

Untangling the Relationship Between Spatial Skills, Game Features, and Gender in a Video Game

Helen Wauck, Ziang Xiao, Po-Tsung Chiu, Wai-Tat Fu
University of Illinois at Urbana-Champaign
Urbana, IL, USA
{wauck2, zxiao5, ptchiu2, wfu}@illinois.edu

ABSTRACT

Certain commercial video games, such as Portal 2 and Tetris, have been empirically shown to train spatial reasoning skills, a subset of cognitive skills essential for success in STEM disciplines. However, no research to date has attempted to understand which specific features in these games tap into players' spatial ability or how individual player differences interact with these game features. This knowledge is crucially important as a first step towards understanding what makes these games effective and why, especially for subpopulations with lower spatial ability such as women and girls. We present the first empirical study analyzing the relationship between spatial ability, specific game features, and individual player differences using a custom-built computer game. Twenty children took a pretest of spatial skills and then played our game for 2 hours. We found that spatial ability pretest scores predicted several player behaviors related to in-game tasks involving 3D object construction and first person navigation. However, when analyzed by gender, girls' pretest scores were much less predictive of player behavior.

ACM Classification Keywords

H.5.1 Multimedia Information Systems: Artificial, augmented, and virtual realities; K.3.0 Computers and Education: General

Author Keywords

Spatial Reasoning; Education; Video Games; Game Features; STEM; Gender; Player Behavior; Children

INTRODUCTION

Spatial reasoning skills are crucial for success in STEM disciplines. Longitudinal studies have demonstrated that spatial skills in adolescence predict success in STEM majors and careers [8, 33]. In addition, gender differences in spatial ability begin to emerge in early childhood [16]. Fortunately, research has found that spatial skills are malleable and transfer to different tasks [34]. Therefore, training students' spatial skills

at an early age, before gender differences become a barrier to success in STEM for girls, is crucial to address both the gender gap and the general spatial ability gap that discourages otherwise motivated students from pursuing STEM majors and careers.

A popular approach to solving this problem in recent years is to use educational video games to produce better learning gains than traditional instructional methods. Video games have been shown to produce high levels of motivation and engagement in the task at hand [2, 20]. Learning in video games occurs in a constructivist context, which allows the player to construct their understanding of the world through their actions and experiences rather than formal instruction [25]. In the context of video games, actions and experiences take place in a virtual environment, which allows the player to be self-directed in learning and encourages a trial and error approach to problem-solving. Video games also scaffold the learning process, introducing new game mechanics through tutorials and giving the player in-game assistance or hints, and then gradually increasing difficulty level such that the game maintains an appropriate level of challenge as the player improves [28]. Both constructivism and scaffolding have been shown to promote larger learning gains in many different educational contexts [26, 27].

Commercial games such as Medal of Honor, Zaxxon, Tetris, and Portal 2 have already been shown to train players' spatial skills [5, 6, 29, 32]. This training often results in learning that transfers more broadly to other skills than traditional workbook exercise training [32, 34]. Commercial video game training has also been successful with children [14], a crucial population for spatial skill training interventions given the early emergence of gender differences in spatial skills [16].

However, not all video games are effective at training spatial skills, and we do not yet know how to attribute training success (or lack thereof) to specific components of the games. For instance, Lumosity, a game developed by neuroscientists who incorporated specific game features to target and train specific cognitive skills, was shown to have no effect on any cognitive skills, including spatial ability [29]. Researchers have also found that the effectiveness of commercial game training likely depends on the genre of the game in question; genres such as puzzle and role-playing seem to be less effective than action games [12]. Cognitive neuroscientists have therefore put out a call recently for game developers to design games that can

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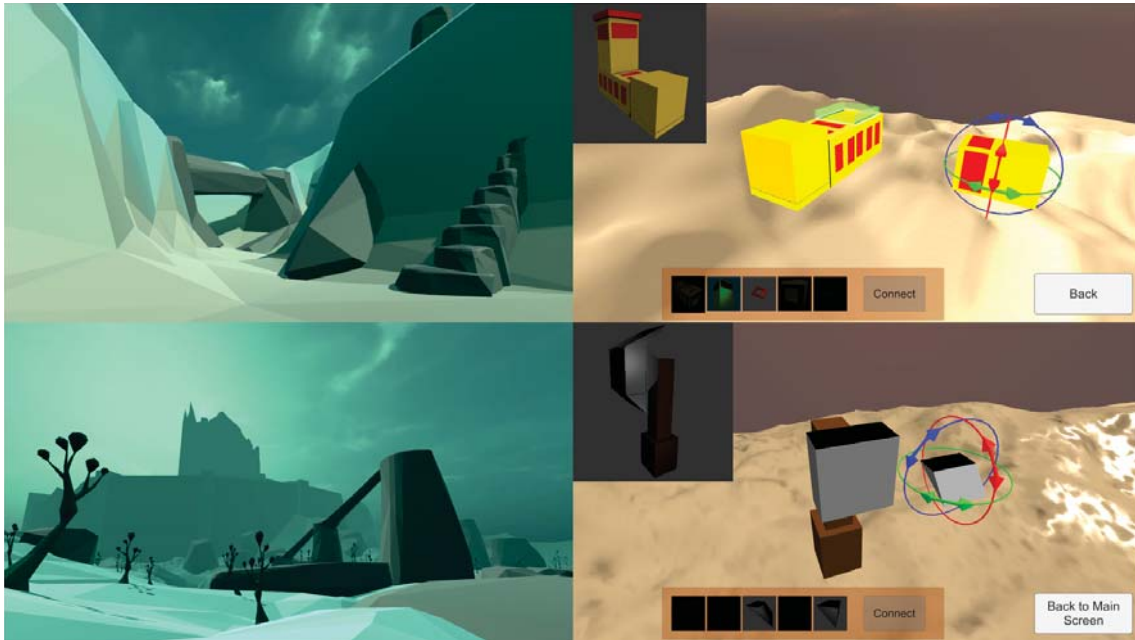


Figure 1. Game features in *Homeworld Bound*, our spatial skill training game. In Exploration Mode, players navigate through the Canyon (top left) and the Highlands (bottom left) to collect parts. In Construction Mode, players build equipment (Rocket Boots, top right and Sledgehammer, bottom right) using the parts they collected.

isolate and test the effects of different features on various cognitive skill enhancements [8].

In this work, we take a preliminary step in this direction. We developed a customizable video game called *Homeworld Bound* as a testbed for isolating the relationship between specific game features and players' spatial ability. We grounded the development of the game in educational theory and cognitive science research to select an initial set of game features likely to tax players' spatial skills (Table 1), including game mechanics like object rotation and alignment (inspired by Tetris) and global and local landmark navigation (inspired by first person games like Portal 2). We hypothesized that the features related to object manipulation and landmark-based navigation would tap into two main components of spatial skill: *mental rotation* and *spatial perception* [18].

We ran a pilot study to test these hypotheses. Twenty children took a pretest of spatial ability and then played *Homeworld Bound* for 2 hours. We found that children's scores on the spatial skills pretest correlated with certain in-game player behaviors related all of the game features in Table 1 that we included in the game. Furthermore, these correlations were strongly affected by gender; boys' pretest scores were much more predictive of in-game behavior than girls', which may be due to the differences in player behavior we observed between girls and boys. Girls tended to be less impulsive and less exploratory, but girls exhibiting more exploratory and impulsive behaviors in certain situations had higher spatial ability.

Our main contribution to the IUI community in this work is threefold: First, we present an approach to developing games that tap into players' spatial ability grounded in both theory and empirical findings. Second, we present the first empirical study using a game developed with this novel approach to

isolate and analyze the relationship between specific game features and players' spatial ability. Finally, we provide practical recommendations for game designers on how to incorporate specific game features for assessing players' spatial skills.

RELATED WORK

Cognitive Skill Training Using Video Games

To date, there are numerous studies in the psychology literature showing the effectiveness of certain commercial video games on perceptual and cognitive skills. Many different types of games have been empirically shown to train a variety of cognitive and perceptual skills [1, 21, 22]. For instance, Glass et al found that real-time strategy (RTS) games can improve cognitive flexibility, a trait associated with the ability to coordinate low-level and high-level cognitive resources to adapt to new, unexpected environmental conditions [7]. Action games in particular have received a lot of attention in the research literature. In a series of studies, Green and Bavelier discovered that players of action video games tend to have a variety of enhanced visual attention skills, and that non-players' visual attention, processing speed, and task switching skills can be improved by playing action video games such as Medal of Honor [9, 10, 11, 13, 12].

Spatial Skill Training in Video Games

One type of cognitive ability that has been gaining increasing attention in recent years is spatial ability. Spatial ability is the single strongest predictor of future success in STEM fields [33]. It is thus crucially important to train this ability given that it tends to be lower for women and girls [15] and there is already a substantial shortage of women in STEM fields [17].

Research has shown that spatial ability can be trained using certain video games, and that this training produces the same or

<i>Game Feature</i>	<i>Spatial Operation</i>
Global Landmarks (Exploration Mode)	Allocentric Navigation Spatial Perception
Local Landmarks (Exploration Mode)	Egocentric Navigation Spatial Perception
Object Alignment (Construction Mode)	Spatial Visualization
Object Rotation (Construction Mode)	Physical Rotation Mental Rotation
Attachment Location Matching (Construction Mode)	2D to 3D Projection Shape Matching

Table 1. Our hypothesized feature-spatial operation mapping, which guided game design for *Homeworld Bound*.

larger gains as more traditional methods of training like workbook exercises. Video game training is particularly useful for obtaining far-transfer effects [34]. Tetris has been consistently shown to train spatial skills [30, 32]. Other games spanning a wide variety of genres can also train spatial skills, such as the space arcade shooter Zaxxon [5], first person games like Medal of Honor [6] and Portal 2 [29], and Super Mario [14].

However, each of these studies used out of the box commercial games, so researchers could not determine why these games were successful at training spatial skills. This is especially problematic because many so-called cognitive training games, such as Lumosity, have failed to produce comparable effects on spatial ability and other cognitive skills [29]. Cognitive training games will likely continue to fail unpredictably unless game designers understand the relationships between specific game features and the effectiveness of a game at training spatial skills.

Our Approach: Specific Game Features

Our work takes the first step towards understanding how games exercise players’ spatial skills by using a customizable game developed from the ground up to isolate relationships between specific game features and players’ spatial ability. Furthermore, we believe that addressing the well-established gender gap in spatial skills [18] as early as possible is essential for making STEM fields more accessible to girls and women (and anyone with low spatial skills!), so we have developed our game with children as the target audience and our population of interest. In this work, we make three contributions to the IUI community and the broader HCI community as a whole: 1) a general approach to developing games that tap into players’ spatial ability, 2) the first empirical study analyzing how specific game features are associated with children’s spatial ability, and 3) practical recommendations implementing these features in games to assess players’ spatial ability.

THE GAME

We designed the game being used for this project, *Homeworld Bound*, to incorporate several features from effective spatial skill enhancing games that, we hypothesized, were the reason for their effectiveness and would therefore tap into players’ spatial skills: first person landmark-based navigation and manipulation of virtual objects. We incorporated these features

into our game by structuring it around two main modes: Exploration and Construction. Table 1 summarizes the game features we incorporated and their relations to specific spatial operations. We hypothesized these relations based on pilot studies conducted over the course of the game’s development where we observed player strategies and then iterated on the game mechanics until they matched the spatial operations we wanted.

The premise of the game is that the player has crash-landed on an alien planet and must scavenge parts from the game world with which to rebuild their spaceship. The player must switch repeatedly between Exploration Mode, where they navigate the game world searching for parts, and Construction Mode, where they build items using the parts they have already found. This smooth integration of exploration and construction has already been used with great success by the incredibly popular video game Minecraft, which has wide appeal with both kids and adults [24].

Since many games that enhance spatial skills, such as Medal of Honor and Portal 2, are first person perspective and require the player to navigate a 3D environment, primarily with reference to nearby or distant landmarks, we built Exploration Mode around first person landmark-based navigation. In Exploration Mode, the player collects parts while navigating through the environment, using a combination of local (small, nearby) landmarks and global (large, distant) landmarks to orient themselves (Figure 1, left side). Since recognizing specific landmarks, regardless of what angle the player views them from, is essential for success at this task, it allows us to measure a spatial skill called *spatial perception*, the ability to imagine how one’s surroundings would look when viewed from a different perspective (also known simply as *perspective-taking*) [18]. Local landmarks require the player to assume an *egocentric* perspective, navigating relative to their own orientation ("I need to turn right at the gas station", for example), while global landmarks require players to take an *allocentric* perspective, navigating relative to other objects in the environment ("My house is north of the lake", for example) [3].

On the other hand, third person games like Tetris and Zaxxon require a stationary player to rotate or align objects and have been shown to train the spatial skill known as *mental rotation*, the ability to mentally visualize the outcome of a particular object rotation [18]. We therefore incorporated object rotation and alignment into Construction Mode. In Construction Mode, the player is shown a 2D image of an object and must build it by placing different parts in the 3D environment, selecting which parts to attach together, and rotating them until they are lined up properly to attach (Figure 1, right side). Determining which parts can be attached to each other in the first place also requires the player to identify the correspondences between the 2D image and the parts in the 3D environment (*2D to 3D projection*) and to recognize whether the specific geometric faces they have selected for attachment have the same shape (*shape matching*).

A potential concern with allowing players to rotate objects at will is that they may not need to exercise mental rotation skills since they are already physically rotating the object and do not

<i>Exploration Mode</i>	<i>Construction Mode</i>
Time spent playing	Time spent playing
Number of times stopped	Sessions
% time spent stopped	Rotations
Avg time spent stopped	Face and rotation errors
Number of batteries	RPAA

Table 2. The in-game player behavior metrics we collected in each mode of the game. RPAA = Rotations per attachment attempt.

have to imagine movement. To mitigate this effect, we added a cost for performing rotation operations in Construction Mode. Each rotation in Construction Mode uses up a small amount of the player's "battery power," and when their battery power runs out, they can no longer rotate objects and must switch back to Exploration Mode to collect more batteries from the environment before they can return to Construction Mode and complete their construction. Allowing the player to take a break from one in-game task and do something else for a while - the principle of parallelism in game design - also has the added advantage of reducing player frustration and helping players come back to the main task cognitively refreshed [28].

Homeworld Bound consists of 3 Exploration Mode levels (Canyon, Highlands, and Ruined City) and 3 Construction Mode levels (Rocket Boots, Sledgehammer, and Ruined City Key), each corresponding to one of the Exploration Mode levels. Players must complete each Exploration Mode level's Construction Mode level in order to advance to the next Exploration Mode level. Just before beginning the first Construction Mode level, Rocket Boots, players are given two tutorial Construction Mode levels, Tutorial1 and Tutorial2, to help them learn how to play.

METHOD

We launched a pilot study of *Homeworld Bound* in order to confirm that the game contains features that tap into players' spatial skills. We were primarily interested in how children's in-game behavior correlated with their current level of spatial skill. We recruited 20 children ages 7-12 (accompanied by parents) to participate in a 3 hour study session via a publicly accessible weekly newsletter distributed by the University of Illinois, a large public university in the U.S. We chose to recruit children ages 7-12 because previous research has established that the effect size of gender differences in spatial ability is significant and uniform across this entire age range.

After parents signed a consent form and children verbally assented to participate, the children took a shortened version of the Revised Purdue Spatial Relations Test (PSVT:R) [35] as a pretest of spatial skills. Since the PSVT:R is designed for people age 12 and up, we shortened it from 30 questions to just the easiest 20 questions (the first 20 since test questions are ordered by difficulty) as recommended to us by the researcher who developed the test. Next, children filled out a short demographic survey on their age, gender, and previous video game experience. Game experience metrics included a quantitative ranking of video game play frequency (1=no experience, 6=daily play) as well as a free response question asking children to list the games they play most often.

After completing the survey, each child played the game for 2 hours or until they finished the game, whichever came first. Children were allowed to stop playing whenever they wanted. After finishing the gameplay session, children completed a post-game survey in which they rated how fun, boring, easy, and frustrating they found the game and why. They were also asked what they would change if they were making the game. Parents were compensated \$10 an hour per child and given a \$20 bonus in addition to the base rate if they and their child stayed for the entire 3 hours.

In-Game Player Behavior Metrics

We collected a large amount of player behavior data from our participants. Data collected focused primarily on time taken to finish each level, number of errors made, and behaviors associated with player impulsiveness. We measured impulsiveness by percentage of time players spent standing still versus moving in Exploration Mode and how many rotations the player performed in Construction Mode before trying to attach two parts. We reasoned that more impulsive players would spend less time standing around thinking about where to go next in Exploration Mode and would spend less time trying to rotate parts in Construction Mode to the correct alignment before attempting to attach them. Analyzing time taken to finish levels and number of errors gives us a sense for how difficult the game was, while measuring player exploration and errors made allows us to see to what extent spatial skills are associated with two approaches to problem solving that education literature has shown to be important for learning: *exploring the problem space* and the *growth mindset*.

The growth mindset is an attitude towards learning that views mistakes and failures as the best possible learning opportunities. It embraces the 'fail fast, fail often' adage championed by many Silicon Valley entrepreneurs and has been associated with increased player engagement and motivation in video games [23]. Exploring the problem space involves trying out many different strategies, approaches, or directions to allow for cross-pollination between them. This idea has gained attention in the design community for its propensity to increase creativity and improve solution quality [4].

Thus, each of the main player behaviors we are interested in measuring allow us to get a sense for how players' spatial skills are related to the game's difficulty (time spent in each level, number of errors), and different types of player strategies (impulsiveness, growth mindset, exploring the problem space) when experiencing specific game features at different levels of granularity (between the two game modes versus between individual levels within each mode). The specific player behavior metrics we collected for each game mode are summarized in Table 2. An explanation of some of the more complicated metrics follows.

Wrong Face and Wrong Rotation Errors

There are two types of errors a player can make in Construction Mode when attempting to attach two parts together. If the player has selected the correct two faces to attach and has rotated the part to be attached so that it is aligned correctly, then the attachment attempt succeeds. However, if the player selects two faces that are not supposed to be attached in the

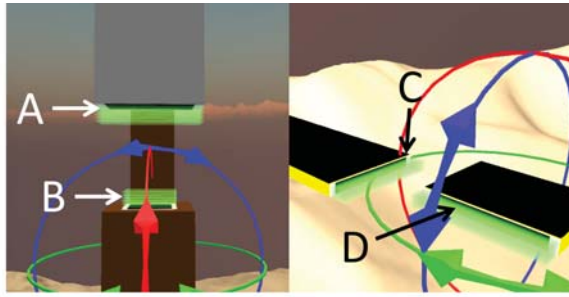


Figure 2. Faces A and B on the left are not the same size or shape, so trying to attach them would be a *wrong face error*. Faces C and D on the right have the same size and shape but are not aligned to face each other, so attaching them would be a *wrong rotation error*.

finished object (A and B in Figure 2) and tries to attach them, this is a *wrong face error*. If the player manages to select the correct two faces to attach but fails to align them properly by rotating (C and D in Figure 2), this is a *wrong rotation error*.

Number of Sessions

Since rotation operations in Construction Mode were "powered" by batteries that could be collected in Exploration Mode, players who ran out of battery power after performing too many rotations would have to switch from Construction Mode to Exploration Mode, collect more batteries, and then switch back to Construction Mode to continue building where they left off. We recorded the number of times players had to make this switch as an additional metric of how much difficulty they had with each Construction Mode level and to what degree their Construction Mode play experience was broken up into smaller units of time versus chunked into larger sessions.

Rotations and Rotations per Attachment Attempt

Players must rotate parts in 3D in Construction Mode in order to line up the two faces of each part correctly for attachment. Each rotation action the player performs with the interface controls corresponds to a 90 degree rotation of the current active object along one of the X, Y, or Z axes. We calculated a player's rotations per attachment attempt in order to see to what extent players were exploring the problem space visually (doing a lot of rotations before making an attachment attempt) or had a more impulsive, growth mindset-oriented strategy (doing fewer rotations before making an attachment attempt).

Hypotheses

We had the following three hypotheses about the relationship between children's spatial ability, in-game behavior, demographics, and game features:

H1: All player behaviors in Table 2 associated with all five of the main game features of *Homeworld Bound* in Table 1 will be correlated with children's spatial skill pretest scores.

H2: Behaviors in more difficult levels (where players take longer to finish and make more errors) will correlate more strongly with spatial skills than behaviors in easier levels.

H3: Correlations between spatial ability and player behaviors will not be significantly affected by demographics such as age and gender.

RESULTS

Of the 20 children who participated in the study, 10 were female, and ages ranged from 7 to 12 (median=10, mean=9.95). All but two had previously played video games, and all but one of those played games at least weekly. In addition, 11 (55%) were not able to complete the entire game. Of those who did not complete the entire game, 4 of them chose to quit early due to frustration, 2 quit early due to a prior commitment, and the remaining 5 played for the entire 2 hours but ran out of time to finish the game. Due to the relatively small number of players who made it as far as the Ruined City in Exploration and Construction Mode (n=9), we excluded data from these levels from our statistical analyses, leaving us with data from the first two Exploration Mode levels and the first four Construction Mode levels (Tutorial1, Tutorial2, and Rocket Boots in the Canyon and Sledgehammer in the Highlands).

The focus of our analysis was the correlation between in-game behaviors and children's scores on the spatial skill pretest. There were 20 questions on the pretest, and scores (number of questions answered correctly) were heavily skewed towards the low end ($\mu = 7.15$, median=6, $\sigma = 4.77$). The lowest score was 1 and the highest was 17. To compare the effects of high-level features across the entire game and low-level features specific to certain parts of the game, we performed a hierarchical 2 stage correlation analysis, starting with mode-level player behaviors and then breaking them down further level-by-level in the second stage. Since pretest scores were heavily skewed, we used Spearman's ρ . Our primary measures of interest for player behavior were time taken to finish all levels, errors made, and impulsiveness. The concrete metrics we used for each of these behaviors, which were the same for each stage of our hierarchical analysis, are summarized in Table 2. We will first present general results for all participants, and then investigate the effects of gender in later sections. Our complete correlation analysis between spatial skill pretest scores, player behaviors, and demographics is summarized in Table 3. We used Spearman's ρ for all analyses since most behavioral measures had highly skewed, non-normal distributions.

Exploration Mode Taps Spatial Skills

First, we analyzed the relationship between high-level player behaviors across all levels in Exploration and Construction Mode and pretest scores. Total time spent in Exploration Mode had a significant negative correlation with pretest score ($\rho = -0.55$, $p = 0.016$). None of the other high-level player behaviors were significantly correlated with pretest scores. Thus, children with higher pretest scores tended to finish Exploration Mode levels more quickly. Since time spent in Construction Mode as a whole was not significantly associated with pretest score, this result suggests that Exploration Mode as a whole requires more spatial skill than Construction Mode as a whole.

Specific Levels Tap Spatial Skills

To get a more detailed picture of the extent to which each game mode tapped children's spatial skills, we analyzed pretest scores and player behavior level-by-level in both Construction Mode and Exploration Mode.

Exploration Mode Levels

In Exploration Mode, pretest score had a significant negative correlation with time spent in the Highlands ($\rho = -0.57, p = 0.01$) and a marginal negative correlation with time spent in the Canyon ($\rho = -0.38, p = 0.097$). Thus, both the Highlands and Canyon level are tapping into children's spatial skills, but the Highlands level taxes children's spatial skills more than the Canyon. This may be due to the fact that the Highlands level is larger than the Canyon and has a more open structure, requiring players to use more global landmarks for navigation. This, in turn, may require them to employ more of their spatial perception skills to keep track of additional landmarks and what they look like from additional angles.

Another possible explanation is that players with higher spatial ability have an easier time jumping with the Rocket Boots, a skill required much more often in the Highlands than in the Canyon. Many of the children frequently reported having difficulty with the jumps, and since jumping mechanics play a significant role in games that have been demonstrated to improve spatial skills, such as Portal 2 and Super Mario [14, 30], the simple act of jumping may be taxing children's spatial skills as well. This explanation also aligns with H3; the jumping mechanic may simply make the Highlands level more difficult and therefore tax players' spatial skills more heavily.

Construction Mode Levels

Pretest score was correlated with three separate behaviors in the Rocket Boots level and one behavior in the Sledgehammer level. Number of wrong rotations performed in the Rocket Boots level had a significant negative correlation with pretest score ($\rho = -0.45, p = 0.047$), and number of total errors and time spent in the Rocket Boots level had marginal negative correlations with pretest score ($\rho = -0.43, p = 0.062$ and $\rho = -0.41, p = 0.069$). For the Sledgehammer level, pretest score and number of rotations had a significant negative correlation ($\rho = -0.56, p = 0.015$).

This suggests that it was primarily the Rocket Boots level in Construction Mode that had the stronger correlation with spatial ability. One possible reason is that the Rocket Boots level was the first non-tutorial level in the game and therefore presented considerably more challenge; we observed that children had a lot of difficulty with two parts in this level that were particularly tricky to attach. As Figure 3 shows, both parts had two different attachment regions, and the player needed to note the location of both of them in order to determine how each part should be rotated to correctly align it with the part they needed to attach it to.

In summary, object rotation and object alignment features seem to tap into players' spatial skills. The fact that the number of wrong rotation errors was negatively correlated with pretest score further supports this notion; players with higher spatial ability may have recognized how to correctly rotate the difficult parts more quickly, so they made fewer wrong rotation errors and finished the level faster. This result also reveals the importance of designing in-game tasks that present the player with a sufficient level of challenge that exercises their spatial skills in a measurable way.

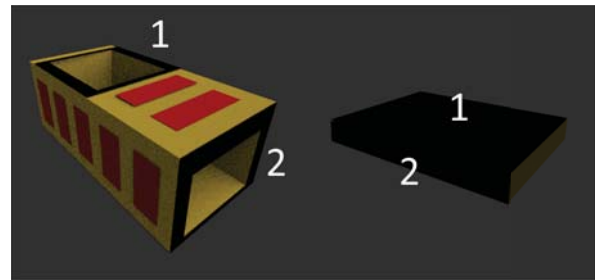


Figure 3. The two most difficult parts to attach in the Rocket Boots Construction Mode level, the Body (left) and the Toebox Sole (right). Players had to use the location of two different attachment faces (1 and 2 on both parts) to correctly align and attach these parts.

Gender and Age Differences

Boys ($\mu = 9.2$, median=8, $\sigma = 5.05$) score than girls ($\mu = 5.1$, median=3.5, $\sigma = 3.63$) on the pretest of spatial skills ($t = -2.08, p = 0.053$), although this difference was only marginally significant. Since the pretest consisted of 20 multiple choice questions with 4 possible answers, it is interesting to note that boys' average performance was above chance, but girls' was not. These results are consistent with previous research establishing gender differences, not only in spatial ability but also on the particular psychometric test we used [16, 31].

Research has shown that boys tend to have higher spatial ability than girls and that this difference begins to emerge when children are around the same age as the children in our study [18]. Therefore, we investigated the extent to which there were gender or age differences in player behaviors that might influence how effectively the game taps into spatial ability for different demographics. Table 3 presents a complete summary of all player behavior, gender, and age correlation analyses we ran at both the mode-level and level-by-level. We used Spearman's *rho* for all analyses since we were analyzing a categorical variable (gender) and the behavioral measures tended to have highly skewed, non-normal distributions.

Age: Younger Players Find Game More Difficult

Age was associated with several mode-level behaviors. At the mode level, younger players spent more time in Exploration Mode and marginally more time in Construction Mode. In addition, younger players spent more time standing still in Exploration Mode. Age was also associated with level-by-level behaviors. Time spent in every level of Exploration Mode and Construction Mode except Tutorial1 had a significant or marginal negative correlation with age. Younger players also spent more time standing still in the Highlands level, and made more rotations and wrong rotation errors in the Rocket Boots level. These results demonstrate that both Exploration and Construction Mode are harder for younger players, particularly the Highlands and Rocket Boots levels.

Gender: Girls take More Time, Boys Make More Errors

There were no significant correlations between gender and any mode-level player behaviors. However, there were a few gender differences in behavior in individual game levels. Girls took longer to complete the Highlands level and spent more time standing still in the Canyon level, while boys made more wrong face errors (and therefore more total errors) in the

Tutorial2 level. While these gender effects occur only for a small subset of behaviors in a small subset of the game's levels, they may indicate that girls and boys are using different strategies when they play certain levels.

For instance, since girls spend more time standing still in the Canyon level, they may be spending more time deciding where to go next than boys, who may prefer to act more impulsively, choosing a direction and walking there without worrying about whether it is the optimal direction to choose. Similarly, boys make more wrong face errors in the second tutorial level of Construction Mode, possibly because girls spend more time thinking about whether they matched up parts correctly before even trying to attach. This more impulsive, exploratory behavior on the part of boys and more premeditated, careful behavior on the part of girls may be related to spatial ability since time spent in the Highlands level was also related to spatial skill pretest scores.

Gender Effects on Pretest-Behavior Correlation

Since gender affected players' in-game behavior and pretest score, it may also affect the predictive power of spatial skill pretest scores on certain player behaviors. We therefore performed another correlation analysis between player behaviors in different parts of the game and pretest scores, but broken down by gender and age.

Boys' Pretests, Not Girls', Predictive of Behavior

For boys at the mode level, total number of errors and total number of wrong face errors had significant negative correlations with pretest scores ($\rho = -0.85$, $p = 0.002$ and $\rho = -0.92$, $p = 0.0002$, respectively). In addition, pretest score was marginally negatively correlated with time spent in Exploration Mode and total number of Construction Mode sessions ($\rho = -0.61$, $p = 0.061$ and $\rho = -0.60$, $p = 0.069$, respectively). Here, in addition to the correlation between time spent in Exploration Mode and pretest scores already observed in the combined gender sample, we also see additional correlations missing from the combined gender sample: total errors, total wrong face errors, and total Construction Mode sessions. Thus, it appears that matching the correct two faces for part attachment tapped spatial ability for boys in Construction Mode, and Exploration Mode also required boys to employ their spatial skills, although to a lesser extent. Surprisingly, there were no significant or marginally significant correlations between mode-level behaviors and pretest scores for girls.

For boys, level-by-level analysis revealed that pretest scores were correlated with behavior in three different Construction Mode levels (Tutorial1, Rocket Boots, and Sledgehammer) and one Exploration level (Highlands). Boys' pretest scores had a significant negative correlation with the number of wrong face errors in the Tutorial1 level ($\rho = -0.67$, $p = 0.036$). For the Rocket Boots level, the significant negative correlation observed in the combined gender sample between number of wrong rotations and pretest score remained ($\rho = -0.65$, $p = 0.04$), as did the marginally significant negative correlation between number of errors and pretest score ($\rho = -0.62$, $p = 0.058$). However, boys' pretest scores also had a significant

negative correlation with number of rotations in the Rocket Boots level ($\rho = -0.67$, $p = 0.034$).

The correlations between Sledgehammer level behaviors and pretest scores were more pronounced than in the combined gender sample. As in the combined gender sample, the number of rotations performed in the Sledgehammer level had a significant negative correlation with pretest score, but the correlation was much stronger for boys ($\rho = -0.94$, $p < 0.0001$). In addition, boys' pretest scores had a significant negative correlation with time spent in the Sledgehammer level ($\rho = -0.64$, $p = 0.046$) and a marginal negative correlation with the number of wrong rotation errors in the Sledgehammer level ($\rho = -0.61$, $p = 0.061$). Boys' pretest scores also had a marginal negative correlation with time spent in the Highlands ($\rho = -0.63$, $p = 0.052$), as in the combined gender sample.

In contrast, girls' pretest scores were only associated with two level-by-level behaviors. Both time spent in Tutorial2 and number of rotations per attachment attempt in the Sledgehammer level had marginal negative correlations with girls' pretest scores ($\rho = -0.62$, $p = 0.074$ and $\rho = -0.69$, $p = 0.06$). Neither of these correlations was found in the combined gender sample.

The finding that girls' pretest scores only marginally predict two level-by-level and no mode-level behaviors, while boys' pretest scores predict eight level-by-level and four mode-level behaviors, is very surprising. It seems that most of the features in our game are not tapping into girls' spatial skills, but it is not clear why. In the next section, we explore a few possible explanations for the gender differences we observed.

Making Sense of Observed Gender Differences

First, we wondered if girls were simply not as interested in the game as boys. To see if this was likely, we analyzed Spearman correlations between gender and children's self-reported 5-point Likert scale measures of fun, easiness, boredom, and frustration from the post-game survey. There was no significant correlation between gender and any of the four self-report measures. We also examined children's explanations for why they rated fun, easiness, boredom, and frustration the way they did and what they would change about the game, but there did not appear to be a distinctive gender difference in the responses. Therefore girls did not seem to have a more negative experience than boys.

Girls' and boys' in-game strategies may also have been different due to the girls in our study being less familiar with games like *Homeworld Bound*. We analyzed boys' and girls' self-reported lists of games they played to see if there was evidence for this hypothesis. Out of 20 children, 15 provided us with information about the games they played. Both genders reported playing a diverse set of games, including racing, first person shooter, construction, sports, and puzzle games. The only noticeable difference was that 7 boys reported playing construction games like Minecraft and Roblox, whereas only 3 girls did. Both Minecraft and Roblox, like *Homeworld Bound*, allow the player to explore and collect materials from a virtual world and use those materials to build objects. Since fewer girls had experience with this kind of game, perhaps they spent

<i>Behavior</i>	<i>Gender</i>	<i>Age</i>	<i>Pretest</i>	<i>Pretest (Boys)</i>	<i>Pretest (Girls)</i>
Time					
Total time	n.s.	-0.67**	n.s.	n.s.	n.s.
Exploration	n.s.	-0.71**	-0.55*	n.s.	n.s.
Canyon	n.s.	-0.65**	n.s.	n.s.	n.s.
Highlands	-0.48*	-0.62**	-0.57*	n.s.	n.s.
Construction	n.s.	-0.46	n.s.	n.s.	n.s.
Tutorial1	n.s.	n.s.	n.s.	n.s.	n.s.
Tutorial2	n.s.	-0.50*	n.s.	n.s.	n.s.
Rocket Boots	n.s.	-0.68**	n.s.	n.s.	n.s.
Sledgehammer	n.s.	-0.44	n.s.	-0.64*	n.s.
% Time Stood Still					
Total, Canyon, Highlands	n.s.	n.s.	n.s.	n.s.	n.s.
Avg Time Stopped					
Total, Canyon, Highlands	n.s.	n.s.	n.s.	n.s.	n.s.
Num. Times Stopped					
Total, Canyon, Highlands	n.s.	n.s.	n.s.	n.s.	n.s.
Num. Batteries					
Total, Canyon, Highlands	n.s.	n.s.	n.s.	n.s.	n.s.
Rotations					
Total, Tutorial1, Tutorial2	n.s.	n.s.	n.s.	n.s.	n.s.
Rocket Boots	n.s.	-0.58**	n.s.	-0.67*	n.s.
Sledgehammer	n.s.	n.s.	-0.56*	-0.94**	n.s.
Combined Errors					
Total	n.s.	n.s.	n.s.	-0.85**	n.s.
Tutorial1	n.s.	n.s.	n.s.	n.s.	n.s.
Tutorial2	n.s.	n.s.	n.s.	n.s.	n.s.
Rocket Boots	n.s.	-0.52*	n.s.	n.s.	n.s.
Sledgehammer	n.s.	n.s.	n.s.	n.s.	n.s.
Wrong Face					
Total	n.s.	n.s.	n.s.	-0.92**	n.s.
Tutorial1	n.s.	n.s.	n.s.	-0.67*	n.s.
Tutorial2	+0.49*	n.s.	n.s.	n.s.	n.s.
Rocket Boots, Sledgehammer	n.s.	n.s.	n.s.	n.s.	n.s.
Wrong Rotation					
Total, Tutorial1, Tutorial2	n.s.	n.s.	n.s.	n.s.	n.s.
Rocket Boots	n.s.	-0.66**	-0.45*	-0.65*	n.s.
Sledgehammer	n.s.	n.s.	n.s.	n.s.	n.s.
RPAA					
Total, Tutorial1, Tutorial2					
Rocket Boots, Sledgehammer	n.s.	n.s.	n.s.	n.s.	n.s.
Num. Sessions					
Total, Tutorial1, Tutorial2					
Rocket Boots, Sledgehammer	n.s.	n.s.	n.s.	n.s.	n.s.

Table 3. Behavior, demographic, and spatial skill pretest correlations using Spearman's ρ . * $p < 0.05$, ** $p < 0.01$, n.s. = marginal or non-significant correlation. Gender was coded as 1=Female, 2=Male, so a positive correlation indicates a behavior associated more with males. RPAA = Rotations per Attachment Attempt.

more time familiarizing themselves with the play style, which may have affected their in-game behavior.

DISCUSSION

Our results indicate that all of the game features from Table 1 that we incorporated into *Homeworld Bound* tapped into players' spatial ability for certain subsets of levels in both Exploration and Construction Mode, supporting hypothesis **H1**. We found that fewer wrong rotation errors and time spent in the Rocket Boots level as well as fewer rotations in the Sledgehammer level (corresponding to the game features object alignment and object rotation) were correlated with higher spatial ability. We also found that less time spent in the Canyon and Highlands levels was correlated with higher spatial ability, suggesting that the local landmarks in the Canyon level and the global landmarks in the Highlands level may be prompting the player to exercise their egocentric and allocentric navigation skills, respectively. In addition, player behavior in levels that tended to be more difficult, such as Rocket Boots in Construction Mode and Highlands in Exploration Mode, had some of the strongest correlations with spatial ability, lending support to **H2**.

However, **H3** was not supported due to substantial gender differences in correlations between spatial ability and player behavior. Attachment location matching seemed to be taxing spatial skills, but only for boys, since the number of wrong face errors boys made in the Tutorial1 level was related to their spatial ability. Unfortunately, it appears that most of the features in our game may not be tapping girls' spatial skills as effectively as boys' since girls' spatial ability was related to almost no in-game behaviors.

These findings have several important implications for game designers interested in assessing their players' spatial ability. First, spatial skills do seem to be correlated with specific player behaviors specific to Exploration Mode and Construction Mode, but also specific to individual levels within each mode. The Highlands level in Exploration Mode and the Rocket Boots level in Construction Mode seem particularly effective at tapping into players' spatial skills. For instance, the Highlands level may be more cognitively taxing than the Canyon level due to its open structure, which required the player to navigate using primarily global landmarks, as opposed to the Canyon level's exclusive use of local landmarks. Another reason for the Highland level's ability to tax players' spatial ability may be the frequent need to jump in this level, which required careful timing and aim. Game designers may therefore consider incorporating large, open spaces that require players to recognize landmarks from many different angles in order to most effectively tap into players' spatial skills in navigation tasks, or possibly include more tasks involving aiming and targeting to tap this dimension of spatial ability. To determine which explanation - open level structure or jumping - is more likely, we plan to add additional player behavior metrics to the in-game data collection for future studies, such as the number of jumps per level or the amount of time needed to jump past a specific obstacle.

A second implication of our findings is that the features we found relevant to spatial ability may explain why certain com-

mercial games like Portal 2 and Tetris are so successful at training spatial skills, while many others are not. Both Portal 2 and Exploration Mode require the player to explore a 3D environment in first person by either walking or jumping. However, Portal 2 includes many additional game mechanics, such as aiming and shooting a "portal gun" at walls to create portals for teleportation and disabling enemy turret guns that shoot at the player. The fact that Exploration Mode includes none of these additional features yet still manages to tap into players' spatial ability suggests that the act of first person navigation alone may be enough to make first person games like Portal 2 and Medal of Honor so effective at training spatial skills. This makes intuitive sense since first person exploration is how we experience the world around us as humans, but further research is needed to assess whether the features tapping into spatial ability in our game actually translate into spatial skill learning gains in players the same way that Portal 2 and Medal of Honor do.

Tetris and Construction Mode share much less in common. Tetris is a two dimensional game with possible rotations along only one axis, while Construction Mode allows the player to make rotations along each of the X, Y, and Z axes in three dimensions. In addition, there is an inherent time-sensitivity to actions in a Tetris game (act too slowly and you lose very quickly), with the result that expert Tetris players tend to rotate Tetris blocks very quickly in order to assess all of their possible options before they run out of time to place the block [19]. There is no such time sensitivity in Construction Mode. In fact, Construction Mode encourages careful, deliberate thought when rotating objects due to the constraint that each rotation uses up battery power, which the player can only replenish by leaving Construction Mode to collect more batteries. The only feature common to both games is the requirement of rotating and fitting objects together. The ability of Construction Mode, and especially the Rocket Boots level, to tap into players' spatial skills regardless of its few similarities to Tetris suggests that the simple act of rotating objects and deciding how to fit them together taps spatial skills in different types of spatial environments and in games with different priorities for speed and accuracy. Therefore, object rotation and alignment appear to be good features to include in a game for assessing players' spatial ability and are generalizable to many different types of games.

However, based on our finding that time spent in the Rocket Boots and Highlands levels is related to spatial ability, difficulty level more generally could be an important factor in how much a game taps players' spatial skills, or even more general cognitive skills. Commercial games have a wide range of difficulty levels, so it may be that games that do not challenge the player sufficiently are not properly taxing their mental capabilities. This may also account for why many cognitive training games struggle to produce empirically verified training effects. Commercial games are designed to be highly engaging and motivating, and people play them because they are fun. Therefore, game designers can make these games very challenging as long as they are sufficiently fun to motivate players to keep trying and eventually succeed. In contrast, the primary goal of cognitive training games is to train, not necessarily entertain,

so players may be less motivated and therefore designers of these games may have to make them less challenging in order to keep players from losing interest and giving up. Game designers seeking to accurately assess players' spatial abilities may therefore want to ensure that their games are motivating and engaging enough for players to persist and difficult enough for them to exercise their mental capabilities.

Lastly, gender differences in player behavior and the degree to which pretest scores predicted in-game behaviors indicate that game designers need to consider gender differences in both spatial ability and player behavior if they want to accurately measure spatial ability for both genders. The data collected in our study do not shed much light on the mystery of the gender differences we observed; girls did not seem to be less motivated to play the game and were only a little less familiar with similar games than boys. However, there are a couple other possible explanations for these gender differences.

First, it may be that girls and boys used different strategies which affected their in-game behavior. Since girls took longer to complete the Highlands level, they may struggle more with global landmark-based navigation and may therefore develop nonspatial strategies to circumvent this difficulty. Girls also spent more time standing still in the Canyon level, indicating that they may be less impulsive and less exploratory than boys, at least initially. This suggests that the growth mindset, which improves learning by encouraging trial and error, may have been more prevalent among boys in our study. Game designers may therefore consider adding game features that encourage the growth mindset in players, such as making mistakes low cost or fun actions, as in the popular rocket building game Kerbal Space Program, where errors in rocket construction lead to highly amusing, spectacular crashes.

A second and perhaps more likely explanation for the observed gender differences is that the particular psychometric test we used for our pretest, the Revised Purdue Spatial Visualization Test: Rotations (PSVT:R), may not have been sensitive enough to capture differences in spatial ability among children with low spatial ability who performed no better than chance, and who were disproportionately girls. We chose this test because to the best of our knowledge, no spatial skill tests currently exist for children in the age range used for our study. Every spatial ability test we could find was designed either for very young children (ages 0-3) or for adults. We felt that the PSVT:R was the best possible option given that it was designed for subjects ages 12 and up. We attempted to reduce the difficulty of the test by eliminating the 10 hardest questions, but it is likely that the test needs to be made even easier to accurately assess the spatial ability of children in late elementary school.

While establishing associations between players' in-game behaviors, game features, and spatial ability is an interesting avenue of research, our ultimate goal is to establish causal connections between specific game features and spatial skill development that can inform the design of games that actually train spatial skills, eliminating some of the guesswork about which games might or might not be effective. In the next section, we discuss several opportunities for future work

investigating the connection between specific game features, players' spatial skills, and individual player differences.

LIMITATIONS AND FUTURE WORK

The main limitation of this study is that while we can identify certain features in our game that tap in to children's spatial ability, we cannot verify that these features actually train spatial ability. Therefore, our next step in future work will be to conduct a controlled study with pre- and post-tests of spatial ability to establish a causal relationship between specific game features and spatial skill development. A second limitation is that our sample consisted of only 20 children and was likely biased towards children of University of Illinois staff given our recruitment method. In future studies, we plan to corroborate our findings with a larger, more diverse sample, recruiting from public elementary schools and libraries as well. Furthermore, additional analysis of in-game player strategies and a more sensitive pretest of spatial ability are both needed to determine whether the gender difference in the predictive power of player behavior on pretest scores is due to boys and girls using different strategies, girls' lower spatial ability, or some other cause. Finally, future work should investigate how adaptive features, such as branching storylines, could be added to *Homeworld Bound* and other games to optimize the level of challenge based on individual differences in player strategy and spatial skill.

CONCLUSION

Certain commercial video games, such as Portal 2 and Tetris, have been empirically shown to train spatial reasoning skills, which are essential for success in STEM disciplines. Unfortunately, the relationship between specific game features and individual player differences in spatial skills, demographics, and behavior has not been studied empirically. This knowledge is crucial for designing effective spatial skill training games, especially for women and girls, who tend to have lower spatial ability.

To address this gap in knowledge, we presented the first empirical study to analyze the relationship between specific game features and children's spatial ability using a game of our own design. We found that spatial ability pretest scores predicted several player behaviors related to the game features object rotation, object alignment, local landmarks, and global landmarks. However, girls' pretest scores were much less predictive of player behavior than boys', which may be due to gender differences in player strategy. Our findings help game designers understand how to incorporate specific game mechanics that tap into spatial skill and suggest ways to add adaptive features that nudge players toward more effective strategies for exercising their spatial abilities, regardless of differences in gender or spatial ability.

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