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# Using Epistemic Network Analysis to Examine Discourse and Scientific Practice During a Collaborative Game

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**Abstract**
According to the National Research Council, the ability to collaboratively solve problems is of the utmost importance in scientific careers, yet students are not exposed to learning experiences that promote such expertise. Recent studies have found that interdependent roles used within collaborative mobile games are an effective way to scaffold collaborative problem solving. School Scene Investigators: The Case of the Mystery Powder, a collaborative mobile game, incorporated interdependent roles in order to foster collaborative problem solving and promote scientific practice. Using epistemic network analysis (ENA), this study examined the conversational discourse of game teams to determine what connections exist between communication responses, language style, and scientific practice. Data included audio transcripts of three teams that played through the game. Transcripts were qualitatively coded for five types of scientific practice aligned to the National Research Council framework for K-12 science education, three types of communication responses (accept/discuss/reject), and an emergent language style (communal). ENA revealed that students developed scientific practices during gameplay. ENA also identified engaged communication responses and communal language style as two types of collaborative discourse used within School Scene Investigators: The Case of the Mystery Powder that fostered key linkages to effective data analysis and interpretation.

**Keywords** Collaborative problem solving · Game-based learning · Augmented reality · Mobile technology · Science education · Interdependence

## Introduction

In today's world, mass collaboration is changing how business is conducted with shared leadership, competitive principles that include openness and sharing, and knowledge workers who expect a participatory democracy (Tapscott and Williams 2006). The skills and expertise necessary for today's work-life, as defined by The Partnership for Twenty-First Century Skills (2018), are critical thinking, creativity, communication, and collaboration.

Not only is mass collaboration important to business, the ability to collaboratively solve problems is of the utmost importance in scientific careers (National Research Council (NRC) 2012). According to the NRC (2012) K-12 science framework, "science is fundamentally a social enterprise, and scientific knowledge advances through collaboration and in the context of a social system with well-developed norms" (p. 27). Job prospects in healthcare, science, and technology are growing (Bureau of Labor Statistics 2015); however, since schools do not cultivate collaborative scientific practices, students are underprepared for the job requirements of these fields. To create the next generation of scientists and those who work in STEM-related fields, students need to be engaged with science education, build a suite of scientific practices, and learn to collaborate successfully.

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Collaborative educational games are one way to foster collaboration in the classroom, and game-based learning has been showing promise as an effective teaching and learning strategy for science education (Bressler and Bodzin 2016; Squire and Klopfer 2007; Sung and Hwang 2013). First, collaborative games can facilitate social and communication skills through peer-to-peer activities; during gameplay, a learner within the group is able to solve problems by acquiring resources from fellow team members through dialogic interactions (Vasalou et al. 2017). Second, well-designed collaborative mobile games offer a unique way for students to socially construct knowledge that moves beyond content mastery. According to Klopfer (2008), when learners play collaborative games, they "help each other, observe each other, and act together to create communities as they learn to solve problems" (p. 223). Third, game-based learning environments offer an excellent context for scientific practices such as argumentation. As players negotiate their way through group gameplay, they naturally engage in scientific argumentation (Steinkuehler and Duncan 2008). Furthermore, collaborative role-playing design can encourage players to observe scientific phenomena, ask questions, investigate data, create hypotheses, and construct explanations—all important scientific practices (Cheng and Tsai 2013).

Designing collaborative games with interdependent roles is a particularly effective way to promote collaboration (Bressler 2014b; Dunleavy et al. 2009; Squire and Jan 2007). With interdependent roles, players receive individualized information; therefore, they need to work together and communicate in order to continue in the game. The use of interdependent roles in collaborative games scaffolds the social interaction and discourse necessary to build scientific knowledge offering an unmatched way for students to socially construct knowledge; however, few collaborative games have been studied to uncover how these social interactions support learning.

Hainey et al. (2016) suggested that there is a need for more studies that examine collaborative gameplay. In addition, Nebel et al. (2017) proposed that future collaborative game studies need to investigate the exchange of information between groups using detailed recordings. The collaborative game model used by Bressler and Bodzin (2016) showed promise for promoting positive social interactions among players; however, collaborative discourse was never analyzed to understand the connections between social interaction and learning. The goal of this study was to investigate how scientific practice evolved during gameplay and to examine how communication patterns connect to the development of advanced scientific practices.

## Background

For over two decades, researchers have known that when students work in groups, it can lead to significantly higher achievement in both reading and math over students in traditional settings (Stevens and Slavin 1995). More recently, students playing collaborative learning games have started to demonstrate similar gains in achievement (Chang and Hwang 2017; Chen and Law 2016). The theoretical framework for this study draws on an established body of research on collaboration and collaborative games.

### Collaboration

Cooperation and collaboration are often used interchangeably; however, the terms have a definite difference. As defined by Dillenbourg (1999), "in cooperation, partners split the work [and] solve sub-tasks individually… In collaboration, partners do the work 'together'" (p. 8). Collaboration is difficult to foster but it is a learnable skill that our students can gain practice with through group activities. Yet, the reality is that—to learn how to collaborate effectively—students must be helped (Bransford et al. 2000). As Demetriadis et al. (2012) concluded, productive learning interactions do not occur when collaborative groups have no support or scaffolding. Interdependence and jigsaw are two major techniques that have been researched and proven effective for promoting collaborative learning in school settings.

**Interdependence** According to Johnson et al. (1993), "positive interdependence is successfully structured when group members perceive that they are linked with each other in a way that one cannot succeed unless everyone succeeds" (p. 9). Interdependence encourages more equitable contributions from each group member diminishing social loafing behaviors; everyone works towards the group's success (Takeda and Homberg 2014). Specifically, interdependent roles have been shown to effectively scaffold collaborative problem solving (Dunleavy et al. 2009; Squire and Jan 2007). Di Blas and Paolini (2014) even found that collaborative roles can have unexpected benefits such as engaging those traditionally disengaged or marginalized by traditional instruction.

**Jigsaw** The notion of jigsaw pedagogy is that each student in a group becomes an expert on one aspect of the activity and teaches it to the other group members (Aronson 1978). As a group expert on a particular topic, each student is highly accountable to the team for his or her informational knowledge. Nebel et al. (2017) used this technique and found groups had increased task performance; more importantly, by being required to collaborate and interact, the researchers found that individual learning outcomes also increased.

### Collaborative Games

Few game-based learning studies have targeted collaboration as a learning outcome (Qian and Clark 2016); however, research on collaborative learning games has shown that gameplay positively impacts the perception of collaboration skills (Sánchez and Olivares 2011). For example, in a large international case study with over 9000 students, students performed specific roles in a multi-user virtual environment and acknowledged that the activity helped them learn to work in a group. Also, research has showed that students gained many collateral benefits related to collaboration. Particularly, researchers detected ethical and affective benefits that included increased social commitment, sense of responsibility, and ability to negotiate with peers (Di Blas and Paolini 2014).

Since science is a "social enterprise," collaborative games can provide context and tools in which to conduct scientific practice; players can learn science by collaborating on science together. Well-designed collaborative games can be designed to incorporate some of the best theories of collaboration, thus promoting social interaction and communication.

**Social Interaction** There is a misconception that the general intelligence of a group predicts its success; rather, success is due in large part to a group's social interactions (Barron 2003; Woolley et al. 2010). Therefore, well-designed collaborative games rely on the social interactions among players as a key to the overall success of the games. According to Stahl et al. (2006), in effective collaborative environments the "learning takes place largely through interactions among students. Students learn by expressing their questions, pursuing lines of inquiry together, teaching each other, and seeing how others are learning" (p. 410). Several key components of the social interactions seem to lead toward a successful group learning experience: equal authority, community spirit, and positive group feelings.

First, researchers have determined that collaborative teams have success when their social interactions demonstrate equal authority; this can be exemplified in an even distribution of conversational turn-taking (Woolley et al. 2010). One way to encourage collaborative game teams to take turns talking is through scripted collaboration. Demetriadis et al. (2012) reviewed game-based learning studies and determined that positive social interactions take place when there is shared power and authority through scripted collaboration. Another way to encourage turn-taking is through alternating quests. Bressler and Bodzin (2013) designed their collaborative game so that not all students had quests, or actions to take within the game, at the same time. They found that there was an even distribution of leadership that shifted between players and this equal authority contributed to group success.

Second, researchers have found that collaborative teams have success when their social interactions promote a sense of community spirit. Often, community spirit can be seen in player's willingness to help each other (Chang and Hwang 2017; Klopfer 2008; Peppler et al. 2013). Specifically, researchers have found that players are willing to read information out loud to each other (Peppler et al. 2013). In a case study of a collaborative game team, Bressler (2014b) discovered that one boy emerged as an expert guide and taught his group how to use the technology and helped them to understand science content. Players can also show concern for their teammates by becoming active, respectful listeners (Peppler et al. 2013). All in all, researchers have found that playing a well-designed collaborative game can engender a sense of community and team spirit (Oksanen and Hämäläinen 2013).

Third, when social interactions are fruitful, researchers have established that positive group feelings emerge. Mansour and El-Said 2009 showed that players have more positive perceptions of their social interactions when they are playing well-designed collaborative games. More recently, Bressler and Bodzin (2013) determined that their collaborative game helped to build better relationships among the players. In one extreme case, two boys who admitted to disliking each other both agreed that they worked well together while playing the game. Oksanen and Hämäläinen (2013) actually conducted a study specifically to investigate perceived sociability and social presence in collaborative games. They found that players developed good working relationships, enjoyed being together, and felt strongly connected to each other. Given that collaborative games support positive group feelings, it is not surprising that middle school students prefer collaborative games because they foster companionship (Trespalacios et al. 2011).

**Communication** In a recent review of research, Qian and Clark (2016) concluded that there is potential to use game-based learning to help students develop twenty-first-century skills such as collaboration and communication. In fact, students enjoy playing collaboratively because it encourages discussion and motivates players to communicate with each other (Sharritt 2008).

Research shows that effective group communication is a key predictor of group success (Barron 2003); therefore, well-designed collaborative games that support effective communication can help students succeed. In addition, Peppler et al. (2013) found that such games promote content-oriented discussion and reflection. Several key components within the collaborative interactions seem to lead toward a successful group learning experience: communication that is positive, on-topic, and communal.

First, researchers have determined that successful collaborative teams communicate with positive language. Peppler et al. (2013) studied game-based learning with collaborative teams and individual players; in comparison to playing alone, players in collaborative mode were significantly more likely to make positive comments to teammates. Barron (2003) found that successful teams offered significantly more engaged responses than less successful teams. According to

Barron (2003), when students accept or discuss a teammate's proposal, then they are offering engaged responses. Bressler (2014a) used a multiple case study approach and qualitatively compared collaborative game teams to teams participating in a control activity; game teams revealed higher levels of engaged responses.

Second, researchers have found that successful collaborative teams stayed on-topic when they are communicating. Peppler et al. (2013) found that collaborative game teams discussed game topics significantly more than individuals playing the game. They also found that collaborative teams were more likely to engage in science talk than competitive teams. In comparison to a control condition, Bressler (2014b) determined that collaborative games teams talked off topic less; their off-topic comments occurred at opportune times that did not impede the learning process, such as the beginning or end of the class period. Vasalou et al. (2017) studied dyslexic students playing a digital game as a group and discovered that "game talk" emerged spontaneously; student mostly talked about game content, actions, and experiences.

Third, researchers have determined that successful collaborative teams frame their discussions with communal language. In examining the most effective collaborative game teams, Bressler (2014a) noticed that players addressed the group collectively, rather than one specific groupmate. They referred to the group as an entity with words such as "we," "we are," and "let us." Bressler (2014a) deemed this language communal language. Peppler et al. (2013) found a similar phenomenon where collaborative games teams referenced their team scores as a sum of individual scores, rather than each individual's unique score.

Overall, when communication patterns and social interactions are effective, players in collaborative games have the capacity to work together in such a way that new knowledge is constructed. In one particularly emblematic example, gamers used an online protein folding game called *Foldit* and generated models that solved a problem that expert biochemists had failed to solve themselves (Khatib et al. 2011). Communicating and interacting during collaborative gameplay are such fundamental experiences, they can cater to a variety of new opportunities for learning, particularly scientific practice.

## Purpose of Study

Despite the research that shows the potential for collaborative games in the classroom, very few learning games emphasize skills such as communication and collaboration (Qian and Clark 2016). *School Scene Investigators: The Case of the Mystery Powder*, a game first studied by Bressler and Bodzin (2016), was a mobile Augmented Reality (AR) game designed to promote communication and collaboration. Findings revealed that—in comparison to a control group—the game fostered higher levels of scientific practice within group discourse and student reports. What remains unclear is *how* scientific practice develops in this collaborative environment and *how* does effective collaborative discourse support such development.

## Study Context

In order to explain the research design, a brief understanding of the game under study will be described in this section. The collaborative mobile AR game was called *School Scene Investigators: The Case of the Mystery Powder (SSI: Mystery Powder)*. The game was built using the ARIS platform (ARIS 2018), an open-source, web-based programming environment where anyone can freely create and play games. Middle school students used the free ARIS application and school-owned iPads to collaboratively solve a forensic science mystery. Students played in groups of three or four. Before gameplay, each group member selected a unique role: social networker, techie, pyro-technician, or photographer. All roles were authentic and interdependent. During gameplay, each player collected unique pieces of evidence and conducted unique scientific tests which they discussed and shared with their group. The game relied heavily on quick-response (QR) codes; using AR, the entire school became a crime scene complete with suspects, evidence, and mysterious substances. In Chapter 1, players were introduced to the incident, they met with the main characters, and they explored the cafeteria crime scene where a mystery powder was found. On an Incident Report, students had to describe the incident and plan their investigation. In Chapter 2, players visited areas of the school where suspects left evidence and ran virtual experiments on the powders collected. On the Incident Report, students had to collect data and write hypotheses. In Chapter 3, students were given a *real* mystery powder and conducted hands-on experiments using iodine, pH paper, vinegar, and heat. They had to collect more data and then analyze and interpret their findings. Their scientific results revealed the contents of the mystery powder which ruled out certain suspects. Over several class periods, students played through multiple game chapters keeping track of their evidence, analyses, and conclusions on their Incident Report. Figure 1 shows students (1) playing the AR portion of the game which took place in the school hallways, (2) filling out the Incident Report, and (3) conducting the hands-on science experiment.

Researchers have found that peer collaboration enhances learning while students play collaborative games (Chatterjee et al. 2011; Sung and Hwang 2013). However, according to Miyake and Kirschner (2014), the problem is that "the mechanism of social interaction and learning are still not fully understood" (p. 418). Often, when analyzing conversational discourse, it is the content of the utterances that researchers consider most important (Patton 2002). If we are to truly analyze


**Fig. 1** Aspects of gameplay

the learning that occurs within student discourse, then we need to investigate the connections students make *across* turns of talk (Siebert-Evenstone et al. 2016).

### Research Questions

In this study, we investigated the network connections between scientific practices, communication responses, and language style of three student groups playing *SSI: Mystery Powder*. In order to assess the extent to which elements of the collaborative discourse become linked with the ways of conducting scientific practice, we used epistemic network analysis (ENA) to measure connections made between communication responses (accept, discuss, and reject), scientific practice (defining the problem, investigation planning, interpreting data, constructing explanations, and arguing with evidence), and language style (communal). Specifically, this study used ENA to assess the evolution of collaborative scientific practice and discourse of student teams as they played through the game. These questions guided the investigation:

1. *How does scientific practice evolve during the course of gameplay?*
2. *Which elements of collaborative discourse support the development of scientific practice?*

## Methods

To investigate the connections between sections of coded dialog, this study used ENA (Shaffer 2006; Shaffer 2017). ENA is a novel method for analyzing elements in coded data and then representing the connections as dynamic network models (Shaffer et al. 2016). Essentially, ENA measures relationships between coded elements by quantifying the co-occurrences of those elements in discourse (Shaffer et al. 2009). ENA utilizes sphere normalization to ensure that those who talk a lot do not obscure individuals who may not talk as much but still make meaningful connections. This sphere normalization process allows ENA to model the pattern of connections an individual makes rather than the total number of connections made due to different amounts of talk (Shaffer et al. 2016). For example, if there are two different people making the same pattern of connections but one speaks twice as much as the other, they would lie in the same place in the ENA space. Not only that, they would lie in a different place in the ENA space than someone with a very different pattern of connections.

To answer the first research question, network diagrams showing connections between scientific practices from the first and last game chapter were compared. To answer the second research question, the first and last game chapter were compared again; this time network diagrams showed connections between communication responses, language style, and scientific practice.

### Participants/Sampling

Participants were eighth grade science students from a middle school in the northeast USA. The school was located in a diverse, urban area with many low-income households. Students were randomly assigned to groups and 35 groups of students played through the game. The process of selecting teams as case studies was purposeful random sampling (Patton 2002). Since the school district used standardized mathematics scores to academically track students into classes of above average, average, and below average mathematics achievement, those categories were chosen to represent the continuum of academic achievement levels. One team was randomly selected to represent each academic achievement level resulting in a total of three teams in the sample. The high-level group had four girls. The average- and low-level groups each had three boys and one girl.

### Data Collection

Gameplay took place over five class periods. During the entire intervention, the selected three teams were audio recorded. Audio recordings were conducted at the individual level; every participant on the team wore a lapel microphone attached to a small digital audio recording device placed inside a pocket. To ensure high fidelity of the qualitative data, all collaborative discourse was transcribed to clearly delineate conversational turn-taking.

### Data Analysis

Transcripts of student discourse went through two separate levels of coding. The first level was a priori coding based on the literature review, while the second level was emergent coding (Willis 2007) based on close reading of the transcripts. In total, 2700 utterances were coded using the coding scheme.

A priori coding including categorizing student utterances into communication responses and scientific practices. Communication responses were categorized as accept, discuss, and reject. The code structure built on the work of Barron (2003). When a student agreed with the speaker, supported the idea, or proposed a next step, the interaction was coded as an *Accepting Response*. When interactions facilitated further discussion, such as questioning an idea, asking for clarification, or challenging an idea with new information, the interaction was coded as a *Discussing Response*. When a student rejected an idea or interacted in a way that would not facilitate discussion, the interaction was coded as a *Rejecting Response*. The scientific practices that occurred in team conversations were coded to align to the scientific practices from the NRC (2012). When students discussed what was known about the investigation or tried to determine what needed to be answered, the dialog was coded as *Defining the Problem*. When students discussed their investigation plan or what information they needed to record, the dialog was coded as *Planning out the Investigation*. When students discussed characteristics of the experiments they were observing, the dialog was coded as *Interpreting Data*. When students tried to explain the relationships between data, the dialog was coded as *Constructing Explanations*. When students supported or refuted an argument by citing relevant evidence, the dialog was coded as *Arguing with Evidence*.

An additional code emerged during a second round of emergent coding. When reviewing transcripts, differences in the general language style were noticed. Students often addressed the group collectively, rather than one specific team member. They referred to the group as an entity with words such as "we," "we are," and "let us." To capture this type of communal language, a new code was created called *Communal*. All codes for communication responses, scientific practice, and language style were included in the dataset as codes. Game group, game chapter, and activity number were included in the analysis as metadata.

To create ENA models, we used the moving stanza window method (Siebert-Evenstone et al. 2016; Shaffer 2017). Each line in the dataset represents a single student utterance that has been coded. To begin the method, one utterance serves as a referent utterance. Each utterance is then examined through a window of several utterances preceding it. The moving stanza window method analyzes connections between codes *within* the referent utterance and *between* the utterance and those in the window. After analyzing each utterance, the window slides to the next utterance and repeats the process of investigating connections within the referent utterance and those in the window.

The connections can then be represented by a network diagram; qualitative codes become the nodes of the diagram. ENA can then calculate the centroid of the polygon created by the network diagram. The centroid, similar to the center of mass for an object, takes into account the weights of the connections and has a corresponding plotted point (Shaffer et al. 2016). Connections between the nodes are represented by weighted lines in the network diagram. The plotted points can be used to determine systematic statistical differences between networks since they represent each unit's network as a single point on a Cartesian plane created by the first two ENA dimensions.

## Findings

The first research question investigated how scientific practice evolved during the course of gameplay. To answer this question, we created an ENA model, and connections between codes for scientific practice occurring in the first game chapter were compared to connections between codes for scientific practice occurring in the final game chapter. Figure 2 shows the plotted points for Chapter 1 (red) and Chapter 3 (blue). [Please refer to the online version for color plots.] The plotted points of individual game activities are the dots. Game activities played by each team within Chapter 1 are indicated by red dots, while the game activities played by each team within Chapter 3 are indicated by blue dots. Each chapter includes multiple activities, so each chapter is represented by several dots. The average of these points is shown as a square with a 95% confidence interval for each dimension represented by the rectangular outline.

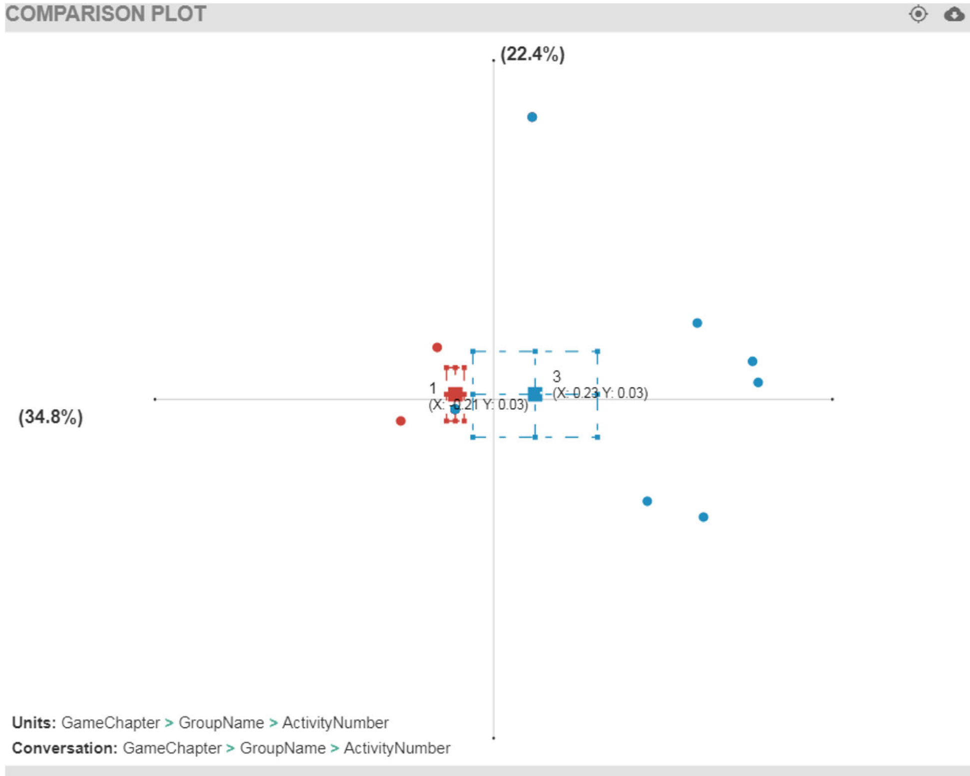


**Fig. 2** Comparison of scientific practice for Chapter 1 (red) and Chapter 3 (blue) using plotted points and centroids

According to Fig. 2, ENA explains 34.8% of the variance in coding co-occurrences along the *x*-axis and 22.4% of the variance on the *y*-axis. A two-samples *t* test (assuming unequal variances) was used to determine if there was a significant difference between the mean for each game chapter. At the alpha = 0.05 level, the *t* test ($t(16.15) = 2.58$; $p = 0.02$) revealed a significant difference between Chapter 1 (M = 0.28, SD = 0.07, $N = 23$) and Chapter 3 (M = − 0.30, SD = 0.93, $N = 17$) along the *x*-axis. Cohen's *d* was equal to 0.96, which is interpreted as a large difference between the mean of the first and final chapters.

There was a significant shift along the *x*-axis in the network connections present in the first chapter of the game and the last chapter. Analyzing the individual network diagrams can explain what codes are causing this shift; the individual diagrams are shown in Fig. 3. The diagram for Chapter 1 has

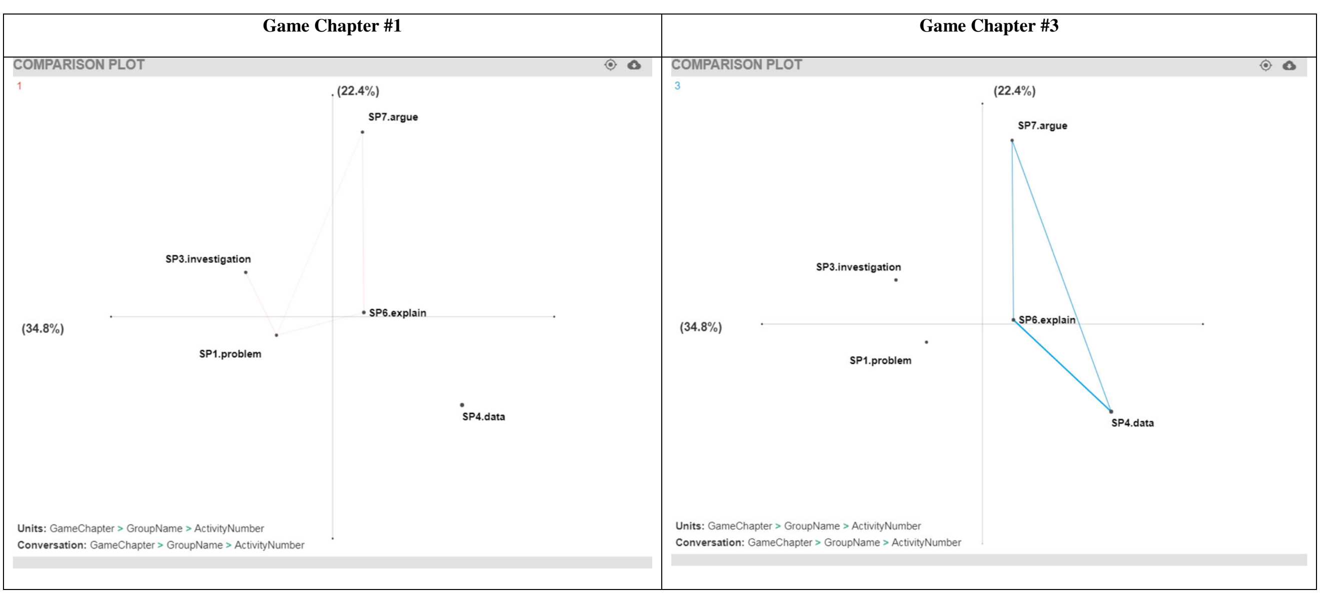


**Fig. 3** Individual network diagrams with weighted lines highlighting connections occurring between scientific practices during gameplay

relatively weak connections between the scientific practices therefore the line weights are lighter; the connections that do exist show a presence of ties to the codes for *Defining the Problem* (*SP1.problem*) and *Planning out the Investigation* (*SP3.investigation*) shifting the centroid to the left on the *x*-axis. The diagram for Chapter 3 has relatively stronger connections therefore the line weights are darker. Also, Chapter 3 has strong connections between *Interpreting Data* (*SP4.data*), *Constructing Explanations* (*SP6.explain*), and *Arguing with Evidence* (*SP7.argue*) shifting the mean of the plotted points to the right on the *x*-axis.

Scientific practices clearly evolved by the time the teams played Chapter 3 in the game. The co-occurrence of *SP3.investigation* and *SP1.problem* in Chapter 1 shows that students were primarily focused on framing out their investigation at the beginning of gameplay; there was little to no discussion about data. However, by Chapter 3, the players really "leveled up." The co-occurrence of *SP6.explain* and *SP4.data* indicates that students were constructing explanations using data and using detailed explanations as they discussed their data. In this example, group A students are discussing the results of the heat test:

S1: Oh, my God, that thing smells really good.
S2: Probably sugar. Probably sugar burning.
S1: Oh, yeah, you are caramelizing sugar.
(*Group A Conversation, Lines 537–539*)

The co-occurrence of *SP7.argue* and *SP4.data* indicates that students were supporting their arguments using data as evidence. As group A tried to decide what powders were present in the mystery powder, S2 supported her statement with evidence from their experiments.

S1: All right, that's cornstarch.
S2: No, it's not just cornstarch.
S3: Because it's also all of these.
S2: It's all of the characteristics of everything. It fizzed, it's clear-watery, and it burned under fire.
(*Group A Conversation, Lines 637–640*)

As group C tried to determine the identity of the real thief, one student supported his idea with evidence from the narrative of the game: "So the janitor because he was at the school late and he was the only one here at the time of the theft" (*Group C Conversation, Line 1033*).

The second research question investigated how collaborative discourse supported the development of scientific practice during the course of gameplay. To answer this question, we created an additional ENA model; connections between codes for collaborative discourse and interpreting data occurring in the first game chapter were compared to connections between the same codes occurring in the final game chapter. Figure 4 shows the plotted points for Chapter 1 (purple) and Chapter 3 (orange). Similar to Fig. 2, the dots in Fig. 4 are individual game

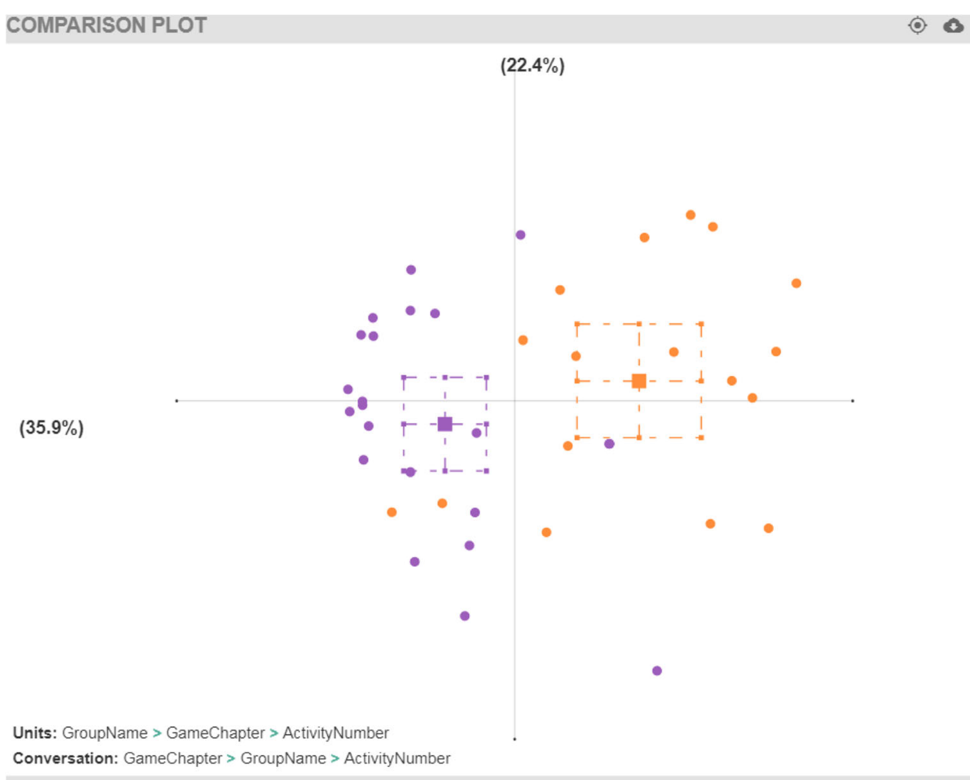


**Fig. 4** Comparison of collaborative discourse for Chapter 1 (purple) and Chapter 3 (orange) using plotted points and centroids

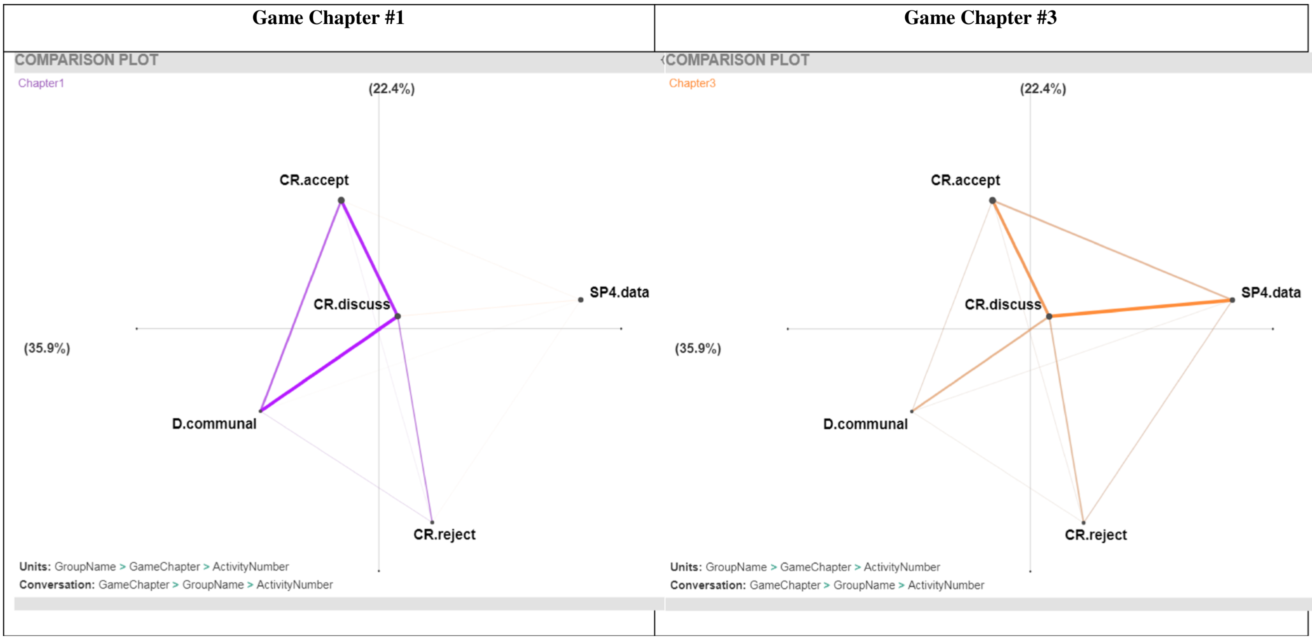


**Fig. 5** Individual network diagrams with weighted lines highlighting connections occurring between scientific practice and collaborative discourse

activities as played by each team. Chapter 1 is represented by purple dots, while Chapter 3 is represented by orange dots. As before, the mean for each chapter is represented as a square with a rectangular outline defining the 95% confidence intervals for the *x*-axis and the *y*-axis.

According to Fig. 4, ENA explains 35.9% of the variance in coding co-occurrences along the *x*-axis and 22.4% of the variance on the *y*-axis. A two-samples *t* test (assuming unequal variances) was used to determine if there was a significant difference between the mean for each game chapter. At the alpha = 0.05 level, the *t* test ($t(29.63) = -5.48$; $p = 0.00$) revealed a significant difference between Chapter 1 (M = − 0.48, SD = 0.65, $N = 23$) and Chapter 3 (M = 0.85, SD = 0.82, $N = 17$) along the *x*-axis. Cohen's *d* was equal to 1.82, which is interpreted as a large difference between the mean of the first and final chapters.

Similar to the results of the first research question, there was a significant shift along the *x*-axis in the network connections present in the first chapter of the game and the last chapter. In order to understand what codes are causing this shift, the individual diagrams are shown in Fig. 5. The diagram for Chapter 1 has strong connections between the codes for *Communal Language* (*D.communal*), *Accepting Responses* (*CR.accept*), and *Discussing Responses* (*CR.discuss*). Specifically, the presence of ties to the code for *Communal Language* (*D.communal*) is shifting the centroid to the left on the *x*-axis. In the diagram for Chapter 3, there is still a tie to *Communal Language* (*D.communal*), but now *Accepting Responses* (*CR.accept*) and *Discussing Responses* (*CR.discuss*) have strong connections to *Interpreting Data* (*SP4.data*) shifting the centroid to the right on the *x*-axis.

Student discourse clearly changed from the initial chapter to the final chapter in the game. The strong co-occurrence of *CR.accept* and *CR.discuss* in both chapters shows that students were using engaged responses according to Barron (2003). Barron (2003) found that successful collaborative teams offer significantly more engaged responses (*CR.accept* and *CR.discuss*) than less successful teams. Neither diagram shows a strong connection to *CR.reject*; therefore, student discussions were highly collegial, supportive, and productive throughout gameplay. For example, in group A, the first speaker proposes a course of action and the second speaker agrees (*CR.accept*) and offers a next step (*CR.discuss*).

S1: Okay, we have to go to the woodshop.

S2: All right, and the art room.

(*Group A Conversation, Lines 422–423*)

The notable shift pertains to *D.communal* and *SP4.data*. In Chapter 1, *D.communal* co-occurs with both *CR.accept* and *CR.discuss*. As demonstrated in the above example, the first speaker uses "we" when talking about herself and her groupmates; this is *D.communal*. By using engaged responses and communal language, students are building a community spirit within their team. In fact, in the first chapter, building community spirit is more important than scientific practice since there is a very weak connection to *SP4.data*. However, by Chapter 3, *SP4.data* co-occurs more strongly with both *CR.accept* and *CR.discuss*. Students are still using engaged responses as they interpret their data—an essential ingredient of scientific practice. For example, when group B was discussing data findings related to the vinegar test (*SP4.data*), S2 offered a supportive response (*CR.accept*) and provided information relevant to the discussion (*CR.discuss*).

S1: Did the baking soda fizz a lot more than the cornstarch?

S2: Here, let me check. So baking soda. Yeah, baking soda fizzed a lot more than; it fizzed a lot more than… cornstarch.

(*Group B Conversation, Lines 1343–1344*)

It is worth noting that *D.communal* is still connected to the network—communal spirit is still the backbone that supports their engaged responses, and their engaged responses promote successful scientific practice.

## Discussion

This study has shown that a collaborative game designed with interdependent roles can promote the development of scientific practices. Students playing the game communicated effectively and collaborated successfully—key skills needed for today's science workforce. Specifically, models generated using ENA demonstrated that students playing *SSI: Mystery Powder* were developing scientific practices by using engaged responses and communal language. This study has confirmed and extended the findings of previous research studies on collaborative game-based learning by providing details on how communal language supports interactive discourse pertaining to important scientific practices. This study has also bolstered the potential for using collaborative games in science education by demonstrating that scientific practice can develop during gameplay.

### Scaffolded Collaboration Fosters Scientific Practice

Previous research published about *SSI: Mystery Powder* demonstrated that the game, in comparison to a control condition, promoted higher levels of scientific practice within group discourse (Bressler 2014a) and written reports (Bressler and Bodzin 2016). The current study represented how scientific practice evolved over the course of gameplay, and proved that there was a statistical significant difference between scientific practices used in Chapter 1 and in Chapter 3.

Productive learning interactions can occur when collaborative groups have support or scaffolding (Demetriadis et al. 2012). In order to establish equal authority between the players, *SSI: Mystery Powder* was designed using jigsaw pedagogy (Aronson 1978). As a team expert on a particular topic, each student was highly accountable to the group for his or her informational knowledge. In *SSI: Mystery Powder*, the social networker was an expert on the vinegar test; he or she had the knowledge of how each powder reacted to vinegar and what the reactions meant. In a similar regard, the techie was an expert on the iodine test, the pyro-technician knew about the heat test, and the photographer had all the information about the pH test. For the entirety of gameplay, each player was accountable to the group for their expertise and this created a natural reason to take turns addressing the group. Essentially, game mechanics distributed responsibilities in such a way that facilitated the conversational turn-taking necessary for group success according to Woolley et al. (2010).

According to Johnson et al. (1993), interdependence is another prerequisite to successful group collaboration. In order to establish interdependence between the players, *SSI: Mystery Powder* was designed using roles. Prior research has shown that when students play in teams with more interdependence, learning outcomes improve (Chang and Hwang 2017; Nebel et al. 2017). In this study, responsibility to the group's success was shared by distributing specific information and tasks to each role as discussed above. Each role was unique yet interconnected within the larger effort of the group. Given that no player could succeed on their own, game teams shared in decision-making and co-constructed solutions, and thus engaged in the social enterprise of scientific practice.

Scaffolding for scientific practice may have also been provided through the game narrative and the Incident Report. According to Squire and Klopfer (2007), narrative-based games provide a structure in which to think. In this investigation, the narrative seemed to give players enough direction and information for discussion while allowing players to think and act autonomously according to their own instincts. Specifically, the narrative provided players with a guideline for collecting and interpreting data. Furthermore, the Incident Report gave players a place to consolidate their thoughts: students organized their data and wrote their conclusions on the Incident Report. In a study of students playing a collaborative game, researchers concluded that players who discussed and organized their acquired knowledge were able to learn more (Sung and Hwang 2013). Therefore, in this study, the narrative and the Incident Report may have facilitated the evolution of scientific practice toward more thoughtful data explanations and may have fostered the skill of arguing with evidence as it is connected to both constructing explanations and interpreting data.

### Positive Ethos Supports Knowledge Construction

Previous research published about *SSI: Mystery Powder* demonstrated that the game promoted higher levels of engaged responses and communal language within group discourse in comparison to a control condition (Bressler 2014a). Game teams were effective collaborators because their interdependent roles promoted positive communication patterns. The current study represented how communal language supports the use of engaged responses and concluded that engaged responses specifically fortify the practice of interpreting and analyzing data. These deeper insights into how collaborative discourse leads to learning make a significant contribution to the fields of collaborative game-based learning and computer-supported collaborative learning.

Prior research found that playing a well-designed collaborative game can engender a sense of community and team spirit (Oksanen and Hämäläinen 2013). In the beginning of the game, communal language had strong connections to engaged responses demonstrating that teams were creating a community spirit. In this research study, the comparison of the network diagrams from the first and final chapter illuminated the reason why community spirit is so important to success: communal language supports the use of engaged responses. In the beginning, teams had ongoing conversations to develop their communal understanding of the constraints of the main problem posed by the game. As the game progressed, useful discussions ensued; engaged responses helped to keep teams on track toward their goals and supported their communal analysis of collected evidence. All in all, the teams in this study developed a positive ethos for building on ideas by using communal language in conjunction with engaged responses.

Previously, research has shown that players in a well-designed collaborative game feel strongly connected to each other (Oksanen and Hämäläinen 2013). In this study, it seems the use of communal language reveals the perception that individual members feel inextricably linked together as a group. Since the player feels like a critical member of the group, he or she uses communal language to help guide the group towards a goal. For example, group B referred to their team as a distinct entity with specific goals to achieve:

So we need to go to the principal. (*Group B Conversation, Line 21*).

We need to fill out the form now. (*Group B Conversation, Line 264*).

Okay. Then we have to press start two in the decoder. (*Group B Conversation, Line 373*).

Game teams seemed to understand their goals and to be willing to work towards them *together*.

When collaboration is scaffolded effectively, the discourse becomes more productive. In a study with collaborative groups using a location-based AR inquiry activity, Chiang et al. (2014) found that the AR users participated in more knowledge construction than a control group. Specifically, they found that "students in the experimental group strove to explicitly convey their opinions and solutions and to engage in in-depth comparisons and discussions" (p. 106). In this study, game teams frequently used communal language—and accept and discuss responses—which demonstrated support and encouragement of teammate's ideas. These players not only offered their ideas, they did it in a positive way. Therefore, productive conversations ensued because all players felt as though their ideas were being heard.

In prior research, researchers found that as collaborative game teams worked toward consensus, they would summarize and consolidate their ideas into an interim conclusion; if they reached an incorrect conclusion, they would naturally shift to revisiting their thinking and re-analyzing their decisions (Chiang et al. 2014). In this study, network diagrams revealed that game teams were engaged in evidence-based argumentation; the networks also showed direct connections between engaged responses and data interpretation. It seems players were discussing the data as a group and using evidence-based argumentation as they struggled to come to consensus about their interpretations.

Overall, the use of communal language promotes harmonious interpersonal relations, specifically the use of engaged responses. With community spirit and engaged responses, game teams discussed their observations. This culture of positivity gave teams the foundation from which to effectively analyze their data and construct new knowledge.

## Implications and Conclusion

Prior research indicated that collaborative mobile games with interdependent roles held promise for promoting effective collaborative practice by scaffolding and supporting discourse during gameplay. This study examined the discourse of three successful game teams to understand exactly *how* effective collaborative discourse supports scientific practice. The results of this study reveal that *SSI: Mystery Powder* supports communication and social interactions in which students authentically analyze data, construct explanations, and argue with evidence. Through the collaborative game presented in this study, science is no longer a set of facts to be memorized; instead, new scientific knowledge is constructed as data are analyzed through respectful discussions.

This study offers practical application for improving formal education. Collaborative games are an appropriate consideration for science educators given the significant challenges K-12 education is facing. According to Ravitch (2016), most schools still place emphasis on content mastery; students acquire isolated skills and memorize piles of facts rather than engaging in learner-driven activities. Essentially, US K-12 students are still learning according to the industrial model yet student-centered alternatives are needed (Freeman et al. 2017). To promote meaningful learning, schools need to make education more authentic and more engaging with non-traditional alternatives. Specifically, K-12 education needs to focus on redesigning their learning spaces to maximize support for "collaboration, self-directed learning, active learning and inquiry and creation" (Freeman et al. 2017, p. 18). Games such as *SSI: Mystery Powder* offer an effective, non-traditional approach by empowering learners to construct their knowledge through inquiry-based, collaborative scientific practice. Additionally, in the real world, science is essentially a social enterprise where knowledge advances through effective collaboration (NRC 2012); therefore, by incorporating more collaborative games into classrooms, we are ensuring students are prepared for the collaborative culture of their future careers.

While *SSI: Mystery Powder* utilized best practices for designing a collaborative game, there were several limitations to the design of this study. First, the study was conducted with a small sample at only one urban middle school; therefore, the findings are of somewhat limited generalizability. Researchers should take care when generalizing to other contexts. Second, the duration of the intervention was very short. Students played the game over four or five class periods. A few days in a student's life may not have a significant impact. Lastly, the teachers and the principal of the school were extremely supportive of this research project. This meant that the researchers were welcomed into the building and were able to freely disturb the inertia of the classroom as well as the hallways of the school—a necessity since the game teams were in the hallways for much of the activity. Game teams may not have achieved equivalent outcomes working with less enthusiastic teachers or within a school that had less supportive administration.

In this study, players communicated effectively and developed scientific practice during gameplay; future research should investigate whether skills practiced during gameplay are transferable. For students to thrive in today's workforce, they need to be effective collaborators; specifically, they need to learn to collaboratively solve problems for success in scientific careers (NRC 2012). Future research should investigate whether collaborative scientific practice demonstrated during gameplay transfers to a situation where less collaborative scaffolding is provided. In other words, can collaborative mobile games train students well enough to demonstrate the same skills in a non-game environment?

In this study, role-playing enabled students to actually learn science by practicing it; future research should investigate whether scientific practices experienced in game-based learning trigger students' interest in science. In this game, students were not learning science by simply acquiring facts, rather they were immersed in a context through which science became a process. According to the National Research Council (2012), when students actually do real science, it can "pique students' curiosity, capture their interest, and motivate their continued study" (p. 42). When students' interest in science is triggered and sustained, it can lead to later careers in science. Middle school is a critical time to foster interest in science; middle school science experiences play an important role in whether students pursue science-related careers (Tai et al. 2006). Future research should examine whether role-playing in *SSI: Mystery Powder* promotes middle school students' interest in science. A future longitudinal research could study whether playing multiple collaborative games in science provide a critical turning point for students' interest in STEM.

Overall, this study makes a strong case for collaborative games as a viable design for fostering scientific practice. During the implementation of *SSI: Mystery Powder*, the science curriculum became a "social enterprise" as opposed to a traditional didactic curriculum that focuses more on science content facts. With a well-designed game, students can be encouraged to collaboratively analyze real data and draw conclusions by constructing explanations and arguing with evidence; in today's world of fake news and alternative facts, providing opportunities for students to learn and practice these skills is beyond important.

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**Conflict of Interest** The authors declare that they have no conflict of interest.

## Compliance with Ethical Standards

The authors declare that they have no conflict of interest. All procedures performed were in accordance with the ethical standards of the institutional research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards. Informed consent was obtained from all individual participants included in the study.

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