3.2 The Roles of Representation in Computer Supported Collaborative Learning

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Abstract: Representational learning is fundamental to CSCL. In this chapter we consider four distinct roles that representations play as collaborators can: 1) interpret existing representations to create shared knowledge; 2) construct new joint representations based upon negotiation and shared understanding; 3) make representational choices concerning how they or other agents in the collaboration are portrayed; and 4) use representations to express and analyze these activities and their outcomes. We show how this research draws upon multiple theoretical perspectives and attempt to look forward to consider where representational paradigms for CSCL may be going.

Introduction and Scope

CSCL offers many diverse ways that learners can collaborate to learn but there is one feature common to all of them – their learning will be representational. Learners may be collaborating face to face as they share photos and videos on a multi-touch table or interact with a physics simulation running on a computer in their classroom. They may be collaborating at a distance as they meet in virtual worlds, or share their views (in text, pictures or by voice) in response to a prompt in a MOOC or as they jointly construct an argument map. They may each have a phone in their hand as they play an educational game or explore a historic location, or could be jointly drawing on a shared whiteboard. They may be collaborating with people who are well known to them, unfamiliar or anonymous behind a chosen avatar or even with an artificial agent or robot. And as teachers or researchers, our understanding of what the collaborators know, how they are interacting with one another, and what they come to understand, will be shaped by representations of this activity. Thus, whether you define representation using cognitive dyadic (a representation is something that stands for something else) approach or a semiotic triadic (a representation is something which stands to somebody for something else) approach, it is clear that representation is a ubiquitous feature of CSCL. This chapter will explore the ways that different theoretical perspectives have shaped the history and development of these diverse aspects of representational learning in CSCL and articulate four key roles we see representations playing, both in terms of the current state of the art and in the how the field may develop in the future.

History and Development

We have argued (e.g., Ainsworth, 2018) that understanding representational learning within the learning sciences tradition integrates multiple theoretical perspectives. Firstly, there are cognitive perspectives of representational learning that have emerged from traditional information processing accounts of human learning. Theories such as Cognitive Theory of Multimedia Learning (Mayer, 2014) or Cognitive Load Theory (Sweller, Van Merrienboer, & Paas, 1998) shaped an understanding of how the design of representational systems can help make learning more successful by overcoming limited-capacity modality-specific memory systems, permitting learners to effectively select, organize and integrate the studied material with long-term memory. van Bruggen, Kirschner, and Jochems (2002) argue that collaborative learning with shared representations inherently increases the cognitive demands upon learners as they must negotiate a shared understanding of a representation's form and meaning. As a consequence, CSCL tools have been designed that attempt to reduce the cognitive demands of collaborative multimedia learning, such as those of Bodemer and Dehler (2011) who argue for the importance of providing awareness of other learners' representational integration practices. However, a similar argument has been proffered in exactly the opposite direction: that as certain representations such as animations are notorious for encouraging passive and superficial processing, the increased cognitive demands of collaboration around representations is to be welcomed (e.g., Rebetez, Bétrancourt, Sangin, & Dillenbourg, 2010).

Although such information processing approaches have had a considerable impact on approaches to individualized representational learning, they have not gained as much traction in CSCL (van Bruggen et al., 2002). Instead, the predominant cognitive approaches used to explain representational learning in CSCL are those which have emerged from situated (e.g., Hall, 1996) and distributed cognition (e.g., Zhang & Norman, 1994; Hutchins, 1995). For example, Hall (1996) argues that people do not simply "have" representations, but they are instead constructed through interaction with one another in time and space. Consequently, learning should be about becoming a competent representer within a domain of practice. Hutchins's account of the role of representation within a distributed cognitive approach sees both internal and external representations as part of the wider cognitive system, which includes individuals and artifacts through with and with which they interact. These cognitive paradigms, which place the emphasis on the situation and the social, are clearly much more closely aligned to the socio-cultural accounts of representational learning that have played such an important role in our understanding of CSCL. In such approaches, representation is key: learning is seen as a process of taking up the physical or representational tools and the on-going practices of a culture (e.g., Vygotsky, 1978; Säljö, 1999). The learning of representational forms depends upon the use to which they are put; representations are not passively acquired in some context-free way but instead through action (in the world) to perform some culturally valued activity. Moreover, this learning is inherently social as (external) representations are shared, negotiated, developed and redeveloped across a community, often across extended periods of time. Thus, for those researchers who follow this tradition, CSCL does not just *involve* joint meaning-making mediated through digital representation, this *defines* CSCL (e.g., see Koschmann, 2002).

Given the central importance of representational learning within CSCL, and the breadth of theoretical perspectives that underpin it, it is not surprising that there are so many examples of innovation within the field. To provide a structure and synthesize the state of the art in this complex endeavor, we suggest a simple taxonomy of four key functional roles that representation can play in CSCL. In doing so, we are indebted to previous researchers who have previously articulated similar approaches, particularly Daniel Suthers (e.g., Suthers, 2006; Suthers & Hundhausen, 2003) whose specific arguments are included in the sections below). In so doing, we will draw from cognitive and socio-cultural perspectives as each of the roles we describe has been explored through both these lenses. Consequently, we suggest that CSCL can involve:

1. Interpreting existing shared representations to guide collaboration and create shared knowledge;
2. Jointly constructing representations to negotiate and express new understandings;
3. Making representational choices to portray oneself or other human and artificial agents in the collaboration;
4. Using representations to express and analyze collaborative activities and their outcomes.

State of the Art

a. Interpreting existing shared representations to guide collaboration and create shared knowledge

In many instances of CSCL, learners are provided with computational representations to interpret that are intended to support their learning. These may take the form of non-interactive representations such as text, pictures, video or (classical) animations that are used to display an expert view of a domain but equally common are the interactive representations such as tables, graphs and equations found in simulations and microworlds. As Suthers (2014) argues, inherent to this activity is an epistemology of learning that focuses on knowledge communication, whereby learners are expected to develop their understanding in a specific direction to increasingly resemble that of the more expert other. When used in this way, representations are intended to constrain the interpretations that can be made of phenomena, whilst making salient specific aspects of a situation for *cognitive*, *affective* and *social* processing. However, as we are concerned with collaborative learning, below we focus on the roles that representations play in specific reference to social processes.

Firstly, learners can refer to the same (set of) representations as they collaborate. Much analysis of collaboration has focussed on the way that collaborators develop shared knowledge via the construction of common ground (Clark & Wilkes-Gibbs, 1986). In collocated CSCL, this process of grounding may be assisted by the learners' shared environment, history and interactions, however, in distant and asynchronous CSCL there may be no such commonalities to draw upon (e.g., Baker, Hansen, Joiner, & Traum, 1999). Grounding is neither effortless nor automatic and collaborators need frequent feedback from one another to know when they have been understood and to engage in repairs when not. Existing research suggests that representations provided in CSCL play a fundamental role in the process. Roschelle & Teasley's (1995) classic analysis of collaborators learning about velocity and acceleration with the Envisioning Machine shows how the interactive representations supported learners to develop their joint understanding of the problems through communication, action, and gesture. For example, the representations supported communication even when the verbalizations between the pairs were less than coherent or fragmented. Collaborators could point or gesture to shared external representations (such as dots left by a moving object to represent speed) as part of their explanations. Accordingly, even if collaborators lacked a technical or shared terminology, the representation helped disambiguate their references. Moreover, in this case as the representations were interactive and runnable, different interpretations and ideas need not only be resolved through argumentation and discussion, actions could be run and a new shared interpretation of the changes in the representations created.

Such advantages are not only limited to traditional computer-based learning but may perhaps be even more apparent when learners collaborate around horizontal screens such as multi-touch tables (Rogers & Lindley, 2004). For example, Higgins, Mercier, Burd, and Joyce-Gibbons (2012) analyzed small groups of children undertaking an investigation into a historical accident using representational resources presented on a multi-touch table. Compared to pen and paper, they found that the multi-touch implementation supported joint attention and shared viewing. Representations must be “left” on the table and not picked up and studied by a single individual. Moreover, by resizing, moving and reorganizing these representations, not only was joint attention facilitated, but the history of joint decision making and ultimate consensus on an interpretation could be displayed and shared.

Secondly, learners can refer to different (sets of) representations as they collaborate. Much existing research has detailed the challenges that learners can have in coming to understand and then reason through new representations (for example, see Ainsworth (2018) for a review and other readings). Therefore, CSCL environments can be designed to manage these difficulties by providing specific representations to different collaborators, and so limit the number of representations that an individual must focus (and thus come to understand) on at any one time. The advantages of this can be seen in the analysis that White and Pea (2011) conducted of students learning about algebra using CodeBreaker, a system that provides dyna-linked representations (equations, graphs, two types of tables) to collaborators in a group. Each participant had their own tablet, which permitted the display of only one or two of the representations at once but the group as a whole could see the actions from the equation representation reflect on the complete set. Over an extended period of time, students became successful problem-solvers and coordinators of these representations as their understanding developed. This was often achieved in ways that had not been fully intended by the designers but that emerged as a consequence of relating, communicating, and coordinating representations to solve local tasks. In this case, the representations were “flexibly assigned”, i.e., each member was given responsibility for a specific representation (although could move to others if they choose) and this assignment was changed daily. However, in Ploetzner, Fehse, Kneser, and Spada (1999), concept maps of **either** quantitative representations (in equation form) or qualitative representations (in diagrams and words) were provided to each member of a dyad who worked first individually before coming together with both representations to jointly solve the same problems. Thus, the collaborative phase could benefit from the understandings that each individual in the dyad had built up first. Their evidence suggests that this did happen, especially when in the joint phase the initial construction of qualitative representations was privileged before subsequent integration of quantitative reasoning.

Of course, simply providing representations to collaborators will not magically result in enhanced learning. All of the research reviewed in this section discussed instances when learners struggled with the system. They revealed learners failing to understand the representations, not actively engaging with the cognitive, affective or social processing that was needed, or perhaps the representations themselves had not been well chosen by designers. However, a commonly noted feature of success was when collaborators, either collocated as the examples above or distant (e.g., Suthers, Girardeau, & Hundhausen, 2003) used the representations to negotiate shared meaning. Moreover, this was not a swift process with collaborators needing extended participation for this to be achieved. Teachers (if CSCL activities are occurring in classrooms) can be crucial, stepping in to help collaborators make sense of the representations and their role in the activities (e.g., Ingulfsen, Furberg, & Strømme, 2018). A final point worth remembering is that interpretation of presented representations is still a constructive process and that as we now turn our attention to collaborative construction, learners in CSCL systems often cycle through activities which depend more upon the interpretation of representation and then to construction or vice versa.

b. Collaborating by jointly constructing representations

The joint construction of representations is our second example of the use of representations in collaborative learning. In contrast to sharing existing, pre-constructed representations for further interpretation, the learners in this context are asked to construct the representations themselves and together with their peers. These may be any kind of diagrammatic representations (like for example, algorithmic flowcharts or concept maps), textual representations (such as written essays) or even tangible and digital artifacts (such as collages and videos).

The joint construction (or else, co-construction) of shared representations entails all the benefits of working over shared representations: developing shared knowledge and constructing common ground, developing joint understanding and so on. Furthermore, the actual task of constructing the representation requires the learners to externalize their knowledge or to elicit knowledge from their peers (Fischer & Mandl, 2005). While constructing a shared representation, learners' knowledge transitions from tacit (that is, internalized knowledge, difficult to communicate to peers verbally) to explicit (a formal, concrete piece of knowledge that the learner can communicate to peers). At the same time, co-constructing a shared representation can support reflection through internalization (Nonaka & Takeuchi, 1995). Whilst working together with others towards a common goal, the learner is exposed to new ideas or new knowledge coming from peers. This new knowledge is further crystallized and becomes one's own when the learner reflects on collaborative practice. Additionally, the collaborators need to evaluate each other's contribution to the shared construct, to use arguments in order to convince their peers and to critically reflect on their practices. Most importantly, peers have to coordinate, to create a common plan of action and to manage their common resources in order to work together constructively and efficiently (Meier, Spada, & Rummel, 2007). There are many key ingredients for creating a meaningful representation. These include successful communication between the members of the group (e.g., maintaining communication flow and coordinating verbal discussion with workspace activity), effective exchange of information (providing explanations for their actions or intentions to their peers) and the creation of a coherent, efficient and agreed plan for the development of the final outcome (defining roles, subtasks and assigning resources to each group member according to the group's needs and the members' abilities).

An example of collaboration between learners over the joint construction of representations is the case of argumentation diagraming. Figure 1 presents a collaboratively-constructed argument diagram that was developed using the online argumentation environment LASAD (Chounta, McLaren, & Harrell, 2017). The joint construction of visual representations may have a positive effect on important cognitive skills, such as critical thinking and argumentation (Harrell & Wetzel, 2013) and can scaffold the co-construction of knowledge (Weinberger, Stegmann, & Fischer, 2010). The use of diagrams for practicing argumentation supports reflection and deep learning because arguments are explicit, inspectable and accessible on every moment. Thus, learners are given the chance to interact over the diagrams, to discuss over arguments' explanations and to exchange information rather than simply reading a text. At the same time, learners can visually inspect the various structures of arguments and also envision structural criteria for assessing their quality (Scheuer, McLaren, Weinberger, & Niebuhr, 2014). For example, van Amelsvoort & Schilperoord (2018) explored how the visual and perceptual cues of diagrams, such as for example the number of arguments, the size of diagrams or even the layout may affect learner's perception and judgments. Their research suggested that learners use both content and perceptual cues to interpret argument diagrams and that the number of arguments had a positive effect on perceived quality. That is, learners tend to assess a diagram that consists of more arguments as of better quality.

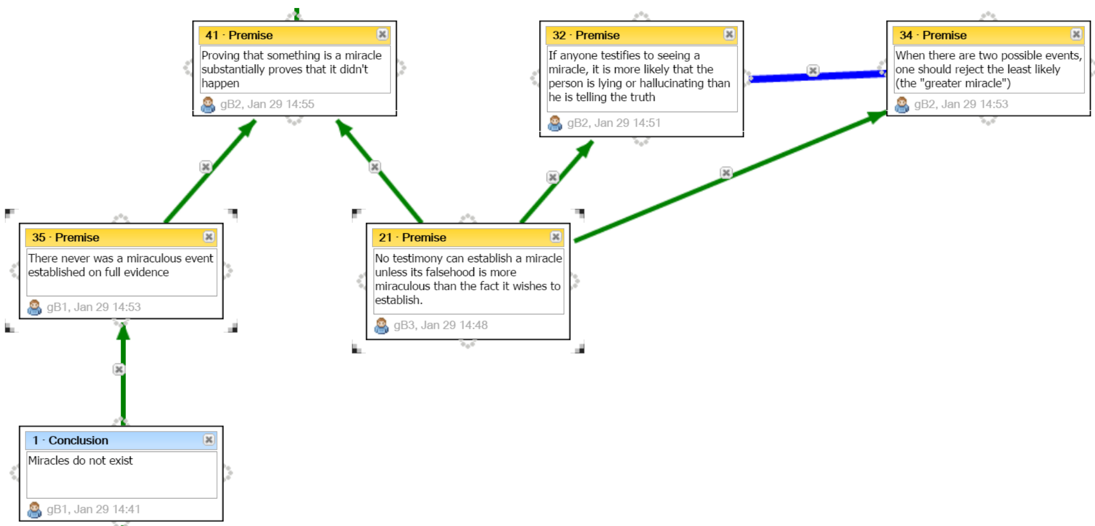

Fig. 1 An example of a collaborative-constructed argument diagram from the online argumentation environment LASAD (Chounta, McLaren, & Harrell, 2017) Students insert premises and conclusions in the collaborative workspace and they link them in order to form the argument.

The co-construction of representations as collaborative activities can be used to bridge potential gaps between students in heterogeneous groups and to support their practice. Manske, Hecking, Hoppe, Chounta, and Werneburg (2015) asked small groups of students to work together in order to create collaborative concept maps and jointly written reports during an inquiry-based, STEM course for K-12 education. The results showed that heterogeneous groups outperform homogeneous groups with respect to learning gains as well as the quality of the co-constructed representations. Chen, Wang, Kirschner, and Tsai (2018) conducted a meta-analysis to synthesize research findings of the effects of CSCL and studied the effects of visual representation tools on task performance and learning outcomes. The meta-analysis indicates that students who construct visual representations perform better (that is, they are more likely to complete a task successfully) than those who don't have access to such tools. Additionally, the use of virtual environments for constructing visual representations leads to improved learning outcomes.

Overall, these findings suggest that the co-construction of representations can be used to successfully scaffold the collaborative practice of student groups with respect to academic achievement; although, of course, success will be conditional upon similar factors to those articulated earlier. At the same time, the products of such collaborative work (that is, the final representations) can be used to assess learning outcomes as evidence of the learning process.

c. Using representations to portray oneself or other agents in the collaboration

A key role for representation in CSCL is to represent oneself or one's collaborator(s) digitally. When learners are engaged in face-to-face collaboration, their choices about how they appear to others are more limited by physical co-presence. They may change their clothing, accent or manner, but digital collaboration affords even greater possibilities.

On the one hand, collaborators may be anonymized online when they deliberately remove clues to their identity. This is somewhat notoriously associated with negative uses of digital technology whereby people may become disinhibited, do not fear reprisal for negative behavior and so can engage in "flaming", "trolling" and off-task behavior with impunity (e.g., Christopherson, 2007). However, anonymity can also have positive aspects. It can encourage people to participate without fear of judgment, reduce the noted tendency for groupthink (where poor choices are made as group members prize conformity) as ideas are evaluated more critically and consequently can lead to better decisions being considered (Nunamaker Jr, Briggs, Mittleman, Vogel, & Pierre, 1996). Current theoretical explanations, therefore, suggest that the effects of anonymity are nuanced, involving both depersonalization and reduced accountability and that people can take strategic advantage of this (e.g., see the Social Identity model of Deindividuation Effects; Lea & Spears, 1991).

Ainsworth et al. (2011) attempted to gain the possible benefits of anonymity in educational situations by asking students anonymous to one another (but known to a teacher) to participate in classroom debates about controversial issues. They found that when afforded anonymity in this way, teenage students were more likely to engage in classroom debate and change their position about these topics. Initially, this did come with an associated degree of off-task behavior, however, positively this behavior rapidly reduced and was no greater than in known situations after less than two hours of argumentation. They speculate that this type of anonymity encouraged students to debate with one another without worrying about the consequences to their social relationships when expressing unpopular views but still were aware of the need to engage productively in the activity.

Technologies such as immersive virtual worlds (e.g., Second Life) can afford people the opportunity to create rich identities online and choose avatars that represent themselves in ways that they would like to be perceived. In so doing, it is argued that collaborators can more easily replace (or even amplify) the non-verbal cues that supporting developing understanding in face to face collaboration such as facial expressions, gestures and even posture (e.g., Bailenson, Yee, Merget, & Schroeder, 2006). Collaborators can represent themselves online in ways that differ to their offline identity and in so doing explore different aspects of their possible selves (Turkle, 2005). They could, for instance, choose to vary their gender, ethnicity, physical appearance or age. For example, Lee and Hoadley (2007) explored how students' experience of the virtual world can foster motivation and engagement in learning. For example, students can adopt different points of view associated with the avatar they are inhabiting, opening them up to new perspectives and challenging them to think in new ways. Alternatively, if students are assigned these new identities to inhabit, they can experience the digital world and their body within it in new ways as reactions to avatars seems to mirror those found outside virtual worlds. For example, female avatars receive different treatment to male avatars, and black avatars invoke more aggressive responses (Lee & Hoadley, 2007). This may be one of the reasons why Peck, Seinfeld, Aglioti, and Slater (2013) found that white female participants who were assigned avatar with a black skin color showed reduced implicit racial bias after this experience. Additionally, inhabiting avatars may not just change how others react to us, but change how we react to others. This can be seen in the work of Yee and Bailenson (2007) who found that participants assigned taller avatars negotiated more confidently than those assigned shorter avatars.

Of course, when collaborating online, the “person” one is collaborating with need not be human. Consequently, there has been extensive research where artificial pedagogical agents act as expert teachers, motivational coaches, and peers (e.g,. Johnson, Rickel, & Lester, 2000). The basic premise is that by encouraging anthropomorphization through representing the computer as human-like enhances students' motivation to learn (e.g., Baylor & Kim, 2005). Moreover, designers of such environments must make a number of representational choices as they create avatars to represent artificial collaborators, including their degree of realism, ethnicity, and gender. Unsurprisingly, given the research reviewed on avatars above, such representational choices can impact upon learners’ motivation, engagement and learning outcomes (e.g., Baylor & Ryu, 2003, Domagk, 2010).

d. Using representations to analyze collaborative activities and their outcomes.

A critical aspect that differentiates collaborative learning through the joint construction of representations from learning together with peers by interpreting or discussing over shared representations is that the representation itself is the tangible outcome of the collaborative learning activity. As such, the representation is the end product of the learning process and it can be used to analyze the way peers worked together and to assess learning outcomes (Hoppe, 2009). Thus, representations, in addition to enabling and facilitating learning, play a key role in the analysis of collaborative activities. On one hand, analytical representations can be used to inform research with respect to the mechanics of collaboration and aspects of the collaborative process, such as communication flow and user activity and interaction. On the other hand, they can support learners to self-regulate and reflect. The use of representations as analytical tools for both researchers (in order to shed light on aspects of collaboration and learning) and students (for supporting self-reflection, self-regulation or other aspects of collaborative learning) is discussed extensively in Wise, Knight, and Buckingham Shum (2020) and in Rosé and Dimitriadis (2020).

As analytical tools, representations can take many forms. They may be graphs (networks) that represent the interactions between students or students with teachers, or state diagrams that represent sequences of student activity while carrying out a task, or other graphical representations (such as bar charts, time-series, or contingency graphs) that depict students' activity and interaction. When used this way, the representations aim both to uncover the underlying mechanisms of collaboration and group dynamics and then display these, potentially along with their impact on students' learning outcomes. The use of visual representations as analytical tools has two advantages: a) they can be easily constructed from data captured in log-files; and b) they are typically straightforward to understand, especially for users who are not familiar with data or statistical analysis.

An example of this can be seen in the work of Bannert, Reimann, and Sonnenberg (2014) who used Petri nets - that is, directed graphs that represent transitions or states and the sequential or conditional relation between them - to represent learning processes and so analyze learners self-regulation mechanisms. To that end, the authors coded learning events and used them to compose event sequences that represented regulatory processes. Then they explored how process patterns would differentiate between activities of successful and less successful students. Contingency graphs are another type of graphical representation that is used to represent and analyze interactions between students, even across multiple media (Suthers, Dwyer, Medina, & Vatrapu, 2010). Contingency graphs are different from social networks because the relations between events represent *uptakes*, that is, ongoing events have taken into account or are based upon aspects of prior activity. Soller, Martínez, Jermann, and Muehlenbrock (2005) utilized representations to graphically reproduce the collaborative process by using metrics of student activity and interaction. These representations were then used to scaffold students' self-reflection, to facilitate monitoring and to support real-time guiding.

Another recent example of using representations for the purpose of analysis and assessment is the use of directed graphs to detect and depict communication patterns and knowledge flow in discussion forums, especially in the case of MOOCs (Gillani, Yasseri, Eynon, & Hjorth, 2014). The social relations between participants are represented by social networks, in combination with content analysis, and provide the means for detecting subcommunities and potentially triggering supportive interventions (Yang, Wen, Kumar, Xing, & Rose, 2014). Networks are also used as representations of information exchange in discussion forums in order to provide insights about the ways MOOC participants adapt their communication strategies in a social context and adopt specific semantic roles driven by these strategies (Hecking, Chounta, & Hoppe, 2017). However, social networks have been used in collaborative learning as analytical tools before the advent of MOOCs, for example, to explore community formation based on semantic interest (Malzahn, Harrer, & Zeini, 2007).

Future

Extensive research over the past years has established the potential of shared representations in scaffolding co-construction of knowledge and supporting peers to establish common ground. Peers interact with each other over the shared representation which enables argumentation, supports decision making and scaffolds the externalization and internalization of knowledge that peers communicate.

However, sometimes it seems that the transition from theory to practice - that is, the application of collaborative representational paradigms in actual classrooms - has faltered. Several methodological and context-related factors have contributed to this, from the way we implement research studies to the practices of teachers and the school environments. Methodologically, much collaborative learning research involves only small-scale and short-term studies. It is argued that most studies involve small numbers of participants who work together over only short periods of time (Chen et al., 2018). Thus, small-scale studies may impact upon the accuracy of our conclusions or simply and lead to inconclusive results. Furthermore, the small number of longitudinal studies limits our understanding regarding the long-last impact and potential benefits of shared representations. Such studies may have accidentally focussed on *learning a representational system* rather than *learning with a representational system*. This can hinder the implementation and integration into real-world situations of collaborative paradigms that employ representations with large numbers of collaborators and over longer periods of time. Future work that addresses this gap is now needed. Another criticism that has been leveled at existing research is the way we design learning tasks. For example, Kirschner, Paas, and Kirschner (2011) argued that to take full advantage of the benefits of shared representations, it is important that we design learning tasks that are inherently collaborative - that is, peers need to work together in order to carry them out successfully - and that can be facilitated by active engagement with representations. It is critical for the successful outcome of the activity, including but not limited to learning gains, that the task will engage peers to interact with representations in an intuitive and meaningful way.

These points impact the way we integrate the use of shared representations in formal learning settings. Teachers, who are primarily responsible for designing and implementing learning activities in the classroom, usually follow guidelines that focus on content and frequently use textbooks as the primary source of learning materials. However, the representations commonly used in textbooks are aimed at individual learning and not collaborative practices. Asking teachers to design engaging and cognitively challenging collaborative tasks requires them to acquire new skills and to establish new work practices. This can either discourage teachers from adopting shared-representations in their classrooms due to additional workload or may not lead to the desired outcomes due to ineffective design and adaptation. We agree with Eiliam (2012) that we need more research concerning how to help teachers to support collaborative learning with representations and acknowledge in our research that such support is often provided and required in practice. Additionally, it is also crucial to conduct fine-grained studies of how learners understand, interpreting and construct representations in order to decide how to use representations (how many, what kinds, to what extent) to support collaborative learning. For example, using multiple representations does not necessarily mean that the students will achieve higher learning gains. Instead, this depends on the properties of the representations, their interdependence or inter-connection and on the ways that learners understand them (Ainsworth, 2014). This is acknowledged as complicated in individual learning, collaborative learning does not make these questions any easier. Thus, one prominent question is clear: how do we overcome this impasse and where do we go from here?

Stahl (2018) argues that now is the time to advance the CSCL vision to extend content to cover the needs of 21st-century learning. Motivated by Stahl's view, we envision the use of representations as a proxy for "21st-century skills". The current technological advances, the easy access to information and knowledge resources and the digitalization of education and everyday life come with the risk of personal overload and potential uncertainty regarding information reliability and privacy protection. Thus, it is important to foster the cognitive, meta-cognitive and social skills that are necessary for acting autonomously and responsibly in the new information society (Taylor, 2016). We believe that important competencies - such as critical thinking, creativity and problem-solving - can be promoted with the use of representations as learning objects, in a similar way as collaboration and construction of shared knowledge. In order to make this transition, we think of representations as something more than shared digital artifacts (usually graphical or diagrammatic objects). For example, representations can be tangible artifacts that serve as outcomes of a creative process (such as the products of makerspaces) or digital models that document the learning practice of digital competences (like, digital e-portfolios). In this sense, representations are the products of a project-based learning experience of 21st-century learners who come together to practice in a social arena using modern tools.

In the same vein, the integration of cutting-edge, digital technologies in education - ranging from commercial products like Kinect or Oculus Rift to experimental prototypes including data gloves or embodied virtual agents - allows the implementation of virtual or augmented reality-enhanced activities for training motor skills, fostering storytelling or supporting learning in science education with realistic experiences. It is interesting to see how these new technologies will affect representations in terms of format, form, and role but also how they will affect the way collaborators (some of whom may be artificial) interact and achieve common ground through and with representations. We envision that digital technologies will more routinely transform representations to tangible objects or even to whole-body interactive experiences (Price, Sakr, & Jewitt, 2016) that, on the one hand, will be customizable, personalized and dynamically adaptable to serve the learner's needs and on the other hand will evolve to resembling embodied approaches interacting with one another.

What is clear from this short review is that the future offers an increasing wealth of representational possibilities for CSCL and that the centrality of representation for the field of CSCL is not changing anytime soon.

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Additional Reading

- Christopherson, K. M. (2007). The positive and negative implications of anonymity in Internet social interactions: "On the Internet, Nobody Knows You're a Dog". *Computers in Human Behavior*, *23*(6), 3038-3056.

  This article discusses the aspect of anonymity and social behaviors' expression in computer-mediated communication.

- Roschelle, J., & Teasley, S. D. (1995). The construction of shared knowledge in collaborative problem solving. In: O'Malley C. (eds) Computer Supported Collaborative Learning, (pp. 69-97). Springer, Berlin, Heidelberg.

  This paper explores the mechanics behind the construction of shared knowledge in collaborative problem solving through the observation and analysis of social and learning processes that occurred while a group of two worked together to solve a Physics task using a computer-based environment. The objective was to understand how common ground was established, how shared knowledge was constructed and how technology - that is, computers - can be used to further support collaborative learning.

- Soller, A., Martínez, A., Jermann, P., & Muehlenbrock, M. (2005). From mirroring to guiding: A review of state of the art technology for supporting collaborative learning. International Journal of Artificial Intelligence in Education, 15(4), 261-290

  This paper reviews related research and discusses how representations can be used to provide feedback, to guide and to enable reflection for students who are engaged in collaborative learning activities

- Suthers, D. D., Dwyer, N., Medina, R., & Vatrapu, R. (2010). A framework for conceptualizing, representing, and analyzing distributed interaction. *International Journal of Computer-Supported Collaborative Learning*, *5*(1), 5-42.

  This work studies the use of graph-based representations of joint activities to depict contingency and uptake relations. Such graphs can be used to inform with respect to the user interaction and sequential patterns in user behavior and to provide insight with respect to the quality of collaboration.

- White, T., & Pea, R. (2011). Distributed by design: On the promises and pitfalls of collaborative learning with multiple representations. *Journal of the Learning Sciences*, *20*(3), 489-547.

  This article studies the use of multiple representations to engaging students in mathematical reasoning and communication, the challenges that may arise when students are asked to understand and interpret multiple representations and how to address these challenges.

------- Additional Instructions ------

Four common top-level headers (heading 1)

To provide a coherent experience for readers, we ask you to organize your writing using four common top-level headers (Introduction & Scope, History & Development, State of the Art, The Future). Each can be customized with text of your choosing after a colon (e.g., "*Definitions & Scope: The Multiple Meanings of Context*").

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