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Procedural Collaboration in Educational Games: Supporting Complex System Understandings in Immersive Whole Class Simulations

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ABSTRACT

With the current rising need for sustainability education, understanding the interconnected political, economic, ecological, and social systems that motivate (system level) change, can be uniquely addressed through immersive multiplayer games. Immersion through a mixed reality experience, face to face interactions, and game mechanics that push players to play with and against their co-learners enhances the familiar benefits of participatory simulations – where learners engage in developing parts of a complex system, and then respond to the consequences of their own decisions through interpersonal negotiation and changing strategies. Here we present City Settlers, a city management (immersive multiplayer) game that supports such learning and elicits different kinds of collaborations. We present these different collaborations as evidence for a range of complex systems understandings. We call these socially performed representations of new learning – procedural collaborations. Using a sequence of vignettes, we present cases of how game and interaction design can foster different procedural collaborations, and how City Settlers enables these procedural collaborations to represent developing understandings of a complex systems perspective on sustainable development. Through our work, we highlight the unique affordances of social immersive simulations in creating space to perform and understand concepts hard to find in many simulation and game-based learning environments.

KEYWORDS

Computer supported collaborative learning; immersive simulations; complex systems; participatory simulations; game-based learning; ecology education

Given the increasing impact climate and environmental events are having on lives, communities, economies, and the world at large, there is a rising need for climate science and sustainability education (Egger et al., 2017; National Research Council, 2013). Climate and environmental sciences cannot be understood abstracted from the interconnected political, economic, social, and ecological priorities that drive them (Hollweg et al., 2011). For instance, politics often drives economic systems, which in turn, leads to key decisions about planning and growth. These decisions can then have far-reaching ecological impacts, which in turn, affect both the economic and social systems. In addition, the factors within a region and its environment are not siloed; the decisions of different territories managing their own economic-ecological-social systems directly and indirectly affect each other,

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particularly when they rely on shared resources to help and compete with each other. By designing learning experiences that incorporate multiple disciplines using interdisciplinary and integrated approaches, we can enable students to develop the sophisticated problem-solving skills they need to solve large-scale problems in the present and in the future (Madden et al., 2013).

An underemphasized aspect of learning about such complex systems in the real world is the actual experience of negotiating across different parties with competing interests. While educational research has shown some effectiveness in supporting learning about complex systems through a computer, and even networked collaborative games (Dearden & Wilson, 2011), their screen- and location-locked interfaces limit the kinds of face-to-face interactions that sit at the core of these complex systems (Kreitmayer et al., 2012). In contrast, immersive multiplayer games, and hybrid (combined digital and physical) games and simulations can leverage space and movement in a classroom to embody the geographical distribution and interdependence found in ecological systems; as well as, enable discussions and conversations at varying levels of privacy that emulate economic and political negotiations (Squire et al., 2007).

In this paper, we present an immersive whole-class multiplayer city management game that supports learners in enacting and understanding these interdependent ecological, political, and economic systems – through their planning and developing their own cities while simultaneously collaborating, cooperating, and competing with their peers as they grow and sustain their own cities' development. In these kinds of complex-system simulation environments, this development of understanding is reflected in learners making increasingly strategic decisions, within and across teams. To recognize and understand this, building on emergent dialogue (Antle et al., 2014) and procedural rhetoric (Bogost, 2010), we developed and applied a lens of *procedural collaboration* – identifying evolving understanding by observing the increasingly complex ways learners strategize and collaborate with each other (within and across teams).

Background

Participatory, Collaborative Simulations

Games and simulations have been shown to be effective in supporting a range of disciplinary learning (Holbert & Wilensky, 2019; Strawhacker et al., 2018), facilitating personally-relevant connections to underlying STEM and humanities content (Lenhart et al., 2008), increasing students' positive attitudes toward science (Verish et al., 2019), enabling them to engage in creative collaborative problem-solving (Strawhacker et al., 2018), and increasing their engagement with content, all while achieving the same learning gains as traditional instruction methods (Annetta et al., 2009). Management games and simulations, in particular, have shown potential to situate learners as the drivers of systems phenomena, and provide opportunities for player-learners to critically reflect on the role their actions have on the larger interconnected system (Dearden & Wilson, 2011). However, many of these games and simulations are locked into single-player formats, or multi-player interactions that restrict peer-to-peer interaction through screens, limiting the kinds of face-to-face interactions that are at the heart of many topics' complexity (Kreitmayer et al., 2012).

In response, participatory simulations provide a particularly fertile approach for students to collaboratively engage with and learn about complex systems (Wilensky & Stroup, 1999). Participatory simulations enable students to act as individual agents in a system and reflect on the system-level phenomena that emerge through their individual and collective agent actions. Participatory simulations often leverage the physical space of the learning environment, by situating elements of the phenomena under study across the room's physical layout and connecting them to students' own location in the room. Further, these simulations often respond to students' proximity to these elements and their peers, which can then directly impact the overall phenomena. For instance, in Colella's (2000) work, students were outfitted with microcontrollers that tracked their respective locations in the room, and when students came in close contact with their peers, to model the underlying concepts around how diseases spread.

A similar approach to participatory simulations is immersive simulations (Lui & Slotta, 2014). Immersive simulations leverage the physical space by transforming the learning environment into an immersive instance of the phenomena under investigation, creating a mixed-reality experience for the learner. For instance, in Wallcology (Moher et al., 2008), students interact with wall mounted monitors that act as virtual lenses into their classroom walls, allowing them to investigate ecologies of simulated bugs that "live" throughout the classroom. In EvoRoom (Lui & Slotta, 2014), students are immersed in Borneo and Sumatra rainforests as they investigate ecological changes over millions of years. While the depth of immersion can vary across these simulations, studies have shown them to be effective in drawing learners into the scenario under investigation, making it more personally relevant and meaningful (Becu et al., 2017). Taken as a whole, these kinds of immersive simulations are well suited to support rich collective inquiry around phenomena or systems that are hard to engage with in the real world, as they can foreground features salient to the desired learning goals.

Diverse Collaborations in Learner-Driven Immersive Simulations

As mentioned above, face-to-face, immersive simulations can allow learners to engage in the kinds of direct person-to-person interactions that lie at the heart of many complex phenomena, which in turn, provides opportunities for unique forms of spatially-dependent forms of collaboration to emerge (Halverson et al., 2018). For instance, students at one end of the room tend to interact with those near them and connecting or collaborating with others requires students to physically move across the room (in contrast to digital environments where space is a non-factor), potentially moving them into new contexts or settings, or even changing the simulation itself. For instance, in BeeSim (Peppler et al., 2010), young learners role-playing as (virtual) bees move around the classroom looking for nectar to share with their hive. Between each round of the simulations, students must work with their peers to nonverbally communicate which flowers in the room are the best for collecting the nectar. Where they move in the room, and which flowers they interact with, directly mediate their understanding of the phenomena. In RoomQuake, students work together to capture the seismic activity across their classroom, sharing their respective data with the rest of the class to triangulate and find the virtual fault line running through their class (Jaeger et al., 2016). However, not all face-to-face simulations and games are inherently collaborative through their mechanics. For instance, in Oztoc, a museum simulation in which visitors are tasked with constructing electrical circuits to capture and catalog fictional fish, participants are free to move between independent and collaborative modes of investigation. In many cases, visitors were observed engaging in divergent forms of collaboration, in which they collaborated for short periods to achieve complementary outcomes, while aiming to complete individual and divergent goals (Tissenbaum et al., 2017). These examples demonstrate how simulations and games developed for physically co-located play can foster learning through a rich variety of collaborative engagements.

At the same time, while many simulations have students working together at varying capacities – from constant teamwork to just parallel play – in pursuit of developing their collective knowledge, designed competitive play is often overlooked or avoided as a learning configuration. Taken on its own, competitive gameplay can lead to lesser engagement and poorer sensemaking in educational games, when compared to games centering on collective action and understanding (Peppler et al., 2013). This is due in part to the fact that in most competitive games, individuals pursue their own success, either disregarding or explicitly contesting others' success or progression (Janssen et al., 2010). However, some critics have argued that this is due to inherent flaws in the design of such activities, such as a "winner take all" approach, or the failure to get learners to consider the potential longer-term goals of their decisions beyond when the gameplay ends (e.g., promoting sustainability) (Fennewald & Kievit-Kylar, 2013). Relatedly, there is limited work that examines environments where participants can flexibly move between competitive or collaborative forms of play, allowing learners to identify for themselves the advantages and shortcomings of each approach.

Learning from Games: Procedural Rhetoric, Emergent Dialogue, and Procedural Collaborations

The need for foregrounding *choice* around forms of collaboration through simulations and games is bolstered by the unique value proposition of games – their ability to convey ideas in an *enacted* form. Bogost's concept of procedural rhetoric (Bogost, 2010) presents how the rhetoric of games – their ability to convey an idea or depict a story – is uniquely empowered by their participatory and choice-laden nature. By embedding player actions within a designed space of constraints and affordances, game designers convey a specific vision of how a world works, and similar to other kinds of rhetoric, players' engagement in this possibility space defines the specific understandings they take away from their gameplay. For instance, in the classic simulation game Civilization (Firaxis Games, 2005), players (in single or multiplayer modes) choose how their respective civilizations grow, interact with other civilizations, and ultimately succeed or fail. The ability to choose different pathways of progress, and ways of victory – colonization (through land control, interstellar travel, or military conquest) or diplomacy – represent a variegated, but particular, set of ways that represent success in the game, and the sequences of choices and strategies players undertake represent (simplified) understandings of how such progress and "victory" can occur in the world.

While these kinds of games can support students to engage in productive discussion with their peers (Lee & Probert, 2010), it may require significant outside scaffolding, and in many cases, students can play the whole game with limited direct discussion or coordination with peers. In this context, Antle et al. (2014) argue for the educational value of *codependent* *access points* – design elements which force players to coordinate disparate pieces of information about a complex system to make an effective decision – as an avenue to enact social learning through design-triggered conversation. These access points create space for differential perspectives across the participants, which are leveraged to generate rich conversation about the whole system, termed *emergent dialogue*. For instance, in their tabletop learning simulation YouTopia, students work together to make decisions about how to grow their city and collaboratively discuss the impacts of their individual decisions on the desired decisions to be undertaken by their co-players. A critical component to codependent access points is that while it encourages collaboration, it does not force it, giving students a certain level of autonomy in their collaborative discussions (Fan et al., 2014).

Inspired by Antle's design recommendations and the underexplored nature of learning complex systems phenomena as embodied in different forms of collaboration, in this work we propose the concept of *procedural collaboration*. As described by Bogost (2010), the nature of the collaboration underlying a game is integral to the systems understanding it fosters – playing partial information cooperative games like Mysterium builds different communication skills, in comparison to full information cooperative games like Pandemic. The conversational dynamics and underlying strategies are similarly different in competitive games like Scotland Yard (partial information) and chess (full information). In these games, the collaboration mechanic only occasionally reflects how the real-world system being emulated works. In Pandemic, players play a team of researchers, medics, and other medical workers and managers making collective decisions to mitigate the spread of an infectious disease. This simplified cooperative mechanic presents a specific model of how different expertise could work in synchronicity to fight a pandemic. For the sake of gameplay and design, it does not engage with the potential of competing interests held by different nations, organizations, and stakeholders in such an endeavor, which strain decision making and coordinated productive action. As a result, Pandemic chooses to engage in learning through only one kind of procedural collaboration – the ability of a fully coordinated and positively interdependent team of medical workers in fighting the spread of a disease.

In this spirit, we describe *procedural collaboration(s)* as modes of engagement which represent system phenomena which are also learning goals. Performance of concepts as social engagements is under-recognized as cognitive learning goals, since conceptual understandings are predominantly assessed and recognized through symbols and text. Procedural collaborations as a design, as well as an assessment mechanic for identifying learning events, is unique, as it invites us to design and look for players choosing to engage in a variety of ways as signs of understanding the relevance of different social engagements for different system goals. That is, instead of isolating a complex system experience to a single lens – constant competition in economic systems or full cooperation for ecological challenges – designing for learning through procedural collaborations pushes us to recognize the varying affordances of different social configurations, and helps learners learn how to transition between such configurations and to engage in the most appropriate ones for different situations. This learning and practice is also more authentic to most social and political systems in the real world – where creating cooperation across competing parties is a frequent requirement and a challenge people are often under equipped for.

Immersive multiplayer games are uniquely well situated to foster such a plurality of social configurations and help learners learn through them, as they support face-to-face interactions, and leverage the physical space to allow these interactions to happen at multiple points across the room (in some cases right on top of each other). In addition to the benefits of identifying emergent behaviors in complex systems commonly employed in physically collocated participatory simulations, games engage learners in role-play that makes their (interpersonal) engagement uniquely involved. Games with fixed interplayer engagements – such as only engaging players competitively, or players coordinating in a shared team – limit how players understand the role of different configurations in making progress in a system. Moving between different configurations, like competitive goals, to coordinated play within the same system provides a more expansive and engaged experience where players feel like agentic city planners (or analogous actors) wanting to succeed and understanding when it is beneficial to coordinate with others or compete, rather than being limited in these choices and only experiencing the work of city planning as a team, or in a competitive environment. It also provides an immersive experience, which surfaces the motivation for why these different configurations across different roles and systems emerge in the real world.

To this end, we investigated how City Settlers, a multiplayer city management game, could help learners experience and engage in rich and complex, collective world building, as they try to coordinate their actions over what are frequently competing resources and interests. To understand this, the research questions driving our work were: 1) How can the design of (city) management games support the development of complex systems understandings? 2) How does negotiation and conversation within and across groups of player-learners reveal development in these understandings?

Methods

Participants and Settings

Ten middle school students from a summer camp, in a mid-sized city in the midwestern United States, played City Settlers for over 2 hours. Seven girls and three boys of different ethnicities were distributed randomly into four teams, introduced to the game, and asked to start playing. We did not run the overall camp and had little information on quantitative aspects of the camp outside of the students who joined this session. That said, we can describe basic impressions. The campers were familiar with all the devices being used (tablets, projectors, etc.) and were familiar with each other through their shared summer camp. All campers had some experience with games, though only 4 identified as "gamers" as collected from our pre-survey. While not collecting demographic data from the learners, the authors' observations provoke analysis on how race and gender might have mediated the creation of certain social configurations during this gameplay.

Research Design – City Settlers

Designed to leverage the affordances of mixed reality and face-to-face learning of immersive and participatory simulations, City Settlers is a whole-room immersive simulation, in which the room "becomes" (through collective imagination, projected screens, and tablet computers) a fictional shared planet on which teams of participants develop their cities. City Settlers has been developed as a web application for easy web browser-based access across phones, tablets, and a variety of computers. Technical development of City Settlers has been led by the authors while being helped by numerous other investigators across different iterations over 2 years. MeteorJS is an open-source full-stack javascript based web development framework that has played a foundational role in developing City Settlers, enabling seamless interactivity and data synchronicity across devices – such that actions on any one device immediately reflect corresponding changes on other devices.

We designed City Settlers with interconnected mechanisms across specific city *metrics* (pollution, population, and happiness) and *resources* (gold, steel, cotton, and food) that depict each city's overall *stats*. These *metrics* are intended to allow teams to pursue different goals for their cities rather than one externally imposed goal state. The bidding and trading systems are designed to support teams to compete or collaborate as they see fit. The game runs on a turn-based system. Every turn involves decisions around bidding resources on buildings in the marketplace, trading resources with other teams, choosing which buildings to run in response to the growth and usage of resources in the city. We (the researchers) run the game as "administrators" during gameplay, and thus control when the rounds change. We encourage players to try to make their decisions within time spans of 4–5 minutes but tend to be responsive to players' desires regarding being ready earlier or needing some more time for their decision-making.

The game has three kinds of buildings – (steel or gold producing) factories, (food or cotton producing) farms, and (pollution reducing) parks; and four resources – gold, steel, food, and cotton. Farms use the products of factories (steel or gold) to run, and factories use the products of farms (cotton or food) to run. Both produce different amounts of pollution which are dealt with through parks.

Buildings are acquired through a hidden bidding mechanic on the marketplace. The marketplace is populated automatically with a set of four randomly chosen buildings every round across the four different resources (Figure 1). The hidden

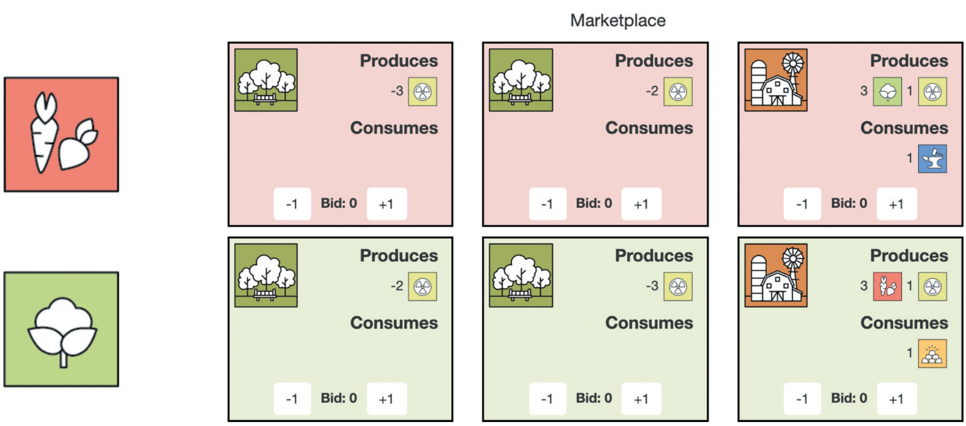

Figure 1. The bidding marketplace: the leftmost column depicts the resources used to bid on the buildings in their corresponding row. The first two buildings in both rows together depict 4 parks. The right-most column has a cotton farm and a food farm. This view depicts the parks and factories that can be acquired by bidding food (first row), or cotton (second row).

bidding system involves players making bids to purchase buildings in competition against other cities, but not knowing any other city's bids without talking to them. This information gap is created as an adaptation of Antle et al.'s (2013) codependent access points – wherein teams' unawareness of others' bids and a lack of coordination around information and strategies often leads to failed bids – creating a space for players to negotiate with each other and choosing to engage in implicit competition or explicit coordinated action through this interdependence that is often negative but can be made positive.

Once buildings are acquired, players choose which buildings to run or "turn off" every round. The number of buildings they can run is limited by the population they have, but buildings can also fail to run if the city did not have enough of the resource required to run it. For instance, a farm might not run if a city did not have enough metal needed for its operation. The pollution in the city (produced by different buildings and cleaned up by parks) affects the happiness of the population, and access to food and happiness leads to corresponding increases or decreases in population. Excessive pollution (specifically when it exceeds "9" in-game units) also spreads to neighboring cities.

Player actions are distributed across three other screens. The "City status" screen (Figure 2), shared by the members of each team, provides information about the resources and buildings in a city, and the relationship between different resources and metrics. The

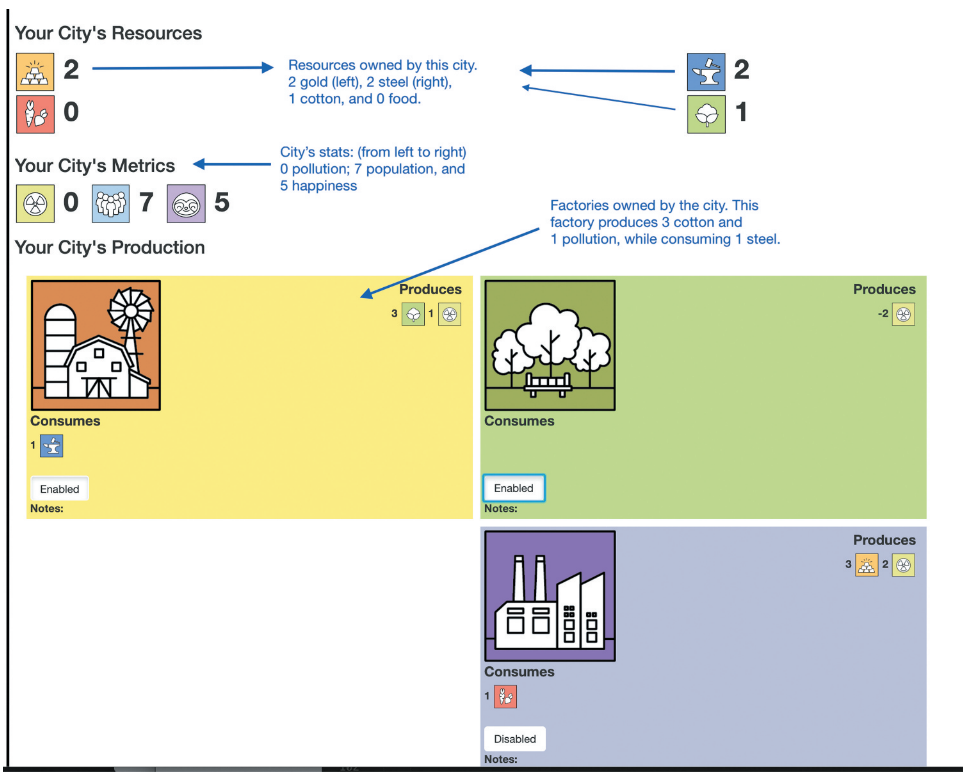

Figure 2. The city status view displays the city's resources: pollution, population, and happiness, as well as the available buildings which city managers can choose to enable or disable each round depending on their goals, plans and current resource status.

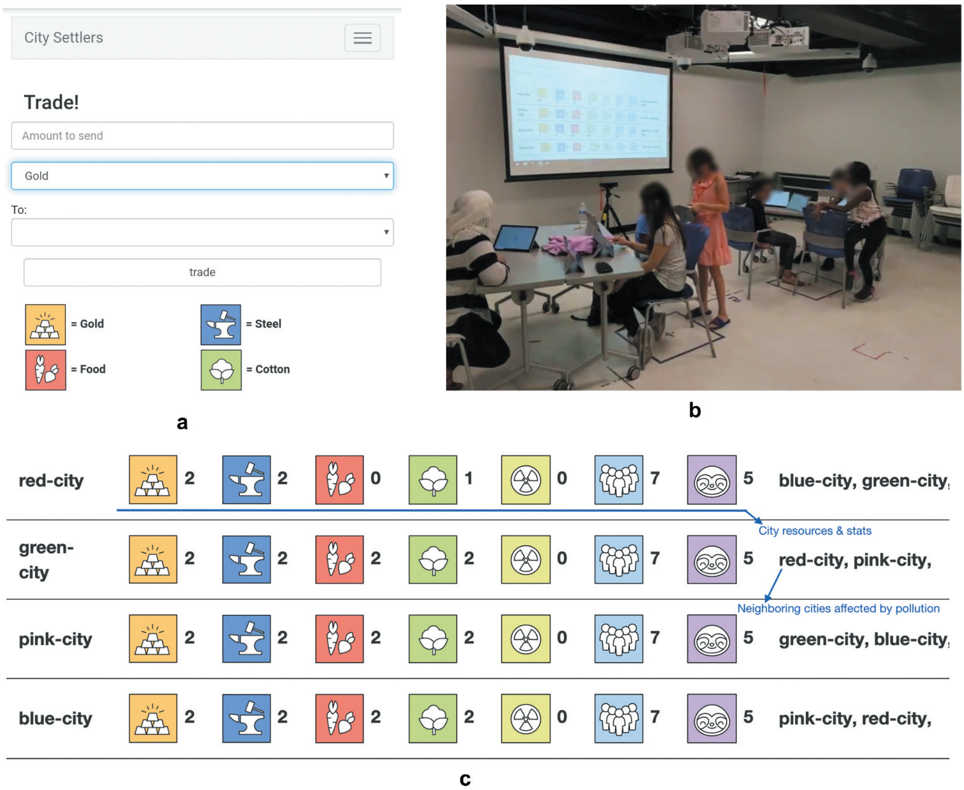

Figure 3.. Screenshot of the mobile interface of person-to-person trading interface given to each player. This is intended to support individualized play and cross-team collaboration.

"trade" screen (Figure 3), available on players' individual devices, enables trading resources across teams. The "Planet status" screen (Figure 4) is a large-format display at the front of the class (Figure 5), providing information on the overall status of each city and the cities bordering it. Neighboring cities can affect each other by leaking excess pollution outside their borders, which provides another intersecting access point to incite players in working with or against each other.

Data Collection and Analysis

We collected gameplay data through telemetry log files, field notes, and video and audio recordings. Using these multiple modalities of data collection, we aimed to identify emerging and changing discourse (talk, gestures, as well as play actions) among participants. The campers were invited to a technologically equipped classroom in a medium-sized city in the Midwest United States. This classroom had five cameras – one placed in the center of the ceiling recording a panorama of the whole class, and four cameras pointed at four quadrants of the classroom (which corresponded with the four tables at which each team's city was situated – Figure 23). We placed a portable microphone at each table to record conversations and synchronized the audio of each table's mic with the corresponding video stream for video analysis. While our audio stream had a limitation of not fully capturing talk

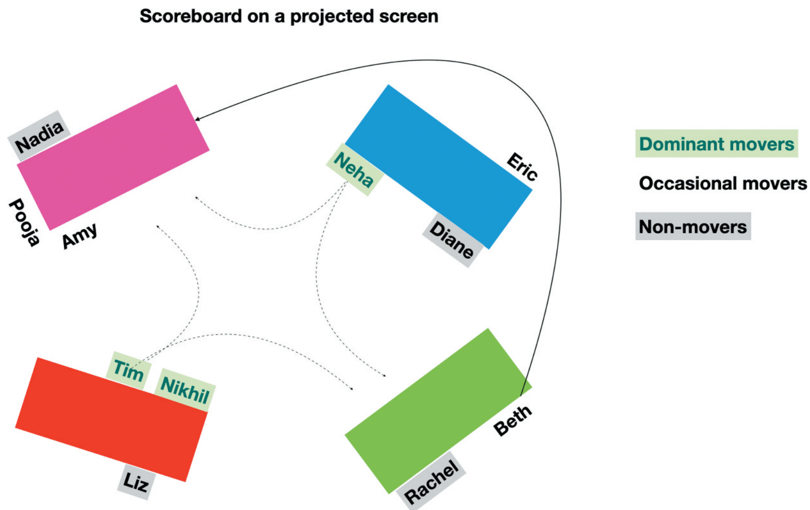

Figure 4. The scoreboard displays all cities' available resources, population, pollution, and happiness. This globally available information provides all the different kinds of information that players might choose as goals.

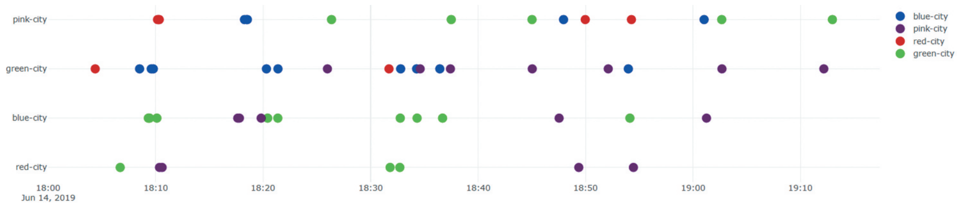

Figure 5. The game is played by teams of players with individual trading interfaces, the city and bidding view shared across their team on a common tablet, and a central shared display showing a "scoreboard" (part c.).

between students in the middle of the classroom away from any table, we were able to confirm, through the panoramic video stream, that this rarely happened. The camp counselor spent most of the gameplay sitting at a separate table away from the game itself. Two researchers facilitated the gameplay, starting with a presentation explaining how to play, orchestrating each round of the game, and responding to students' different queries.

In this work, we focus on presenting a case study (Merriam, 1988) of the learners' talk with each other, and how this talk moves between competing over common interest building decisions and coordinating across different building decisions and complementary goals – which in turn, reflect different kinds of procedural collaborations. To reveal these different cases of procedural collaborations, we began with a systematic coding process which drew from the Divergent Collaborative Learning Mechanisms Framework (DCLM – Tissenbaum et al., 2017) and Russ et al.'s (2008) framework on recognizing mechanistic reasoning. DCLM helped us highlight the different ways people interacted with each other – for instance, by **narrating** their strategy, **modeling** different actions, or **negotiating goals** among each other. Additionally, we coupled DCLM frames with descriptions of within and across group codes – to surface contrasting patterns of interaction among teammates and across members of different groups/cities. Coupling this description of the collaborative modality with codes of mechanistic reasoning about the game (for instance, identifying **causal** relationships between **resources** and **population** change, or **predicting** the effect of running specific **buildings** and having different **resources** to gain **happiness** and other metrics) foregrounded developing understandings about the game, and the underlying system phenomena. These codes were applied at episodes characterized through a change of the involved participants. A long continuous interaction between two students would receive multiple codes indicating all the different ways and topics they talked with each other about. If another student came in, the episode, as characterized by the group composition, would change and be coded as a new episode. The grouping of participants was done at the city level, so an episode of within-city talk would change when someone from another city would come in and interact with them. This coding work was done across three researchers who trained on select samples, coding shared snippets across three researchers. This made our analysis design fully-crossed (multiple codes being applied on the same subjects across multiple coders). As a result, following Light's (1971) recommendation, we use the mean of Cohen's Kappa across the three raters as our measure of attaining satisfactory intercoder reliability. The pairwise agreements on our scheme across our coders were 0.61, .68, and 0.72 providing an average Kappa value of 0.67. After reaching this agreement, we coded the video across all four groups' video streams independently. This analysis revealed broad patterns of how players interacted with each other across their gameplay and how these interactions changed over time and in response to different game mechanics (i.e., system phenomena). We used our data analysis and this pattern identification to choose cases that exemplified these different forms of collaboration in response to game understandings.

These collaborations are presented in chronological order, in a vignette style (Miles & Huberman, 1994) to provide a sense of temporality and progression between the different kinds of collaborations, and how they are built on top of each other. To thoroughly understand these interactions, we present these conversational excerpts paired with a discussion about the system phenomenon understanding reflected in the interaction, and how the design of the game and setting affected these interactions (i.e., an expanded explanation of what our codes compactly represented). This talk and analysis are coupled with highlighting the movement of players across the classroom's physical space. This was drawn from the thicker description we had already applied to the coded interactions (for instance, for interactions coded as **across group** talk between two teams, we added a description of which table the interaction occurred at and which specific students were participating).

Lastly, we couple these analyses with a summative description of gameplay actions that took place between groups. We collected telemetry data of students' gameplay on the same server that maintained the entire game state and responded to players' actions. The City Settlers server (situated on the university's AWS servers) is where we host the game, lead all players to register, login and play on, and which records the different actions that players take, records the corresponding changes in the game state and reflects this game state data to the players to think about and play with. The most overt across-group interaction in the gameplay data was reflected in the trading of resources between cities (conducted by individual players on their mobile interfaces, and not the city level shared tablets). We present a plot of which cities traded resources with each other to point out patterns of the interconnectedness between cities' collaborations and how that intersected with the different participatory behaviors and patterns exhibited by the players.

We present these changing collaborative interactions as a result of the game's features centering flexibility across forms of play and engagement, and how the evolution of learners' interactions represents a development of understanding. These understandings are reflected in the goals they choose and the strategies they attempt through inter-player talk, negotiations, and in-game actions.

Results

As shown by the within group and across group conversations – largely centering around what buildings the teams want to buy and how much they want to bid on them (Table 1) – initial gameplay began with players attempting to acquire buildings from the marketplace. This engendered a **competitive or "parallel"** form of play – where players largely focused on their own goals, and were only engaging in competition as embedded in the game's mechanics without deliberately trying to undermine each other's progress.

This is a direct consequence of the design of the game, where starting one's economy and actions in a city relies on acquiring buildings, which in turn are obtained through a scarcity driven market. This is resonant with basic models of economic development, which describe an initial direction at producing resources to enable participation in broader economies, and gradual cognizance of broader social systems affected by the economy (Stern, 2004).

Once players' cities began to develop (e.g., producing or acquiring most of the resource types), teams expanded their goals. Since a city's population limited the number of buildings it could run, and access to different resources affected population and happiness, teams started paying attention to the other changing metrics of their city. This led to an increase in players attempting to understand how these metrics work. Players also started articulating and grasping more complex causal relationships in the game in order to aim for specific goals (Table 2). This continued the trend of **parallel** play, setting the stage for understanding the underlying mechanics of different phenomena in this world, not just from the interface, but also from each other. Here they largely focused on understanding **intra-city phenomena** – how a population is needed for running buildings, and how food and pollution affect population.

The conversation in Table 2 provides an example of a "need based" inquiry into the game's underlying economic systems, which involves producing resources that are specific to sustaining social systems. Here, players engage in inquiry aimed at barriers to growth.

Table 1. Competitive or "parallel" interactions aimed at striving for individual growth – acquiring capital (resources or buildings) by bridging information gaps – and only coordinating pursuits in the short term (asking for other teams to not Bid on a building; offering them an alternative option that would help both teams, but not incur any cost on the proposer).

Speaker-Group	Dialogue
Nikhil – Red City	"Are you bidding for the cotton park? "(referring to the park that is to be purchased using cotton)
Beth – Green City	"Can you let us have the steel factory? You can have the cotton one instead."

Table 2. Competitive or "parallel" interactions aimed around individual growth, and negligible goal or strategy coordination across teams.

Episode	Speaker-Group	Dialogue
1	Eric – Red City	(Reading off the screen) We do not have population, cause the food is more than population, people are well fed and the population increases; if it's less than 0.7x it drops, so we can't have population
2	Eric – Red City	How much pollution do we have? We have 7 pollution?! What?! We have so much pollution!
	Nikhil – Red City	We have minus people, we need food
3	Eric – Red City	We need to turn off one of your factories to run our park Now I get it

Table 3. Recognition of damage caused by industrial "development" – locally and globally (in terms of cities).

Speaker-Group	Dialogue
Nikhil – Red City	"Make everybody's lives miserable, even our own people!" (this was said both in humor as well as despair, as it was followed by "Why am I so happy?!")

This growth was not just in terms of increasing resources, but also aimed at reducing pollution. It soon became evident that their rising pollution was affecting them as well as others (Table 3). This became the starting point of recognizing **inter-city interconnectedness** which in turn opened up a space for engaging in a variety of cross-group collaborations.

Here, the push toward competitive orientation – with groups comparing their relative populations to those of other cities – was facilitated by the scoreboard presented on a separate large central display. This display was intentionally designed to require all students to use the same centrally located information space to unpack macro-level (i.e., whole simulation) game states. As a result, the display afforded unique opportunities for students to engage in shared expressions of the state of the game, with students shouting out how their city was doing to the rest of the class, and in many cases comparing different success metrics between the cities. For instance, right before Table 4's episode 2 (see Table 4 below), Pink City's members had public (distressed) inquiries regarding "Who is polluting us? Who is spreading pollution?" This led to a public conversation across Red, Green, and Pink City where they found out that both Red and Green city were spreading pollution.

As mentioned above, a key aspect of immersive participatory simulations is the ability for physically situated phenomena to affect other elements in close proximity. In City Settlers, one of the ways this was achieved was through the spread of excessive pollution to neighboring cities. This could in turn have cascading effects, causing the pollution in those cities to rise, and eventually spreading to even more distant cities. The spread of pollution from one city to others led to the creation of **complex inter-team collaborations** (Table 4).

This negative feedback loop across teams – one team's pollution causing negative effects to their physically proximal peers in the class – was designed to be a driver for inter-group communication. Being negatively interdependent is an integral factor in the real-world phenomenon of sustainable development, as well as a mechanic that pushes for players to

Table 4. Recognizing the interconnectedness of cities, and moving from understanding, to demanding others independently change their actions (independent or competitive participation), to eventually negotiating exchanges which enable mutually beneficial pathways for growth (positive coordination).

Episode	Speaker-Group	Dialogue
1	Neha – Blue City	Can other cities' pollution affect us?
	Researcher/ Facilitator	Yes they can.
	Neha – Blue City	How is that fair? What should we do?
	Researcher/ Facilitator	You need to talk to red city and see if they can reduce their pollution"
2	Pooja – Pink City	Green city! Stop it! Stop polluting us! You need a park! We need a park!
	Beth – Green City	If you don't bid on the park that has cotton, we can give you . . . (Speaking to Pink City)
	Pooja – Pink City	If we try to get a park then they will not get a park. We can ask for steel so they can get a park . . . (Discussing within her own Pink City group)
	Nadia – Pink City	You better get a park! (directed at Green City)
3	Beth – Green City	We don't have enough people
	Amy – Pink City	Which park are you doing?
	Beth – Green City	Wait no no no, we're not bidding for a park, literally, we don't have enough people to run them. We have two parks right now. If you give us food, then we . . . If you give us food for free, then we won't pollute your land
	Nadia – Pink City	Why for free? You should give us something. We give you food then you give us
	Beth – Green City	No that's not; I mean if people aren't there . . .

have to discuss and negotiate with each other directly. We expected this mechanic to increase the occurrence of players physically *moving* to others' cities. This was reflected in the implementation, where after multiple rounds of pollution growth, it began to spread from Green and Red City to their neighbors. When this happened, Beth from Green City moved to Pink City's table for an extended period of time, with Beth and Pink City's members discussing the impacts their cities were having on each other and the system as a whole (Table 5). This provided an example of **involved** cross-team **collaboration** and mutually beneficial strategization – a simple but key real-world method to access

Table 5. Mutually beneficial coordination developing into cross-team strategization and collaboration.

Speaker-Group	Dialogue
Pooja – Pink City	Get a park, you're polluting us (as Beth comes over to Pink City)
Beth – Green City	I know
Pooja – Pink City	You aren't just polluting us, we're polluting you guys
Nadia – Pink City	Wait, who's polluting us?
Amy – Pink City	Green city
Beth – Green City	And blue city
Amy – Pink City	Blue city's polluting us?
Pooja – Pink City	No, we're polluting them [. . .]
Amy – Pink City	Our happiness is so low!
Beth – Green City	So what do you need for that? (Scrolling through their City Interface and looking at their marketplace bids) Yeah 4 steel. You need steel, let me see how much steel we have.

Table 6. Individual pursuits on newer goals chosen after having overcome inter-city conflicts and challenges.

Episode	Speaker-Group	Dialogue
1	Neha – Blue City	Yeaah! and we have 0 pollution and 3 people. Oh my god, pink city has 9 people”
2	Eric – Red City	Yes! Our pollution is so low now!
3	Nadia – Pink City	Yay! We got happiness!

sustainable development. While this enacted collaboration appeared obvious, it was noticeable that no other teams managed to appreciate and/or develop such an involved collaborative work process.

Most cities managed to overcome the problem of over-pollution by working together (different teams engaging in different amounts of involved collaboration), and eventually went back to individualistic pursuits stemming from trying to improve metrics (independently – “our pollution is so low now!”), or perform better in comparison to other cities (“[. . .] we have 3 people. [. . .] Pink City has 9 people!”) (Table 6). This indicated a return to **parallel play –** the default way of approaching development in the absence of crises or other pressing needs to engage collaboratively.

The face-to-face nature of the immersive simulation played a key role in these interactions, with most interactions taking place in a fly-by manner – with players visiting other teams’ tables and only pausing long enough to receive an acceptance or rejection of their proposal. This was characterized by exchanges shorter than 3–4 turns and lasting less than 30 seconds. These interactions also engendered the creation of mover-sitter roles – some players who did a majority of the moving around, and others who never moved from their table (Figure 6). While Red and Blue City had active movers, Pink and Green City had completely stationary members and occasional movers. Pooja & Amy from Pink City only went to Green and Red City tables, less than 5 times in total; and Beth from Green City only went to Red City twice, located immediately next to their table, and to Pink City 4 times, located across from them. Figure 6 depicts the distribution of players across the room, and a highlight of the movements by different players. The gray highlights players who never moved from their table. A recurring factor among the non-mover players included limited access to the City tablets, which other members in the team were tending to control and carry with them while moving.Figure 6.Positioning of the different cities’ tables and players over the room. Green highlighted dominant movers mostly only visited Pink and Green City for short fly-by visits (dotted arrows). Pooja, Amy, Pooja and Beth moved occasionally, Beth’s 5 extended visit to Pink City discussed in Table 5 (indicated by the block arrow). Grey highlighted players who never left their tables.

A glimpse of the inter-city connections enabled by these different movement performances is depicted in Figure 7, which presents which teams conducted trades with each other – pink and green city traded with all other cities, and red and blue never traded with each other. This is particularly remarkable since Red and Blue City had dominant movers, and Pink and Green City’s members were much more limited and deliberate in their movements across tables.Figure 7.A plot of which cities traded with other cities across the gameplay session. A key highlight here is how Blue city and Red city never traded with each other, only with Pink and Green city; whereas Pink and Green city had trades with all other teams.

Discussion

This paper examined a spectrum of collaborations that took place within and across teams while situated in a whole-class participatory simulation, and how these collaborations resulted in changes in students' domain understandings, goals, and strategies, both within and across groups. In the context of sustainability education, these collaborations serve as means for students to develop the kinds of interdisciplinary and interconnected reasoning required to understand such a complex topic. This system level understanding, both as a collaborative act and as a central learning goal sits at the heart of what we call *procedural collaboration*. Focusing on procedural collaboration enables us to inspect the value of in-game interactions as conceptual understandings themselves. In terms of the research questions that drove our work – the relationships between the design of collaborative games to support the development of complex systems understandings, and how changing different forms of collaborative interactions reflect evolving understandings – this paper reveals several key findings. First, we discuss how the design of (city) management games can support the development of complex systems understandings (Research Question 1).

As students took part in City Settlers, they needed to work with their group members and the other cities (groups) to navigate and understand how their collective decisions impacted both the micro (city level) and macro (whole class) system phenomena. While early decisions in the game were largely prescribed – such as students bidding on and buying their first building (Table 1 above) – how the simulation would unfold became increasingly unknown and driven by the groups' decisions and collaborations. As discussed above, many of these decisions were made on-the-fly, as students moved around the room and made plans based on their awareness of what other teams were doing, and their ability to coordinate trades and bids (e.g., avoiding competing with other cities or using their awareness of what others were doing to overbid them).

The hidden auction system invited an inherently competitive orientation in rewarding the highest bid with the building. The hidden aspect of other teams' bid information was intentionally designed to create information gaps between groups, by not showing each city how much others were bidding. This created space for the creation of cooperative interactions, such as cities coordinating what to bid, or not bid for. This enabled cities that worked in this way to spend fewer resources on pursuing specific buildings and strategies, as was seen in the negotiations between groups in Table 1.

This work also revealed how technological design decisions concerning which interfaces and devices carried which pieces of information, play a key role in facilitating procedural collaboration and students' complex systems understanding. Our choice to use tablets for the team interface was intended to provide a medium sized display that could be seen by team members around a table. An unintended effect of not tethering the tablets to their corresponding tables, was that the *movers* often decided to carry the team tablet around with them while engaging with other teams. This often left the stationary (*non-mover*) team members to be left with a lack of information to process (buildings on the marketplace; state of the city and which buildings to run or not) and decision-making power. Despite the stark difference between the *dominant mover* and *non-mover* roles, the space-oriented and multi-interface supported gameplay afforded contribution across roles. This was made evident by how the trade connectivity (i.e., the number of teams they traded resources with) of teams that had dominant movers was less than that of the teams with moderate movers. We also saw some non-movers engage in public as well as cross team talk and strategizing – specifically Nadia from Pink City (in Tables 4 and 5) contributed to in-team strategizing as well as engaging in negotiations with Green City. While these were unintended consequences of our design, they point to the importance of recognizing the role of the physical space itself in supporting student engagement with, and learning of, the underlying complex systems in these types of games and simulations.

To understand how these games support students' systems understandings, our findings also indicate that designs that encourage or constrain this movement may affect the learning across students. For instance, we observed from Table 1, and other observations, that Red and Green city members did interact, occasionally engaging in quite complex negotiations. To this end, understanding the learning experiences of different roles in such environments is a much needed space of inquiry, as research around emergent roles often raises the concern of providing variegated learning gains across different learners (Strijbos & Weinberger, 2010). While some non-movers did participate in this gameplay, others (specifically Rachel from Green City, Liz from Red City, and Diane from Blue City) did not at all. This lack of participation is often a gameplay challenge in learning environments and requires thoughtful design to make space for productive engagement across more players. We are currently exploring different possible design solutions to mitigate the nonparticipation of players. These include the introduction of limited scripted roles, so different players have unique abilities and responsibilities creating motivation as well as space for broader participation. We also saw the negative consequence of portable city interfaces – wherein *mover* players carried the tablets away leaving their other teammates with a lack of control over or critical information about their city. This informs us of the value of constraining portability over some interfaces (specifically small group displays in the case of City Settlers).

For the second research question, the examination of students' negotiation and conversation within and across groups (Tables 1–6 above), we have presented a flow of how systems understandings developed in this gameplay session around City Settlers.

Our observation of students moving around the room and getting information from other groups, fostered a spectrum of competitive and collaborative orientations. As noted in the results, the understanding of a scarcity driven market's mechanics (as enacted around the bidding mechanic of limited buildings) was engendered through the *procedural collaboration* in the form of competitive play at the start (Table 1). In the case in Table 4, pollution spread caused Red City to identify which cities were the key polluters, and to push them (specifically Green City) to change their actions to reduce damage across the game world. This engagement was a *procedural collaboration* in the form of demanding and prompting cooperation engendering an understanding of how to develop and grow in an interdependent system. This eventually became a deeply cooperative set of mutually beneficial moves (Table 5), where they pursued mutually exclusive buildings and set the stage for supporting each other as allies. This *procedural collaboration* enacted through collective strategizing and coordinated action represents an integral component of understanding sustainable development (Littledyke et al., 2013). The students' development of deeper understandings of the system and its underlying processes, resulted in complex collaborative strategies. This kind of collaborative understanding and negotiation of desired outcomes stands in contrast to many traditional classroom learning experiences wherein individual students (or groups) focus on "states" as markers of progress, and what they need to outperform their peers in. This narrow focus, in turn, limits space for divergent, or parallel goals.

Building on this, the cases shown in Tables 4 and 5 highlight the complex interactions that groups developed in response to their growing understanding of the underlying interdependence within the simulation. Once they realized that pollution could spread across the physical layout of the classroom, they began to adjust their strategies and goals toward more parallel and less competitive orientations that allowed their respective cities to best succeed. In Table 4, we see teams extending pressure to the polluting cities and responding with efforts to coordinate. Exchanging resources as a way of coordinating actions on the marketplace, as well as running different sets of buildings was a unique negotiation that emerged out of the deeply interconnected systems within and across the cities. This coordination between Green and Pink city became more involved, where in the next round, Beth from Green city actively interacted with Pink city's bidding interface to figure out how to trade resources appropriate to get parks for both teams (Table 5). This was a particularly powerful shift in students' orientation on their goals, from being purely competitive (i.e., *us* against *everyone*) toward an understanding that in order to succeed, they would need to work with others to maximize their own growth (and reduce negative system-level effects).

These cross-group procedural collaborations did not mean that groups were unable, nor dissuaded, from diverging from the collective goals to orient toward their own micro-level goals once the macro-level issues were satisfied. As Table 6 shows, at the beginning of each round, students still were deeply concerned with how their individual cities performed, and largely made decisions that aimed to improve what they identified as the key metrics for themselves, and how it related (competitively) to other cities in the room. For instance, while Pink city succeeded in raising its happiness, and Blue and Red cities celebrated their low pollution, Blue city lamented their lower population in comparison to Pink city (which, however, had much higher pollution than them).

We acknowledge some limitations to the work presented here. The short duration of our data collection – testing gameplay over one afternoon with learners from a summer camp – limited our understanding of the long-term educational value of such activities. It is likely that extended play and embedding the simulation in a classroom curriculum could result in players engaging in different social configurations around the game (Lee & Probert, 2010). Relatedly, this study did not collect demographics data or more detailed data about students' preexisting relationships with each other. While we know that most of the students had come from different schools to the summer camp and did not know each other apart from the last 3 weeks, learners' common styles of interpersonal engagement across a variety of environments, and learners' prior preferences (of comfort or discomfort with respect to each other) play integral factors in conducting and experiencing successful gameplay and learning experiences (Tolmie et al., 2010).

Conclusion

Designing for and assessing learning activities in ways that explicitly aim to support *procedural collaboration* expands the ways productive learning is conceptualized and subsequently enacted. By being able to design systems that support a wide variety of collaborative interactions – from building their separate cities, competing on a marketplace, collaborating for individual or collective gain through resource trading – in an authentic deeply interconnected system, we were able to support learners organically engaging in the collaborative coordination that were required for them to achieve their micro and macro goals, and in the process, understand the overall system. This builds on work by Pellicone et al. (2019) on collaborative digital games, in which the design of a social museum game enabled the concepts of parallelism and agent-based modeling to be reflected in how learners divided tasks and acted on a shared artifact. These diverse need-driven social configurations afford unique access to agent-perspective-based learning. In these interactive and participatory spaces, learners are embedded in perspectives where they develop different understandings, priorities and strategies in the system, and contribute to each other's learning in richly contextualized ways. The pursuit of sustainability is an emergent complex phenomenon and features unique multiple-agent relationships that are unique to each instantiation, both in the real world and in each playthrough of City Settlers. This authenticity creates space for learners to develop richer and novel ways of thinking about complex systems, and practices of negotiation and collaboration which enable them to meaningfully act on and within them.

The examples of diverse collaborative interactions in different social games add to the work on divergent and emergent collaborations (Halverson et al., 2018; Tissenbaum et al., 2017) which demonstrate how environments designed to enable different forms of collaboration, see learners fluidly move across modalities which afford them learning opportunities most appropriate for their preferences and needs. DeLiema et al. (2019) also demonstrate how a classroom game developed to support a diversity of social configurations afford multiple entry points into complex science inquiry. In City Settlers, we find traditional forms of learning through on-screen text and access to the teacher (who was around to give answers). More uniquely, the learners experientially uncover phenomena in the world as they took place (the challenges of a starving population shortage; or the spread of pollution to outside one's city), and deal with these by creating different forms of coordinated activity across each other – ranging from trading resources, to helping each other acquire buildings in mutually beneficial manners.

This work also shows the role that augmented and immersive spaces, and participatory simulations in particular, can play in supporting these collaborative and competitive interactions. Transforming the physical classroom into the simulation itself places the students directly into the learning, enabling them to *live* the phenomena as it emerges. Further, by creating augmented spaces in which the physical environment of the classroom and the digital representations of the simulation and devices work in concert to immerse the learners in the content (Klopfer & Squire, 2008), enables us to transform the classroom from a passive medium to a driver of collaboration and sensemaking.

While this work surfaces a wide array of social learning phenomena and procedural collaborations that emerge in immersive whole-class simulations, studies across different populations, contexts, time durations, and curricula are integral in deeply understanding how these engagements could help, and possibly hinder, learning. In response, we are currently working with teachers in history classrooms, science classrooms, and longer duration summer camps to develop versions of City Settlers which complement different curricula and learning contexts. Our goal is for this extended research to highlight a variety of procedural collaborations valuable in different domains, the cross disciplinary nature of learning accessed through many procedural collaborations, and develop design examples for how such social learning simulations can be modified and used across different curricula.

In closing, while this version of City Settlers was implemented in a summer camp setting, we envision it being a highly effective cross-disciplinary learning tool in formal classroom settings. As mentioned above, we have been working with local teachers to integrate City Settlers into a more persistent month-long curriculum that spans both science and history classes. Designing this more persistent version of the game has involved working closely with teachers to develop a more complex pedagogical script that provides additional scaffolding to connect City Settlers to classes' broader curricula. This scaffolding includes prompts for them to reflect on how the decisions made in the game mirror or contrast the historical contexts they are investigating out of the game. Further, the turn-based structure of City Settlers allows for a unique level of flexibility that many games do not, allowing teachers in formal settings to adapt the game to their particular curricular needs, with students playing only a few rounds at a time before launching into connected or relevant non-game investigations or activities. City Settlers can also be used to model possible scenarios, which the class can enact and then unpack at small group or whole-class levels. While we are still at the co-design stages of this work, we are optimistic about the potential of City Settlers to support learning in formal classrooms.

Disclosure Statement

No potential conflict of interest was reported by the author(s).

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