Conceptualization and Quantification of Thinking Sustainability in Dialogic Collaborative Problem Solving

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Abstract: Dialogic collaborative problem solving describes how students solve a problem collaboratively, mainly or wholly through academically productive talk. Peer talk could manifest the trajectory of group thinking. Existing studies intensively explored potential talk moves that could facilitate effective collaboration. Yet, very few studies explored in-depth move-taking sequences that indicated sustained group thinking trajectory. To help address this gap, the present study conceptualized thinking sustainability to characterize the co-constructiveness of individuals' thinking and quantified it as an index on the interdependence of productive talk moves taken by individuals. The study further demonstrated how thinking sustainability dynamically developed in collaborative mathematical problem solving by 30 four-person groups in primary schools. Results showed that each group engaged in productive talk for around 3.85 consecutive turns. There was no significant correlation between thinking sustainability and group outcomes. Thinking sustainability was sensitive to early exchanges in peer talk and reached a stable level quite soon. This demonstrated it as another possible fixed-point attractor underlying random-looking peer interaction systems.

Introduction

Involving students in Collaborative Problem Solving (CPS) has the potential to produce social, emotional, and cognitive gains (e.g., Blatchford, Kutnick, Baines, & Galton, 2003; Johnson & Johnson, 2016; Slavin, Lake, Hanley, & Thurston, 2014). However, such potential benefits are limited to certain kinds of well-structured peer talk (Michaels & O'Connor, 2009; Roll, Baker, Aleven, McLaren, & Koedinger, 2005). Dialogic CPS describes how students solve a problem collaboratively, mainly or wholly through academically productive talk. It has been a fruitful domain of research to identify fine-grained productive talk moves to understand peer talk and scaffold group work. Existing evidence has established the benefits of various talk moves, also detailed as questioning frames or sentence openers, in promoting productive peer interactions, such as "say more", "add on" "agree/disagree", and "press for reasoning" (e.g., Gillies, 2017; Webb et al., 2013). However, we do not fully understand whether and how students sustainably take these moves in high-quality peer talk and whether such kind of sustainability could lead to better group outcomes.

There have been some studies focusing on characterizing the sequential structure of high-quality peer talk. For example, Chi and Menekse (2015) claimed that students achieved largest amount of learning when they engaged in co-constructive talk where they elaborate, explain and build on each other's ideas. High-performing groups engaged more often in co-constructive process rather than only discursive information sharing or isolated contributions (Heo, Lim, & Kim, 2010). When students involved in exploratory talk where they interacted constructively and critically, their reasoning ability would improve (Mercer & Littleton, 2007; Wegerif et al., 1999). However, there has been no consensus on how to measure or describe the degree of co-construction of peer talk.

To address this gap, the present study aimed to propose a quantitative index, named as thinking sustainability (TS), to characterize the co-constructiveness of individuals' thinking. This index would be calculated through quantifying the degree of interdependence of productive talk moves taken by individuals in group discussions. It would further allow cross-group comparisons on the consecutiveness of group thinking trajectory. Furthermore, this study would also examine how this index differed across groups with diverse outcomes and how it dynamically developed in group discussions.

Theoretical perspectives

Language plays an essential role in CPS. It is a powerful tool supporting human intra- and inter-thinking (Vygotsky, 1978; Mercer & Littleton, 2007). Talk sequence implies an individual's underlying cognitive structure (Greeno, 2015). Academically productive talk sequences involve high-order cognitive processes. Therefore, the co-constructiveness of human thinking could be manifested by the interdependence of academically productive talk moves to some degree.

Although discourse only makes sense for at least two people (Vygotsky, 1987), an individual is still capable of producing unitary cognition through intra-thinking processes in group work, such as expressing new ideas, elaborating/justifying one's own contributions or reflecting on one's own performance. Intra-thinking involves self-regulation that refers to the planning, monitoring, control or regulation, and reflection process of individual learning (Pintrich, 2000). Inter-thinking is a social form of human thinking (Littleton & Mercer, 2013), such as elaborating/explaining/evaluating/challenging others' contributions, inviting others to elaborate/explain/speculate, or reflecting on group performance. It could appear at a dyad level shaped by co-regulation, a transitional process on how individuals appropriate self-regulated learning through interactions with supportive others (Hadwin & Oshige, 2011), or a group level adjusted by socially shared regulation which describes how multiple others regulate their collective activity to build joint understanding of the task, co-construct their goals and plans, and reach their common target (Järvelä & Hadwin, 2013).

Collective inter-thinking also interacts with individual intra-thinking through dynamic trans-level regulations, which leads to a sustainable thinking trajectory in group discussions. Humans have mirror neurons that allow them to spontaneously gain experiential insights into each other's minds and empathically imitate others (Gallese, Keysers, & Rizzolatti, 2004; Iacoboni, 2009). Empirical studies have found that individuals could *appropriate* new problem-solving strategies from their peers during exploratory talk (Littleton & Mercer, 2013) or mother's strategies when collaborating to complete a jigsaw puzzle (Wertsch & Stone, 1999). Recent studies have also focused on how students *uptaked* teacher dialogic strategies during peer discussions (van de Pol, Mercer, & Volman, 2019).

The present study adopted systems perspectives to further theoretically frame the dynamic hierarchical regulation processes detailed above (Fig. 1). Systems perspectives have gained increasing attention in research on collaborative learning to combine multi-level analysis and decompose the complexity of learning process (e.g., Borge & Mercier, 2019; Jacobson, Kapur, & Reimann, 2016; Sergis & Sampson, 2017; Taylor & Bovill, 2018). Many studies have shown that dialogic CPS has features of an adaptive complex system. For example, it has been well established that the peer interaction process is not temporally homogenous but dynamically shaped by historical and contextual factors (e.g., Kapur, Voiklis, & Kinzer, 2008; Mercer, 2008; Schegloff, 2007; Wise & Chiu, 2011). Interaction patterns affect learning outcomes in collaborative learning (Cen, Ruta, Powell, Hirsch, & Ng, 2016). Some other studies also found *attractors* in CPS systems (e.g. Kapur et al., 2008; Umaschi, 2001). *Attractor* refers to 'the value, or set of values, that a system settles toward over time' (Boeing, 2016). It includes fixed-point attractor, which leads the system to a static equilibrium state; limit cycle, which leads the system to a periodic equilibrium among a set of fixed points; and strange attractor, which makes the system oscillate forever but never repeat itself (Grebogi, Ott, & Yorke, 1987).

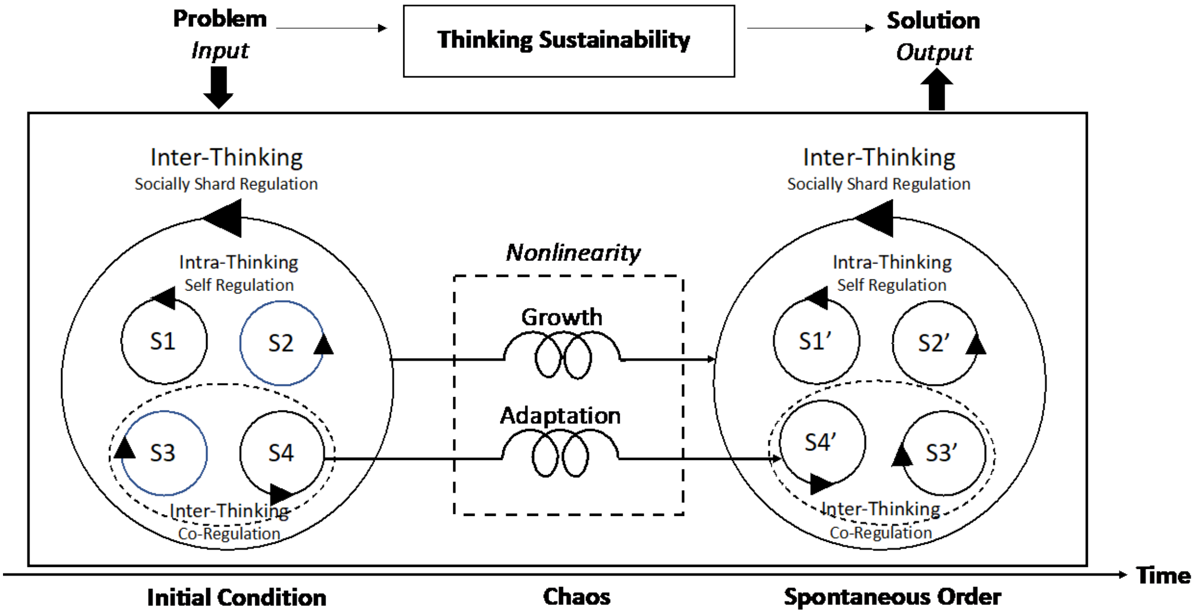

Figure 1. Theoretical framework for thinking sustainability in dialogic collaborative problem solving.

For example, in student argumentative talk, the object of discussion has been identified as a potential strange attractor. Umaschi (2001) found that the new concepts/notions constantly generated around the object of discussion increase the complexity of student discussion. In this process, arguments and counterarguments form positive and negative feedback loops and further increase the complexity of the discussion, while maintaining a similar structure. Kapur and his colleagues (Kapur & Kinzer, 2007; Kapur, Voiklis, & Kinzer, 2005; Kapur et al., 2008; Voiklis, Kapur, Kinzer, & Black, 2006) consistently found that the participation inequity and cognitive convergence of different groups solving either well-structured or ill-structured problems online rapidly reached plateaus. Participation inequity was operationalised as the standard deviation of individual participation proportions, and cognitive convergence was operationalised as the mean impact of utterances that help move the group towards its goal. Both were identified as potential (fixed-point) attractors in dialogic CPS, indicated by the early lock-in pattern (Kapur et al., 2008).

Method

Participants and materials

This study involved 30 groups of fourth-grade primary school students from five classes in two schools in mainland China. All students were grouped in four with balanced gender and prior math grades. Each group was allowed half an hour to collaboratively solve three structured open-response mathematical problems in normal class settings. The three problems had increasing item difficulties and were adapted from TIMSS2015 and the Olympiad Mathematics at the primary level. Each question had one unique answer but not an explicit routine to follow. Instead, students could propose different solutions to the task. Before the test, students independently finished questionnaires on their demographic information, self-concept in math, enjoyment of learning math and social anxiety. Self-concept and enjoyment were measured through adapted items from the questionnaire in TIMSS 2015 for the fourth graders in Taiwan. Social anxiety was measured through the 10-item Chinese version of Social Anxiety Scale for Children-Revised (SASC-R) (La Greca & Stone, 1993). Students were also required to report the degree to which they were willing to cooperate with their partners.

Data collection and analysis

Group discussion was audio taped and transcribed. Written solutions and questionnaires were also collected. Group solution was graded following particular scoring criteria and further categorized into high and low levels through comparison with the average score. Content analysis was adopted to capture productive talk moves adopted in collaborative discourse following the coding framework presented in Table 1. This coding framework was constructed through pooling up all discursive productive talk moves identified in various contexts including abstracted principles or rules like *exploratory talk* (Fisher 1993; Mercer, 1995; Mercer & Littleton, 2007; Littleton & Mercer, 2013), *argument stratagems* (Anderson et al., 2001; Clark et al., 2003), and *knowledge building talk* (van Aalst, 2009), structured and detailed questioning frames or sentence openers (e.g., Gillies, 2017; King, 2002; Lazonder et al., 2003; Teo & Daniel, 2007; Webb et al., 2013) and relatively complete repertoire of productive talk moves in dialogic teaching (Hennessy et al., 2016; Michaels & O'Connor, 2009). Two trained coders independently finished the coding of these two groups and addressed all disagreements. Group solutions were graded following a standard criteria further categorized into high and low levels through comparison with the average solution score.

Table 1: Coding framework for productive talk moves

Dimension	Code	Abbreviation	Interpretation
Intra-thinking	New Idea	S-N-I	Contribute to group knowledge such as proposing a new solution, viewpoint, suggestion, or plan.
	Self-Elaboration	S-EB	Clarify/extend one's own contributions.
	Self-Explanation	S-EP	Explain/justify one's own contributions.
	Self-Speculation	S-SP	Speculate/hypothesize/imagine different possibilities/theories based on one's own contribution or without specific reference.
	Self-Reflection	S-RF	Reflect on one's own learning process/outcome.
Inter-thinking	Invite New Idea	I-N-I	Invite one to express new opinions/ideas/knowledge.
	Invite Self-Elaboration	I-S-EB	Invite one to clarify/extend one's own contributions.
	Invite Self-Explanation	I-S-EP	Invite one to explain/justify one's own contributions.
	Invite Self-Speculation	I-S-SP	Invite one to speculate/hypothesize/imagine based on one's own contribution or without specific reference.

	Invite Self-Reflection	I-S-RF	Invite one to reflect on one's own learning process/outcome.
	Invite Co-Elaboration	I-C-EB	Invite one to clarify/extend another's or collective contributions.
	Invite Co-Explanation	I-C-EP	Invite one to justify/explain another's or collective contributions.
	Invite Co-Speculation	I-C-SP	Invite one to speculate/hypothesize/imagine based on another's or collective contributions.
	Invite Co-Reflection	I-C-RF	Invite one to reflect on collective learning process/outcome.
	Invite-Co-Revoicing	I-C-RVC	Invite one to repeat/paraphrase what another one said to ensure engagement and shared understandings.
	Invite-Co-Evaluation	I-C-EV	Invite one to judge/evaluate another's or collective contributions.
	Co-Elaboration	C-EB	Clarify/extend another's or collective contributions.
	Co-Explanation	C-EP	Explain/justify another's or collective contributions.
	Co-Speculation	C-SP	Speculate/hypothesize/imagine different possibilities/theories based on another's or collective contributions.
	Co-Reflection	C-RF	Reflect on collective learning process/outcome.
	Co-Revoicing	C-RVC	Repeat/paraphrase other's contributions to make the contributions explicit, motivate someone to think twice, or confirm whether the speaker understands correctly.
	Challenge	C-CHLG	Challenge/confront other's view/assumption/argument.
	Agree	C-AG	Agree with other's or collective contributions.
	Disagree	C-DIS	Disagree or partially disagree with other's or collective contributions.

Conceptualization of thinking sustainability

For ages, positive interdependence among group members has been emphasized for successful CPS. It refers to the connection among group members in terms of contributions, objectives, rewards, and accountability (Brush, 1998; Wang, 2009). There is an index called *mutuality* to measure the extent to which each member's contribution is reciprocal and balanced (Barron, 2000). Mutuality indicates the collective aspects of knowledge building process (Borge, Ong, & Rosé, 2018). Existing studies have investigated the mutuality of individual contributed knowledge (Joolingen & Tong, 2007). For example, mutuality can indicate the collective aspects of knowledge building process. External analytic tools like Knowledge Connection Analyzer in the Knowledge Forum has been developed to help analyze to what extent individual contributed knowledge are connected (van Aalst, Mu, & Yang, 2016). Yet, very few studies focus on the mutuality of individuals' thinking in group work, especially high-order group thinking trajectory manifested by interconnected productive move-taking sequence. Thinking sustainability (TS) proposed in this study aims to describe the extent to which productive thinking could sustain consecutively, which could be viewed as another dimension of group mutuality.

At a fine-grained time scale, productive thinking in dialogic CPS has been characterized by certain productive talk moves based on the assumption that discourse is cognition as well (Resnick et al., 1997, p.2). High-level thinking or cognitive abilities, as something humanly unique, comes from collective activities mainly the verbal and nonverbal interactions. Interpersonal communication is a social mode of thinking, not just a stimulant for individual thinking (Mercer & Littleton, 2007). In turn, individual thinking (including reasoning) is an *individualized form of interpersonal communication* (Sfard, 2015). Thus, *discourse is cognition* (Resnick et al., 1997, p.2). Disciplines are specialized form of communication (Sfard, 2015). Disciplinary knowledge represents that students have the capacity to think and communicate with others in a domain-specific way. This is different from traditional definitions of knowledge and learning which focuses on individual internal development. Rather, knowledge and learning in a discipline also represent whether students could engage in domain-specific conversations through language. Thus, student achievement in discourse is the educational goal itself (Mercer & Littleton, 2007; Sfard, 2015). As such, shaping student ways of communication equals to facilitating student individual thinking as well as disciplinary learning (Sfard, 2015).

Cognition includes multiple levels (Stahl, 2014). Collaborative discourse can reveal group cognition. From the socio-cognitive perspective, social cognition is not only about thinking about other's cognition. The mirror neural system provides a neural basis for social cognition. That is human has a mirror mechanism to get an experiential insight into other's minds (Gallese et al., 2004). Social metacognition is the extension of individual metacognition in social interactions. It can distribute metacognition responsibilities among group members. That is, people monitor and control each other's knowledge, emotions, and actions through interactions in a group. Social metacognition could mitigate challenges facing individual metacognition such as limited cognitive resources, inaccurate self-evaluations, and one-sidedness of solution strategy. Yet, social metacognition is also limited by asymmetry social status, emotional conflicts, bad communication skills, and cultural differences (Chen et al., 2012b).

As such, intra- and inter-thinking in dialogic CPS was characterized by specific talk moves involved in collaborative discourse. The flow of thinking could therefore be manifested by sequences of move-taking. It has been well-established that intense social interactions do not necessarily lead to high-quality group performance (Choi & Kang, 2010; Heo et al., 2010). Rather, the quality of interactions also matters. High-performing groups engaged more often in co-constructive process rather than only discursive information sharing or isolated contributions (Chi & Menekse, 2015; Heo et al., 2010). Therefore, thinking sustainability in the present study was featured by two aspects. One is effectiveness. It focused on productive thinking characterized by productive talk moves. The other is sustainability. It should be consecutively and functionally sustained during the process of turn-taking. That is, the present study conceptualized thinking sustainability as the extent to which individuals could consecutively and reciprocally sustained productive move-taking.

Quantify thinking sustainability

A sustained productive flow of thinking is more than providing feedback to the last speaker. It emphasizes the involvement of productive talk moves in a reciprocal way. As such, a straightforward quantification of group mutuality in thinking is the average length of turn-taking sequences that involved interconnected and reciprocal productive talk moves.

Take for example one extract of group talk in solving a mathematical problem (see Figure 2). The whole turn-taking sequence was cut into four parts based on whether it was connected by involved productive talk moves: F1 (Invite Co-Elaboration) -> F2 (Agree), F2 (Self-Elaboration), M2(Co-Elaboration) -> F2 (Invite Self-Explanation) -> M2 (Self-Explanation), and M1(Invite Self-Elaboration) ->M2 (Self-Elaboration) -> F2 (Invite Self-Elaboration) -> M2 (Self-Elaboration) -> F1 (Co-Elaboration) -> M2 (Invite Self-Elaboration) -> F1 (Self-Elaboration). Therefore, the average length of interconnected turn-taking sequence for this extract was (2+1+3+7)/4 = 3.25. That is, this group talked co-constructively for an average of 3.25 turns in this extract. The present study named such quantitative index as thinking sustainability (TS).

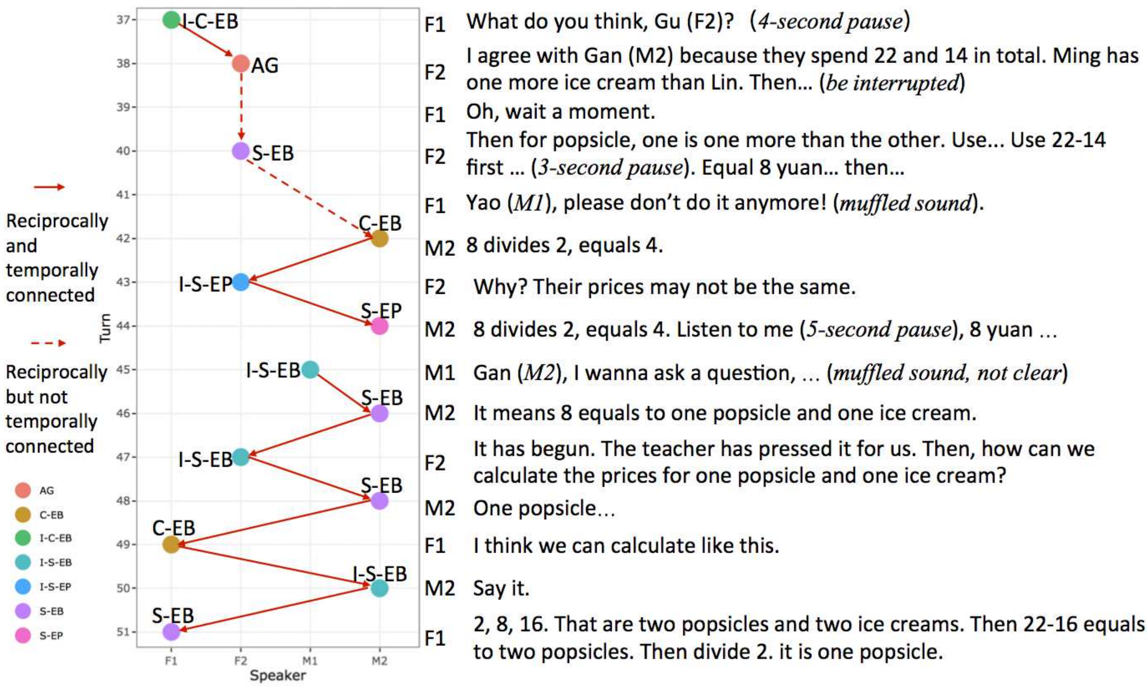

Figure 2. One extract of peer talk for the demonstration of sustained thinking.

To generalize the above calculation process, a random walk model was further adopted to mathematically simplify the impact of one turn on sustaining the flow of thinking. A turn will be denoted as *1* if it contains at least one productive talk move that is reciprocally connected with another one in the last turn. On contrary, it will be denoted as *-1* if it contains productive talk moves that are disconnected with the last turn. This happens when the current speaker overlooks the last speaker and initiates a new thinking thread. As to turns that neither sustain nor initiate the flow of thinking such as off-task talk or discursive information sharing, they will be denoted as 0. As such, the flow of thinking at turn level could be represented through an integer array. For example, the flow of thinking in Figure 1 could be expressed as (-1, 1, 0, -1, 0, -1, 1, 1, -1, 1, 1, 1, 1, 1, 1). The average length could be calculated through: [N (1) + N (-1)] / N (-1) = (9+4) / 4 = 3.25.

Thinking sustainability as an emergent group feature

Groups were further categorized into low- (n = 13, *M*= 4.95, *SD* = 1.43) and high-performing ones (n =17, *M* = 7.67, *SD* = 1.03) through compared to the average score (n = 30, *M*= 6.49, *SD* = 1.82). Results showed that thinking sustainability of these 30 groups ranged from 2.30 to 6.30 turns with an average of 3.85. There was no significant difference on thinking sustainability between high- (*M* = 4.02, SD = 1.18) and low-performing groups (*M* = 3.63, *SD* = 1.22), t (28) = 0.898, p = 0.38.

The dynamic development of a group's thinking sustainability was explored through a line graph that illustrated the cumulative thinking sustainability across time. This allows the examination whether thinking sustainability will become stable after a certain amount of discussion and thus become an emergent group feature. Results revealed that thinking sustainability of most groups vibrated a lot in the beginning but tended to reach a stable level quite soon (see Figure 3). That is, thinking sustainability is a possible stable index to characterize group discussion process across different tasks.

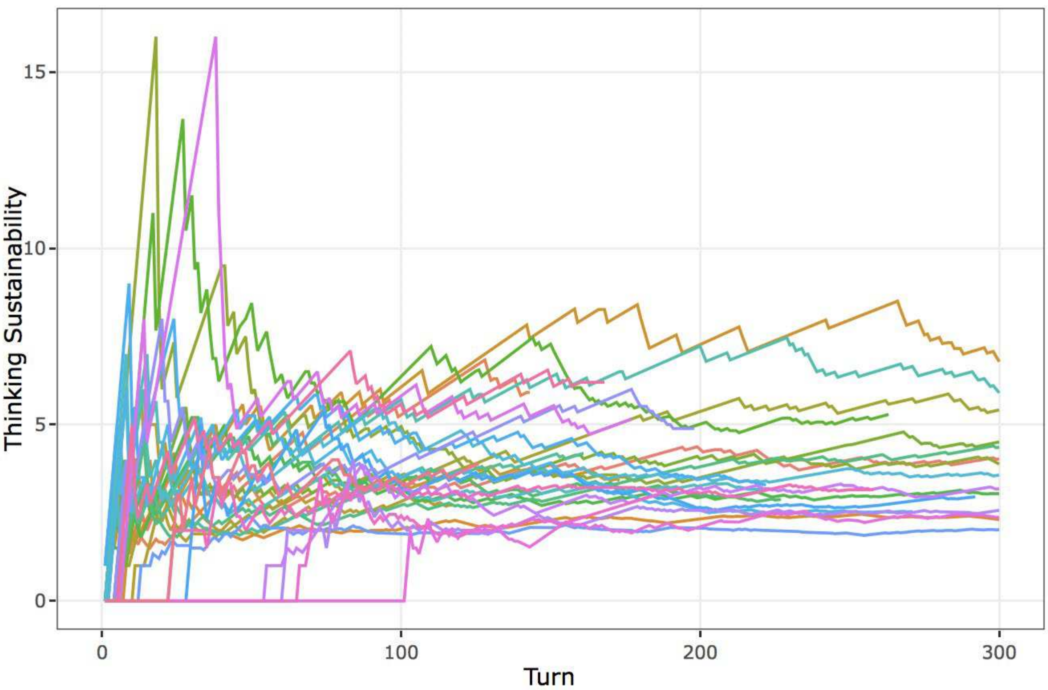

Figure 3. Development of thinking sustainability for 30 groups solving three different tasks (colors denote different groups).

The present study also found that thinking sustainability was sensitive to early-stage group discussion. This echoes Kapur et al.'s (2008) finding that participation inequality was also similarly sensitive to early exchange (around 30-40%) in group work and quality of contributions made earlier had more impact on group performance than those made later on. This demonstrated thinking sustainability as another possible fixed-point attractor of adaptive complex collaborative learning systems. Therefore, monitor and scaffold of group thinking sustainability at the early stage of discussion in quite important. It might be interesting for future research to investigate thinking sustainability across different CPS contexts such as participants of different ages, groups of different sizes, or problems of different domains, so as to identify strange attractors in CPS systems that could explain variations in thinking sustainability.

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