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An Earthquake Engineering Education Research Methodology for Game-Based Learning

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Abstract

The authors present a research paper about an innovative research and development (R&D) methodology for game-based learning to integrate engineering education and 21st century learning. Prior to game development, a literature review on gaming revealed a lack of systematic methods for integrating research into design and implementation strategies of many game-based learning environments, much less one for enhancing learners' understanding of engineering and advancing abilities to think critically, argue scientifically, and use metacognition to analyze strategic thinking. We employed a non-linear, holistic methodology framed by Dick, Carey, and Carey's instruction-based R&D template to develop a collaborative-competitive board game for middle and high school students, entitled *Earthquake*. We integrated critical game-design techniques for the game to be enjoyable while increasing players' knowledge and expertise through repetitive play. The instruction-design template contains five R&D phases: *Analyze, Develop, Design, Implement, Evaluate.* In the *Analyze* phase, we established learning objectives to introduce players to earthquake engineering while enhancing critical thinking, scientific argumentation, and metacognition. With learning objectives established, we began the *Develop* phase for game prototyping, assisted by nine focus groups of experts (n=16) from various backgrounds, including science education, civil engineering, gaming, teaching, and educational administration. We used this resulting prototype in the *Design* phase for teachers (n=14) to test-play. The use of teacher-participants satisfied fundamental game-design principles: that three to five game-testers sufficiently elucidate mechanical and aesthetic kinks, and that prototype-testers represent a sample of individuals familiar with the context in which the game would eventually be implemented. Four teacher-groups played *Earthquake* once in a professional development engineering education workshop. Abiding by game-design protocol, each group contained three or four teachers. After the test-play, we conducted semi-structured interviews of each teacher-group. Questions probed what teachers learned about earthquake engineering, what they did and did not like, what they would change, and how effective they thought the game was in teaching interconnectivity of urban infrastructure components. We analyzed interview transcripts with constant comparison qualitative methodology to capture emergent patterns among teachers' comments. Results indicated needs for more player roles, clarifications in playing cards, and the production of an introductory video to highlight the game's function. We integrated these *Design*-based results during the *Implement* phase to modified *Earthquake* again for the *Evaluate* phase. During the *Evaluate* phase, six high school students formed two groups to play the game twice in one after-school session. Students remained in the same group for both games. We video-recorded students' game-play for both games. Using a game-based learning checklist (inter-coder reliability of 87%), we analyzed videotapes to identify qualities of students' dialogue and actions. The checklist served to document and compare evidence of met learning objectives. Our comparisons of first and second plays showed student-gains for earthquake engineering content knowledge, critical thinking, scientific argumentation, and metacognition, thus providing evidence of effectiveness of this particular instructional innovation in advancing students' knowledge and abilities in engineering. Furthermore, we found the R&D methodology provided an appropriate, systematic framework for integrating research methodologies at every phase in the R&D process.

1.1. Introduction

Instruction must be reoriented for 21st century engineering learning[1] to keep the United States globally competitive to lead, innovate, and create future jobs.[2] Contemporary society demands a citizenry familiar with the complexity of real-world problems associated with societal systems coming into direct contact with the Earth's natural systems.[1, 2, 3] Particularly in urban areas, where natural Earth systems can seriously threaten human life and property, people must be educated to make informed decisions. As our society becomes increasingly interconnected, future engineers face more complex challenges.[4] Students in today's classrooms are workers, teachers, researchers, policymakers, voters, and do-ers of tomorrow. We are responsible for providing today's students with tools, experiences, and knowledge guiding tomorrow's 21st century decision-makers. In this paper, we chronicle a research and development (R&D) methodology for the design of 21st century earthquake engineering instruction.

Engineering requires both domain content knowledge and 21st century abilities. Games cultivate qualities attractive for students[5] to engage in 21st century learning.[6] As games can function as an effective medium to embrace 21st century learning, game-based learning (GBL) offers a relevant context within which students can meet a variety of learning objectives[7] for engineering.[8] Specifically in GBL civil engineering,[9] real-life situations provide a safer game-world that affords ways for players to enhance 21st century abilities[5, 10, 11, 12] and interpret society.[13]

A debate no longer focuses on whether or not GBL works[14]–it does.[5, 11, 12, 15, 16, 17, 18, 19, 20] Educational researchers, teachers, and other educational stake-holders, however, need specific evidence to fill knowledge gaps about the validity and credibility of GBL.[21, 22, 23] A conspicuous knowledge gap in GBL literature is research with direct empirical evidence of educational efficacy.[14, 21] We now ask how to carry out more evidence-based GBL research[7] for evaluating a game's educational efficacy[15, 23, 24] with respect to engineering education.

1.2. Rationale

Forming the rationale of this study is the need to advance engineering education research and methodology within GBL. Games are effective learning tools.[25, 26] Well-designed games provide opportunities for players to develop and practice important 21st century abilities,[10, 11,12] such as critical thinking, scientific argumentation, and metacognition.[1, 27, 28] These abilities have been regarded as essential to becoming an engineer.[8] Well-constructed educational games can also blend engineering design and science,[19] which is an important new perspective adopted by the *Next Generation Science Standards*. Within the safe realm of a playing space, students can resolve cognitive disequilibrium and progress into the problem solving.[26] Furthermore, embedding play within a game grounded by social learning may satisfy players' motivational needs[16] to participate in their own learning.[11]

Playing quality educational games can promote 21st century engineering and science learning together. Unfortunately, culturally uncommon in U.S. classrooms are opportunities to develop and use systems thinking, small-group complex communication, non-routine problem solving, generating questions, re-framing problems, and abstract thinking.[29] Extracting contextual relevancy from instruction weakens the foundation of science education.[7] As 21st century instruction is process-oriented, evaluation of instruction can thus reflect a process-oriented schema to more clearly reflect that under evaluation.[30] The field of engineering education needs more contextually relevant evidence-based research about evaluation methodology for GBL. Adding the results of this study to the literature base can help bridge educational research methodology and actual practice of GBL for engineering education. The authenticity of our education research methodology has wide applicability for engineering education researchers desiring to assess the effects of GBL unobtrusively on students' learning while doing.

2. Problem statement

A critical component missing in education research literature are methods to reliably and credibly evaluate educational games.[31] Missing are literature about research and development (R&D) as a whole in and of itself, and studies which have specifically included an R&D evaluation phase. That the GBL community lacks a range of evaluation research studies on games deserves to be addressed.[23] For example, the literature base does not provide sufficient evidence to link GBL with targeted performance objectives.[14, 15, 22, 23] With scientific evidence of GBL effectiveness, educational stakeholders can be more aware of GBL benefits. Educational stakeholders need information to fill knowledge gaps about GBL evaluation.[22]

Educational gaming researchers have called for more empirical evidence[7, 12, 19, 32] on the effectiveness of games as learning environments[33] and on factors related to learning outcomes.[20] The commonly used pre- and post-test[20, 34] and survey evaluation formats[14] may not adequately capture how students interact with an educational game during play, thus failing to to provide sufficient evidence about performance objectives.[19] Traditional surveys and pre- and post-tests typically extract data outside the time frame of the play-sphere, not during actual game-play. The evaluation of instructional design models should occur throughout the entire process rather than at the end of the game.[35] As GBL is a process-oriented method,[15] R&D data captured during a GBL environment can be a more authentic method for collecting data on students' performance as they are engaged in GBL, which can be pivotal in understanding how learning occurs in the GBL environment.[34]

3. Purpose of the study

In the light that evaluation of instruction in educational gaming is severely lacking,[19, 20] researchers in the field of GBL have called for evaluation of educational games, suggesting that investigations of how students actually play the game would allow for emerging evidence of meaningful learning.[11, 19] A critical component of this research initiative, therefore, was to empirically study students' play as they engaged in a board game anchored in engineering design. The over-arching purpose of this study was to improve engineering education research methodologies for assessing learning in game-based learning environments. Broader impacts of this study were to inform stakeholders in engineering education about the role of educational gaming in supporting successful 21st century learning as related to critical thinking, scientific argumentation, metacognition, and engineering design.

We iteratively designed, tested, and improved an engineering game while simultaneously incorporating an R&D process that allowed us to unobtrusively chronicle students' play of the game. We chose earthquake engineering as the game context because of the complexities, systems thinking, collaborative discourse, and real-life relevancy of the domain of earthquake engineering. The game, called *Earthquake*, provided players opportunities to practice and improve critical thinking, scientific argumentation, and metacognitive abilities as players constructed content knowledge about engineering. To develop an emergent research methodology suitable for assessing the complexity of the GBL environment, we integrated features of instruction- and game-design, social learning, 21st century science learning, and engineering education. We capitalized on the motivational essence of play to improve learners' higher-order thinking and acquisition of knowledge about engineering design, which are key aspects of 21st century science learning[2] and in line with recommendations of the *Next Generation Science Standards* for a scientifically literate citizenry. We designed *Earthquake* to provide players with opportunities to do and understand engineering design and science, acquire engineering knowledge and 21st century abilities, and blend science with engineering design.

4. Research questions

We posted research questions based on the evaluation of the *Earthquake* game to find evidence supporting two knowledge claims about the game. Knowledge claim number one was that the game provides players opportunities to practice and enhance the 21st century science learning abilities of critical thinking, metacognition, and scientific argumentation. Knowledge claim number two was that the game teaches fundamental earthquake engineering content knowledge. In accordance, the research questions were:

(1) What data collection methods can be systematically employed to collect evidence supporting the two knowledge claims about the outcomes of the *Earthquake* game regarding (a) students' cognitive abilities and (b) students' fundamental earthquake engineering content knowledge?
(2) To what magnitude does the evidence support the two knowledge claims?

We developed these questions to provide inference into the educational efficacy of *Earthquake* and into GBL research methodology. These questions specifically targeted the fifth and final R&D phase, *Evaluate*, of Dick, Carey, and Carey's model for instruction development.[37] Answering the two research questions above will conclude our R&D process, thus addressing the purpose of this paper.

5. Overview of literature on game-based learning

Educational gaming is a rapidly evolving field of increasing attention.[34] While many members of the GBL research community have made diverse contributions to the literature, educational stakeholders and those in schools need data geared toward literal practicality.[22] Researchers have called for studies focusing on the utility of GBL for the development of specific educative outcomes.[15, 19] That is, the field has called for more evidence-based evaluations of GBL tools. The lacking information about this methodological issue in research design has hindered researchers to link GBL with evidence of learning outcomes[23] needed for educational stakeholders to make educated decisions.[22]

Literature across domains and for ranges of age groups has inferred the effectiveness of GBL. Games have been utilized as methods of instruction for an array of areas[34] including scientific inquiry,[38] mathematics principles,[39] negotiation skills,[40] argumentation,[41] and critical thinking.[42] GBL has been associated with encouraging various cognitive and psychomotor skills.[43]

Games have long served as instructional tools in classrooms.[22] Humans have been learning though play since recorded history.[44] Yet, necessary theoretical and research bases have been lacking to establish practice, guidelines, and protocol.[26, 45] GBL research has undergone strong criticisms: features in educational games have been superfluous to the learning task[34] and that research has been present only for game-mechanics.[46] Additionally, authors have not agreed on the definition or parameters of GBL.[47] Most researchers have coupled GBL and 21st century technology, like laptops or personal computers, while only a few other researchers have suggested that face-to-face group play on a physical board game also stimulates 21st century abilities, like critical thinking and collaborative discourse.[11]

Most research has relied on inference from psychological and educational theory rather than direct and sustained empirical evidence.[23, 48] The little research available on the efficacy of GBL primarily focuses on the development of specific competencies and connections to motivation, emotion, or affect.[34] A common assessment format for those few educational games that have gone through an evaluation phase primarily reference only pre- and post-tests[20] or appearance of engagement as valid evidence[11, 19] to claim instructional success–engagement and learning have been posited as not synonymous.[34] Wording and exogenous factors can influence survey data, opening up degradations to weak methodological designs reliant on surveys.[49] Further explorations do not exist that highlight empirical evidence of success[19, 20] of the instruction itself under evaluation by relevant, process-oriented means.

6. Conceptual framework

A socio-cognitive conceptual framework[50, 51] aligns the evaluation of the *Earthquake* game with instruction organized for the development of 21st century cognitive skills and for content knowledge acquisition. The conceptual framework for this study resides in situated learning, social cognition, and socio-cognitive theory focusing on learning-by-doing[52] within the context of collective agency[53] through sharing, defending, reflection, and revision.[28] For the purposes of this study, we delineated a framework for the critical terms of *play* and *game* and the phrase *game-based learning* (GBL).

While a variety of definitions of the term *play* have been suggested, we followed conceptualizations proffered by Johan Huizinga.[44] Others have derived a philosophically grounded framework generalizable enough for salient compatibility with classroom learning from Huizinga.[19] A play theorist, Huizinga outlined one of the first recorded play platforms (Huizinga, 1938/1980):[44] entry into play is a voluntary act, unable to sustain suspension or deference; play transcends ordinary life into a mystic consciousness; play requires order, through which rules should not be broken lest one becomes a spoilsport; and that productive play is socially rooted.

The definition of a *game* reflects ideas of Csikszentmihalyi, who has conceptualized that "games fill out the interludes of the cultural script" (p. 81).[54] Games offer players more freedom to learn from mistakes, errors, and failures.[55, 56] A quasi-bounded and socially justified arena of arranged potentialities that produce interpretable outcomes,[57] a *game* can be a medium through which *play* functions.[58] *Game-play* is considered an alternative to conventional schooling techniques.[23] GBL invites players to apply deeper levels of knowledge and skills while developing 21st century abilities.[48, 59, 60, 61]

7. Methodology

7.1. A research and development framework

We followed the instructional R&D proposed by education researchers Dick, Carey, and Carey.[37] The instructional model consists of five R&D phases: *Analyze*, *Develop*, *Design*, *Implement*, and *Evaluate*. These phases function together as an instructional design and are referred to as *Instructional Systems Development* (ISD), which is associated with contemporary views of instruction adopting socio-cognitive and situated cognitive theories.[37] Dick, Carey, and Carey have developed the ISD model as a general methodology for producing instruction, which has been used by both instructional novices and seasoned practitioners. Iterative and nonlinear, the model is an appropriate template for inductive projects[62] such as an R&D approach for educational games about engineering.

7.2. Synthesis of instruction and game design into R&D

We began the R&D framework for synthesizing instruction- and game-design with the instructional foundation of Dick, Carey, and Carey's ISD model.[37] We superimposed both game- and instruction-design principles onto this foundation. Following game-design recommendations for GBL from Schwartz and Bayliss,[19] we replaced the word *learning* with *playing* in the ISD model. As synthesis is important, the two big themes of synthesizing instruction-design and game-design emerged distinctly within two phases.

During the *Develop* phase, we constructed the game prototype. Focus group members represented backgrounds in science education research, science teaching, earthquake engineering, game-design, and gaming community membership. Including those with varying backgrounds during prototyping has been proffered as an essential skill for a game designer.[63] Further, we used Schell's game-design tips for productive prototyping in the *Develop* phase,[63] which established a game-design layer on an instructional foundation. For example, the game construction process began as a physical prototype, which enabled problems to be spotted sooner than if *Earthquake* had been digitized at the beginning of the R&D.

During the *Design* phase, we used teachers participating in the study as prototype testers. Teachers were the established prototyping priority. We knew that the game would be meaningless if the teachers–those delivering the game into the intended environments–found the game invaluable[63] educationally. The teachers provided feedback to improve the game. We integrated the feedback into the *Implement* phase. Including teachers' voices further imputed an instructional layer into synthesis.[47] Additionally, we iteratively used the game-design principle of including no more than five players per game to work out game-design issues.[64] By targeting teachers as the prototype testers and bounding game groups to an empirically derived number,[64, 65] we established further instruction- and game-design synthesis.

8. Game R&D phases

To frame the purpose of the study, we organized explication of the R&D phases into two sections. The *Analyze, Develop, Design,* and *Implement* phases include summarized procedures and results. This first section presents context for the second section, which is a more detailed explication of the *Evaluate* phase procedure and results.

8.1. R&D phases: *Analyze, Develop, Design*, and *Implement*

8.1.1. *Analyze* phase

Before creating instruction, an instructional need must first be determined. Thus before making the *Earthquake* game, we analyzed relevant literature to locate research conducted previously, identify literature gaps, and provided a strong foundation for the study. In the context of the R&D for the game, we conducted a GBL literature review and wrote performance objectives for what would become the game.

We determined earthquake engineering as the ideal domain on which to anchor the game. This complex and systems-oriented domain has several implications for 21st century science learning. These implications include blurring the domain boundaries between science and engineering,[2] providing opportunities to understand complex connections between Earth and man-made systems,[1] inviting students' real-life experiences into the discourse of decision-making,[2] and empowering students to be producers of knowledge.[2, 28] We determined the game's content knowledge performance objective to be that players would acquire introductory content knowledge about earthquake engineering.

We used a socio-cognitive constructivist lens to outline the knowledge content performance objective to introduce earthquake engineering. We adapted this perspective to allow players to construct their own knowledge frameworks in a GBL environment–an environment driven by the motivation of play within a community of learners. Zooming out, the overall performance objective of the *Earthquake* game was to engage players in 21st century science learning for engineering education. Well-designed games provide opportunities for players to develop and practice important 21st century abilities,[10, 11, 12] such as critical thinking, scientific argumentation, and metacognition.[1, 23, 27, 28] Well-constructed science educational games can blend science and engineering design,[19] which is an important new perspective adopted by the *Next Generation Science* Standards *Standards*.[2] We determined broader performance objectives, pragmatically resonant with earthquake engineering, to be that players can gain the 21st century learning abilities of critical thinking, scientific argumentation, and metacognition.

8.1.2. *Develop* phase

With learning objectives established, we began the *Develop* phase for game prototyping, assisted by nine focus groups of experts (n=16) from various backgrounds, including science education, civil engineering, gaming, teaching, and educational administration. Over the span of two years, nine focus groups met for two to six hours. The focus group incentive was to draft an engaging product that would hook students, allow them to become immersed in the context of the game, and to learn-by-doing. We video recorded the focus group meetings to reference decisions for the creation of a prototype version of *Earthquake*.

8.1.3. *Design* phase

The completed prototype was included as an activity in a science, technology, engineering, and mathematics (STEM) teacher workshop. This professional development workshop for secondary school teachers was held in the summer of 2012. Fourteen teachers (n=14) from across the U.S. volunteered to play the game and participate in a subsequent group-interview. We video-recorded four game groups of teachers. After playing the game, we then facilitated the participation of each group in an audio-recorded 30 minute interview to capture their playing experiences. Open-ended research questions guided discussions about mechanics and educational relevance: *What did you learn about earthquake engineering from playing the game? What did you like and dislike about the game? What would you change about the game? How effective is the game at teaching the interconnectivity of urban infrastructure components?*

We transcribed the group interviews and analyzed them with constant comparison methods for naturalistic inquiry.[66] The goal of analysis was to develop general categories that best captured the game's essence and indicated a need for modifications. We derived thought segments from transcriptions. We coded thought segments while constantly comparing code categories to isolate the final emergent themes: *educational value, game logistics, playing experience,* and *classroom orchestration*. For organization purposes, each thought segment contained identifiers for the group, person speaking, question of topic, and transcription page number. We included science education researchers throughout the process to aid in minimizing potential bias and unforeseen threats to validity and reliability.

To credit findings related to interview analysis, we employed triangulation during the constant comparison analysis of the teacher interviews, maintained a journal to record changes throughout the constant comparison process, and recruited individuals of varying backgrounds for triangulation meetings. A science education researcher who had served as an interviewer and a focus group member, an education graduate student unfamiliar with the game, and the game developer conducted the final stage of the analysis of teachers' interviews. These three unique perspectives aided in establishing credibility within and among the themes, categories, and sub-themes[66] of the constant comparison. This group met four times for several hours each.

8.1.4. *Implement* phase

We generated a list of modifications and revised the *Earthquake* game on the basis of the teacher qualitative results. Findings were to add player roles to scaffold the learning process, to make an introductory video of how to play to supplement the "rulebook," and to simplify descriptions on certain "event" cards. These forms of modifications essentially served to improve the game's function as a GBL instructional tool. We implemented the modifications directly by producing a brief introductory video and improving game logistics by clarifying sentences on targeted "event" cards and creating game-specific roles for each player. We physically created the modified game prototype, completing the *Implement* phase.

8.1.5. Overview of the modified game prototype

As students' prior knowledge critically affects learning,[28] we made the *Earthquake* game to harness prior knowledge to enhance the learning environment. The educational goal with respect to earthquake engineering content knowledge was to teach the interconnectivity of urban infrastructure components:[67] water, transportation, communication, and power. Broader goals were to provide opportunities for the development and practice of higher-order 21st century thinking skills. The game targeted some of the most important of these abilities, which are critical thinking, scientific argumentation, and metacognition.[1]

The shared objective of all groups playing the game was to build a habitable and resilient city in an earthquake-prone area of the world. Each group collaboratively decided which "hubs" to build and how, based on available resources. "Hubs" served various functions; some mitigated earthquake damage while others generated "resource tokens." When an "earthquake" card was drawn from the "event" deck, players removed a number of "resource tokens" from the board, randomly determined by a die roll. After about two hours, the group with the most "people points" won. When a group built a "residential hub," they received "people points."

Qualities of productive small group interactions, found in gaming groups, have been posited as valuable aspects of 21st century science learning.[1,2] Devised for three to six players per board with several games set-up in a classroom, the board consisted of sectors on which "hubs" were built by playing "resource tokens." Each game group worked collaboratively together as a "city council team," competing against other groups engaged in playing their own games. The game group schema was designed to function as a pedagogical tool. Following Leemkuil,[68] we used the interaction within gaming groups as a method to improve collaboration and cooperation through group discussions and debriefing.

8.2. R&D phase V: *Evaluate*

In this cumulative and final phase, we collected data to examine possible evidence supporting the two knowledge claims of the game's educational efficacy. We analyzed data from high school students' game-plays to acquire evidence supporting the claims that the game provided players opportunities to practice and enhance critical thinking, scientific argumentation, and metacognition, while constructing content knowledge about earthquake engineering.

8.2.1. Participants and data collection

Six high school students (n=6) volunteered, with parental consent, to participate in the study. Three students comprised Group 1 and three students comprised Group 2. Students picked their own game-group. Prior to game play, the teacher-recommended introductory video was shown. The two groups played the game in the same room but on separate tables. The groups of students collaborated within their group to play the game, while competing against the other group. The two groups played their own game for an hour and a half. This timeframe was chosen based upon qualitative field notes from the STEM teacher professional development workshop, the teachers from which were R&D *Design* phase participants; teacher-participants had informally recommended the game last about the same time interval as that of a block schedule class (i.e., 90 mins.). After a complementary dinner break, the two student-groups played the game a second time. Players remained in their same groups for Game 1 and Game 2. The students played the second game for an hour and a half, as well. Game-play was video-recorded to capture how students played Game 1 and Game 2. One video camera recorded Group 1 while another video camera recorded Group 2.

8.2.2. Data analysis

We transcribed the video recordings, including player dialogue as well as relevant player non-verbal communication such as actions pertaining to game-play (e.g., pointing to a "hub" built on the board instead of verbalizing a location). To analyze the transcriptions, we developed a GBL checklist specifically to assess the degree to which *Earthquake* players demonstrated use of critical thinking, metacognition, scientific argumentation, and earthquake engineering content knowledge. The GBL checklist was developed to compare measurements of cognitive gain and knowledge acquisition between Game 1 and Game 2 for both groups.

Found in Appendix A, the GBL checklist functioned as an instrument to tally players' behaviors demonstrating critical thinking, metacognition, and use of earthquake engineering content knowledge. We compartmentalized these categories into sub-categories, each with respect to scientific argumentation components: making a claim, defending, clarifying, revising, and asking for input. We scored the categories for which players' actions were scored as cognitive domains of critical thinking,[69] scientific argumentation,[28] the self-regulation and control components of metacognition,[70] and earthquake engineering content knowledge.[71, 72]

We modified Paul and Elder's checklist for the cognitive domains of critical thinking[69] and Pintrich, Wolter, and Baxter's checklist for metacognition[70] to be utilized through the GBL lens within the context of scientific argumentation. Accordingly and following educational game-design recommendations from Schwartz and Bayliss,[19] the word *learning* was replaced with *playing* in Dick, Carey, and Carey's instructional design model.[37] Though simplistic, this word replacement allowed for the instructional design to transfer onto game evaluation. The resulting sub-categories for the critical thinking category were: (1) raises a vital question and/or problem, (2) gathers and/or assesses relevant information, (3) comes to a well-reasoned solution, and (4) thinks open-mindedly within an alternative system of thought. The resulting sub-categories for the metacognition category were: (1) plans by setting goals for playing and timing; (2) strategizes by deciding which strategy to use for a task or when to change a strategy; (3) regulates time use, effort, pace, or performance; and (4) regulates motivation, emotion or environment (i.e., volition control). The resulting sub-categories for the earthquake engineering content knowledge category were: (1) interconnectivity, (2) importance of water, (3) redundancy, (4) resilience, (5) human element, (6) safety, and (7) real-life applications.

When a player showed evidence on the video record for an item on the GBL checklist, we used Microsoft Word to code the corresponding segment of the video transcription according to checklist categories. A *Design* phase focus group member and the game developer established an inter-coder reliability of 87% by individually coding transcriptions with the GBL checklist followed by minor negotiations till agreements were met. We independently transcribed the first 10 pages of Game 2 for Group 1. From preliminary analysis, this portion of all the transcriptions yielded the most diverse and dense dialogue of all the game-plays. Once the GBL checklist passed an acceptable inter-coder reliability, the checklist then served as the instrument to capture features of the students' game-plays that related to the performance objectives.

To accommodate the large amount of video data, we analyzed transcriptions every two pages; each page was read to maintain context for each coded page. Upon completion of transcription analysis, we tallied the codes for each player from Microsoft Word comments onto the GBL checklist for Game 1. The same procedure was followed to analyze Game 2 and to indicate any gain between games. A page of example coded player transcriptions is shown in Appendix B. To examine GBL checklist category gains, we compared between game frequency counts of GBL checklist categories.

9. Results

We compared completed checklists for Games 1 and 2. Aggregated tallies showed gains for each checklist category from Game 1 to Game 2 for both student groups. The differences between Game 1 and Game 2 (in units of "counts") for tallies on the GBL checklist were considered "gains." Results for Group 1 and Group 2 are presented below by GBL category and then by scientific argumentation spread. Player data is labeled to include a player's group by number and the individual player's letter codename for their respective group. For example, the data label for player "A" in Group 1 is "Player1A." Results for Game 1 and Game 2 are labeled additionally.

9.1. Critical thinking

9.1.1. Group 1

The Group 1 gains for the sub-category, "comes to a well-reasoned solution," were higher for each player in Game 2 than in Game 1. Shown in Table 1, the frequency count difference for the group is 171 counts (player A = 69, player B = 46, player C = 56); that is, the players show a gain in coming to a well-reasoned solution through scientific argumentation components. Figure 1 displays the spread of exhibited scientific argumentation components for each player in Group 1 in coming to a well-reasoned solution.

Table 1. *Group 1 Counts and Gains for the Critical Thinking Sub-category of Comes to a Well-reasoned Solution*

Critical Thinking	Game 1			Game 2		
Comes to a Well-reasoned Solution	Player 1A	Player 1B	Player 1C	Player 1A	Player 1B	Player 1C
Claim	8	14	13	32	38	37
Defend	12	12	12	22	16	18
Clarify	8	18	8	23	20	16
Revise	2	6	2	15	14	15
Ask	11	5	4	18	13	9
Within Game Totals by Player	41	55	39	110	101	95
Game Gain by Player	69	46	56			

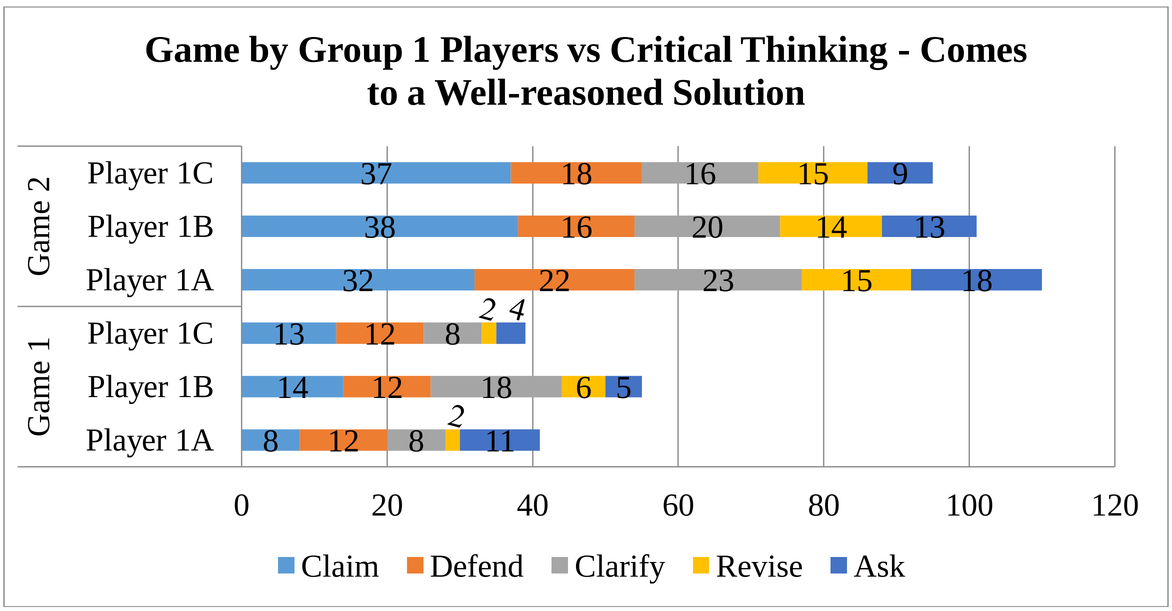

Figure 1. "Comes to a well-reasoned solution" sub-category spread of how Group 1 players scored a tally mark on the GBL checklist with respect to scientific argumentation components: claim, defend, clarify, revise, and ask.

The other three sub-categories of the critical thinking category displayed gains and similar spreads. The total group gain for "raises a vital question or problem" was 42 counts, for "gathers and/or assesses relevant information" was 82 counts, and for "thinks open-mindedly within an alternative system of thought" was 18 counts. The gain for Group 1 in the critical thinking category was 313 counts.

9.1.2. Group 2

The Group 2 gains for the sub-category "gathers and/or assesses relevant information" were higher for each Group 2 player in Game 2 than in Game 1. As shown in Table 2, the gain for Group 2 was 340 counts (player A = 160, player B = 123, player C = 57). That is, the players showed a gain in gathering and/or assessing relevant information through video-recorded expression of scientific argumentation components. Figure 2 displays the spread of exhibited scientific argumentation components for each player in this third sub-category of the GBL checklist critical thinking category.

Table 2. *Group 2 Counts and Gains for the Critical Thinking Sub-category of Gathers and/or Assesses Relevant Information*

Critical Thinking	Game 1			Game 2		
Gathers and/or assesses relevant information	Player 2A	Player 2B	Player 2C	Player 2A	Player 2B	Player 2C
Claim	56	56	14	119	83	28
Defend	10	12	10	16	35	22
Clarify	20	20	6	73	54	23
Revise	12	9	4	23	22	7
Ask	17	12	3	44	38	14
Within Game Totals by Player	115	109	37	275	232	94
Game Gain by Player	160	123	57			

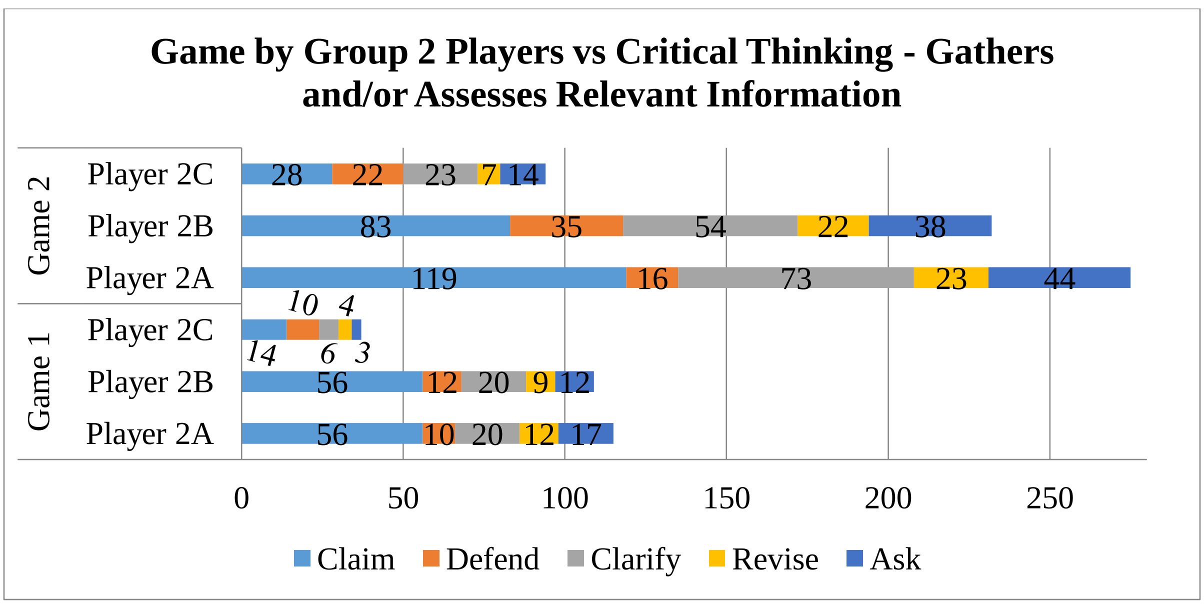

Figure 2. "Gathers and/or assesses relevant information" sub-category spread of how players in Group 2 scored a tally mark on the GBL checklist with respect to scientific argumentation components: claim, defend, clarify, revise, and ask.

The other three sub-categories of the critical thinking category displayed gains and similar spreads. The Group 2 gain for "raises a vital question or problem" was 34 counts, for "comes to a well-reasoned solution" was 182 counts, and for "thinks open-mindedly within an alternative system of thought" was 12 counts. Group 2's total gain for the critical thinking category was 568 counts.

9.2. Metacognition

9.2.1. Group 1

The Group 1 frequency counts for the sub-category of, "regulates time use, effort, pace, or performance" were higher for each player the second game than the first game. As shown in Table 3, the frequency count difference for Group 1 was 123 counts (player A = 52, player B = 44, player C = 27). That is, the players showed a gain in regulating time use, effort, pace, and/or performance through scientific argumentation components. Figure 3 displays the spread of exhibited scientific argumentation components for each Group 1 player in demonstrating this regulation.

Table *3. Group 1 Counts and Gains for the Metacognition Sub-category of Regulates Time Use, Effort, Pace, or Performance*

Metacognition	Game 1			Game 2		
Regulates Time Use, Effort, Pace, or Performance	Player 1A	Player 1B	Player 1C	Player 1A	Player 1B	Player 1C
Claim	19	39	34	40	44	38
Defend	5	3	3	10	11	7
Clarify	11	5	7	23	21	21
Revise	3	6	2	7	11	8
Ask	16	18	11	26	28	10
Within Game Totals by Player	54	71	57	106	115	84
Game Gain by by Player	52	44	27			

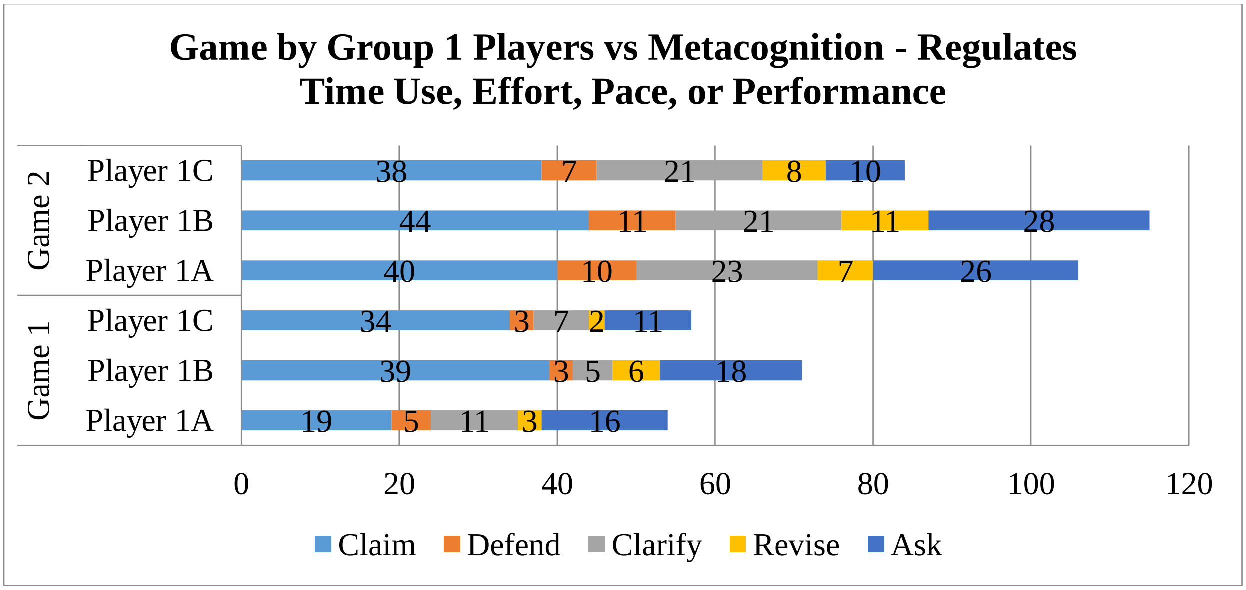

Figure 3. "Regulates time use, effort, pace, or performance" metacognition sub-category spread of how players in Group 1 scored a tally mark on the GBL checklist with respect to scientific argumentation components: claim, defend, clarify, revise, and ask.

The other three sub-categories of the metacognitive category displayed gains and similar spreads. The Group 1 gain for "plans by setting goals for playing and timing" was 75 counts, for "strategizes by deciding which strategy to use for a task" was 109 counts, and for "regulates motivation, emotion, or environment" was 43 counts. The total gain for Group 1 for the metacognition category was 350 counts.

9.2.2. Group 2

Group 2 frequency counts for the sub-category of "regulates time use, effort, pace, or performance" were higher the second game than the first game. In Table 4, the count difference for Group 2 was 343 counts (player A = 171, player B = 126, player C = 46). That is, the players showed a gain in regulating time use, effort, pace, or performance through scientific argumentation components. Figure 4 displays the spread of exhibited scientific argumentation components for each Group 2 player in demonstrating this regulation.

Table 4. *Group 2 Counts and Gains for the Metacognition Sub-category of Regulates Time Use, Effort, Pace, or Performance*

Metacognition	Game 1			Game 2		
Regulates Time Use, Effort, Pace, or Performance	Player 2A	Player 2B	Player 2C	Player 2A	Player 2B	Player 2C
Claim	72	40	13	130	79	26
Defend	7	6	6	17	19	17
Clarify	18	10	9	83	56	18
Revise	8	9	1	19	17	7
Ask	19	16	8	41	36	15
Within Game Totals by Player	119	81	37	290	207	83
Game Gain by Player	171	126	46			

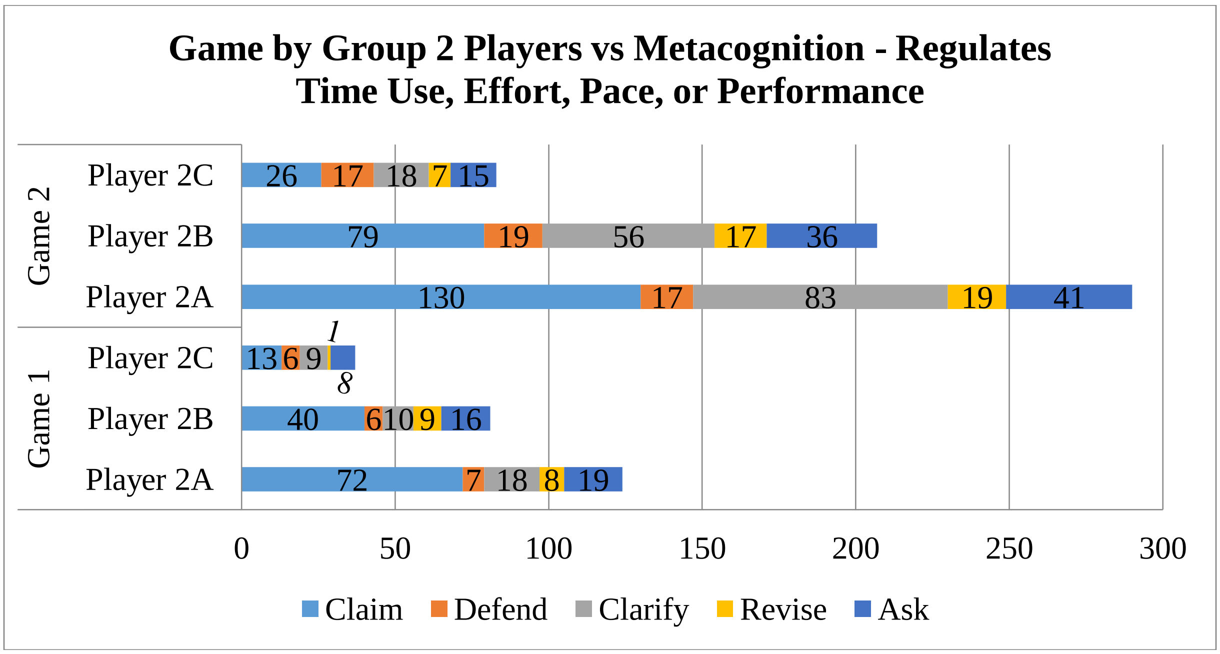

Figure 4. "Regulates time use, effort, pace, or performance" metacognition sub-category spread of how players in Group 2 scored a tally mark on the GBL checklist with respect to scientific argumentation components: claim, defend, clarify, revise, and ask.

The other three sub-categories within the metacognition category displayed gains and similar spreads. The Group 2 gain for "plans by setting goals for playing and timing" was 82 counts, for "strategizes by deciding which strategy to use for a task" was 155 counts, and for "regulates motivation, emotion, or environment" was -9 counts. The total gain for the metacognition category was 571 counts for Group 2.

9.3. Earthquake Engineering Content Knowledge

9.3.1. Group 1

Group 1 frequency counts for the earthquake engineering content knowledge sub-category of "safety" were higher the second game than the first game. As shown in Table 5, the count difference for Group 1 is 27 counts (player A = 15, player B = 6, player C = 6). That is, Group 1 players showed a gain in using content knowledge about the safety associated with urban infrastructure. Figure 5 displays the spread of exhibited scientific argumentation components for each Group 1 player demonstrating use of safety knowledge.

Table 5. *Group 1 Counts and Gains for the Earthquake Engineering Content Knowledge Sub-category of Safety*

Earthquake Engineering Content Knowledge	Game 1			Game 2		
Safety	Player 1A	Player 1B	Player 1C	Player 1A	Player 1B	Player 1C
Claim	0	2	1	8	8	3
Defend	0	1	0	4	0	3
Clarify	0	0	0	2	1	1
Revise	0	0	0	0	1	0
Ask	0	1	0	1	0	0
Within Game Totals by Player	0	4	1	15	10	7
Game Gain by Player	15	6	6			

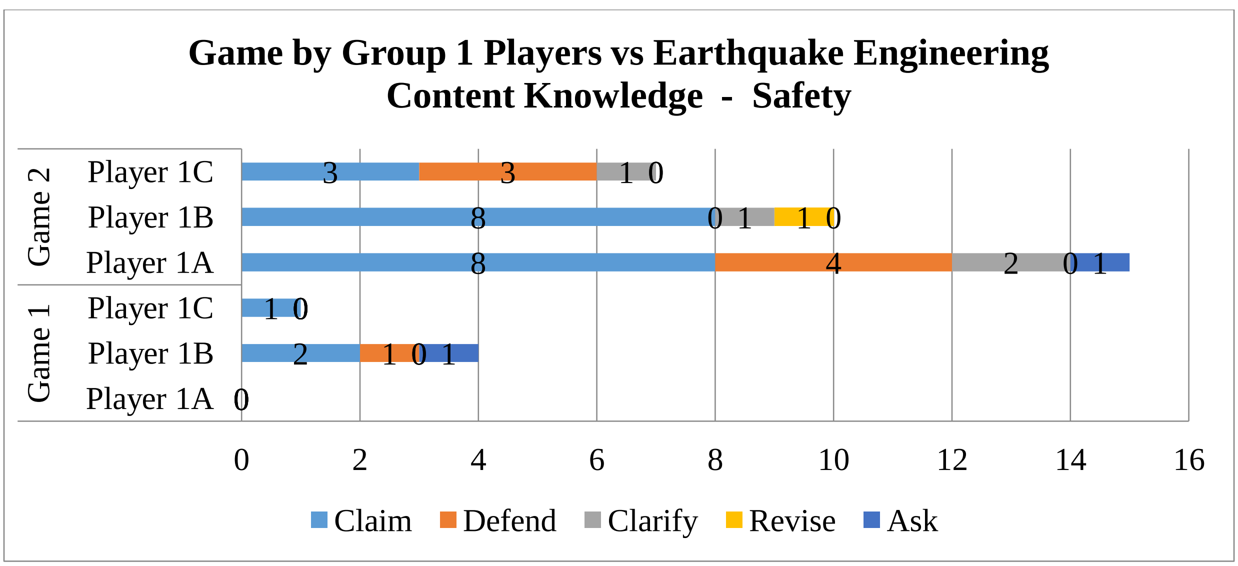

Figure 5. "Safety" earthquake engineering content knowledge sub-category spread of how Group 1 players scored a tally mark on the GBL checklist with respect to scientific argumentation components: claim, defend, clarify, revise, and ask.

The other six sub-categories of the earthquake engineering content knowledge category displayed gains and similar spreads, except for the "redundancy" subcategory with a negative gain. The total group gain for "interconnectivity" was 13, for "importance of water" was 16, for "redundancy" was -13, for "resilience" was 19, for "human element" was 11, and for "real-life application" was 4. Group 1's total gain for the earthquake engineering content knowledge category was 77 counts.

9.3.2. Group 2

Group 2 frequency counts for the earthquake engineering content knowledge sub-category of "human element" was higher the second game than the first game. As shown in Table 6, the count difference for Group 2 was 54 counts (player A = 30, player B = 13, player C = 11). That is, the players showed a gain in using content knowledge about the human element involved with urban infrastructure. Figure 6 displays the spread of exhibited scientific argumentation components for each player who demonstrated use of knowledge pertaining to the value of human life.

Table 6. *Group 2 Counts and Gains for the Earthquake Engineering Content Knowledge Sub-category of the Human Element*

Earthquake Engineering Content Knowledge	Game 1			Game 2		
Human Element	Player 2A	Player 2B	Player 2C	Player 2A	Player 2B	Player 2C
Claim	4	4	2	17	8	4
Defend	1	0	1	2	5	1
Clarify	2	2	0	13	5	6
Revise	0	1	0	0	0	1
Ask	1	0	0	6	2	2
Within Game Totals by Player	8	7	3	38	20	14
Game Gain by Player	30	13	11			

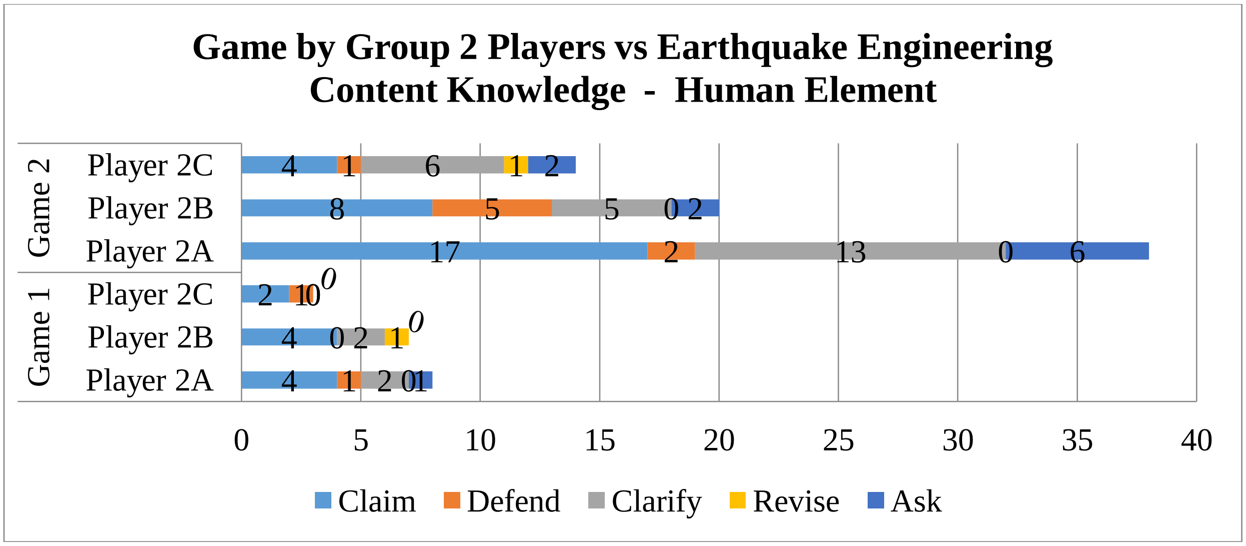

Figure 6. "Human element" earthquake engineering content knowledge sub-category spread of how Group 2 players scored a tally mark on the GBL checklist with respect to scientific argumentation components: claim, defend, clarify, revise, and ask.

The other six sub-categories of the earthquake engineering content knowledge category display gains and similar spreads. The Group 2 gain for "interconnectivity" was 27 counts, for "importance of water" was 13 counts, for "redundancy" was 13 counts, for "resilience" was 43 counts, for "safety" was 21 counts, and for "real-life application" was 16 counts. Group 2's total gain for the earthquake engineering content knowledge category was 187 counts.

10. Conclusions and Discussion

The inductively developed GBL checklist served to document and compare evidence of met learning objectives. In this study, our comparisons indicated gains realized for earthquake engineering content knowledge, critical thinking, scientific argumentation, and metacognition from first to second playing of the game. These results provide evidence of effectiveness of this particular instructional innovation in advancing students' knowledge and abilities in engineering. All six students showed about the same self-relative gains for each GBL checklist category. Furthermore, we found the R&D methodology provided an appropriate, systematic framework for integrating research methodologies at every phase in the R&D process.

The empirical evidence supported the claim that the *Earthquake* game can provide players opportunities to practice and improve 21st century learning. For the first game, students exhibited use of critical thinking, metacognition, and earthquake engineering content knowledge by means of scientific argumentation, supporting the claim that the game can provide opportunities to practice the specified abilities. During the second game, students exhibited more use of critical thinking, metacognition, and earthquake engineering content knowledge by means of scientific argumentation, thus supporting the claim that the game can provide players opportunities to enhance the specified abilities. All players showed improvements from their respective Game 1 to Game 2 in GBL checklist categories. Because the GBL checklist was oriented around scientific argumentation, the findings suggest that social learning may contribute to improved critical thinking, metacognition, and earthquake engineering content knowledge.

The spread of scientific argumentation components was better-rounded for both student groups from the first to the second game for all GBL checklist categories. This could have been due to players' familiarity with game mechanics the second time around. The GBL checklist category of earthquake engineering content knowledge indicated mostly claims having been made, though gains were found in all subcategories but Group 1's "redundancy." This could have been due to this group taking some time during Game 1 to specifically discuss the pros and cons of resource redundancy. Once the general strategy was agreed upon, the students did not verbalize the topic during Game 2 with enough rigor to code a transcription segment confidently as addressing the "redundancy" subcategory. Additionally, earthquake engineering content knowledge requires cohesive articulation to confidently tally the GBL checklist. The critical thinking and metacognitive categories are not as strictly bound to content conditions, which may account for the higher gains observed in the critical thinking and metacognitive categories for both student groups.

10.1. Limitations

We created the *Earthquake* game specifically for the R&D of engineering education. Any results or implications are thus limited to this study. The R&D process of this study is limited to the 16 focus group members of the *Develop* phase, the 14 teachers who played the game and were interviewed in the *Design* phase, and the six high school students who played the game in the *Evaluate* phase. The study was limited in that the teacher workshop only lasted one week and the students played the game only twice in one visit. Any implications and conclusions are limited to the small size of the participants. The teachers who participated in playing the game and the subsequent interviews were already recruited for the professional development workshop and not specifically for game analysis.

Few researchers designing educational games have reported completing an R&D process synthesizing instruction- and game-design principles. Of these, few reported educational games designed with respect to instructional theories. A review of the literature revealed game- and instruction-design as relatively separate research domains.[15, 20] Within and between both fields, there has not been an accepted agreement on the definitions of "game" or "play." The lack of cohesive terminology and concepts within and among domains, therefore, have contributed to the lack of methodological research guideposts.

The GBL checklist was also limited in the scope of analysis. We produced the GBL checklist specifically to examine data about critical thinking, metacognition, scientific argumentation, and earthquake engineering content knowledge. This instrument restricts generalizations about students' feelings and notions not specifically addressed in the GBL checklist.

10.2. Implications

Completing an instructional research and development (R&D) model can foster 21st century learning opportunities. Superimposing game mechanics from the domain of game development can blend 21st century science and engineering education. The study directly addresses the evaluation of an educational game to fill the currently large gap in the literature base. This research may be especially significant for educational game designers by providing an R&D case study emergently evolving with respect to itself and not to an inappropriately prescribed assessment scheme. Researchers[11, 19, 20] have identified the need for and call for such a study. This study of empirical results may provide detailed information about elements of game construction involved in completing the R&D as a whole and the *Evaluate* phase of the R&D process. R&D methodology for GBL can progress non-linearly. As more voices participated in the R&D, more opportunities to improve the *Earthquake* game became visible. This implication corroborates that of other GBL researchers, who have proffered that GBL can support student learning for productive teamwork abilities.[73]

The relationship between the structure of instruction and student agency in learning is complex.[74] Game-based learning environments can foster learning while also promoting engagement.[34] The broader impacts of this study may inform stakeholders of how educational gaming can actually support successful 21st century learning as related to critical thinking, scientific argumentation, metacognition, and engineering design. With empirically validated evidence of the game's success, stakeholders may be more willing to view play as a legitimate way to learn. If brought into classrooms, this game may elucidate to school administrators, teachers, parents, and students that playing is an important part of 21st century life.

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Appendix A

Table A.1

Critical Thinking Category of Game-based Learning Checklist

CRITICAL THINKING:	Scientific Argumentation:	Player A	Player B	Player C
(C1) Raises a vital question or problem	Makes a claim (M)			
	Defends (D)			
	Clarifies (C)			
	Revises (R)			
	Asks for advice or ideas (A)			
	TOTAL			
(C2) Gathers and assess relevant information	Makes a claim			
	Defends			
	Clarifies			
	Revises			
	Asks for advice or ideas			
	TOTAL			
(C3) Comes to a well-reasoned solution	Makes a claim			
	Defends			
	Clarifies			
	Revises			
	Asks for advice or ideas			
	TOTAL			
(C4) Thinks open-mindedly within an alternative system of thought	Makes a claim			
	Defends			
	Clarifies			
	Revises			
	Asks for advice or ideas			
	TOTAL			

Appendix A

Table A.2

Metacognition Category of Game-based Learning Checklist

METACOG-NITION (SELF-REGULATION AND CONTROL):	Scientific Argumentation:	Player A				Player B				Player C			
(M1) Plans by setting goals for playing and timing	Makes a claim (M)												
	Defends (D)												
	Clarifies (C)												
	Revises (R)												
	Asks for advice or ideas (A)												
	TOTAL												
(M2) Strategizes by deciding which strategy to use for a task or when to change a strategy	Makes a claim												
	Defends												
	Clarifies												
	Revises												
	Asks for advice/ideas												
	TOTAL												
(M3) Regulates time use, effort, pace, or performance	Makes a claim												
	Defends												
	Clarifies												
	Revises												
	Asks for advice/ideas												
	TOTAL												
(M4) Regulates motivation, emotion, or environment (volition control)	Makes a claim												
	Defends												
	Clarifies												
	Revises												
	Asks for advice/ideas												
	TOTAL												

Appendix A

Table A.3

Earthquake Engineering Content Knowledge Category of Game-based Learning Checklist

EE CONTENT KNOWLEDGE:	Scientific Argumentation:	Player A | Player B | Player C									
	Makes a claim (M)										
	Defends (D)										
	Clarifies (C)										
	Revises (R)										
	Asks for advice/ideas (A)										
(E1) Inter-connectivity	TOTAL										
	Makes a claim										
	Defends										
	Clarifies										
	Revises										
	Asks for advice/ideas										
(E2) Importance of water	TOTAL										
	Makes a claim										
	Defends										
	Clarifies										
	Revises										
	Asks for advice/ideas										
(E3) Redundancy	TOTAL										
	Makes a claim										
	Defends										
	Clarifies										
	Revises										
	Asks for advice/ideas										
(E4) Resilience	TOTAL										
	Makes a claim										
	Defends										
	Clarifies										
	Revises										
	Asks for advice/ideas										
(E5) Human element	TOTAL										
	Makes a claim										
	Defends										
	Clarifies										
	Revises										
	Asks for advice/ideas										
(E6) Safety	TOTAL										
	Makes a claim										
	Defends										
	Clarifies										
	Revises										
	Asks for advice/ideas										
(E7) Real-life applications	TOTAL										

Appendix B

Example of Coded Transcriptions

C: Alright, now. So, you could do this (points to future orange residential hub).
A: Make a residential. Make that residential there.
C: Yea (as one action, replaces residential token in orange sector).
A: (Verifies location on record).
C: Now power. Where's the power?
A: Um,
B: Take your (points to player a) power out.
A: Yea (replaces power token in orange residential sector).
C: Wait, you (points to player b) can't do anything else because we put back this (points to orange residential hub token that was just put back in).
B: Oh, yea.
C: It does (pointing to same orange residential hub token) when you play it.
A: (Discards water resource cards).
B: Wait, what are you (points to player a) doing? (Puts player a's discarded water resource card back in a's hand) Why do you (points to player a) keep putting it there?
A: What? Because I used that water there.
B: No no no.
B: And then you put the power.
B: And then that's it.
C: The hub is an action.
A: The hub is an action. So, "player b," you have to do that (points to hub deck).
C: Wait no, but remember, we already have it (points to the residential hub card in hub central) here.
A: Yea okay.
B: (event) "Highway maintenance." We don't have a highway (discards). I draw my card (doesn't verbally say what resource card it is).
A: (looking over record sheet).
C: Okay so, let's put, (points to removed tokens from what was the red residential prior to earthquake).
A: (Looking at record sheet) Where did that go (points to power token)?
B: (Discards power resource card).
C: (moves power back into main hub).
A: (References record) No, move it over.
C: (moves player b's power token over a hexagon).
A: Yea, there ya go (verifying on record sheet).
C: Do you (points to player b) want to (build a residential in red)? Oh, we have to have water first.
A: (for b's 2nd action) just put the water down in there first (pointing to former red residential sector).
B: Alright, I'm done (discards water).
C: (Places player b's water token in red sector). Alright.
A: (verifies placement with record).

Player C: C3M, M1M, E3C
Player A: C3D, M1D, E3D
Player C: C2A
Player B: C3M, M2M
Player A: C3D, MD2
Player C: C1M, M3M
Player B: C1D, M3D
Player C: C1D, M3D
Player B: C2A, M3R
Player A: C3D, M3D
Player B: C2C, M3C
Player B: C2C, M3C
Player B: C2C, M3C
Player C: C2C, M3C
Player A: C3M, M1M
Player C: C2R, M1R
Player A: C3R, M1D
Player C: C4M, M1M, E4M
Player A: C2A, M3A
Player B: C3M, M2M
Player C: C3C, M2M, E1M
Player A: C3R, M2M
Player C: C3R, M2D
Player A: M4M
Player C: C1A, M1A
Player C: C1M, E1M
Player A: C2M, M1M, E1D
Player B: C2D, M3M
Player C: C2D