Learning through Computer-Assisted Collaborative Game Design: Mathematical, Design, and Computational Thinking

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Abstract: Employing a concurrent mixed-method research design, this study examined the potential of computer-assisted, collaborative game-design activities in promoting design-based mathematical thinking for school children. Sixty four middle school children, with a high percentage of Native American and Hispanic students, participated in a six-week mathematics game design program. Data were collected via in-field observation, design interaction analysis, interviewing, and an attitudes survey. The findings indicated that the design-based interaction and programming-oriented problem solving processes embodied mathematical thinking and reinforced positive attitudes toward mathematics. On the other hand, the prioritization of world/character design and the cognitive demand of computational programming led to a superficial integration or representation of mathematics in children's design products.

Introduction and Theoretical Perspectives

Constructivist and enactivism learning theories argue that learners actively construct knowledge out of their experiences, especially when they are engaged in building objects (Papert, 1980; Kafai, 1995; Li, 2012). Rooted in this theoretical disposition, this study postulated that school children, by collaboratively creating computer math games, will work on and explain the math concepts and problems during design activities. Particularly, students will engage in two learning interactions that transform collaborative, creative activity into mathematical thinking – learner-design interaction and game-design-based social interaction

Interaction between students and the game-design task: A math game-design task may be deemed as a microworld, a promising tool for the development of mathematical thinking (e.g., Mitchell, Kelleher, & Saundry, 2007; Roblyer & Edwards, 2000; Shaffer, 2005). As students design a math game, they will need to explore, represent, and test their mathematical thinking and integrate them into a game's play mechanics. The process will help students articulate, self-check, and constantly accommodate their prior mathematics mental framework (Shaffer, 2005). Empirical research on the use of design practices as contexts for math learning (e.g., Kafai, 1995; Kolodner et al., 2003) indicates that students can "formulate mathematical conjectures during, and as a consequence of, their design activity" (Shaffer, 2005, p. 7). These mathematical conjectures, representing students' ability to "form inferences about general principles from specific observations", are significant for mathematical understanding (Davis & Hersh, 1982; Fitzgerald, 1996; Shaffer, 2005, p. 7).

Interaction between students and design partners: During the design process, middle school children will explain the math topics they have valued and explore alternatives of gameplay quest to represent these topics. Design partners can provide feedback and prompt each other to elaborate more conceptual insights or mathematical reasoning. Self-explanation and communication in mathematics thus become necessary and motivated. In the research literature, self-explanations have been identified as one important factor for enhancing and correcting students' understanding of mathematics concepts (VanLehn, Jones, & Chi, 1992; Wong, Lawson, & Keeves, 2002). Teachers or adult mentors then can act as critics who not only facilitate mathematics communication but also model the in-context usage of mathematics vocabulary that gives young learners the means of communicating math concepts universally.

Methods

An in-situ, mixed-method case study approach (Yin, 2008) was used to examine the phenomenon of learning through collaborative design within computer gaming contexts. The study focused on two research questions: (1) What nature is the collaborative-game-design-based cognitive and interaction processes for inviting and sustaining forms of mathematical thinking (i.e., representation, communication, and reasoning of mathematics)? (2) Has participating in computer math game design helped students to develop positive attitudes toward mathematics?

Sites and Participants

The study was conducted in a rural pueblo school of Native American students and an urban school with a high percentage of Hispanic students. Sixty-four middle grade students were recruited from the two schools, with around 20% of participants being Native American, 80% being Hispanic, and 43% being girls. A group of education graduate students, along with two middle school teachers and the researchers of the study, acted as mentors who provided design and technical support during the game design sessions.

Design Task and Procedure

Iterative Design processes

In this study, students were first probed to identify a mathematical concept or procedural skill that they considered important (e.g., percentage and ratio, multiplication and division, as reported by the participants). They were then requested to create a mini-game to explain the concept or afford the learning of the procedural skill. The game design activity lasted for 6 weeks with 2 one-hour sessions each week. The design sessions took place at the two schools' computer labs. Before performing the game-design task, student participants had all played a selection of exemplary computer mathematics games over a month. A debriefing session was set to probe them to reflect on the games that they had played and discuss on game world and play actions that had engaged them in math learning. They also received training on using *Scratch*, a 2D programming environment designed and developed by the MIT Media Lab for children and youth.

The game design task was semi-structured, following the proposition by the prior research on game-design studios (e.g., Sotamaa 2005) and learning-through-design programs (e.g., Kafai 2006; Kolodner et al. 2003; Shaffer 2005). Different design groups were seated at different tables. Every group generally went through the following design procedure: (a) identifying the target math topic and design goal, (b) brainstorming on solutions to the design challenges, (c) sketching to describe and demonstrate the design ideas, and (d) *Scratch*-based computer game development. To reinforce interaction and collaboration, we requested every member of a design team to take on a particular role based on his/her expertise and interest, such as the team leader, artist, leading developer, content expert, creative writer, and design assistant.

During the first phase of the design task, students focused on paper-based prototype development. They were told to share, accumulate, and negotiate their design ideas via paper sketching. When a *paper-based design prototype* was ready, a design group then moved to computer stations and engaged in computer-based *functional prototype* development during the remained sessions. They were provided a Scratch-oriented *prototype template* sheet in which they had to further specify their design ideas from a computational programming perspective, including the number and outlook of the characters (called *sprites*), the world description, and the major play actions. *Scratch* was used as both a development and a cognitive tool to further externalize, refine, and embody students' design ideas. In the end, all design groups were requested to upload their computer game prototypes to the Scratch web site. A post-design group debriefing session was set to make student designers evaluate and reflect on their design artifacts and experiences.

A group of graduate students, who majored in education and were enrolled in an educational game design course, facilitated all design sessions. They answered both design and content questions, gave feedback between design moves, and occasionally prompted children participants for idea elaboration or math content explanation. They also provided help on *Scratch* programming during game development.

Design-Based Programming

Scratch, a programming environment designed and developed by the MIT Media Lab, was used as students' game design tool for this project. *Scratch* has been implemented and reported on in multiple recent studies that involve computer-supported learning and learning-though-game-design workshops for school students (e.g., Emmerson, 2004; Manroy-Hernández & Hill, 2010). Prior research indicated that *Scratch* is user-friendly for school children who can learn mathematical and computational ideas by creating and sharing Scratch projects.

Data Collection and Analysis

This study utilized both qualitative and quantitative data collection and analysis methods. Data were collected through in-field observation on the game design interactions and activities, interviewing, and an attitudes survey.

The researchers of the current study have conducted categorical aggregation analysis (Stake 1995) with design conversations and observed activities to examine key patterns of design-based cognitive and interaction processes. The design discourses throughout every session were recorded and coded. The researchers of the current study conducted *categorical aggregation analysis* (Yin, 2008) with the transcripts and infield observation notes to examine the function and content of design interactions, and potential evidence of mathematics learning and thinking within design processes, by coding the critical properties of meaningful actions or instances and classifying them into aggregations. Via a systematic coding method (Marshall & Rossman, 2006), we then reduced and summarized the coded data based on the aggregations emerging from the data. The analysis of all qualitative data contributed an initial list of themes that depicted facilitators' experiences and perceptions, which were then refined and extended via a constant comparison, pattern matching and frequency coding. Peer debriefing and member checking were part of the data collection (Lincoln & Guba, 1985). Peer debriefing consisted of formal reviews of data among the coders of the study data. Member checks were conducted informally with participants during the process of data collection.

A group of purposefully sampled student participants were interviewed at the end of each design session for their perspectives of game design and learning experiences. A qualitative thematic analysis was conducted with the interviewing scripts to examine recurring themes, which were then compared and congregated with the findings of in-field observation and transcript analysis results.

All student participants completed the *Attitudes towards Math Inventory* (ATMI, Tapia & Marsh, 2004) before and after the game design intervention. This five-point Likert-scaled inventory is a 40-item survey, assessing students' attitudes toward mathematics with a focus on four identified factors: self-confidence, value, enjoyment, and motivation. The KR-20 reliability of the inventory in this study was 0.87.

Student participants' scores of a state assessment of general math achievement before and after the tutoring program were also collected. In the urban Hispanic-serving school, state assessment scores of both participants and non-participants were collected; in the rural pueblo school, all of the 13 middle school students were participants and hence there was no static control group.

Results

Potential Impact on Attitudes toward Mathematics

A pairwise t-test was conducted to compare all student participants' attitudes towards mathematics in pre-intervention and post-intervention conditions. The t-test indicated a significant result, $t(62) = -2.56$, $p < .01$. The result indicated that participants in this study had developed significantly more positive attitudes toward mathematics after participating in the team-based game-design activities.

The survey finding got corroborated by the qualitative interviewing results. In particular, the following comments had highlighted how participants re-interpreted math:

> *It's like you are learning new ways (on) how to like make better games and stuff. It's like making you practice this for the future and if you want to study then you can get practice over that.*
> *You could make it like square root and stuff instead of adding and subtracting.*
> *Math is everywhere, like math is in everything you have (to) do.*
> *I learned that even though math is everywhere you still have to learn it and when you learn it you will see it more in life that it will be in everything you do. Like cooking, technology, practically everything.*

The aforementioned comments, notably, had encompassed raised awareness of math's value, a broadened expression of math content (e.g., "square root instead of adding and subtracting"), a proactive disposition towards math learning (e.g., "when you learn it you will see it more in life"), and confidence on "new ways" to math learning (e.g., "you can get practice over that").

Nature of Collaborative Game-Design-Based Cognition and Interaction

The analysis with the qualitative data is not fully completed when this proposal is submitted. But three salient themes depicting the nature of collaborative game-design-based cognition and interaction have emerged from the data. These themes were outlined below.

Mergence of Mathematical Thinking and Computational Problem Solving

A mergence between mathematical thinking and computational-programming-based problem solving had been frequently observed and coded from participants' design interaction and their programming artifacts. During Scratch-based game programming, participants were heavily involved in customizing motion scripts of other game cases to realize their design on game actions. During the process, they had: (1) developed solid conceptual understanding of variables and coordinates through analyzing and replacing numerical values of control variables and defining locations and motions of each charter, (2) demonstrated procedural accuracy and quantitative reasoning in computing background transitions and syncing multiple motions via control loops, (3) modeled with math by creating math-relevant simulations (e.g., a car distance calculator), and (4) showed conscientiousness for problem solving during the iterative process of debugging, testing, and refining. Notably, mathematical thinking development was more observed among children who were found reluctant to perform critical thinking during previous game play activities.

Embodiment of Mathematical Communication in Design-Based Interaction

During design-based questioning and clarification, mathematics was found to be adopted and learned as a situated, contextualized design language, especially when the design teams were involved in decomposing a design goal and generating solutions. It was observed that the collective development of mathematics vocabulary in a design team had been reinforced by varied, distributed memory among individual members on mathematics concepts and math game cases played.

During the design talk, there was a presentation preference for algorithms over explanatory narratives. When designing math-related game quests, most children simply presented a challenge via a formal algorithm (e.g., "4 x 7 = ?") rather than situating or visualizing a contextualized word problem (e.g., "There are seven rocks in each box. That is total of …"). Correspondingly, 45% of their design prototypes simply displayed math elements as algorithm equations.

Dissection between Design, Computational Thinking, and Mathematical Representation

Content preference for procedural skills over conceptual presentation: When pondering on the math content to be addressed by the game, almost all student designers voluntarily guided their design thinking via the question, "*Where* will I *use* math in real life?" Accordingly, they tried to establish the scenarios and contexts before considering the gameplay mechanics or content integration, and focused on the practice of procedural skill (e.g., a numerical calculation) as the major learning goal of the games to be created. Few participants gave consideration to the question of "*What* does math *mean* in real life," and hence rarely represent or explain a math concept within their games.

Design versus learning: Design elements could distract student participants from learning. For example, students, especially girls, were observed actively searching and designing game characters and visuals while ignoring the programming of game action and feedback – the design elements that were found as more learning-related and deemed more effortful.

Implications of Research

The study findings should help to generate a clearer profile of learning through collaborative design in computer game and mathematics learning settings. This research should serve as a catalyst for insight and increased research in learning through collaborative design as well as inform the design and implementation of a game-integrated collaborative learning system.

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