Using Digital Games to Grow Spatial Skills in Upper-Elementary Learners

Abstract: The ability to make spatial judgment and visualize has been shown to be a strong indicator of students' future achievement in STEM-related courses. Spatial intelligence has also been shown to be one of the only areas in which females perform worse than males, with noticeable differences emerging in the middle school years. This spatial reasoning gap can potentially reinforce stereotypes about gender roles in certain male dominated fields such as engineering and computer science, thus exacerbating the lack of gender diversity in the STEM workforce. However, research has also shown that training exercises, even those with very short duration, can close the spatial reasoning gap between males and females. As such, a portable training system that can be easily deployed in middle grades could serve to build students' spatial skills, resulting in improved STEM achievement and increased broader participation in STEM for all learners, especially females. Therefore, the goal of this investigation was to design an early version functional prototype of a portable and scalable Minecraft-based spatial skills intervention for middle grade (4^{th} – 8^{th} grade) students. Two pilot modules were built that target the following spatial skills: mental rotation and 2D to 3D transformation. Participants (n = 32) engaged in a series of two-day Minecraft camps focused on those two spatial skills. Pre- and post-tests were administered to better understand the possible influence of the Minecraft-based activities on learners' spatial skills. Despite the small sample size, findings suggest that learners did increase their mental rotation skills. However, no growth was found in students' 2d-to-3d transformation skills. Results from this study will be used to adjust the spatial skills activities and inform the design of new Minecraft-based activities focused on other specific spatial skills.

Introduction

Spatial skills are a collective and diverse set of cognitive abilities that involve generating and manipulating mental representations of objects (Kahle, 1983; Miller & Bertoline, 1991). Spatial skills allow one to make spatial judgments, and to mentally visualize and manipulate objects in space. Many argue that these skills play a central role in learning and creativity, and in face, serve a necessary and core component of intellectual ability and learning (Ganley, Vasilyeva, & Dulaney, 2014; Kell, Lubinski, Benbow & Steiger, 2013; Gardner, 1983, 1999, 2011; Maeda & Yoon, 2012; Thurstone, 1938; Tzuriel & Egozi, 2010).

More specifically, spatial skills have been shown to be significantly correlated with achievement and retention in science, technology, engineering, and math (STEM) (Towle, Mann, Kinsey, O'Brien, Bauer, & Champoux, 2005; Veurink & Hamlin, 2011). Additionally, spatial skills have also been shown to be one of the only areas in which males outperform females (Wang & Degol, 2013). These noticeable differences tend to emerge in the middle school years. Some research has found that this difference has might be a contributing factor to the under representation of women in engineering fields (Towle, et al, 2005). Research has also shown that targeted trainings, and in some cases, very brief spatially-skill focused interventions, can significantly improve student spatial ability (Clark, Tanner-Smith & Killingsworth, 2016; Green & Bavelier, 2003 and 2007; Hsi, Linn & Bell, 1997; Martin-Dorta et al., 2014; Nguyen & Rank, 2016; Sorby, 2009). Despite the empirical research suggesting the role spatial skills play in STEM success for al learners, little instructional focus in K-12 contexts is made on developing interventions to help learners improve their spatial skills.

Background

Cognitive psychologists, educational researchers, and educators tend to rely on several different definitions for understanding spatial thinking. Some suggest that spatial ability is "the ability to generate, retain, retrieve and transform well-structured visual images" (Lohman 1996, p. 112). Others argue that spatial abilities are a diverse set of skills that involve generating and manipulating mental representations of objects (Ganley, Vasilyeva, & Dulaney, 2014; Kahle, 1983; Miller & Bertoline, 1991). Further complicating the landscape about spatial ability are the diverse terms used to describe it. Whereas some researchers use terms like spatial ability and spatial skills (Sorby, 1999, 2000; Lohman, 1996), others use spatial visualization (Kahle, 1983; Linn & Peterson, 1985). And yet others use terms like spatial intelligence (Gardner, 1983, 1999, 2011). For the purposes of this study, the researchers have operationalized spatial *abilities* to be representative of are the innate skills with which we are born. Spatial *skills*, on the other hand, are representative of what can be learned (Sorby, 1999). Therefore, for this investigation, we use the term spatial skills to frame the research.

Although many theories exist for how adolescents develop spatial skills, researchers have found that sketching 3D objects substantially assist development of spatial skills (McKim, 1980; Sorby & Baartmans, 1996; Sorby & Gorska, 1998; Field, 1994; Bowers & Evans, 1990). Based on this previous research, we have hypothesized that the 3D gaming environment Minecraft (Microsoft, 2018) can be used as the delivery mechanism for a series of spatial skills interventions. Minecraft moves the "sketching" of 3D objects into a virtual space; instead of using a pencil and paper, learners construct 3D objects through the virtual manipulation of blocks. However, little to know research exists on this approach. It remains unknown if this process of virtually building and manipulating 3D objectives in a digital context like Minecraft can result in similar growth in spatial skills.

To better understand the influence of Minecraft on learners' spatial skills, researchers delivered a summer camp in 2018 at which participants engaged in Minecraft-based activities that were designed to specifically target two spatial skills: mental rotation and 2D-to-3D transformation. Data collection strategies included spatial skills assessments that were delivered in pre- and post-test capacity. This specific summer camp was part of a larger research study on spatial skill development, that will include additional summer camps in summers 2019 and 2020, as well as academic year testing.

Research Questions

Consequently, the purpose of this investigation was to study if Minecraft-based activities that target specific spatial skills influence learners' spatial abilities, and how that skill growth differs across genders. As indicated, we hypothesize that a Minecraft-based spatial skills curriculum can be used to improve learners' spatial abilities. To address this hypothesis, and respond specifically to each of our research questions, we have designed an investigation that will target middle grade learners and be implemented in several phases. The following research questions will frame the investigation, and will guide our efforts during this particular phase of the study:

1. Does a Minecraft-based intervention that targets specific spatial reasoning tasks influence middle grade learners' spatial ability?
2. Does spatial skills growth differ by gender?

Study Overview

To better understand if Minecraft-based design challenges that target specific spatial skills influence learners' spatial abilities, a land grant university located in the Northern Rocky Mountain region offered a spatial-skills focused and Minecraft-based summer camp for upper elementary and middle school learners. As indicated, it should be noted that this summer camp was delivered as one part of a larger research study on spatial skill development. More specifically, the Summer Camp 2018 focused on the spatial skills of mental rotation and 2D-to-3D transformation. The Summer 2018 camp was designed to evaluate two of four total Minecraft-based spatial skill modules. Day one of the camp was focused on four key components: 1) Spatial skills pre/post-tests; 2) Minecraft basics; 3) Minecraft-based mental rotation activities; and 4) free play/free building. Day two of the camp focused on three key components. These Day two components included: 1) Minecraft-based 2D-to-3D transformation activities; 2) free play/free building; 3) Spatial skills post-tests. Details on the pre-test and post-test spatial skills measurements are provided in the Methodology section and in Table 1 and 2.

On Day 1 of the two-day camp, students completed pre-tests measuring both their mental rotation and 2D-to-3D transformation skills. Following the pre-tests, students completed a series of activities focused on Minecraft basics that taught them the foundational skills needed to move around in the Minecraft environment and to build within it. Once students had completed the introductory activities, they completed a series of rotation activities. The spatial skills activities were highly structured activities that students completed in the Minecraft environment, and we purposefully aligned to the spatial skills instruments. For example, for the mental rotation skills, students completed a series of puzzles in which they were asked to replicate the rotation of a 3D shape per the rotation that was applied to another shape. If students build the appropriately rotated shape, they advanced to a more complex rotation puzzle. For the 2D-to-3D activities, students build objects from a coded plan similar to those questions asked on the Lappen (1981) test. In addition, students competed together in a "Food Delivery Game" in which they were tasked with using a paper-based 2D map to locate delivery locations in a town built inside Minecraft, mirroring the map-reading 2D/3D transformation items from the Ramful, Lowrie, and Logan (2017) instrument.

In addition to the spatial skills activities, students were provided several opportunities each day to engage in semi-structured free play/free building. During this time, students could build in response to a menu of design "challenges" (e.g. build a floating island with your dream house on it), they could free build, or they could move around the Minecraft environment interacting with each other and engaging in collaborative play like a snowball fight. The Minecraft environment used was a private, education-specific platform that was a closed system. This allowed the students to readily interact with one another.

Participants

Research indicates that middle school is where the gender gap in spatial abilities tends to emerge (Ben-Chaim, Lappan, Houang, 1988; Maeda & Yoon, 2013; Sorby, 2009). Further, middle school serves as a critical juncture in students' STEM interests, especially among girls (Girl Scouts Research Institute, 2012; UMass Donahue Institute, 2011). If students become interested in STEM before they enter high school, they will enroll in courses that will prepare them for STEM majors and careers. Based on this research and the goal to develop spatial skills interventions targeted at learners before they arrive at the critical middle school juncture, the target population for the investigation was middle grades learners (4^{th} through 7^{th} grade).

To control for previous Minecraft experience, which might overly influence findings relevant to spatial skills, we used a sampling procedure that ensured the summer camp participants were new to working in the Minecraft environment. Sample selection began by conducting a background survey of possible student participants' that focused on prior experiences with Minecraft or other first-person shooter games that might have prior beneficial effects on spatial reasoning. Students that indicated little to no relevant Minecraft or first-person shooter gaming experience were selected for participation. In addition, the research team was particularly interested in the influence of the Minecraft activities on girls' spatial skill development. Therefore, gender data was collected in the background survey, and those data were used to work toward a sample with even distribution of males and females. Unfortunately, this even distribution was not obtained, likely due to the increased interest in Minecraft in younger players. For future summer camps, the research team plans to consult with specialists in girls' STEM learning to better market the camp and build interest among females to attend.

Although all camp participants that provided research consent (*n*=32), only 27 participants completed the background survey. Ultimately, 74% (*n*=20) of participants identified male, and 26% (*n*=7) identified as female. In terms of the grade participants were entering in the fall of 2018, a large majority (52%, *n*=14) were entering 4^{th}, whereas 11% (*n*=3) were entering 5^{th} grade, 18% (*n*=5) were entering 6^{th} grade, and 18% (*n*=5) were entering 7^{th} grade. And lastly, a majority of participants were beginner or novice Minecraft players with little to no experience playing the game (50%, *n*=13). Thirty-one percent (n=8) of participants had some experience with Minecraft, and only a small portion of the participants had considerable Minecraft experience (19%, *n*=5). Despite the research team's efforts to limit the camp to only beginner Minecraft players, some concessions were made to fill the available seats in the camp, and several expert Minecraft players did join. Table 1 provides a summary of data for the sample related to Minecraft experience.

Table 1. Participants' Experience Playing Minecraft

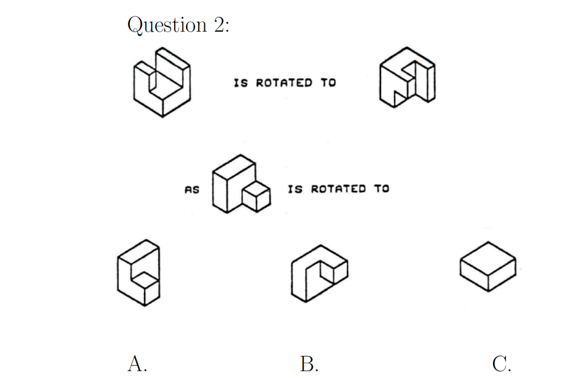
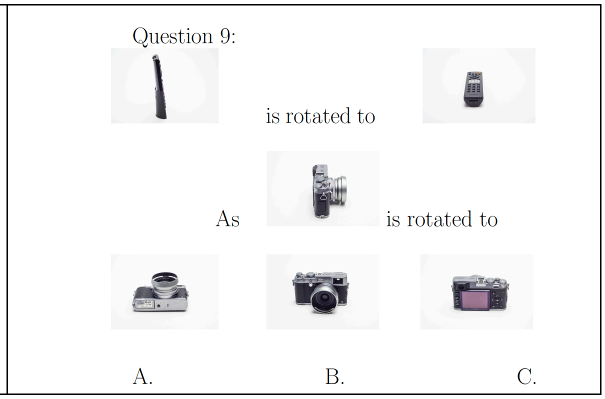
	n	Percent
Experience Playing Minecraft		
I have no experience.	3	12
I have a little experience.	10	38
I have some experience.	8	31
I have a lot of experience.	3	12
I am an expert.	2	8

Methodology

To assess the effect of the treatment on learner's spatial skills, a pretest/posttest design was used that focused on the mental rotation and 2D-to-3D transformation skills. At the start of day one, participants were pre-tested on each spatial skill. The measurements were designed to take around 10 minutes to complete and were adapted from previous instruments used with similar populations and found to be valid and reliable. Further, the assessments will be adapted to ensure rigorous data, but also so that it is manageable for students and avoids test fatigue. The mental rotation instrument was an adapted version of the Purdue Spatial Visualization Tests: Visualization of Rotations (PSVT:R) (Guay, 1977; Sorby, 2009). In addition to the original PSVT:R items that employ simple 3D shapes, the research team included several real-object items. See Table 2 below for example items.

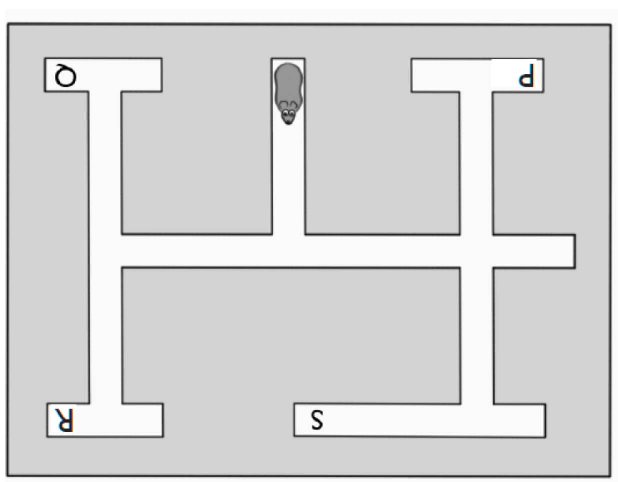
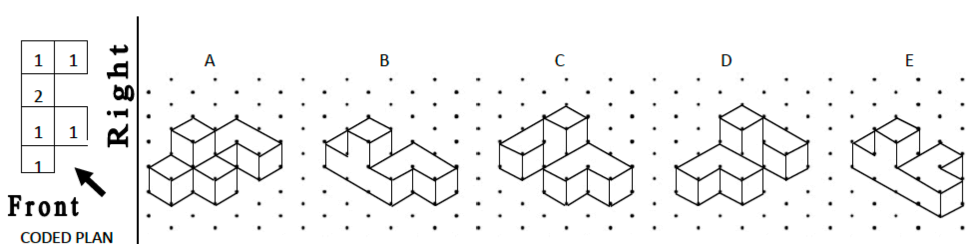
Table 2. Sample Items from Mental Rotation Instrument

3D Shape Example Item (Original PSVT:R)	Real Object Example

The 2D-to-3D transformation measurement was adapted from Ramful, Lowrie, and Logan's (2017) Spatial Reasoning Instrument. With the help of a spatial skills expert, those items from the Spatial Reasoning Instrument that specifically align with 2D-to-3D transformation skills were selected. Those items were combined with several items from Lappen's (1981) Spatial Visualization Test. Examples of these items from the 2D-to-3D transformation measurement are found in Table 3.

Table 3. Sample Items from the 2D-to-3D Transformation Instrument

Example Item from Spatial Reasoning Instrument (Ramful, Lowrie, & Logan (2017)
6. Briana placed a hamster at the start of a maze shown below. The hamster ran through the maze. It turned to its right, then turned left, then turned right. Where did the hamster finish? 
Spatial Visualization Test (Lappen, 1981)
10. Find the view from the FRONT-RIGHT corner. 

Pre- and post-test data was entered and cleaned for analysis. Data for this early pilot was analyzed using a paired-samples t-test. Given the small sample size (n=32), more sophisticated analyses were not prudent at this time.

A power analysis indicated a much larger sample size would be needed. However, in the future, once the spatial skill activities are completed by more students, an analysis of covariance (ANCOVA) methods to test for significant differences between gender groups on changes in spatial skills will be conducted. Once the desired samples size is acquired, researchers will use pretest scores as a covariate for the ANCOVA, allowing the researchers to determine the difference in post-test scores controlling for pre-test scores, as well as whether pre-test scores differ significantly from post-test scores. ANCOVA methods are appropriate for testing differences between groups on a continuous dependent variable where a single covariate has been identified to be controlled for, and random assignment has mitigated other confounding variables (Ben-Chaim & Finlay, 2009). Effect sizes was also calculated using Cohen's *d* for the ANCOVA to estimate the magnitude of the treatment effect. Unlike significance tests (e.g. T-tests), these indices are independent of sample size, and can be used to confirm the significant differences due to an overly strong observed effect of the spatial skill exercises.

In addition to the quantitative data from the pre- and post-test spatial skills measurements, the research team also collected qualitative data. Although analysis of this qualitative data is outside the scope of this specific component of the study, these data are in the form of observations and focus groups with student participants focused on their perceptions of the spatial skills prototypes. These data will be analyzed later in an effort to collect evidence of the prototype's validity. Further, a follow-up post-test will also be conducted six to eight months after Summer Camp 2018 to measure lasting influence of the spatial skills curriculum on learners' spatial abilities.

Findings

Preliminary findings from this small pilot study suggest that learners' mental rotation skills did increase, but no growth was found in students' 2d-to-3d transformation skills. A paired-samples t-test was used to examine if there was any spatial skill growth across all learners between the pre-test and post-test. Analysis of the mental rotation measurement data indicates that, across all learners, participants scored higher on the post-test than on the mental rotation pre-test; a statistically significant increase of 1.0625 (95% CI, -1.6114 to -.5135) km, $t(31) = -3.9473$, $p < .0005$. The Cohen's *d* was approximately .59, suggesting a medium effect of the treatment. However, analysis of the 2D-to-3D transformation measurement data suggests students did score higher on the post-test than on the pre-test, but the difference was not statistically significant (0.40625 (95% CI, -.9391 to .1266) km, $t(31) = -1.5549$, $p = .1301$. Combined, these paired-samples t-tests suggest that students, when gender is not used as a covariate, scored significantly higher on the mental rotation post-test, but not on the 2D-to-3D transformation post-test. As indicated, once the research team is able to increase the sample size with further academic year implementations of the spatial skills activities coupled with summer camps in 2019 and 2020, ANCOVA was used to determine if any differences exist between gender groups.

Conclusions

Despite the small sample size and lack of experimental design, findings from this small pilot study do indicate that students' mental rotation spatial skills did increase from pre-test to post-test. More research and a true experimental design are needed to determine if this growth in mental rotation is the result of the Minecraft-based spatial skills activities. Further, the research team intends to revisit the design of the 2D-to-3D transformation Minecraft activities, and fine tune the interventions to better align with the transformation spatial skill. The goal of those adjustments would be to iteratively arrive at design where the similar significant growth is found from pre-test to post-test for 2D-to-3D transformation skills. To this end, additional summer camps coupled with academic year pilot testing will be conducted to increase the sample size and provide additional data points and opportunities for assessing the Minecraft-based activities' influence on spatial skills. More specifically, findings from data collected during Summer Camp 2018 will be used in tandem with findings from Summer Camp 2019 and academic year interventions from academic years 2018-2019 and 2019-2020, where additional spatial skill interventions will be added. For example, the research team has plans to integrate Minecraft activities that specifically target the spatial skills of mental slicing and perspective taking next. The research team will then assess the effectiveness of those new activities with the refined mental rotation and 2D-to-3D transformation activities, ultimately arriving a packaged Minecraft-based intervention functional prototype that most effectively grows a variety of spatial skills in middle grades learners.

This study has potential to contribute to the body of knowledge of using gaming systems to teach skills critical to achievement in STEM. Moreover, this research holds potential to contribute to the body of knowledge of gender differences in spatial skills and could help meet the societal goals of strengthening and diversifying the STEM workforce. More specifically, findings from this study have potential for several more far-reaching impacts. First, the Minecraft-based activities could be used to enhance the spatial intelligence of middle grade students, thus improving their future performance in STEM coursework. This will result in improved STEM education, specifically at the middle grade level. Second, results specific to gender differences in spatial intelligence and can be used to close the performance gap in spatial skills, contributing to increasing participation of women in STEM. A strong STEM workforce is crucial to the vitality of our society due to the pervasiveness of technology throughout our economy and increasing global competition. This could result in a stronger, larger, and more diverse workforce than what is currently being produced.

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