Understanding the Connections of Collaborative Problem Solving Skills in a Simulation-based Task Through Network Analysis

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Abstract: As one of the identified key 21st century skills, collaborative problem solving (CPS) attracted attention from both education research and the assessment industry. Studies and assessments were developed to conceptualize and to measure CPS skills. Most studies operationalized different dimensions of CPS skills as discrete measures even though they may be interweaving in the construct. In this study we went beyond the separate measures on the different dimensions and focused on the connections among these skills. Using log data of 20,947 events on actions and chats from 43 teams, we studied how different dimensions of CPS skills were connected as reflected in problem solving. CPS skill networks were constructed to capture the co-occurrence of the skills in turns during collaboration. The results showed that teams with high and low performance had significantly different CPS network structures.

Background

Competencies such as collaborative problem solving (CPS) are considered increasingly important for career and academic success in the 21st century. As individuals move through school and into the workforce, they will be expected to work with others to make decisions, solve complex problems, and generate novel ideas, and many times in contexts in which team members are not in the same physical location. The awareness of these changes has motivated interest in education and assessment industries in developing and assessing skills such as CPS. A number of recent efforts have been put forth that seek to conceptualize CPS and create assessments for CPS (e.g., Andrews et al., 2017; Hesse, F., Care, E., Buder, J., Sassenberg, K., & Griffin, 2015; Liu, von Davier, Hao, Kyllonen, & Zapata-Rivera, 2015; OECD, 2013) However, most projects operationalize different dimensions of CPS skills as discrete measures, and the connections among CPS skills are rarely considered.

Epistemic frame theory (Shaffer, 2004) suggests that communities can be characterized by not only the possession of knowledge, skills, value and practices, but more importantly the associations among these different elements and the configurations of them. For example, two communities with similar levels on their knowledge and skills, may have very different perceptions of how different dimensions of knowledge and skills are related to each other, and how these are related to values and practices. In the current study, we drew ideas from the epistemic frame theory, and focused on understanding how CPS skills are connected to each other. We constructed networks of CPS skills for individuals solving a simulation-based task collaboratively. The goal was to characterize the CPS skill networks and to compare the structural features of the networks for teams with different performance levels.

Method

Participants

Eight community college and university instructors and their corresponding engineering and electronics classes participated in the study. A total of 129 students were randomly assembled into groups of three for each class (43 teams). Of those who reported their gender (2% were unreported), 81% were males and 17% were females. Of those who reported their race (2% were unreported), 51% were White, 7% were Black or African American, 6% were Asian, 2% were American Indian or Alaska Native, 10% reported being more than one race, and 2% reported Other. For ethnicity, 22% of the sample who chose to provide demographic information reported being Hispanic. The ages of participants ranged from 16 to 60 with an average age of 24.

Task

Students were asked to complete a simulation-based task on electronics concepts called the Three-Resistor Activity (see Figure 1). Each student in a team of three worked on a separate computer that ran a simulation of a portion of an electronic circuit composed of three resistors connected to form a series circuit. Each of the three resistors was controlled by a different teammate. Each team member had the goal of reaching a specified goal voltage across their resistor. However, since each resistor was connected in series, any changes that one teammate made on their resistor value to obtain their own goal voltage would affect the current through the circuit and therefore the voltage drop across each teammates' resistor. Therefore, students needed to communicate via a chat box and coordinate their actions to reach the goal voltages across each resistor in the series. The task included four levels of increasing difficulty. In higher levels of the task, students were additionally asked to work together to determine the unknown resistance and voltage of an external, fourth resistor in the series that none of the teammates could control. As students worked together to solve the problems, all of their relevant actions and discourse (e.g., measurements, resistor changes, calculations, answer submissions, text chats) were logged to a database and used for our subsequent analyses.

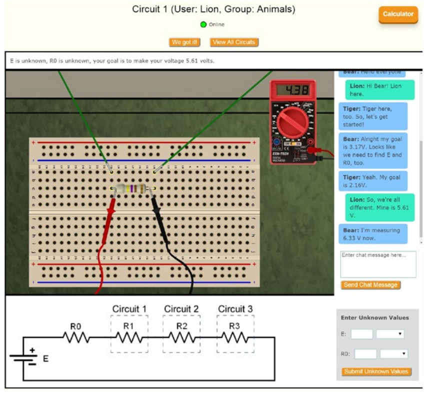

Figure 1. Screenshot of Three-Resistor Activity.

CPS ontology

A CPS ontology was developed to conceptualize the CPS construct. Ontologies are similar to concept maps and provide a theory-driven representation of targeted skills and their relationships and link them to observable behaviors in a task that would provide evidence of the skills. The CPS ontology includes nine high-level CPS skills. Four skills correspond to the social dimension of CPS (i.e., maintaining communication, sharing information, establishing shared understanding, negotiating) and five skills correspond to the cognitive dimension of CPS (i.e., exploring and understanding, representing and formulating, planning, executing, monitoring). *Maintaining communication* includes content irrelevant social communication whereas *sharing information* refers to content relevant information shared in the service of solving the problem. *Establishing shared understanding* corresponds to communication used to learn the perspective of others and ensure that what has been said was understood. *Negotiating* refers to communication used to identify conflicts in ideas among teammates and resolve conflicts that may exist. In the cognitive dimension, *exploring and understanding* corresponds to actions taken to explore the task environment and build a mental representation for components of the problem. *Representing and formulating* refers to communication used to represent the problem and formulate hypotheses. *Planning* includes communication around developing a strategy for solving the problem. *Executing* includes actions taken to carry out a plan and communication used to carry out a plan. *Monitoring* corresponds to actions and communication used to monitor progress toward a goal and monitor the organization of the team. For more in depth discussion of the CPS ontology, see Andrews-Todd and Forsyth (in press).

Qualitative coding

Two raters coded the content of students' discourse and their actions for nine CPS skills outlined in the CPS ontology. Executing and monitoring were shown in both actions and chats and were thus split into two separate action and chat skills. This created 11 total skills for the qualitative coding (i.e., *maintaining communication (SMC), sharing information (SSI), establishing shared understanding (SPT), negotiating (SN), exploring and understanding (CEU), representing and formulating (CRF), planning (CP), executing actions (CE), executing chats (CEC), monitoring actions (CM), and monitoring chats (CMC)*). Raters coded the log data at the level of each log file event, with each event receiving only one code. Inter-rater reliability between two raters was calculated on a sample of 20 percent of the data that was double coded and was found to be high (Kappa = .84). There were a total of 20,947 log file events, which were coded for the presence of one of the 11 CPS skills.

Analyses

To explore connections among the CPS skills, we built co-occurrence networks of the CPS skills. We defined each turn for an individual as a series uninterrupted chats or actions, and considered the co-occurrence of the CPS skills in each turn. For each team, we scanned the records containing events from all team members, and built the aggregated CPS skill network for the team. In these networks, the nodes represent CPS skills, the links represent the co-occurrence of the CPS skills in the turns, and link weights represent the frequencies of the co-occurrence. To characterize the constructed CPS skill networks, we used six well-adopted network measures (Newman, 2003; Wasserman & Faust, 1994). *Density* captures the number of existing links divided by the number of possible links. *Weighted density* is the sum of link weights divided by the number of possible links. *Centralization* (Freeman, 1979) captures the extent to which the number of links connected to nodes vary across all nodes in the network. Further, *Maximum Component Size* is the size of the biggest connected component in the network. *Connectedness* is the number of dyads (a set of two nodes) with existing direct connections or indirect connections through other nodes divided by the total number of dyads. Lastly, *Maximum Degree* is calculated as the maximum number of links connected to a single node.

For each team, we calculated the above measures to characterize the CPS skill networks. To compare the network measures of teams with different performance levels, we considered two measures of team performance. In the Three-Resistor Activity, each team had the opportunity to complete up to four levels. We used the number of successfully completed levels and the number of levels attempted as two separated measures of team performance. For further analysis, we dichotomized the two performance measures using the medians as the cut point to yield low and high performing subgroups. Multiple independent sample t-tests with Bonferroni correction were conducted on the network measures for subgroup comparisons.

Results

All 43 teams attempted to solve at least one level, but were not all successful. Among all teams, 20 attempted all four levels, seven attempted three levels, eight attempted two levels, and eight attempted just one level. Nine teams successfully completed all four levels, 12 completed three levels, five completed two levels, eight completed one level, and nine did not complete any levels successfully. For the dichotomization, we used the medians of 2 and 3 for the number of successful levels and the number of levels attempted, respectively. Teams with values higher than the medians were coded as high (H), and teams with values lower or equal to the medians as were coded as low (L). Examples of CPS skill networks from two teams with high and low performance are shown in Figure 2. For each network, the size of the nodes indicates the frequencies of the CPS skills presented in the team's chats and actions, and the thickness of the links indicates the frequencies of the co-occurrence of the CPS skills in turns. Visually, the high performing team network in Figure 2 (a) has not only bigger nodes but also more and thicker links than the low performing team network in Figure 2 (b).

(a) Attempted 4 levels, solved 3 (b) Attempted 1 level, solved 0

Figure 2. Example networks from a high performing team and a low performing team.

Using number of levels successfully completed, high performing teams (*$M = 854.43$, $SD = 328.56$, $N = 21$*) demonstrated higher frequencies of CPS skills than low performing teams (*$M = 369.45$, $SD = 198.47$, $N = 22$*), $t(33) = 5.83$, $p < .001$. When measured by the number of levels attempted, CPS skills frequencies of the high performing teams (*$M = 824.95$, $SD = 322.66$, $N = 20$*) were also significantly higher than low performing teams (*$M = 416.17$, $SD = 281.85$, $N = 23$*), $t(38) = 4.39$, $p < .001$. However, higher frequencies of CPS skills did not necessarily indicate more links in the network. In fact, the correlation between CPS skill frequencies and network density was 0.57. We next compared the CPS skill network statistics for the high and low performing teams using independent sample t-tests (adjusted $\alpha=.05/6=.0083$), and the results are summarized in Table 2. When using number of levels successfully completed, we found that high and low performing teams differed in most network measures except centralization. The differences in *Density*, *Weighted Density*, *Maximum Component Size*, *Connectedness* and *Maximum Degree* all showed that the CPS skill networks for the high performing teams were better connected and had more coverage than the low performing teams. The lack of significant results for centralization indicates that both high and low performing teams did not show preferences towards connecting certain CPS skills with others. Instead, the connections among the CPS skills were evenly distributed with no CPS skills more central than others. When using number of levels attempted, only weighted density was significantly different for high and low performing teams.

Table 2: Comparisons of teams with H/L performance

	By Number of Successful Levels			By Number of Levels Attempted		
	M_H (n=21)	M_L (n=22)	*t-test*	M_H (n=20)	M_L (n=23)	*t-test*
Density	0.45	0.30	$t = 3.62$, $df = 41$, $p = .0008$	0.43	0.32	$t = 2.62$, $df = 41$, $p = .012$
Weighted Density	1.64	0.79	$t = 4.59$, $df = 38$, $p < .0001$	1.58	0.87	$t = 3.57$, $df = 41$, $p = .0009$
Centralization	0.43	0.43	$t = -0.05$, $df = 40$, $p = .958$	0.44	0.42	$t = 0.61$, $df = 41$, $p = .547$
Maximum Component Size	10.10	8.77	$t = 2.95$, $df = 39$, $p = .005$	10.00	8.91	$t = 2.37$, $df = 40$, $p = .023$
Connectedness	0.85	0.65	$t = 3.18$, $df = 41$, $p = .003$	0.83	0.67	$t = 2.49$, $df = 41$, $p = .017$
Maximum Degree	7.95	6.50	$t = 2.79$, $df = 41$, $p = .008$	7.90	6.61	$t = 2.44$, $df = 41$, $p = .019$

Discussion and future directions

In this study, we constructed CPS skill networks from log data on team actions and chats during collaborative problem solving. The results showed that high and low performing teams significantly differed not only on the frequencies of the CPS skills displayed, but also on how the skills were connected with each other. This study makes contributions to the measurement of CPS skills by demonstrating a new way of assessing and understanding CPS skills: through the exploration of connections among CPS skills. For future directions, different approaches to constructing the CPS skill networks will be explored. This study used the co-occurrence of skills in the same turn, and focused on the connections of skills represented in the chat and actions of individual team members. Alternatively, the moving window approach (Siebert-Evenstone et al., 2017) captures the evidence of the connections displayed during the interactions among team members. We intend to identify the connections using this alternative approach and explore the similarities and differences of the resulting networks.

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