathode in electrolysis, finding electrolyte solutions to produce gases during electrolysis at particular electrodes, and finding electrode pairs for copper sulfate electrolysis without changing their colors.

During the CPS process, each student must propose at least two PS solutions (Fig. 3A). Upon submitting their proposed PS solutions, they were required to communicate with their partners for revising and modifying their proposals as needed (Fig. 3B). Once their PS solutions have been finalized, they needed to implement their PS solutions with their teammates by running simulations in rotation, and their simulation screens would be automatically shared. During the simulation, they were able to test their proposed PS solutions and observe the changes of macroscopic (color change, electrochemical reaction product, etc.) and microscopic phenomena (ions, electrons, etc.) (Fig. 3C). By implementing their PS solutions with 3D simulation, they were able to validate whether their PS solutions were feasible and workable. Students had to record the simulation results. Students were also required to provide evidence-based explanations to assess their physics understanding after completing these problem-solving processes (Fig. 3D & E). The feedback with the correct answer was given after completing the evidence-based explanations (Fig. 3F).

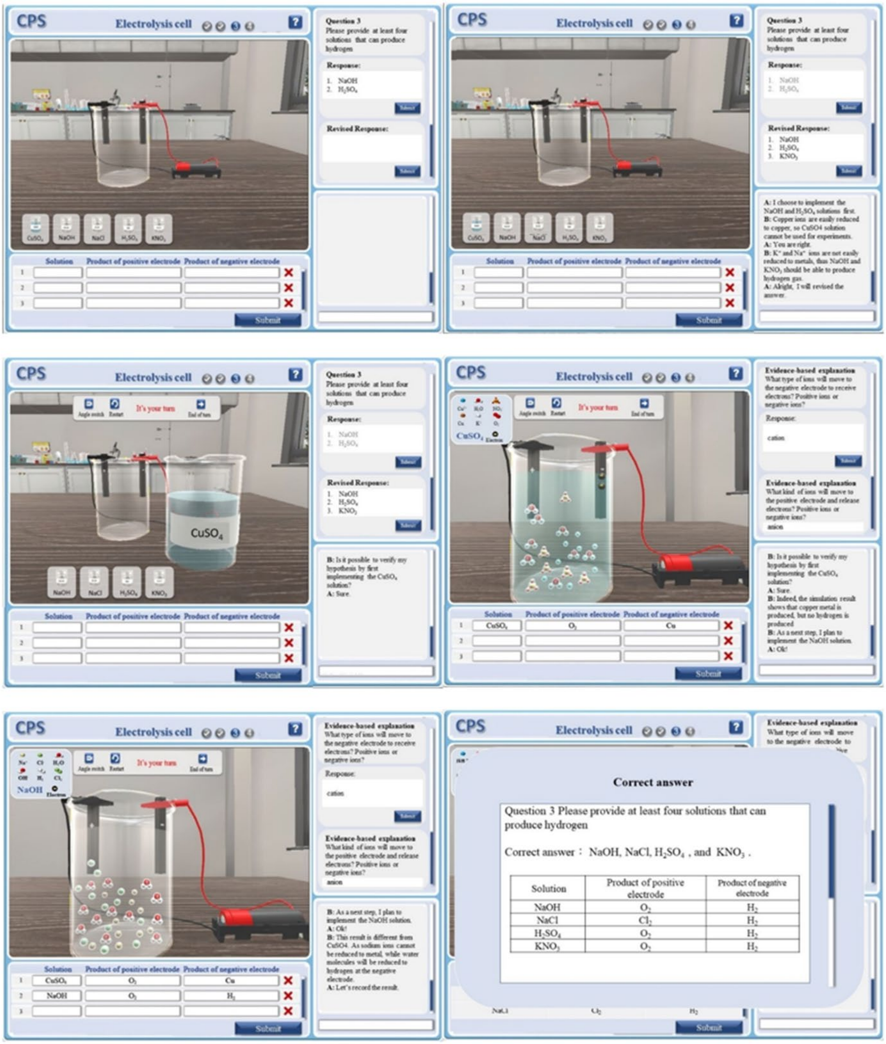

Fig. 3 Screen shots for online simulated-based CPS learning platform

5.3 Electrochemical problem-solving test (ECPST)

The ECPST is an open-ended diagnostic instrument designed to measure students' electrochemical problem-solving performance before and after the intervention. The same panel of three developed the ECPST to ensure the questions were properly constructed and relevant to an online electrochemical problem-solving program. It consists of three galvanic cells and three electrolytic cells which required students to propose three viable solutions to each question and explain the reasons for their proposed PS solutions. Each correct solution was worth 2–4 points, depending on how many subcomponents were required. Students were awarded two points for a correct response, one point for a partially-correct response, and zero point for an incorrect response. A maximum achievable cumulative score was 64 points. Two raters scored students' ECPST results based on the coding system, and the inter-rater reliability was 0.916.

5.4 Attitudes toward collaborations

PISA 2015 designed eight items of the attitudes toward collaboration questionnaire, including two indices of cooperation that reflected students' valuing of relationships and teamwork (OECD, 2013). The four statements that comprised the index of valuing relationships were related to altruistic interactions which the student engages in collaborative activities not for their own benefit: "I am a good listener"; "I enjoy seeing my classmates be successful"; "I take into account what others are interested in"; and "I enjoy considering different perspectives." By contrast, three of the four statements that comprised the index of valuing teamwork were related to what teamwork produces as opposed to working alone: "I prefer working as part of a team to working alone"; "I find that teams make better decisions than individuals"; and "I find that teamwork raises my own efficiency."

5.5 Analyses of the online problem-solving processes and communication dialogues

Students' online problem-solving processes were analyzed: communicating with partners, proposing the PS solution, implementing PS solutions with simulations, making evidence-based reasoning. In the PS solutions, the student who proposed each correct solution would earn a point. In the evidence-based explanations, two points for a correct response, one for a partially correct response, and zero for an incorrect response. The coding system for students' implementation of PS solutions with simulations results assigned one point when they correctly reported their simulation results and one point for running accurate simulation. The inter-rater reliability of these three rubrics for PS solution, implementing PS solutions with simulations, and making evidence-based explanations were 0.963, 0.966, and 0.927, respectively. Students' online discussion dialogues were analyzed with a coding system, which included giving support, requesting support, and reminding partners of the three categories; and the inter-rater reliability was 0.913.

5.6 PLS-SEM model

Hair et al. (2022) advocated that partial least squares structural equation modeling (PLS-SEM) is appropriate for analyzing small sample sizes and validating theoretical frameworks. PLS is increasingly used in education for developing exploratory models (Barclay et al., 1995). The PLS-SEM comprises two components, the measurement, and the structural model (Henseler et al., 2009).

The measurement model assesses indicator reliability using outer loading, where the value should exceed 0.50. The Cronbach's α and the composite reliability (CR) are measures of internal consistency and both should be greater than 0.60. The average variance extracted (AVE) assesses convergence validity, which should be greater than 0.50 (Fornell & Larcker, 1981; Hair et al., 2022). To assess the discriminant validity of the PLS-SEM model, two commonly used criteria are the Fornell-Larcker criterion and the heterotrait-monotrait ratio (HTMT). According to the Fornell-Larcker criterion, the square root of each construct's diagonal AVE must be greater than the correlation between that construct with all the other constructs. The HTMT determines whether the correlation between the two constructs is less than 0.90 (Henseler et al., 2015). Accordingly, we used the PLS-SEM methodology to examine hypotheses 1 through 5, as previously stated.

The structure model obtains various coefficients for evaluating the research hypothesis formulated (Henseler & Chin, 2010). To calculate the goodness of fit of the structural model when using PLS-SEM, the standardized root mean residual (SRMR) was used. An SRMR value of less than 0.10, or equal to 0.08, indicates a good fit in the PLS-SEM model, according to Ringle et al. (2015). However, PLS-SEM is still in its early stages and may not always be applicable. As a result, reporting these criteria should be exercised with caution. In addition, the path coefficient and of determination (R^2) coefficient were reported, and all statistical analyses were performed using SmartPLS 4.

6 Results

6.1 PLS-SEM model

6.1.1 Measurement model

Table 1 presents the convergent validity and reliability of the proposed constructs of the model. There was satisfactory reliability among each of these indicators, with the loadings ranging from 0.82 to 0.97. The Cronbach's alpha coefficients were all above 0.71, indicating adequate reliability. The CR indices were above 0.87, confirming each construct's internal reliability. According to the convergent validity, the

Table 1 Parameter estimation of the measurement model

Constructs	Indicators	Mean	SD	Loadings	Cronbach's α	CR	AVE
Communication	Giving Support Dialogue	0.94	0.03	0.93	0.71	0.87	0.77
	Reminding Dialogue	0.78	0.14	0.82			
Proposed PS solutions	PS solution before communication	0.94	0.02	0.94	0.86	0.93	0.88
	PS solution after communication	0.93	0.02	0.93			
Implementing PS solutions with simulation	Simulation results	0.84	0.09	0.85	0.82	0.91	0.83
	Accurate solution implementation	0.97	0.04	0.97			
Evidence-based Explanations	Macroscopic level	0.88	0.04	0.88	0.77	0.90	0.81
	Microscopic level	0.92	0.02	0.92			
ECPST	Provide PS Solutions	0.91	0.02	0.91	0.73	0.88	0.78
	Provide explanation	0.86	0.05	0.87			

average variance extracted (AVE) ranged from 0.77 to 0.88. It reveals that the indicators account for more than 77% of the variance of each construct.

The discriminant validity was also assessed using the Fornell-Larcker criterion. Based on the results, the square root of each construct's AVE was greater than the correlation between that construct and all others. Further, the HTMT of the correlations was below 0.90, thus confirming discriminant validity (Table 2).

6.1.2 Structural model

Evaluation of the structural model involved assessing the significance level of the relationships between constructs and the prediction quality of each construct. An evaluation of the path coefficient of the structural model using PLS-SEM appears in Fig. 4. The SRMR value of the structural model was 0.095, which is less than 0.10, indicating a good fit in the PLS-SEM model, based on Ringle et al.'s (2015) recommendation. However, the criteria for model fit in PLS-SEM are still in the early stages of research and may not always be applicable (Ringle et al., 2015). Table 3 summarizes five hypotheses supported by the proposed structural model to show the direct effect between constructs. Among proposing PS solutions, communication, implementing PS solutions with simulation, evidence-based explanations, and ECPST, the R^2 values ranged between 0.18 and 0.48, indicating small to moderate predictability. The f^2 values for communication → proposed PS solutions, proposed PS solutions → evidence-based explanations, proposed PS solutions → implementing PS solutions with simulation, implementing PS solutions with simulation → evidence-based explanations, and evidence-based explanations → ECPST were 0.26, 0.14, 0.21, 0.15, 0.92, respectively.

Furthermore, the results of the indirect effect are presented in Table 4, where it can be observed that three paths demonstrated statistical significance. The results indicated that significant indirect effects exist in communication → proposed PS solutions → evidence-based explanations, communication → proposed PS solutions → implementing PS solutions with simulation, and proposed PS solutions → evidence-based explanations → ECPST. However, since communication can predict the evidence-based explanations ($\beta = 0.217$, $p < 0.001$) and implementing PS solutions with simulation ($\beta = 0.189$, $p < 0.005$), and proposed PS solutions can predict ECPST ($\beta = 0.333$, $p < 0.001$), therefore, the indirect effect for these paths were partially mediated.

6.2 The effectiveness of simulation-based CPS model on low- and high-achievers' problem-solving

6.2.1 Electrochemical problem-solving test (ECPST)

To answer the first research question, this study used the one-factor repeated measure ANOVA to examine whether high- and low-achievers would significantly improve their performance on the electrochemical problem-solving test (ECPST) after learning (Table 5). The results indicated that the ECPST performance improved

Table 2 Discriminant validity using Fornell-Larcker Criterion and HTMT

	Communication	ECPST	Evidence-based Expla-nations	Implementing PS solutions with simulation	Proposed PS solutions
Fornell-Larcker Criterion					
Communication	0.88				
ECPST	-0.00	0.89			
Evidence-based Explanations	0.18	0.69	0.90		
Implementing PS solutions with simulation	0.15	0.35	0.49	0.91	
Proposed PS solutions	0.45	0.47	0.48	0.42	0.94
HTMT					
Communication					
ECPST	0.16				
Evidence-based Explanations	0.24	0.92			
Implementing PS solutions with simulation	0.19	0.40	0.54		
Proposed PS solutions	0.55	0.59	0.58	0.46	

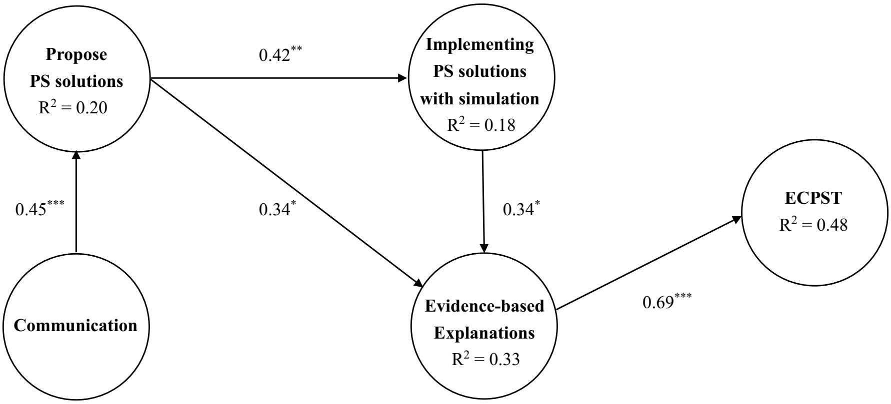

Fig. 4 Path coefficient of the model ($^{***}p<0.001$, $^{**}p<0.01$, $^{*}p<0.05$)

significantly from the pretest to the posttest (F = 172.94, $p<0.001$), and achievement level also significantly affected performance (F = 21.94, $p<0.001$). Based on a simple main effect analysis, both high-achievers (F = 63.77, $p<0.001$) and low-achievers (F = 136.66, $p<0.000$) made significant progress from pretest to posttest (Table 6). As for achievement levels, high-achievers scored significantly higher than low-achievers in the pretest (F = 16.16, $p<0.001$) and posttest (F = 13.38, $p<0.01$) ECPST.

6.2.2 Online PS solutions

To answer the second research question, this study used a one-factor repeated measure ANOVA to examine whether high- and low-achievers would significantly improve their performance in proposing problem-solving (PS) solutions after peer communication (Table 7). The students' PS solution performance improved significantly from before to after peer communication (F = 12.30, $p<0.01$), as well as their achievement levels (F = 9.73, $p<0.01$). This study found a significant interaction between the achievement levels and the PS solutions before and after peer communication (F = 4.65, $p<0.05$). Therefore, the simple main effect proceeded accordingly (Table 8). Based on the simple main effect analysis, only low-achievers (F = 16.36, $p<0.001$) made significant progress on students' PS solution performance from before to after peer communication. A significantly higher PS solution performance was only observed in high-achievers before peer communication than in the low-achievers (F = 15.52, $p<0.001$). After peer communication, high- and low-achievers did not significantly differ in their performance in providing PS solutions (F = 3.97, $p=0.051$).

6.2.3 Online communication dialogues

To answer the third research question, this study used the one-factor multivariate analysis of variance (MANOVA) to determine whether high- and low-achievers

Table 3 The path analysis results

Path	Path coefficient	t value	95% confidence interval		Hypothesis
			LL	UL	
Communication → Proposed PS solutions	0.45	6.40^{***}	0.32	0.60	H1 supported
Proposed PS solutions → Evidence-based explanations	0.34	2.56^{*}	0.07	0.58	H2 supported
Proposed PS solutions → Implementing PS solutions with simulation	0.42	3.42^{**}	0.17	0.64	H3 supported
Implementing PS solutions with simulation → Evidence-based explanations	0.34	2.45^{*}	0.07	0.61	H4 supported
Evidence-based explanations → ECPST	0.69	8.08^{***}	0.50	0.83	H5 supported

Note. ***$p < 0.001$, **$p < 0.01$, *$p < 0.05$

Table 4 Specific indirect effects for mediation

Path	Path coefficient	t value	95% confidence interval	
			LL	UL
Communication → Proposed PS solutions → Evidence-based explanations	0.15	2.29*	0.03	0.29
Communication → Proposed PS solutions → Implementing PS solutions with simulation	0.19	3.12**	0.08	0.31
Proposed PS solutions → Evidence-based explanations → → ECPST	0.23	2.40*	0.05	0.43

Note. ***p < 0.001, **p < 0.01, *p < 0.05

Table 5 Results of one-factor repeated measure ANOVA of electrochemistry problem solving test (ECPST)

Effect	Wilk's Λ	*df*	*F*	*p*
Tests of within-subjects effects				
ECPST	.24	1	172.94***	< 0.001
ECPST * Achievement levels	1.00	1	0.12	0.729
Tests of between-subjects effects				
Achievement levels			21.94***	< 0.001

Note. ****p* < 0.001, ***p* < 0.01, **p* < 0.05

Table 6 Simple main effect for within-subjects effects and between-subjects effects for electrochemistry problem solving test (ECPST)

	SS	*df*	*MS*	*F*	*p*	Post-hoc
Within-subjects effects						
High-achievers	4590.16	1	4590.16	63.77***	< 0.001	Post > Pre
Low-achievers	4275.93	1	4275.93	136.66***	< 0.001	Post > Pre
Between-subjects effects						
Pre-test	972.20	1	972.20	16.16***	< 0.001	High > Low
Post-test	1204.65	1	1204.65	13.38**	0.001	High > Low

Note. ****p* < 0.001, ***p* < 0.01, **p* < 0.05

would engage in a different amount of supportive dialogues, including giving support, requesting support, and reminding (Table 9). According to the results, high-achievers allocated significantly more dialogues to giving support than low-achievers ($F = 5.97$, $p < 0.05$). However, high- and low- achievers, however, allocated similar amounts of requesting support and reminding dialogues ($F = 0.01$, $p = 0.941$ and $F = 0.042$, $p = 0.839$).

Table 7 Results of one-factor repeated measure ANOVA of problem solving solutions (PS solutions) in online learning process

Effect	Wilk's Λ	*df*	*F*	*p*
Tests of within-subjects effects				
PS solutions	0.82	1	12.30^{**}	0.001
PS solutions * Achievement levels	0.92	1	4.65^{*}	0.035
Tests of between-subjects effects				
Achievement levels			9.73^{**}	0.003

Note. $^{***}p<0.001$, $^{**}p<0.01$, $^{*}p<0.05$

Table 8 Simple main effect for within-subjects effects and between-subjects effects for problem solving solutions (PS solutions) in online learning process

	SS	*df*	*MS*	*F*	*p*	Post-hoc
Within-subjects effects						
High-achievers	0.04	1	0.04	0.90	0.353	
Low-achievers	0.67	1	0.67	16.36^{***}	<0.001	After > Before
Between-subjects effects						
Pre-test	2.07	1	2.07	15.52^{***}	<0.001	High > Low
Post-test	0.68	1	0.68	3.97	0.051	

Note. $^{***}p<0.001$, $^{**}p<0.01$, $^{*}p<0.05$

Table 9 Univariate analysis of high- and low- achiever's online communication dialogues

	High-achiever (n=28)		Low-achiever (n=29)		*F*	p	Post-hoc
	M	SD	M	SD			
Online communication dialogues							
Mean frequency of Giving Support	0.33	0.51	0.08	0.18	5.97^{*}	0.018	High > Low
Mean frequency of Requesting Support	0.19	0.31	0.19	0.30	0.01	0.941	
Mean frequency of Reminding	0.48	0.52	0.45	0.58	0.042	0.839	

Note. $^{***}p<0.001$, $^{**}p<0.01$, $^{*}p<0.05$; High: High-achievers; Low: Low-achievers

6.3 Attitudes toward collaborations and their association with online PS solutions

To answer the last research question, we used a one-factor analysis of covariance (ANCOVA) to examine whether high- and low-achievers differ in their attitudes toward collaborations after completing the online electrochemistry CPS learning (Table 10). Results show that the low-achievers' attitudes toward collaboration after learning were significantly higher than those of the high-achievers ($F=4.05$, $p<0.05$) when the effects of collaboration attitudes before learning

Table 10 ANCOVA results of comparing different achievement levels in collaborations attitudes

Source	SS	df	MS	F	p	Post-hoc
Collaboration attitudes						
Achievement levels	0.72	1	0.72	4.05*	0.049	Low > High
Value of relationship						
Achievement levels	0.00	1	0.00	0.01	0.914	
Value of teamwork						
Achievement levels	2.30	1	2.30	7.12*	0.010	Low > High

Note. ***$p < 0.001$, **$p < 0.01$, *$p < 0.05$; High: High-achievers; Low: Low-achievers

were controlled. Also, the low-achievers' value of teamwork was significantly higher than that of high-achievers ($F = 7.12$, $p < 0.05$).

The scatter plot illustrated that most low-achievers' PS solutions performance had moved upward from the lower right part of the plot after peer communication when the effects of collaboration attitudes were controlled (Fig. 5). However, most of the high-achievers' PS solutions performance remain unchanged. In other words, students with low-achievement levels scored much higher on PS solutions after peer communication when their collaboration attitudes were controlled. However, high-achievers did not differ much in their PS solution performance after peer communication. Similar scatter plot patterns were also found for teamwork value and PS solution performance when the effects of teamwork value were controlled (Fig. 6). After peer communication, the association between high-achievers' post-collaboration attitudes with their PS solution performance became more negative, while low-achievers' collaboration attitudes did not change much. We found the same association pattern for the teamwork value with PS solutions.

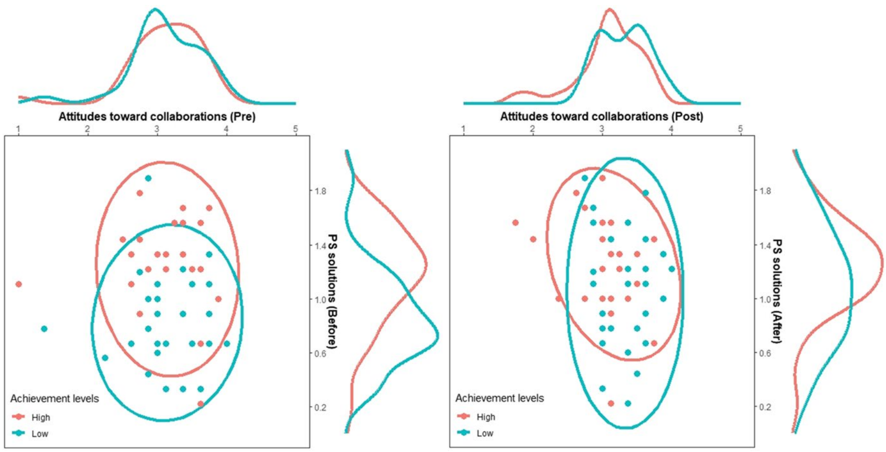

Fig. 5 Scatter plot and marginal distribution displayed the relationship between high- and low-achievers' attitudes toward collaborations and their online PS solution performance before and after collaboration

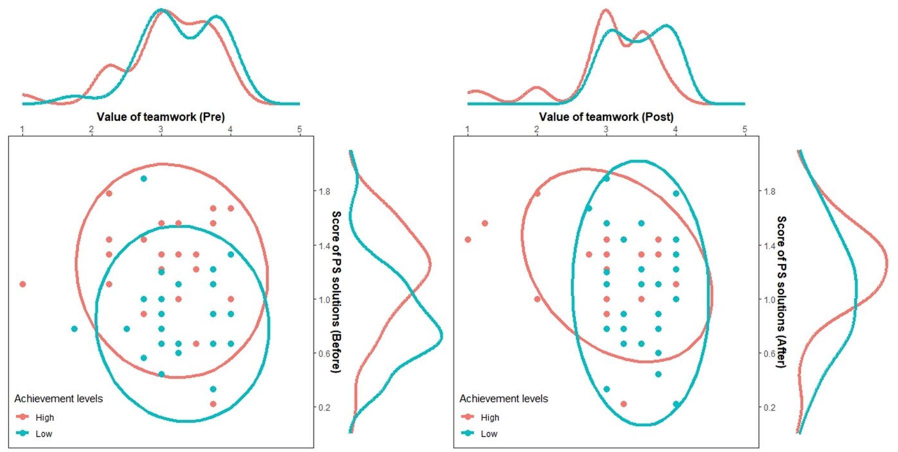

Fig. 6 Scatter plot and marginal distribution displayed the relationship between high- and low-achievers' value of teamwork and their online PS solution performance before and after collaboration

7 Discussion

In the present study, we established an empirical proved theory-laden model of online simulation-based CPS for learning science effectively. Using PLS-SEM, we examined the influence of casual relationships between proposing PS solutions, peer communication, implementing solutions with simulation, making evidence-based explanations, and overall problem-solving performance. In summary, our proposed research model achieved an impressive predictive level and supported our five hypotheses. According to previous studies, having a human who can communicate effectively with others in addition to solving problems in the real world makes them more competitive (Bender, 2012; Erozkan, 2013). The students required communication skills to explain a valid conclusion based on the evidence of science in problem-solving (Yusuf & Adeoye, 2012). They support our finding that communication directly influences proposing PS solutions and indirectly influences implementing PS solutions with simulation and making evidence-based explanations. Previous studies reported that computer simulations are an effective tool for supporting the use of CPS for scientific learning (Andrews-Todd & Forsyth, 2020; Ceberio et al., 2016). Additionally, by integrating simulations with CPS instruction, students gain a better understanding of abstract concepts (Sinensis et al., 2019) and CPS skills (Lin et al., 2018). Our findings indicated that simulations directly influence students' evidence-based explanations and contribute to their effective problem-solving, which supports above literatures.

The present study demonstrated that using simulation-based CPS effectively leverages both low- and high-achievers to achieve great success in their problem-solving performance. Regarding online CPS learning process, only low-achievers made significant improvement in their scores of PS solution after peer communication, whereas high-achievers did not. High- and low-achievers' online PS solution scores differ significantly before peer communication, but not after. As a result of peer communication, the low-achievers advanced and achieved the same PS solution score levels as high-achievers. No study has reported similar findings, despite an extensive review of the literature. A deeper investigation into this question revealed interesting findings. According to the communication dialogues between students, high achievers gave significantly more support than low achievers. Andrews-Todd and Forsyth (2020) suggested that collaborative problem-solving groups with at least one member with high cognitive skills lead to enhanced learning performance. It helps explain when high-achievers offer more support to the low-achievers, they are more likely to significantly improve the PS solutions performance of the latter. It implies that the presence and support of high-achievers play a significant role in improving the problem-solving performance of low-achievers. Our results indicated that communication has a direct influence on students' proposal of PS solutions, which supports why low-achievers significantly improved their PS solution scores. This highlights the unique contribution of our simulation-based CPS model in enhancing low-achievers' online PS solutions performance through communication and collaboration.

Regarding attitudes toward collaborations, low-achievers perceived a significantly higher collaboration attitudes and its subscale of teamwork value after learning compared to high-achievers. A fascinating pattern derived from the scatter plot and marginal distribution showed that most low-achievers had scored much higher on PS solutions performance after peer communication, when the effects of collaboration attitudes were controlled. However, high-achievers did not differ much in their PS solutions scores after peer communication. The subscale of teamwork value followed a similar pattern. Earlier studies reported that students who have experienced online collaborative learning learned more than they would have individually (Hernández-Selles et al., 2019; Ku et al., 2013). The OECD reported that disadvantaged students in most countries and economies value teamwork more than advantaged students (OECD, 2013), similar to our case. These studies lead us to conclude that the use of theory-laden simulation-based CPS model effectively enhances low-achievers' collaboration attitudes and their teamwork value, which contributes to their PS solution performance.

This study has shown that online simulation-based CPS models that feature communication, PS solutions, simulation implementation, and evidence-based explanations effectively enhance students' problem-solving performance. Some potential implications and practical applications are provided below. Firstly, it is highly recommended that future applications of CPS in classroom or online learning include these four components. These four components are crucial not only to provide the opportunity for students to communicate and collaborate but also to enhance their generation of problem-solving solutions, which further impacts their implementation of PS solutions and evidence-based explanations and ultimately leads to greater problem-solving success. Secondly, future applications of CPS in classroom or online learning should group students heterogeneously to minimize the gaps between high and low achievers. Both high and low achievers showed statistically significant improvements in electrochemistry problem-solving using this simulation-based CPS. After peer communication and collaboration in which high achievers offered more support to low achievers, the low achievers improved and achieved the same PS solution score as the high achievers. Therefore, the low achievers developed a more positive attitude toward collaboration and teamwork than the high achievers. Consequently, it is imperative to include members of varying cognitive abilities and achievement levels when forming CPS groups. This practice can reduce the disparities among group members and improve the learning performance of low achievers. Thirdly, students should be given opportunities to visualize microscopic-level phenomena through simulation or animation when solving science problems because scientific concepts are inherent in many micro-level phenomena. It is vital to leverage visual tools such as images, animations, and simulations during this process. The use of simulations, especially, provides a microscopic view of phenomena and allows users to actively manipulate variables and interact with them. Ultimately, we hope that our study will provide insight into the future of simulation-based CPS in all aspects of science learning and problem-solving.

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Declarations

Conflict of interest The authors have no conflict of interest to disclose.

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