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ORIGINAL RESEARCH

Developing a smart classroom infrastructure to support real-time student collaboration and inquiry: a 4-year design study

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Abstract
K-12 classroom settings are not yet incorporating emerging technologies such as ubiquitous computing, augmented reality, nor even touch surfaces, despite the significant impact that such media have made in many other aspects of our lives. Unfortunately, classroom environments have not generally evolved to support students in the new modes of collaboration, idea sharing, and inquiry that characterize many of our research-based innovations. Responding to this challenge, our research was conducted by a multi-disciplinary design team including educational researchers, a high school physics teacher, and technology designers. We embarked on a series of design-based research projects to investigate a smart classroom infrastructure that scaffolds students and teachers in new forms of collaboration and inquiry, including a substantive role for large projected displays and small touch surfaces, as well as a dependency on students' physical location within the room. This paper describes our designs, including: (1) the role of large displays for communicating aggregate and ambient information, (2) the role of real-time communication between students, (3) the application of intelligent software agents to enact real-time pedagogical logic, (4) support for learning across contexts, and (5) orchestration of inquiry roles, materials and environments. These designs are particularly relevant for the Learning Sciences community, as they offer insight into how the orchestrated classroom can support new forms of collaborative, cooperative and collective inquiry. One important outcome of this work is a set of design principles for supporting smart classroom research.

Keywords Smart classrooms · Computer supported collaborative learning · Distributed intelligence · Future learning spaces · Learning communities · Design-based research · Technology enhanced learning environments

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Introduction

As we move out of the industrial age and into the knowledge age, researchers and policy makers are advocating for students to learn a broad set of skills, often referred to as "21st century skills," such as collaboration, critical thinking, design, and evidence-based reasoning (National Science Teachers Association, NSTA 2011; Partnership for 21st Century Skills, P21 2009; National Research Council, NRC 2010). However, traditional classroom learning spaces are ill-suited to the task demands of such curriculum, locked in configurations and linked to practices that descended from the industrial era (Facer 2014; Dovey and Fisher 2014; Makitalo-Siegl et al. 2010). Indeed, current classroom and technology configurations can actually restrict the free-flow of participants, information, and ideas that are critical for students to engage in more active, collaborative and creative forms of learning (Lipponen 2002).

If educators wish to engage students in the kinds of collaborative and inquiry-based practices that characterize this twenty first century knowledge society, we must reconsider the physical environment of the classroom as something more than a neutral lecture room. The ways in which we design our learning spaces and the ways in which students interact with peers, tools and information within these spaces will directly influence the kinds of learning interactions that occur. Scardamalia and Bereiter (2006) have argued that learning environments should be crafted to reflect their underlying pedagogical and epistemic goals. We extend this notion to guide our design of a smart classroom environment and corresponding inquiry curriculum.

Smart classrooms for inquiry

Many researchers have advocated for the design and implementation of smart classroom spaces in which the walls, floor, ceiling, and furniture all become mediators of students' inquiry, such that students' locations within the environment can mediate who they collaborate with and the materials they work on (Makitalo-Siegl et al. 2010). The design of smart classrooms requires us to understand an informational second space which is layered on top of, within, and between the fabric of traditional physical space (Graham 1998), and to leverage the spatial affordances of the classroom to make this second space accessible and meaningful for users.

Within a smart classroom, students are not simply browsing information passively, but are also creating, attaching, connecting, and taking data with them from one location to another, and from one group to the next (Rekimoto et al. 1998; Simon et al. 2003). By leveraging the physical space as a means for selectively displaying elements of a community's knowledge we can reduce information overload by only providing the information that is contextually relevant to learners in specific locations in the room (Oh and Woo 2009). Instrumenting the physical learning space with rich and interactive technologies, such as tablets, interactive whiteboards and tabletops, and RFID sensors, can transform the ways learners experience these spaces and their sense of presence both individually and in groups (Ciolfi 2004).

McCarthy et al. (2004) used RFIDs embedded in conference badges to display the names and interests of nearby attendees on large-format displays to promote interactions and conversations. In *RoomQuake* (Moher et al. 2005), seismic activity was simulated by mapping it to the spatial layout of the classroom. In order to figure out where a fault line ran across the classroom, students needed to use a combination of handheld computers (placed at specific locations around the room), measuring tapes, and Styrofoam balls to triangulate the epicenter of quakes. In *RoomQuake*, the physical layout of the room was a major driver of the inquiry processes, as a group's location in the room directly determined the information provided on their mobile computers, and required them to collaborate with other spatially distributed groups in order to solve the task.

Knowledge communities and inquiry

As the daily practices of individuals in workplaces become increasingly data-driven and collaborative (Gray and Szalay 2007), scholars have begun to explore the notion of a learning community approach to classroom instruction (Resta and Laferriere 2007; Slotta and Najafi 2013). Learning communities represent a shift away from didactic methods of traditional classrooms, focusing instead on approaches that engage students deeply in collaboration and reflection, with an emphasis on community resources and idea progression (Slotta and Najafi 2013). In general, such approaches advocate for various forms of inquiry-oriented activities (Bybee 2004; Kuhn et al. 2000; Marx et al. 2004; Slotta and Linn 2009), where students engage in autonomous investigations of personally relevant questions. To support inquiry learning, students are scaffolded by various forms of technology-enhanced environments (Linn and Eylon 2011), and the teacher also benefits from scaffolds including authoring and configuration tools (Slotta and Linn 2009), classroom management tools, and real-time feedback and assessment environments. In learning communities, students engage in independent and inquiry projects, focused on topics of consequence to their community (Brown and Campione 1996) or real-world problems (Hakkarainen 2003), gaining content knowledge, inquiry skills, and epistemic perspectives (Bielaczyc and Collins 1999; Hoadley and Pea 2002).

However, the learning community approach has not seen wide uptake by researchers or practitioners, in part because of the need for teachers to significantly change their approach to teaching and instruction (Anderson 2002; Slotta and Peters 2008). In order to address the pedagogical challenges of the learning community approach, Slotta and his colleagues have developed the KCI model to guide the design of science curricula in which the whole class works as an inquiry community (Slotta and Peters 2008; Slotta et al. 2018). KCI provides structural requirements and design principles for (1) an epistemological orientation to help students understand the nature of science and learning communities, (2) a knowledge base that is indexed to the targeted science domain, (3) an inquiry script that specifies collective, collaborative and individual activities in which students construct a knowledge base that serves as a resource for subsequent inquiry, and (4) student outcomes that allow assessment of progress on targeted learning goals. The teacher has a clear role within a KCI script, supported by features within the *physical environment* (e.g., displays of students' pooled votes, resources or other products) as well as the *technology environment* to help track student progress, distribute instructions and prompts, pause students for planned or spontaneous discussions, etc. Fong and Slotta (2018) provide a more detailed account of the KCI model.

Scripting and orchestrating complex inquiry

Curricular designs that immerse students in rich inquiry environments where they contribute their own content to advance the community's knowledge are likely to be more complex and dynamic than previous generations of computer supported learning environments (Slotta 2010). Designs must now carefully consider the configuration of students, activities, technologies, and the role of the teacher, as well as their reconfiguration during the course of instruction, based on emergent class themes, patterns, or metadata. In response, the notion of scripting has been introduced (Dillenbourg 2002) to refer to the structure of student and teacher roles, goals, and interaction patterns. Pedagogical scripts can help students and teachers by segmenting the learning processes into more cognitively manageable phases, and provide guidance on the formation of student groups, the distribution of roles, the phases of work, the timing of the activity, and expected deliverables (Kaplan and Dillenbourg 2010; Kirschner et al. 2004).

Early efforts to scaffold learners with computer-based learning environments included inquiry scripts delivered through the Web-based Inquiry Science Environment (WISE; Slotta and Linn 2009), or scientific experimentation environments such as Molecular Workbench (Xie et al. 2011) or Vlab (Tsovaltzi et al. 2008). These technologies supported students by automatically connecting them to required resources (including multi-media artifacts like videos), and guiding them to progress through well-defined steps or phases of the script. Although such allocation of resources and guidance in activities could be done without the help of technology, the role of the computer-based learning environments made the process much smoother and reduced the load on the teacher (e.g., in tracking the state of every student in the classroom and their individual resource needs—see Nussbaum et al. 2009). Some of these inquiry technology environments even provided teachers with authoring tools, allowing them to determine the order in which activities are enacted, the types of discussion or reflection that students engage in, and even small group configurations. An example, in the WISE environment, the teacher can specify the number and type of activities that students engage in, the level of scaffolding provided to students, and the kinds of supporting materials that are available (Slotta and Linn 2009).

Whether or not they use technology tools, enacting inquiry scripts can place a heavy load on teachers, requiring them to simultaneously manage changing student roles and groupings, assigning activities, and organizing materials—including potentially large and diverse community-generated content from the knowledge base (Dimitriadis 2012; Tissenbaum and Slotta 2015). The process of supporting the enactment of scripts across multiple temporal scales and social levels is generally termed orchestration (Dillenbourg et al. 2009). Unlike scripting, which deals with the structuring of activities *before they are run*, orchestration is the regulation and management of an activity *during the instruction* (Soller et al. 2005). Orchestration introduces a layer of flexibility to script enactment, allowing for real-time adaption (or re-scripting) of group configurations, materials, and even the next steps of an activity depending on emergent class patterns, community voices, or new or interesting avenues for investigation. Particularly within the context of computer-supported collaborative learning (CSCL) classrooms, the orchestration of students, materials, roles, and goals has been acknowledged as a major research challenge (Dillenbourg 2011).

Rather than regulating teachers to the sidelines of classroom activities, orchestration places the teacher at the center of the learning process—not as a knowledge provider, but as an empowered driver, adaptor, and regulator of the learning, ensuring successful progression of activities (Dillenbourg 2013). This includes responding to students as they engage with materials and conducting vital whole-class discussions. Technology tools and environments can support teachers, reducing the attentional load, scaffolding students as they work in specific activities, and allowing teachers to make timely and relevant adjustments to the script based on assessments of student progress, collaboration, and growth of ideas (Sharples 2013). Thus, technology supports can greatly facilitate the orchestration process, allowing them to focus on the most important factors or concerns, such as monitoring group activities and helping students or groups in need (Dillenbourg 2012; Dillenbourg et al. 2009; Nussbaum et al. 2009). Some scholars have advanced the notion of a smart classroom as one that is intentionally designed to support such rich forms of orchestration.

Co-design of smart classroom curricula

Even when well designed, the implementation of innovative technology enhanced curricula into the everyday practices of teachers is a challenging task. The successful adoption of such curricula is heavily dependent on the teacher's perception of the fit between the innovation and their own goals for students, teaching strategies, and expectations for student learning (Roschelle et al. 2006). In response, there is a growing call to involve teachers as co-designers of the curricula and technology from the outset. This co-design approach contrasts other design approaches that expect teachers to simply follow pre-defined scripts, instead viewing teachers as important members of the design team and as professional contributors (Linn et al. 1999; Penuel et al. 2007).

Moving towards a co-design approach requires a shift away from traditional designer-as-expert approaches, towards an understanding that teachers' experiences in the real-life of the classroom can provide important insight into curricular designs. Despite the additional load (i.e., added concerns or perspectives from another important stakeholder) placed on the design process, this approach to technology-enhanced curricula has seen continued adoption in the development of learning environments for many domains, including ecology (Spikol et al. 2009; Vogel et al. 2010), physics (Charles et al. 2015), math (Nilsson et al. 2010), as well as for informal learning spaces such as museums and science centers (Bortolaso et al. 2011; Fuks et al. 2012).

A co-design approach is particularly vital in smart classroom designs, as they require a significant reconceptualization of classroom practices, interactions between teachers and students, and the role of the physical space itself. To ensure these interventions are properly understood, implemented, and most importantly, are addressing real classroom needs, the teacher must be brought into the design process as early as possible.

Design-based research

There is an ongoing demand in the learning sciences for projects that address theoretical questions about the nature of learning in real-world contexts and settings, rather than in well-controlled laboratory settings (Collins et al. 2004). In response, many researchers have advocated for a design-based approach to research, which grounds research in real-world contexts and exposes the research to the range of variables such contexts present (Wang and Hannafin 2005). In design-based research, the design process is neither linear nor prescriptive; rather, interesting forms of learning and new lines of inquiry often occur opportunistically during the design's enactment, and retrospective analysis may often be required to validate them (Mor and Winters 2007). This retrospective analysis then becomes the driving force for successive design iterations, fostering continuous cycles of design, enactment, analysis and redesign (Design-Based Research Collective, DBRC 2003). The tenets of design-based research find an ideal synergy with co-design. Dede (2004), goes as far as stating that in order for design-based research to succeed or have any hope of adoption by practitioners and policy makers, we as researchers *must* "view them as partners with valuable knowledge for co-design rather than as experimental subjects to manipulate" (p. 114).

In design-based research, the design itself and its enactment are seen as being a significant outcome of the research (Barab and Squire 2004).

A sequence of design studies

In response to the challenges of developing technology-enhanced curricula to support students in engaging as a learning community, two central questions have guided the work presented below:

- How can a smart classroom infrastructure support students' engagement in a collective learning community?
- How can we support teachers in the orchestration of activities within a smart classroom?

To answer these questions, we describe a 4-year design-based research project, in which we formed a co-design team with a high school physics teacher, and a group of technologists to design, enact, and refine a smart classroom learning environment. This paper focuses on two aspects of our design: (1) the use of aggregates of student work to support idea negotiation and problem solving, and (2) the role of large-format displays for both student collaboration and classroom orchestration. By examining the evolution of these technology elements, we show how the smart classroom infrastructure supported increasingly complex pedagogical scripts. We also demonstrate how teacher input and feedback served as an integral part of our design process.

We begin by describing a sequence of three successive small-scale studies of high school physics lessons, with increasing levels of sophistication and duration. The first addressed our very basic interests in the possible role of the classroom physical environment in mediating cooperative and collaborative learning designs, as well as the role for aggregative visualizations of student ideas. The second explored the notion of learning across contexts (i.e., classroom vs. home environments), with the interest of allowing out-of-school activities to make direct contributions to classroom physics curriculum. The third study investigated the role of intelligent agents in helping to coordinate the assignment of materials to students (freeing up the teacher from an otherwise complex activity), and also designed a tablet computer that would prompt the teacher, in support of his classroom orchestration.

The small-scale studies led to the design and implementation of a larger, semester-long curriculum, culminating in a smart classroom activity. In the curriculum, students engaged as a learning community over the entire semester, contributing content, designing and solving problems, and engaging in complex inquiry activities within the smart classroom environment. We describe the complementary roles of teacher, physical environment, and intelligent agents in orchestrating the flow of student groups, materials and activities, and close with a summary of project outcomes and design principles for researchers interested in conducting similar smart classroom designs. While some of these data have been presented separately in other places (as cited below), the overall sequence of studies has never been presented as a coherent account, to show how each study informed the design decisions of the next, and guided our development of a comprehensive smart classroom infrastructure. In reviewing these earlier studies, we will focus on how they provided critical information about what worked, and what did not, between each iteration.

Study 1: Tagging and solving physics problems, and aggregated visualizations of student contributions

Study overview

The first study responded to our partner teacher's desire to have students understand problem solving "to be able to look at problems more as experts…when experts look at a new question, they quickly identify the key concerns (or boundaries) of the question and how they will attack it. This is a question that should be approached in a 'conservation of energy' style, for example." We also collectively decided that we wanted to develop a classroom space that gave him greater insight into the work of his students. In response, we developed the first version of our smart classroom and curriculum, described in the next section.

Implementation

Two grade 12 physics classes (n = 32) took part in the intervention, which was conducted over 2 days with two different instructional conditions (1 on each day) and 16 students in each condition. In one condition students had access to large-format displays (described below) for their group work and in the other they only had their individual laptops.

In our first smart classroom design, we divided the room into four zones, each with a large, projected display on the wall (Fig. 1). Students used laptops for individual work, and the large-format displays were used for collaborative tasks. The underlying SAIL Smart Space (S3) framework (Slotta et al. 2011) handled student account management passing students in each group problems in real-time as they completed prior ones.

Students worked in small groups to answer and then tag a set of 16 multiple-choice concept-based physics questions, with tags such as Newton's first law, net force, kinetic energy, conservation of momentum, etc. (see Fig. 2). Students were sorted into groups of 4, with each group member assigned 4 of the 16 problems. Our goal was to engage students in categorizing problems and helping them reflect on the difference between their classifications and those of physics experts (in this case the teacher) (Chi et al. 1981).

Once students had completed their individual tagging and answering of the problems, they remained in their groups and were tasked with reviewing the aggregated answers and tags provided to their four questions by students from the other groups. The group was then asked to form a consensus concerning a final answer and a final set of tags, along with a rationale for their choices. Collaborative visualizations displaying those results were generated to facilitate this process. Students were instructed to critique the various solutions contributed by their classmates, as well as the collective tags, then re-negotiate the definitive answers and element sets, and write a brief rationale to explain their choice of elements.

In a final step, the groups were given a longer physics problem and asked to choose which of four concept questions was best suited to helping them set up and solve the longer problem.

Data sources

The data collection for this study involved capturing all individual and group tags, answers and rationales captured by the system's data logging, researcher field notes during the in-class activity; video was recorded of all student and teacher interactions during the activity, and a follow-up debrief was held with the teacher.

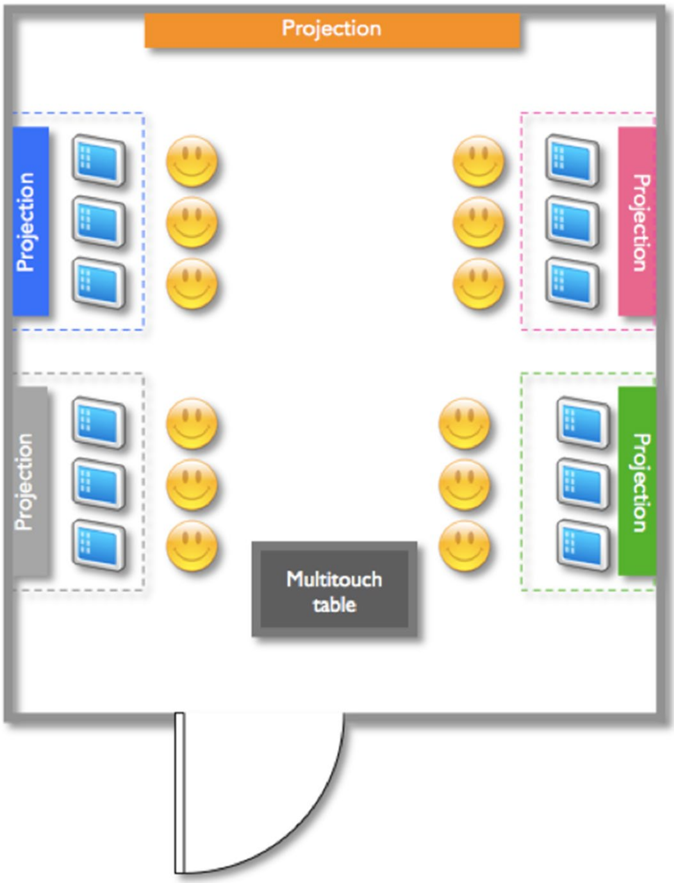


Fig. 1 Smart classroom layout

The data logs were analyzed to determine changes in student and group accuracy in responses, including the assignment of element tags. These data were also compared with tags and solutions provided by the teacher, which served as the *expert model*. The debriefing with the teacher gave us insight into the match between the intervention, the technology, and the teacher's curricular goals. The debriefing also helped us understand the teacher's feelings about the orchestrational affordances and challenges posed by the smart classroom infrastructure. Captured video was used to understand how students used the various technologies to support their problem solving and discussion.

Findings

Overall, when students worked collaboratively they were more accurate and had better structure in their concept and equation tagging than they did individually (Slotta et al. 2011). Moreover, because one class section was held in the teacher's regular classroom, where the large projected displays were not available, we were able to conduct an ad-hoc comparison. While both conditions improved their percentage of correct answers,

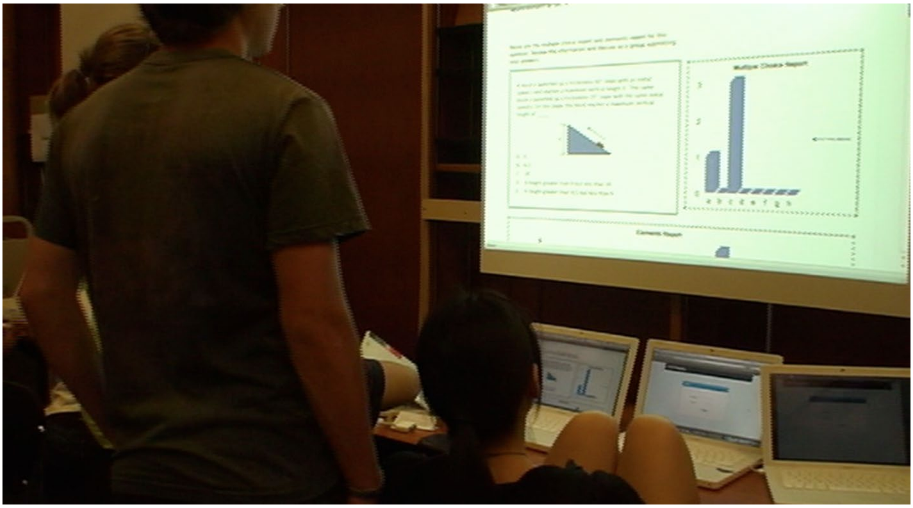
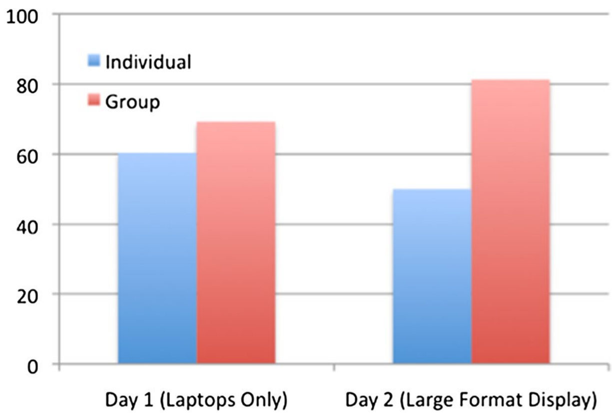


Fig. 2 Students solving physics problems

when compared to working alone, the groups using the shared displays showed higher gains (from 50 to 81.25%), compared to the groups who used only laptops (from 60.38 to 69.23%) (Fig. 3—Tissenbaum et al. 2012). One of the possible explanations for this improvement between conditions was the teacher's ability to see what students were doing on the large format displays and adjust his teaching accordingly. For instance, during one episode, the teacher was watching a group discuss their problem and noticed that none of the students during the individual stage had approached the problem correctly. In response, the teacher approached the group and suggested that they think about the problem from a different angle what had been suggested individually by their peers (Tissenbaum et al. 2012). Video analysis also indicated that the large format displays were effective as a common reference for student discussions and as an indicator of class progress (Lui et al. 2011).

The teacher also expressed how much the activity, and in particular, students' access to the aggregated visualizations supported them in actively discussing whether they agreed

Fig. 3 Individual student scores and group scores on laptops versus large format displays in Study 1



or disagreed with the tags attached by other students. This enabled students to argue about how a question could be considered, for example, as a 'conservation of energy' type problem and a Newton's Second Law problem at the same time—perhaps coming to recognize that both approaches could work. During the exit interview, the teacher expressed that he had never been able to achieve this before in his career using only print-on-paper questions. He reflected that while the ability to 'Tag', 'Like', or 'Dislike', is a commonplace expectation for students in a digital environment, he did not expect this activity would provide as rich of an experience as it did. In particular, he noted that the overall physics discourse of the class changed:

> They were talking about the questions in a new way, deconstructing them and peer-reviewing their process at multiple stages. The students were not simply discussing how to solve the physics problems, but rather engaged in conceptual discourse using physics terminology and reflecting on problem solving approaches. [Teacher]

By providing students opportunities to first engage with the physics concepts individually, then see the aggregates of the class' work on the large format displays, we were able to support rich discussion and sense making. As evidenced by the increase in groups' structuredness (their tagging and answering matching that of the teacher as an *expert*), this resulted in helping students see how questions could be expertly grouped into a small number of 'types' and how new questions might be connected to previous ones.

One aspect of the curriculum that stood out to the teacher was that some of the early tagging portions of the activity took a lot of in-class time, which could have been better allocated to problem solving and discussion time. He noted that the individual work probably did not need to be done in the classroom itself, as he felt the collaborative discussion and his ability to engage with the students was a more valuable use of class time.

Discussion and implications for future designs

From a technical perspective, we were encouraged by the successful implementation of the design, as the environment was able to support students in working collaboratively, could retrieve and aggregate relevant materials from the database in real-time, and (in the case of the large format displays) spatially orient student work within the room. Some key takeaways from this first implementation, including how they helped inform our subsequent design, are as follows.

Large format displays are an effective means of supporting collaboration and teacher orchestration

The design of the room, with the large format displays around the edges and the teacher in the middle, was effective in supporting the teacher as a wandering facilitator (Hmelo-Silver 2004), moving throughout the class, seeing the work of the students in real-time, and providing support as necessary. This allowed the teacher to hold expert-like, problem-solving conversations with students as he walked around the room. As exemplified by the teacher intervening when he saw the errors in the aggregated solutions of the individual students, the large format displays allowed the teacher to see when students were heading down an incorrect path and to intervene at a critical moment in the students' learning.

Representations of community knowledge can provide opportunities for classroom discourse

By having the students work first individually, before engaging in small group discussion, we were able to provide the groups with representations of their prior work, which supported collaborative argumentation and negotiation. As discussed above, students were more accurate and structured in the assignment of tags to individual problems after being able to see and discuss their peers' aggregated individual answers.

Consider what can be done outside of the classroom and what is best done during class time

Based on the teacher's comments that he found the individual work took up a lot of the classroom time that could be better spent on collaborative and conceptual discourse, we felt that future iterations should allow individual tasks to be completed outside of the classroom. In order to do this, we needed to adapt the technology to allow for remote access to the materials, and more advanced user login and account management. We also needed to adapt the pedagogical script to adapt to both the at-home and in-class activities.

Study 2: Adding cross-context learning and teacher orchestration tools

Study overview

Building on the findings of the first study, we wanted to continue the use of the large format displays to support group collaboration and teacher orchestration, while also responding to the teacher's feedback about freeing up more class time for discussion and problem solving.

In response, we adapted the curriculum to move the first round of individual student Tagging, Answering, and Reflecting (TAR) of problems to an asynchronous homework activity (Fig. 4). Moving the TAR step to a homework activity allowed the teacher review student work beforehand, offering him new opportunities for adjusting the class script based on his perceptions of student understanding. This also allowed us to investigate cross-context learning (i.e., blending home and school activities). Below we describe the newly designed technology elements and adapted cross-context curriculum.

The teacher also wanted students to be able to have both collective (the aggregated tags and reflections for all the answers) and the filtered (only the tags and reflections for individual answers) views of the class' work, as he hoped that this would support finer grained discussion about the particular approaches used by students in framing their answers.

Implementation

To support cross-context learning, we developed a web portal (Fig. 5), which the teacher could use to customize the number and type of questions provided to students.

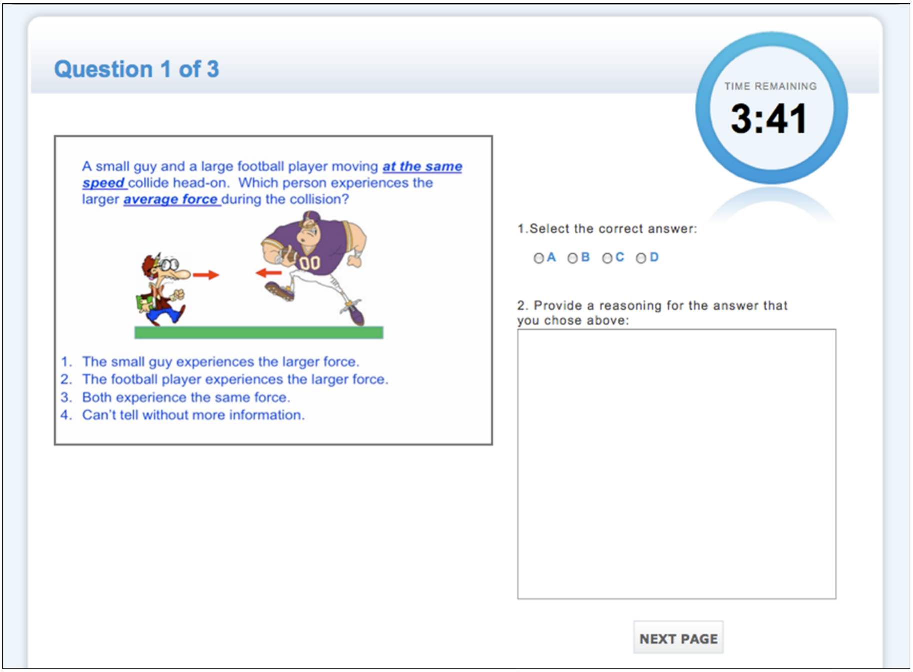


Fig. 4 Individual homework problem solving screen

The portal could also provide him with a report on student responses. The teacher could also use the portal during the classroom activity to examine the groups' work in real-time, providing support for class orchestration decisions.

In response to the teacher's feedback about the need for more detailed information on the classroom displays, we redesigned the aggregated information that was projected onto

Fig. 5 Teacher portal

the large display, to give groups more information about peers' prior work and to make it more interactive. The display now contained four different elements for each problem: (1) the image of the problem that students were charged with discussing, (2) the number of students who chose each multiple-choice answer, (3) the aggregate of the tags chosen by the class, and (4) the reflections on their answers provided by each individual student (Fig. 6). Students could also filter what was shown on the visualization by clicking on any of the multiple-choice answers. We also designed a new summative representation of the whole class' work that was projected at the front of the room for the teacher to use for discussion (Fig. 7).

Working with the same co-design team, we engaged two new cohorts of the teacher's physics classes (n = 20 and 16 respectively) to compare two conditions of a group activity: (1) working in their regular classroom as dyads without the aggregate displays, and (2) working in the smart classroom as small groups with the displays.

To start, the teacher logged into the portal and uploaded the homework questions. Students were alerted via email that the activity had been posted and were given 2 days to log into the student site and complete the individual TAR activity. Before the classroom session, the teacher logged into the portal and reviewed the aggregated student work to get a sense of students' ideas (i.e., from the individual rationales and tags). During the in-class activity, students repeated the TAR step (i.e., "re-TAR") from the first iteration working in their groups or dyads. During the smart classroom activity, the teacher was free to use the aggregated visualizations on the large format displays as a source of information about emergent student ideas. In both cases the teacher could see student answers on the web portal.

Data sources

Data collection for this iteration closely followed that of the first study. All student and group tags, answers, and rationales were captured by the system's data logging; researcher field notes were taken during the in-class activity; a follow-up debriefing was held with the teacher. No video was collected during the in-class or smart classroom activities.

Similar to the first study, the data logs provided us insight about the changes in student accuracy in individual and group tagging and answering of the problems. The field notes helped us understand how students engaged with their peers during the activity. Similar to the first study, we used the teacher debrief to reveal the teacher's feelings about his perceived effectiveness of the added technology scaffold in meeting his curricular goals.

Findings

Similar to the previous study, the groups/dyads faired significantly better (97% correct) than individuals working at home (80% correct), with $t = 2.02$, $df = 41$, and $p < 0.05$ (Tissenbaum et al. 2012). Throughout the activity, students used the aggregate representation (Fig. 6) to discuss the tags and rationales of their peers in an attempt to make sense of any disagreements. The teacher felt that collaboration between students was easier for them in this iteration. The teacher commented that the "group members suggested re-wordings when they were explaining the reasoning behind their answer selections and they seemed to be interacting with each other more than in the previous version" and that they seemed to be working less in 'parallel'. He found the students "entered better rationales using the webpage than when [he previously] had them explain their answers on paper".

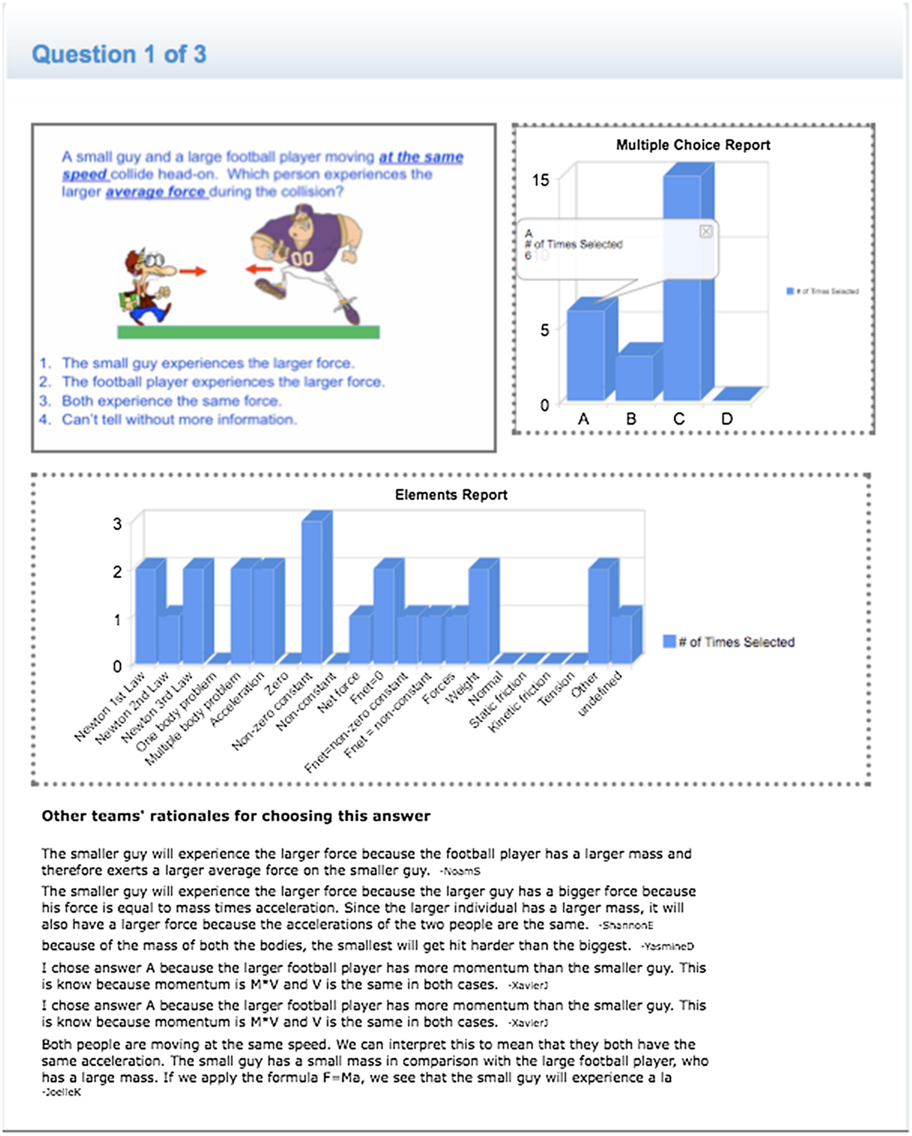


Fig. 6 Aggregated student TARs for group activity

The teacher felt that that groups who answered questions correctly were more likely to have an expert-like interpretation of the type of question they were solving. However, when the ‘tags’ of the groups who answered correctly were compared to the ‘tags’ of groups who answered incorrectly, the differences were not as pronounced as he would have expected. “It seemed as though the reasons why a group picked the correct (or incorrect) answers were not clear-cut” (Teacher). In other words, students’ choice of tags for a problem did not seem to reflect any clear conceptual misunderstanding that might be connected to that problem. He suspected that students might be including

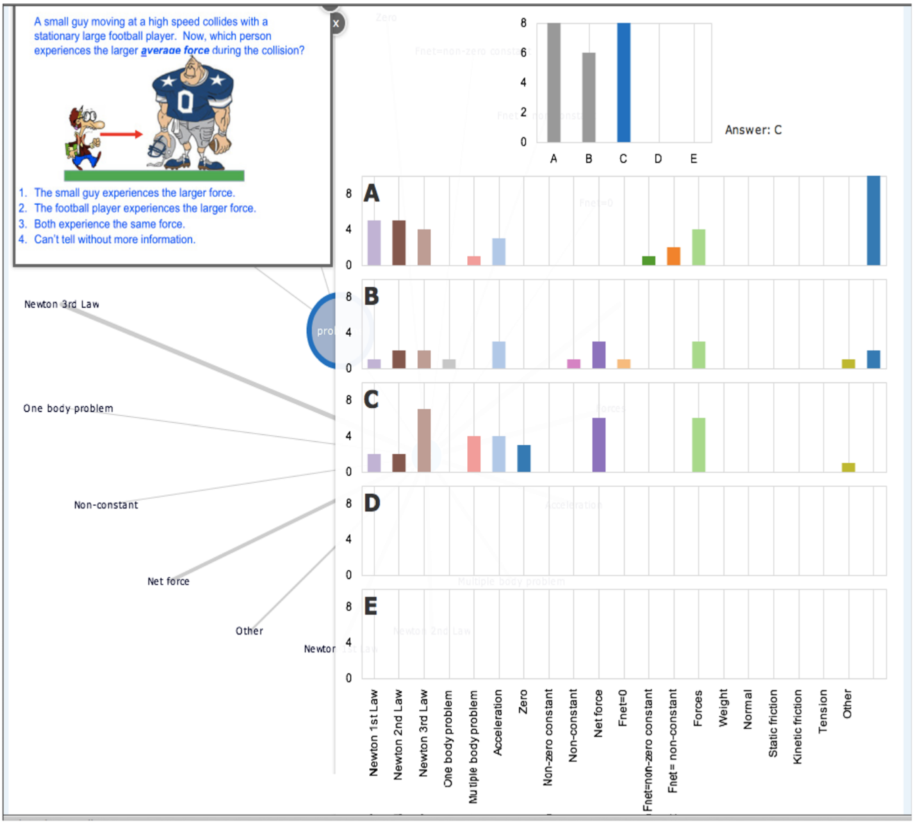


Fig. 7 Whole class aggregated visualization

tags from other group members even if they did not agree or understand why those tags should apply. They seemed to engage in discussions about which answer was correct in a decisive way, but hesitated in engaging in argumentative discourse about the tags, perhaps because they did not have to come to a strict consensus and multiple tags were allowable.

Some of this replication of the work of peers could be seen in the students' final rationales for their answers. When we compared the individual versus group rationales (with intercoder agreement of 83%), 24 of the 61 rationales provided were unique (i.e., they were not identical or nearly identical to any other answers), 20 were considered identical, and 17 had no rationales provided (with 15 of these coming from only 3 groups) (Tissenbaum et al. 2012). Of the rationales that were identical, it was unclear if the students were simply repeating the answers of their peers without consideration, or if they really believed they were the best answer.

When interviewed after the activity, the teacher said that he found the student reports (accessed through the portal) helpful in understanding where students had problems with the homework prior to class. However, his attempts to use the dashboard during the live activity were less satisfying, because they were only available on a laptop computer that was too cumbersome to carry around the room.

The lack of real-time information was compounded during the second session, which was held in the regular classroom and did not have the large projected display for each group. The lack of the display meant he was unable to see the groups' work at-a-glance. After the activity, the teacher benefited from the ability to compare students' *answers* with their (tagged) belief about *what type of question* they were solving. He felt that this was a great way of assessing his students' understanding before returning to class the following day to discuss the problems.

Discussion and implications for future designs

Several of the outcomes of this study aligned with the findings from our first study (e.g., the importance of having students refer to aggregates of individuals' contributions). Three additional design implications are as follows:

Teacher tools need a level of automation for real-time support

The teacher needing to remember to update his tablet in order to see what was going on in the class added some orchestrational load to his classroom practices that caused him to miss critical moments during the class activity. He would often forget to press refresh and would miss timely changes in the state of the class. In response, we felt that the next version of the teacher tools would need a level of intelligence and real-time updating that would not require the teacher to be responsible for remembering to update it on his own.

Orchestration supports should not interfere with the teacher's ability to engage with students

In addition to its inability to automatically update, the lack of portability of the teacher tools meant that the teacher could not effectively act as a wandering facilitator. The need to continually go back to a central spot, or open up the laptop each time he wanted to use it, interrupted his flow in the classroom and increased his orchestrational load. While we did not know at the time that tablets would soon be available, we knew that we would have to find a way to better support the teacher's movement in the class and real-time updating at the same time.

Having every student bringing the same experience to a problem may limit the diversity of answers

The issue surrounding the groups' final rationales, that many of them were identical (or nearly identical) to students' individual answers, may have been due to the fact that all the students had seen the problems before and were bringing similar perspectives to the refinement and reflection portion of the activity. As a result, we were interested in how we could structure the tasks so that students were seeing new ideas and could bring multiple, differing expertise to the problem solving and discussion.

Study 3: Student expertise areas, a real-time teacher orchestration tablet, and intelligent software agents

Study overview

This study, like the previous, was concerned with collaborative problem solving, tagging, and reflection, with the goal of informing technological supports and pedagogical design principles. By leveraging technological supports, we aimed to expand the teacher's orchestrational capacity and better understand how students can benefit from visualizations of the aggregated work of their peers. We developed intelligent agents to help ensure (1) that students were presented with physics problems they had not seen before, and (2) were added to groups of balanced expertise areas. Student expertise balancing and problem distribution are the kinds of orchestrational moves that teachers could potentially make within a complex inquiry design, but which would require inordinate level of attention. Our vision of a smart classroom is one in which such moves are scaffolded by technology, sparing teachers' attentional resources for more nuanced pedagogical moves, like interacting closely with students. The present study investigated such intelligent supports for the script elements of student grouping and problem distribution.

Implementation

We worked with the same physics teacher and two new 12th-grade class cohorts (i.e., in a new school year), with 15 and 18 students, respectively. In addition to being a design study of agent-based orchestrational supports, the study also included two distinct conditions by only providing one of the two classes the aggregate visualizations of their peers' responses.

As in the previous study, the teacher uploaded homework questions—in this case, 35 problems representing 5 distinct topic areas. Each student was assigned to one topic area, and received five out of the seven problems from that topic to tag, answer and reflect on for homework. The following day, in the smart classroom space, students were placed in groups of five (one student from each topic area), and given five questions—one from each topic area—with the requirement that *no group member had seen any of the problems* before during homework. In other words, we had to ensure the problems from any topic area had not been seen by the particular group member who had specialized in that area (and who had seen five of the seven overall problems). So, we had to pick one of the two problems the student had NOT seen as homework, and do this for all five topic areas, to ensure that the group received five problems—one from each topic area—that no member in the group had seen before. This was a sufficiently complex algorithm that it was deemed by the teacher as being "way too hard to achieve using only paper-and-pencil". In order to support the complex logic relating to the distribution of problems, we developed our first version of an S3 *Bucket Agent*. The *Bucket Agent* tracked the group in terms of all the items that students in the group had previously encountered (i.e., during homework or in prior cycles of that group's activity) to make real-time decisions concerning which problems to serve to the group (i.e., to pull out of the bucket of problems).

The summer leading up to this study witnessed the introduction of Apple's iPad and Google's Android tablets, radically changing our notions of portable, personal computing in the classroom. In response, we developed a tablet application to support the teacher as he was moving around the room, monitoring and responding to student groups. This tablet application used a color-coded grid, with each group as a row and the five topics (problems) as columns, to track all groups' status in real-time. Within the grid, a square was colored green if the group had answered that problem, correctly and red if it was answered incorrectly (see Fig. 8). If the teacher tapped on any of the colored squares, he was presented with that group's TAR, providing additional insight on how the group had approached their solution. We hoped that the teacher would be able to use the tablet application to engage individual groups in discussion (e.g., if he noticed anything interesting or erroneous in their solutions). Alternatively, he might use the information to engage the whole class, if he noticed patterns in responses across groups (e.g., several red squares for a particular problem or topic). We were particularly interested in whether the tablet could provide the teacher with new insights into students' learning in real-time, and how this might affect his orchestrational moves. In order to understand how the teacher was influenced by the tablet, we compared his orchestration between two class sessions, where he was provided the tablet only in the second session.

Data sources

Data collection for this study closely mirrored that of the previous two iterations, with all individual and group tags, answers and rationales captured by the system's data logging. Researcher field notes were taken during the in-class activity, and video was recorded of all student and teacher interactions during the activity. Similar to the previous studies,

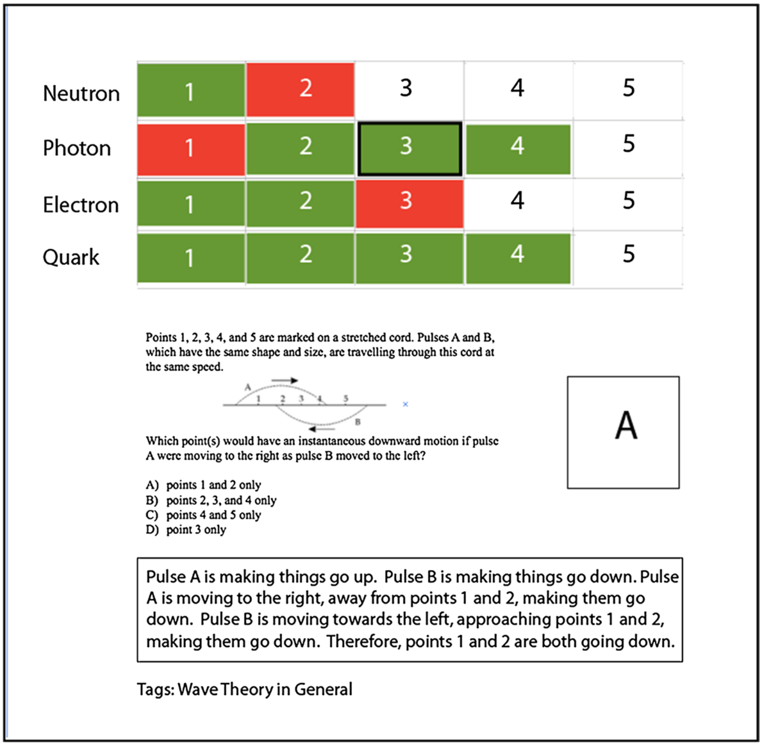


Fig. 8 Teacher tablet

data logs served to reveal changes in students' individual and group responses across both conditions. In addition, all teacher interactions with the tablet were recorded (e.g., which squares he touched, if any). Finally, a post-activity discussion was held with students after the activity to understand students' feelings about the intervention; and a follow-up interview was held with the teacher. The post activity discussion with students provided insights concerning their feelings about the curriculum and the learning environment. The teacher interview provided insight into the effectiveness of the tools and environment toward future refinements.

Findings

Overall, students who had access to the aggregated responses of their peers significantly outscored both individuals during the homework activity and the groups that did not have access to the aggregate visualizations. Individual and group rationales were coded using a four-point scale (0 to 3) that was developed in collaboration with the teacher to evaluate the depth of student understanding. Two researchers evaluated all student and group responses using the co-developed scale with an intercoder agreement of 91%. The groups that had the aggregate visualizations of responses from the homework activity significantly outperformed both the individuals (from the homework activity) and the groups that did not see the aggregated responses (Fig. 9—Tissenbaum et al. 2012).

The teacher particularly liked that the S3 intelligent agents could sort the homework questions and student groups for him. The agents' ability to track problem type 'experts' in each group and deliver relevant problems to them allowed us to create a 'jigsaw' structure that he found pedagogically valuable. He noted that he would not have been able to plan 'who gets which homework problem' the night before 'and who goes where' in class on his own, not to mention the serious challenge of ensuring that groups received *only* problems that no member in the group had seen before. Such planning would have been time intensive for the teacher and tiresome during class for students.

With regard to the tablet, initially, the teacher was highly engaged with the device, clicking on and reading different group responses, using it to see where students may have made mistakes, and noting (in comments made during class) that he had never had that level of insight into students' thinking *during class* before. However, after a few minutes, he

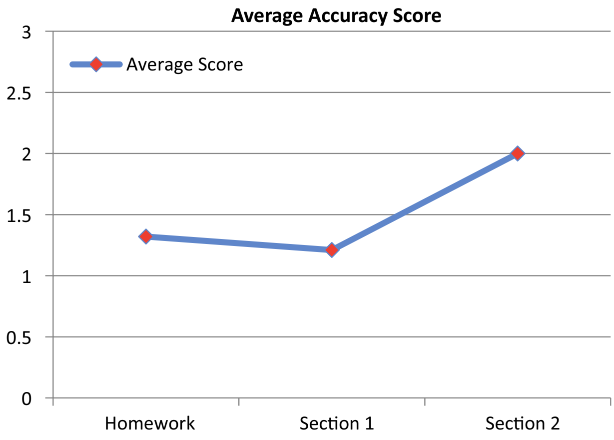


Fig. 9 Students in section two, who had access to all TAR data, achieved a higher average accuracy score (2.0), than students during section one, who did not have access to the aggregated data (1.21), and students working individually at home (1.32)

abandoned the tablet, as he experienced what he described as "cognitive overload" trying to interpret and respond to the information provided. He recounted that it was just "too interesting", and distracted him from his usual rich interactions with students—so that he needed to ignore it! Perhaps if an S3 agent could have filtered or highlighted some of the information that was of greatest relevance or concern, he could have used it with less attentional load (e.g., to simply help him decide which student groups to visit next). The teacher said that he "truly wanted to see all the data, but did not realize that it was going to be so engaging and hence distracting during class time, so [he] decided to focus on the large projected displays instead" during class time.

Another issue the teacher had with the tablet was that most of the information that it provided him was valuable more for post hoc reflection, rather than something that he could immediately act upon. Knowing that a group had answered a question incorrectly several minutes in the past did not necessarily help him engage with the group in that moment (unless he wanted to pull them out of their current work, which he found too disruptive).

During a post-activity discussion with students, they commented that while they found the aggregated information from their peers valuable for considering different approaches for answering their problems, the aggregated visualizations (bar graphs that showed how many students chose each answer) often made deciding on their final answer too easy (Tissenbaum et al. 2012).

Discussion and implications for future designs

The aggregate representation should not give too much information away

The student interviews revealed that while students' accuracy was increased when provided with the aggregated information of their peers, the direct connection between these aggregates and their final answers (i.e., choosing one option from a set of multiple-choice answers) can make the task too linear. While this may have some opportunities for pedagogically interesting discussions when the majority of the students answer incorrectly, as in the one example in Study 2, these were not the norm. As a result, we realized that future iterations of the activity would need to use the aggregates as the staging point for further discussion, idea negotiation, and interpretations of the data, rather than as a final single choice.

The teacher handheld device offered increased mobility within the classroom

The introduction of tablet computers was a major shift in how we instrumented the classroom (vs. bulkier and less portable laptops). Although only the teacher was equipped with a tablet during the third study, his increased mobility (while he used the tablet) highlighted the potential for increased movement of all participants in the learning environment.

The teacher tablet was too distracting

The teacher abandoning the tablet during the activity and his acknowledgement that it was too distracting (i.e., preventing him from engaging with the class) ultimately rendered the tool ineffective. The teacher found the large-format displays more useful in helping him understand what the groups were up to in real-time, perhaps owing to the fact that he could observe the large displays at-a-glance, while also working directly with the students. The current design of the tablet prevented the teacher from using one of his most effective tools and ultimately increased his orchestrational load (i.e., how much information and logistics they need to deal with at any given time—Cuendet et al. 2013). We realized that future iterations of the teacher tablet should consider what was already working well for the teacher, and compliment those elements rather than compete with them.

The tablet information was not consistently actionable by the teacher

Similarly, given the nature of the task—students solving physics problems—providing the teacher data in real-time about whether or not each group answered correctly or not was not immediately actionable (as the students had automatically moved on to the next question). This made us reconsider the role of the tablet in the classroom, from a device that only showed status updates (which can be distracting and have limited utility during live activities), to a device that could let the teacher have more control over the flow of activities and more actively help him know where he was needed *in the moment*.

Study 4: A persistent learning community for high school physics

Study overview

Building on the three small-scale studies described above, our team sought to design a more substantive, semester-long curriculum in high school physics, informed by KCI, to guide our articulation of collaborative and collective forms of inquiry and the corresponding technology environments. We also wanted to expand our investigations on learning across three contexts of home, classroom, and smart room, and to include an emphasis on student-contributed content. Hence, we pursued an approach in which students created their own artifacts (i.e., physics examples, problems, and connections) which were then reused in meaningful ways, feeding activities in the classroom and smart classroom.

We also wanted to expand the orchestrational capabilities of the S3 framework, adding a layer of intelligence to our learning environments through real-time data mining and computation performed by intelligent agents. An important characteristic of such agents is that, while their overall roles may be defined (e.g., grouping students with peers who have done similar work), the specific computation entailed by that role remains obscure or ill-defined until the time that the agent is called upon (i.e., the particular students within a group may not even be defined until some point during the curriculum enactment). We described this property of agents as being "un-bound", with specific bindings emerging only once the S3 curriculum is underway. Thus, our intelligent agent for group assignment cannot be hard wired to simply assign a certain student to a certain group, because we cannot know at the outset of the curriculum which students or groups will need such assignment. Hence, the S3 agents are designed to conduct real-time data mining. A grouping agent, for example, may be programmed "to assign a given student to a group where he has never yet worked with any of its members, or to a group with the most members who had "liked" one of the student's prior contributions. Hence, S3 agents are designed to execute real-time pedagogical decisions and grouping logic (Tissenbaum and Slotta 2015).

Implementation

The same co-design team participated in this intervention, which involved two classes of grade 11 physics students totaling 45 students (n = 22 and 23, respectively). During the initial design meetings, the teacher identified two main goals for his class: (1) He wanted students to recognize physics in their everyday lives and to bring this view of physics back into the traditional classroom setting, and (2) similar to previous studies, he wanted students to develop a coherent understanding of the underlying physics principles by understanding the connections amongst these principles.

To address these goals, we co-designed a 12-week curriculum called PLACE (Physics Learning Across Contexts and Environments), which engaged students across formal (classroom) and informal (their homes and neighborhoods) settings. PLACE included three units: (1) kinematics, (2) forces and motion, and (3) work, energy, and power. For each of these units, we developed a script in which students used *PLACE.web*, a collaborative social network, to upload their own examples of physics principles (i.e., from their everyday life experiences), adding tags and explanations of relevant physics principles. The wider community was then tasked with debating and voting on the tags or explanations, and adding new tags—with the aim of developing consensus about each item. Throughout these three units, all student contributions were aggregated into a dynamic knowledge base that gradually emerged (i.e., as students added materials, votes, and tags) as a community-wide resource to be used in subsequent phases of the curriculum. For example, in the culminating smart classroom activity, students made use of problems they had created during the three units to help scaffold their solving of ill-structured physics problems relating to selected Hollywood movie clips.

In PLACE, the script was carefully designed to integrate the technology and materials into the curriculum, with a clearly specified role for the teacher. For example, he could assign online homework questions that were responsive to what had been happening in class that day, and he liked how students could see physics concepts visualized through other students' personal lives.

The KCI model called for a culminating activity in which students needed to apply the materials from their co-constructed knowledge base as resources for a collaborative inquiry project. This guided our design of the S3 agents and other features, to scaffold the distribution of materials, assign students to groups, and help to orchestrate the sequence of activities. The activity script involved three phases, each of which specified students' and teacher's roles: (1) homework, (2) classroom, and (3) the smart classroom.

At home, students reviewed a collection of problems drawn from the proceeding knowledge base (including student-generated challenge problems), verified the principle tags applied by their peers, and added equations that might be used in solving the problems. *In class*, students worked in small groups to achieve consensus on a final set of the tags and equations for each problem. This refined set of problems (tagged with principles and equations), were then used as raw materials for the final smart classroom phase. While support for student learning and classroom orchestration for the overall PLACE curriculum is covered in other publications (Tissenbaum and Slotta 2014, 2015), here we focus on the culminating smart classroom activity, with particular attention paid to how its design was informed by the earlier studies.

While the design team acknowledged that the teacher should be a wandering facilitator, KCI demands that he should also have a clearly defined, meaningful and consequential role within the script, so that student–teacher interactions are more than incidental. Moreover, we recognized that the smart room activity would present the teacher with a substantial orchestrational load (Dillenbourg 2012), as he would need to manage the overall activity (e.g., ensuring that students went to the group where they had been assigned), monitor the timing of tasks and support student inquiry. In order to reduce this load, we developed several orchestrational supports. First, following a method shown to be effective by Alavi et al. (2009) we developed a large ambient display at the front of the room (Fig. 10) to show the location of students in the room and track the remaining amount of time for particular steps. Second, in response to the teacher's feedback from Study 3, we adapted the tablet app to serve as a regulatory tool that provided the teacher with actionable alerts. For example, the tablet now alerted him when he needed to review and approve groups' work (Fig. 11).

Another critical tool for managing the teacher's orchestrational load was the expansion of S3's real-time data mining, in the form of intelligent agents that allowed the smart classroom to respond to emergent class patterns and make decisions on-the-fly. We developed four software agents for this culminating smart room activity: (1) *The Sorting Agent*, which sorted students into groups and assigned them room locations based on the frequency of their tags at each board during Step 1, and then between Steps 2 and 3, placing students with peers they had not previously worked with, (2) *The Consensus Agent* required groups to reach consensus before allowing them to progress to the next step, (3) *The Bucket Agent*

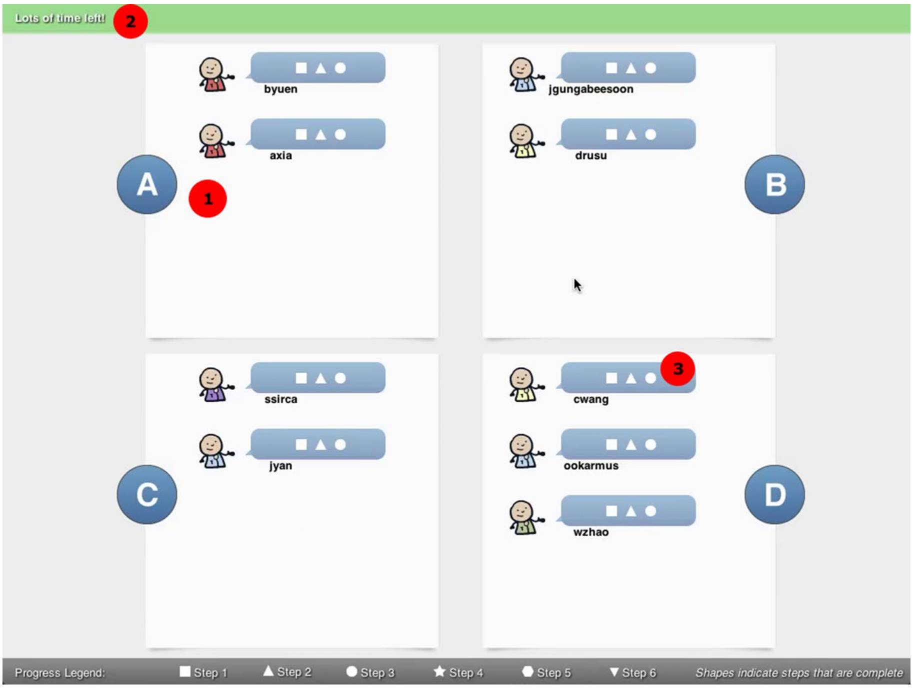


Fig. 10 The ambient display (1) tracked each student within the room—when students moved location (or were sorted by an agent) their avatars moved on the display, (2) the timing of activities was tracked using a colored bar at the top of the display, which moved from solid green to flickering red time ran out, and (3) updated student progress by displaying an icon next to their avatar on the completion of each task (the progress legend at the bottom of the screen shows which task connects to the various icons). (Color figure online)

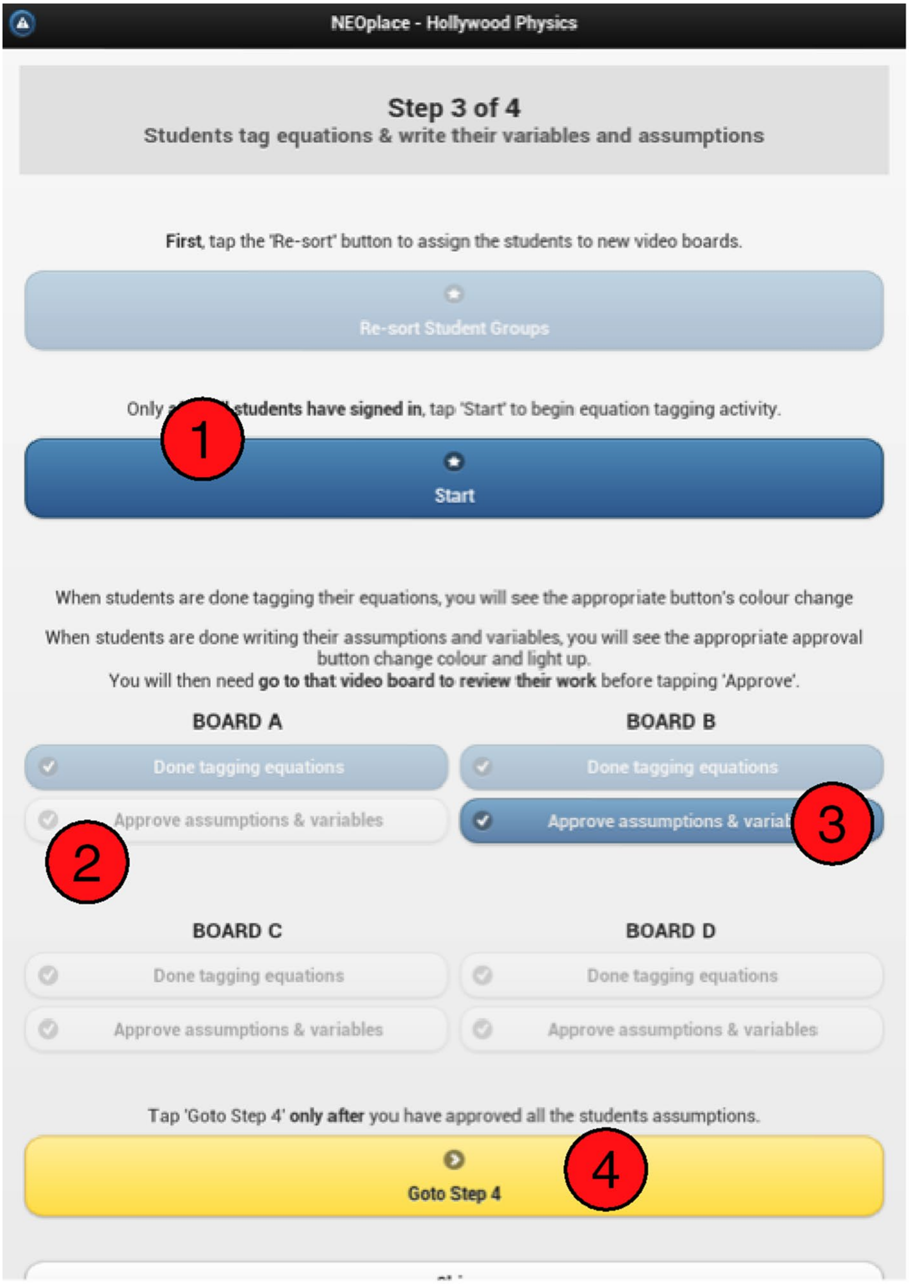


Fig. 11 The Teacher Orchestration Tablet. The tablet (1) enabled the teacher to start a stage for the whole class, (2) showed each group's progression through the activity, (3) alerted the teacher when a group reached a point for intervention (pre-defined by the teacher), and (4) let the teacher advance the class to the next step

coordinated the distribution of materials to ensure all members of a group received an equal but unique set of materials (i.e., problems and equations in Steps 2 and 3) and (4) a *Student Progress Agent* which tracked individual, small group, and whole class progress to send status updates to other devices (e.g., the teacher orchestration tablet).

To support the students, we developed a suite of tablet applications and interactive displays (see Fig. 12). The students' personal tablets allowed them to log in and contribute at each video station in the room, provided task specific materials and instructions, and collaboration support. All individual work done on tablets in a particular zone (e.g., adding tags, suggesting variables) instantly appeared on the zone's interactive display. This display was also used to coordinate group negotiation (e.g., deciding which tags applied to the video), with students physically dragging the individually contributed items into *Yes* or *No* boxes until consensus was achieved. The large display maintained an evolving representation of all negotiated contributions at each video station.

When students entered the *smart classroom*, they were presented with four scenarios drawn from popular Hollywood movies (e.g., from the movie Ironman, a short scene where he survives a ballistic fall to earth). Each video was shown in one quadrant of the room on a large projected display, along with other information added by students throughout the activity (see Fig. 12). The script comprised four distinct activities, with students re-assigned to new groups for each:

(1) Principle tagging: Each student received a set of three or four principles (i.e., out of the 14) on their tablet, which were determined by querying that student's prior expertise groups. The students were asked to go to one video at a time, and to swipe (by physically dragging the item to a portal on their tablet) any of their four principles that they found relevant to the video onto the large display at that station. Because each principle had been assigned to at least two students, there were often multiple instances of each principle on the boards.

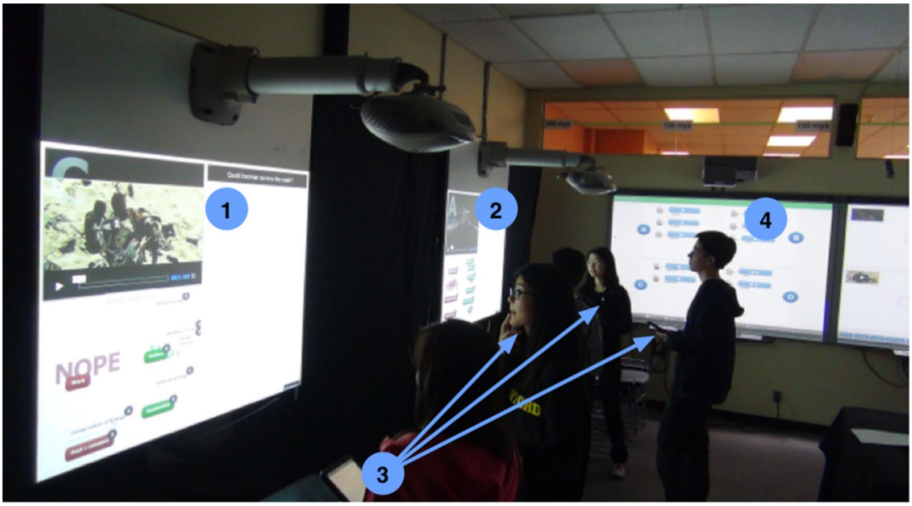


Fig. 12 The smart classroom environment with (1) and (2) interactive whiteboards that orient students towards a specific Hollywood scenario, aggregate scenario-specific student contributions and facilitate negotiation of ideas, (3) student tablets that provide instructions and guidance linking to resources from the knowledge base, and contribute ideas to the shared display, and (4) an ambient display showing where students are in the room, completed tasks and time left in the current task

(2) Principle negotiation and problem assignment: The S3 agents equally assigned students to one of the video boards based on the frequency of their tagging. This was done because the teacher felt this would create robust opportunities for students to engage in discussion and debate. Students were then tasked with negotiating the final principles to be applied to their videos by dragging each to the “Nope” or “Yup” space on the interactive display. After reaching consensus on the principles, the S3 *Bucket Agent* distributed all the physics problems that matched those principles (as tagged by students in the in-class activity) equally among the students. The students then promoted problems they thought might be helpful in solving the video from their individual tablets to the interactive display, before engaging in collaborative negotiation (similar to the negotiation of the principles—see Fig. 13). This movement between the private space of the tablet and the interactive displays was designed to allow students to move between individual thinking and group discussion.

(3) Assigning equations, variables and assumptions: Students were reassigned to new video stations, based on the condition that they would be collaborating with students who they had not worked with in any previous step. The S3 *Bucket Agent* distributed an equal sub-section of the negotiated problems from Step 2 to each group member. Each student saw all the equations connected to their assigned problems (from the previous in-class activity). Students then promoted any equations they felt might help them to the interactive display for collaborative negotiation by the whole group. Group members then individually came up with assumptions and variables to fill in any information gaps, and engaged in the negotiation and consensus script to produce a final set. After the students completed their final set of assumptions and variables, the S3 *Student Progress* agent alerted the teacher on his tablet to review the group’s work. The teacher could approve their work or send them back to refine their thinking.

(4) Solving recording and uploading solutions: In this final step, the groups used the collaboratively constructed information on the large-format displays as support, and using pen and paper, solved their challenge problem and recorded their final answer as a video narrative using the tablet’s built in camera. Having the students video record their answers meant the teacher could play back students’ answers to all four sections as a means for rich discussion on the differences in groups solutions across each video and each section.

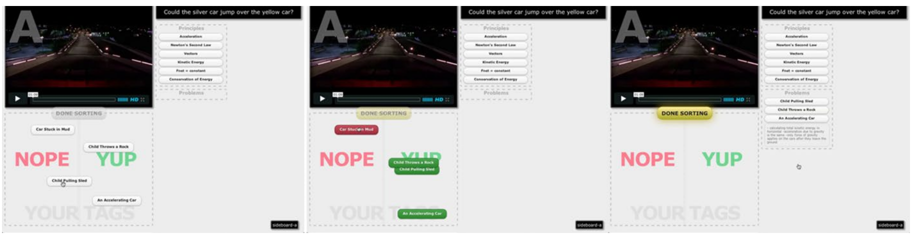


Fig. 13 The three phases of the Problem Selection Task (Step 2), where students (1) submit problems from their tablets to the interactive board, (2) negotiate which problems to keep or discard by dragging them to the “Yep” or “Nope” zone of the negotiation space, and (3) after negotiation the final set appears on the right

Data sources

Data logs were used to capture student interactions with the system and track their collaboratively generated knowledge at each zone in the room (i.e., each physics video station). Screen recordings were captured of each zone's large-format display. Video was recorded across all four sections of the smart classroom activity. Semi-structured interviews were conducted with nine randomly chosen students. Finally, a debriefing interview was conducted with the teacher.

The data logs and video capture served to reveal how students collaboratively developed the knowledge base around each video and how it was ultimately used to solve each video's problem. The data logs and video recordings provided insight into the teacher's orchestration practices, including the efficacy of the real-time alerts for the teacher to review groups' work. The interviews with students and teacher informed our understandings about their impressions of the system and the curriculum as a whole.

Findings

The PLACE curriculum, supported by the underlying S3 technology, was successful in engaging students in investigating physics across multiple learning contexts and building on the work of their peers as a learning community. One key example of how students relied on the collective work of their peers (i.e., from the knowledge base) was in their comparison of their final constructed answers to the video challenge with problems that had been created, uploaded and solved previously by their peers (see Fig. 14). We found that on average groups used 54.6% of the assigned equations and 76.8% of the assigned variables and assumption (Tissenbaum and Slotta 2014).

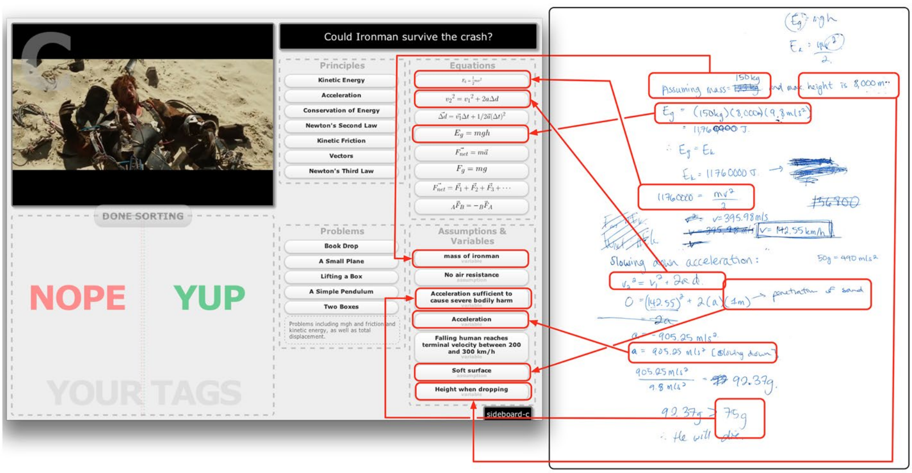


Fig. 14 Comparing the collaborative display and group's final worksheet for solving their challenge problem. The red boxes highlight which elements (i.e., equations, variables, and assumptions) on the worksheet correspond to the co-developed elements from their zone's interactive collaborative display. (Color figure online)

We wanted to know why students' use of the equations was so much lower than their use of the variables and assumptions. Exit interviews with students revealed that they preferred to keep more equations on hand until they were sure which ones they would use. As one student stated, "If [we were] not totally sure, like it's a grey area, we would put it in 'yes' just in case". Students also recognized the usefulness of the displays in scaffolding their problem solving, with another student commenting that "just looking at what other groups had left [them] gave [them] a good sense, and then from there the group could take over and be like this is what [they] need to do to solve it". This was echoed by another student who stated that "having the tags and the equations gave [them] a general idea of what the problem related to, so [they] knew the kinds of information to draw from, so it narrowed [their] scope a lot."

When asked to reflect on how the orchestrational tools supported him during the enactment of the culminating activity, the teacher said that he appreciated how the tablet had helped him coordinate tasks on a class-wide level with a click of a button. This was especially true during the re-sorting of students (i.e., assigning to new groups) after Steps 1 and 2. The teacher noted that,

> each [sort] was a different ensemble, based on all sorts of good physics pedagogy based on where they should be. During transitions when you're a teacher getting kids up, moving them to different seats – you waste so much class time doing that. Even in a common group, cooperative learning scenario, like a game activity, where kids are really learning from each other, just getting the kids to move around the classroom adequately for that, I find cumbersome –I just kind of dread moving the kids around the class and organizing that, rather than doing the activities themselves, and so I just loved the logistical assistance that [the S3 agents] offered.

The tablet helped the teacher to know when and where he was needed in the class, sending him an alert whenever he needed to review a group's work. Video analysis of the teacher during one session showed that he used the tablet more than any other cue in the classroom to check on the status of groups (Tissenbaum and Slotta 2014). The alerts allowed him to observe a group's work and either approve it (i.e., and allow them to move on) or ask them to refine their thinking. An analysis of the data logs and accompanying video showed that across all four sections of the activity the teacher asked six groups to refine their answers before allowing them to progress to the next step. In one case, the teacher asked the students to refine their answers twice.

Initially, we debated whether students would have sufficient time to visit and effectively consider the physics of all four movie clips during a single 75-min session. From years of experience with inquiry methods, the teacher was concerned that the full sequencing (i.e., of all students rotated through all stations) would be overly ambitious, requiring too much overhead of switching groups, assigning materials and monitoring progress. Thus, by designing a script that would be seen by teachers as being intractable, we actually provide a strong test of the smart classroom concept, as it intended to reduce this kind of orchestrational barrier.

Discussion and implications for further design

The culminating smart room activity, while complex, was successfully enacted, with the S3 smart classroom helping to coordinate all grouping, material, and activity support. The teacher had a meaningful role to play in each group's progression, and at each of the video stations, supported by intelligent monitoring of students' progress. At end of Step 4, all students had engaged with each video station, working in small groups to advance the physics inherited from the group previously assigned to that station every student had recorded their answer to only one of the four problems. However, the teacher felt that they had all engaged meaningfully with and contributed substantially to the solution of all four problems. He expressed surprise over how well the students were able to shift between the different stations after watching the movie clip and picking up where the previous group had left things.

Intelligent software agents can support the flow of activities within complex activity scripts

The teacher's initial expectation was that students would only have enough time to dig deeply into two of the four the ill-structured problems over a single class period. He was impressed that there was enough time for students to change groupings in transitioning between Steps 1, 2, 3 and 4, and was impressed that the lesson seemed to "gain time"—as if the lesson packed more physics learning into the allotted time than should normally be expected. An important part of this was the S3 infrastructure, and in particular the S3 agents which coordinated the flow of materials and students in the classroom. Overall, the teacher found that—while the smart classroom and the PLACE curriculum required a paradigm shift (e.g., the pacing, kinetics, motion in the room, and kids moving around)—the underlying S3 technologies allowed him to not worry about such matters, and instead focus on the important task of working with the students and their ideas.

Aggregated and emergent information can be used to support student inquiry, collaboration, and negotiation

As evidenced by the students' use of co-constructed evidence on the large-format displays in their final answers, community-contributed knowledge can be effectively used to develop solutions to complex problems. This was a major shift from previous iterations of our smart classroom design, in which students simply chose *which aggregated data to use* rather than *how to use it*. The fact that the students did not need to use all the information, but could instead be selective, required them to negotiate and decide what to use (and what not to). This was reinforced by a student who stated that "there was a lot of sharing and applying knowledge, because you had to explain to other people why [a principle or an equation] would apply, and it was kind of recapping your knowledge and also persuading others, expressing your opinion, everything that we did together." This added agency in this version of the smart classroom allowed students to engage with the aggregated ideas and their peers in ways that were less prescribed than in previous iterations.

Large-format displays and teacher tablets can work together to support classroom orchestration

By changing the tablet from a tool that provided simple reports on student work to one that supported the teacher with specialized alerts and enabled consequentially interventions (i.e., into whether a student group was allowed to progress within a step), we were able to help reduce the teacher's orchestrational load. By using the tablet as a tool to let the teacher know when and where he was needed, we ensured that he did not have to always have his head down, looking at the tablet, and could engage as a wandering facilitator, using the large displays and cues from students to aid him in deciding where he was most needed. The teacher was often observed using the middle of the classroom as an orchestrational hub, looking at the various displays before moving to help a particular group. Overall, we found that the two tools—the tablet and the large projected displays—were able to work in harmony, each affording unique but important orchestration supports to the teacher.

Synthesizing design principles from the four studies

The four iterations of our smart classroom curriculum, and the evolution of the S3 framework, have informed our understandings of how to support distributed, collaborative, real-time inquiry within a learning community. An important outcome of this work is a set of design principles, divided below into *orchestrational*, *pedagogical*, and *technological* categories, which can inform our own future design efforts, as well as the wider community of researchers and educators.

Orchestrational design principles

Orchestrational design principles are aspects of technology and activity design that pertain to the successful enactment of a desired activity sequence—including teacher supports, use of ambient displays, agent-based assignments of materials or groups, and other strategies or scaffolds. Our design iterations highlighted four important orchestrational principles.

Avoid a head-down experience for the teacher

The teacher's abandonment of the tablet during the third study brought to light the need to carefully consider what information a tablet should provide, as such devices tend to promote a head-down focus, and what information should be provided on the walls or other surfaces (i.e., promoting a more head-up experience). Reducing the teacher's head-down time increases his ability to scan the room and interact with students. Across all four studies the combination of the collaborative interactive displays and (in Study 4) the re-designed teacher orchestration tablet, were effective in promoting a heads-up experience for the teacher. This allowed him to see the products of the different groups around the room, and to make decisions about where he was needed.

Large, dynamic representations of student work can provide important ambient cues

As noted by Sharples (2013), making the work of students and the progression of class activities available and actionable is a significant orchestrational challenge. Our studies successfully addressed this challenge using large-format displays (i.e., projected displays or large monitors) for each group and for the whole class. These studies showed the important role that such displays can have in supporting a teacher's real-time orchestration decisions, by providing at-a-glance information about the work of the groups distributed around the room. These displays serve to promote a heads-up view of the classroom, helping the teacher decide where he or she is needed in the flow of the classroom activity.

Notification and feedback about activity states should be actionable and timely

In supporting teachers and students in the orchestration of class activities, it is critical to understand how feedback and prompts fit into the flow of activities. Information or prompts that are not actionable or that disrupt the flow of activities should be reconsidered in terms of when occur in the script (or if they should occur at all). During Study 3, providing the teacher reports on how students had answered past questions was of little use to him or the students, as they had moved on to another task; hence, the use of a prompt that tried to re-engage them with old content was disruptive.

Study 4 addressed this concern with the teacher's orchestration tablet. Using the *Progress Tracking* agents, the tablet informed him when each group had finished an activity and when a group needed his approval of their assumptions and variables. Unlike the earlier studies, where such notifications were not actionable, here the prompts were designed to give the teacher important cues on the state of the class that supported his orchestrational decisions.

Intelligent software agents can help coordinate the flow of activities and materials based on emergent class patterns

We were encouraged by the ability of the intelligent software agents to manage the complex task of tracking students' use of artifacts in the knowledge base, and informing real-time assignments of materials and groups. It would have been unrealistic and unmanageable to require the teacher to remember what materials every student had worked with, their current and prior group configurations, and their immediate resource needs. By off-loading such tasks to software agents, we free the teacher to focus on working directly with the students. Indeed, given the time and cognitive resources such orchestration would have required, it would have been practically impossible in a paper-based curriculum.

Discussion of orchestrational design principles

Following Dillenbourg (Dillenbourg and Jermann 2007; Dillenbourg 2013), our principles were extracted from multiple design studies in authentic classroom settings and close collaboration with the teacher. The principles are focused on the design of learning that is distributed across learning contexts, and emphasizes a community of learners, various technology elements, and a strong role for the physical learning environment. The inclusion of intelligent software agents further builds on the recommendations of Roschelle et al. (2013), who note there is considerable promise in analyzing and acting upon the learning traces of individual, small group, and whole class interactions to support classroom orchestration.

We can see important synergies between our design principles and those of Dillenbourg (2013), but also some divergence. For instance, Dillenbourg's principle of Control suggests that the teacher should always be able to supersede any system decision. However, in complex classroom designs, this may not be possible. Building from our research, Principle #4 acknowledges that in order for complex orchestrations to occur, the teacher may have to give up some level of control in order to gain more time and control over other aspects. This was exemplified when our teacher noted that he was freed up to focus on the students because the system took care of so many of the managerial tasks. Thus, we find our results to be in some tension with Dillenbourg's principle of Flexibility. He acknowledges as much himself when he states that "not all design decisions can be modified without losing the pedagogical value of the scenario" (Dillenbourg 2013, p. 490). On the other hand, our Principle #3 connects with Dillenbourg's concept that the teacher should be aware of what is happening in the classroom and that they should be able to act upon it and adjust their teaching based on emergent factors. Similarly, our Principles #1 and #2 touch on Dillenbourg's notions of physicality and visibility, as they both concern how the "shape of computers" (p. 490) affect the learning and orchestration. They key difference between our own principles and those of Dillenbourg is that his work aimed for a general set of principles for orchestration, where our own work focused on the specific context of smart classroom settings.

Pedagogical design principles

Pedagogical design principles refer to the design of technologies and scripted interactions that can support productive student collaboration and problem solving, including the assignment of individual or group roles.

Student inquiry can be informed by emergent, aggregate representations of the learning community's progress

We understood from the outset that one of the major challenges in supporting students as a learning community was the need for them to be able to see their own work and the work of others as part of the larger community, and to use this work to support their own inquiry needs (Hewitt and Scardamalia 1998; Gilbert and Driscoll 2002; Hoadley and Kilner 2005). Across all four studies, aggregate representations played a significant role in supporting student problem solving and developing high quality, domain specific insights. One early insight was that we must be careful to not give too much away in these representations: leaving sufficient room for students to develop their own extensions or interpretations of ideas, and ask questions about the information. We also gained some insight into how such aggregated forms of collective knowledge might support the formation of a cohesive learning community. By seeing their work aggregated with that of their peers, students could interpret their contributions as being part of a larger corpus of collective knowledge. By showing students' emerging representations of their collective knowledge (i.e., via ambient displays), we allow them to monitor the community's progress and track their own contributions. This suggests that well-designed visualizations of students' emergent knowledge can play an important role in supporting their discussions, their refinement of existing ideas, and their development of new ideas.

Students can benefit from curricular scripts that include individual activities which feed into larger group activities as well as overarching collective goals

Our early design studies highlighted how the products of individual student work can be leveraged for larger group and class-wide goals. This was particularly evident during the third design study, where the groups who were able to leverage the aggregated work of their peers (while in the smart classroom), outperformed both the individual students working at home and the groups who did not have access to the aggregated representations. Having individual students work on similar and/or connected aspects of a larger task, can provide a larger pool of opinions, evidence, and insight, which can then be used as a reference point for further discussion, debate, and refinement by the larger community. During the culminating activity of Study 4, S3 maintained an awareness of students' locations in the room, their position within the script, and their history of group membership. The smart classroom relied on intelligent agents (i.e., data mining) and real-time messaging to coordinate both the flow of materials to students on their individual devices, and the pooling of student contributions from the individual student devices onto the collaborative displays.

Assigning expertise groups can help distribute knowledge across the community and provide structure and support for further distributed tasks

Distributing responsibility by assigning expertise groups or areas of focus can help divide up tasks within the class and provide opportunities for collaborative knowledge construction that builds on these multiple perspectives. In the third study, rather than having each student look at *every* homework problem, we were able to divide the problems amongst expertise groups. Students were able to bring their expertise area to bear on solving problems that their group had not seen before. This principle suggests that distributing the task load and student expertise across the community can be an effective means of supporting more complex inquiry activities, consistent with work from the Fostering Communities of Learning (FCL) project (Brown and Campione 1996).

During the culminating activity of Study 4, the sorting of students based on their tagging frequency (between Steps 1 and 2) highlighted another interesting avenue for the emergence of expertise within a community. By sorting students based on their prior actions, we open up the possibility for responding dynamically to the growing expertise in the community, and for connecting students to each other or materials from the knowledge base based on these conditions. This principle is an ideal match to the notions of an evolving inquiry-focused learning community, and holds exciting promise for agent-supported distributed intelligence and community expertise.

Discussion of pedagogical design principles

Pedagogical Design Principles #1 and #2 descend primarily from our interest in learning communities, as investigated in prior work (e.g., Slotta and Peters 2008; Slotta and Najafi 2013). This research is concerned with how best to engage students individually and collaboratively, so that the products of their inquiry contribute to a larger sense of progress and achievement at the community-level. Principle #3 derives from seminal work by Brown and Campione (1996), concerning the role of structured scripts for supporting collective inquiry in a community of learners. It is consistent with the interpretation of collective inquiry that no one member of the community has all the relevant knowledge, information or expertise, and that students must collaborate to leverage their individual expertise in solving the task.

Technological design principles

Technological design principles deal with the specific hardware and software frameworks that support classroom inquiry—including the use of particular devices and displays, and the methods for distributing materials or students in the room.

Tracking users within a smart classroom offers unique opportunities for ad hoc groupings and collaborations

The ability to track where individual users and groups were in the class allowed us to create zones within the physical space of the classroom, then provide materials to students according to where they were in the room. This allowed us to conceptualize the notion of ad hoc groupings—where students work together and share materials for a short time depending who is currently tagged as co-occupying a zone (achieved by assigning students zone-specific metadata when they logged into a location). As we progressed across the studies, the use of intelligent software agents allowed for the introduction of more complex scripted interactions.

The ability to keep track of students' locations in the room also provided a degree of freedom to students, as it allowed them to go wherever in they wanted, in order to engage with different grouping of peers or different inquiry elements and their traces of what they had done previously and who they had worked with could, in essence, travel with them. Although the movement of students within the room, and their engagement with the materials at each zone, was somewhat limited because of the linear progression of the script, and the limited duration of the activity (165-min class period), this principle raises the potential to support longer duration and less coerced inquiry scripts. One could envision smart classrooms where students were engaged in longer investigations, in which the products of inquiry evolve over several sessions or across learning contexts. In such cases, the students could be tracked as they move throughout the room spontaneously, collaborating with their peers and contributing to a particular facet of the inquiry in a more ad hoc fashion, becomes integral to the success of the curriculum.

Small group interactions can benefit from large, shared displays that support collaboration and idea refinement

Giving students a large shared display to help focus their discourse and structure the products of their work can provide a common point of reference for discussion and debate, and reduce the exclusion of group members. These patterns were consistent across the first three studies when comparing student groups who engaged with shared large-format displays with those forced to cluster around a single laptop screen.

Discussion of technological design principles

Technology supports for student inquiry have been well chronicled in the learning sciences (Hug et al. 2005; Quintana et al. 2005; Slotta and Linn 2009). These technology design principles build on this prior research and our own findings from the initial design studies, with a specific focus on distributed learning. In particular, these design principles highlight the increased awareness of the role of the spatial environment, student mobility, and enabling interactions across multiple personal and collaborative devices can play in supporting learning in these kinds of environments.

Conclusions

Design studies that span several years and keep track of what worked, what did not, and how both feed into successive iterations of design are quite rare. The issue is pressing enough that Yael Kali made it the focus of her keynote at the 2016 International Conference of the Learning Sciences (2016). Successful design-based research requires conjectures about how learning is supported by our design features, and then refining both the intervention and our theories of learning in response to enactments of the designs (Sandoval 2004). This paper shows the value of design-based research towards advancing technology-based learning environments. We began with the notion that large-format collaborative displays had a strong potential for supporting students and teachers during live classroom activities, but we were unsure of which visualizations and forms of collective and collaborative interaction would work best. Similarly, the first several iterations of the smart classroom technology and activities alerted us to the potential role data mining and software agents could play in such a highly interactive space. However, as we were starting our investigations from square one, it was necessary for us to develop this research through successive cycles of design, enactment, evaluation, and redesign. The scope of this work and the refinements made to both technology and curriculum could not have been made in a single design iteration.

This approach allowed us to assess the efficacy of one or two features at a time rather than attempting some large complex design right from the outset, and then trying to make sense of what worked and what did not. An example of this was the introduction of the teacher orchestration tablet. Rather than abandon it based on the limited efficacy of our initial design, we were able to evaluate what particular attributes the teacher found useful (i.e., portable and provided real-time updates) and where it fell short (too distracting and too post hoc to be actionable during class). In response, we were able to redesign the tablet so that it became an integral part of the teacher's classroom orchestration and supported student learning outcomes.

This paper highlights how, across successive designs, we refined our understandings of how students can build on the ideas of their peers to develop more accurate and complex approaches to physics, how we can support the teacher in knowing when and where he was needed in the class, and the role that technology and the physical space can play in supporting both. In many cases we were able to build upon what worked, but equally important was our ability to honestly account for and adjust to *what did not work*. The acknowledgement that not everything works should not be a problem in the learning sciences. In truth, our failure to acknowledge it within our discussions of our work is far more problematic. We encourage students to make mistakes and learn from these mistakes (Kapur 2008; Litts and Ramirez 2014; Schön et al. 2014) and yet, we often bury our own. If design-based research is going to meet its goal or support the broader community of researchers, we need to recast what does not work not as failures, but as opportunities to rethink our assumptions about how to support teachers and learners and for developing new conjectures for investigation.

Another outcome of this work is the development of the design principles outlined above. Despite the highly technical aspects of our studies, many of these principles could be applied within a wide range of curricular designs. The use of large-format displays to support students and teachers can be achieved in a variety of ways that could still produce many of the same benefits. For instance, new forms of "active learning classrooms" have leveraged similar large-format displays to support student learning and teacher orchestration (Cotner et al. 2013). Many schools have under-utilized technology, such as unused projectors, extra displays, and in some case smartboards, that are lying dormant because teachers and administrators are unaware of how they could be used in productive and transformative ways. Our design principles can be seen as an adaptable blueprint for teachers, who could have students collaboratively plan out experiments or research projects and have their work broadcast to large-format displays from a single laptop, or through a web-based platform like Google Docs.

Similarly, the pedagogical design principles that arose from our work can be adapted in a wide range of contexts, depending on the capacity or needs of teachers and researchers. For instance, while the S3 technologies made use of aggregates of student work (Principle #1) and individual work feeding into larger collective goals (Principle #2) at high levels of complexity and interdependence, they could be adapted to a range of physical learning spaces. Wikis and other collaborative technologies have been shown to support similar kinds of learning (Peters and Slotta 2010; Scardamalia and Bereiter 2006). However, as our present work has shown, a critical look at the spaces in which the learning takes place and not just the technology supporting it, can be a key factor in supporting these designs. As such, others who would want to enact similar designs, even with other technologies, should carefully consider the physical aspects of their classroom.

Finally, there are some limitations that should be acknowledged. First, we acknowledge that this work required a team of researchers, technologists, and teachers several years to develop and enact. Teachers or researchers who might want to enact similar designs would be unlikely to have the same levels of persistent support in their own design and enactment efforts. Further, as this work is solely focused on physics classrooms, work in other domains could reveal unique features for learning in smart classrooms. Finally, it is worth noting that we worked with the same co-design teacher throughout the four design studies. This was important to our success, as it allowed us to keep track of all design decisions, and the teacher to reflect on what worked, and what did not, across successive designs. This suggests that teachers who are new to the unique pedagogical and curricular strategies employed in these kinds of designs might require some ramping-up before they can become comfortable.

This paper has described one research program that has attempted to address this challenge and provide design principles and research approaches for others to build upon. This 4-year design sequence describes the progression of our smart classroom framework from its initial conceptions to a full-fledged learning environment that was tightly integrated into an inquiry-based curriculum for high school physics, cutting across home, classroom, and smart room contexts. This progression would not have been possible without the involvement of the participating teacher as an integral member of the co-design team. Having the teacher on-board from the outset ensured that we were building a learning environment that addressed our pedagogical and epistemological goals and responded to the challenges of real classroom settings.

Finally, there is a growing interest in thinking of the physical places in which learning takes place as more than just static environments, but rather as dynamic and interactive places that can respond to their occupants, to peer arrangements and interactions, and to the varied contexts of learning (Makitalo-Siegl et al. 2010). We are excited by the growth of new technological paradigms, such as the Internet of Things, wearable computing, maker spaces and augmented reality, which offer new ways for students to connect with each other and the learning environment, extending the classroom beyond its walls into the world at large, and bringing the world back into the classroom in new and exciting ways.

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