A Testbed for Fun and Effective Features in Spatial Skill Training Games

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Abstract

Certain digital games hold promise as interventions for training spatial skills, a subset of cognitive skills essential for success in STEM fields. However, not much is known about what features of these games are relevant to training spatial skills. Without such knowledge, it is impossible to design spatial skill training games with confidence that they will be effective. In addition, existing games for spatial skill training are not designed to appeal to those who stand the most to benefit from them: students with low spatial skill. In this work, we present a new and improved version of *Homeworld Bound*, a game designed as a testbed for studying spatially relevant game features. Our updated version is grounded in spatial skill theory and designed to appeal to low spatial skill university students. We present our future plans for analyzing the training effectiveness and player experience of this new game, *Homeworld Bound: Redux*.

Author Keywords

spatial skills; cognitive skills; educational games; player experience; STEM education; students

CCS Concepts

•Applied computing → **Interactive learning environments; •Human-centered computing** → *User studies;*

Introduction

In recent years, there has been considerable excitement generated by the possibility of game-based interventions for training players' spatial skills [24, 1, 7]. Spatial skills are a subset of cognitive skills related to the way people perceive the spatial relationships within and between themselves and the objects in their environment [28]. They are also one of the strongest predictors of future success in STEM coursework and STEM careers; low spatial skills serve as a gatekeeper for STEM fields, as those students with low spatial skill drop out of STEM majors and coursework after struggling with spatially demanding introductory STEM courses in majors such as engineering, chemistry, and mathematics [27]. There is also a gender gap in spatial skill beginning in early childhood to late elementary school that mirrors and exacerbates the STEM gender gap: boys and men tend to have higher spatial skills than girls and women [11, 9, 10].

Fortunately, spatial skills are highly malleable, and empirical research studying video game training has shown that commercial games such as *Medal of Honor: Pacific Assault* [6, 5], *Portal 2* [22, 29], and *Tetris* [23, 25, 17, 18] can train players' spatial skills. Thus, video games would seem to offer a great deal of potential as training tools for improving students' spatial skills. However, other video games such as *Ballance* [4] and even *Lumosity*, a game designed with the purpose of training spatial and other cognitive skills [12], fail to show training effects in the research literature [6, 22]. The potential of video game-based training for spatial skills cannot be realized without building a base of knowledge around which game features are actually tapping into players' spatial skills.

Another issue is that existing games, whether they be commercial games like *Portal 2* and *Medal of Honor: Pacific Assault*, or cognitive training games designed by researchers for the purpose of spatial skill training [13, 31, 2, 32], do not take into consideration the preferences of a population we argue should be the target audience of spatial skill training games aiming to improve STEM proficiency: students with low spatial skill. Since the research literature suggests that spatial skills are most predictive early on in STEM learning, before students have a chance to gain domain-specific skills that might make up for a lack of spatial skill, improving low spatial skill students' spatial skills up to a certain "threshold" might be sufficient to remove this barrier to their pursuit of STEM fields [27]. If the goal of a spatial skill training intervention is to improve students' STEM proficiency, but it is not designed with the target audience of low spatial skill students in mind, then they are less likely to enjoy the game. The game then loses the primary advantage game-based training interventions have for low spatial skill players over more traditional training exercises: a playful, fun experience.

To help researchers and game designers understand what game features are most important for a game's effectiveness at training spatial skills and what features are most important for enhancing the player experience of low spatial skill students, we have designed a new, updated version of *Homeworld Bound*, a 3D exploration and construction game originally designed to train children's spatial skills. Our new version of the game, *Homeworld Bound: Redux*, is grounded in a stronger theoretical mapping between spatial operations and game features as well as the recommendations of Wauck et al. 2019 for designing spatial skill training games for low spatial skill populations [30]. In this work, we discuss the implementation of our new theoretical mapping for spatial game features in *Homeworld Bound: Redux*, the changes made to improve the player experience for low

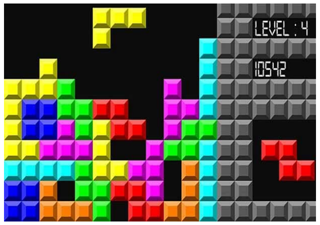

Figure 1: A screenshot of the game *Tetris*. Blocks fall from the top of the screen and the player must rotate and arrange them to fit as tightly together as possible. Every time a row is completely filled with blocks, it vanishes. The player loses when there is no more room below to place the next falling block.

Figure 2: A screenshot of the game *Portal 2*. The player's goal is to navigate a series of 3D environments using the Portal Gun, which allows players to place a pair of portals on most flat surfaces in the environment.

spatial skill players, and our future plans for studies analyzing the game's player experience and training effectiveness.

Original Game

Homeworld Bound is a game we designed using the Unity game engine and presented in previous work [31] as a potential tool to train spatial skills. The game is designed around two central mechanics, 3D object construction and first person navigation. The premise of *Homeworld Bound* is that the player has crash-landed on an alien planet and must explore the environment and collect scrap material they can use to rebuild their spaceship and construct other useful items that will help them return to their home planet. Gameplay is divided between Exploration Mode, where the player explores the alien world in first person, collecting scrap material, and Construction Mode, where the player builds items in 3D by finding where constituent parts attach together, rotating them to line up correctly, and then fusing them together. Controls for Exploration Mode follow the standard use of W, A, S, and D keys for movement, mouse movements for changing the player's heading, and the spacebar for jumping. Construction Mode uses only mouse clicks, click and drag, and scrolling.

Originally, *Homeworld Bound* was designed for children ages 8-11, but in order to adapt the game for use in introductory STEM coursework at the college level, we modified the game to appeal more to the interests of low spatial skill college students and developed a stronger theoretical mapping between spatial operations and game features. This mapping helped us make modifications to *Homeworld Bound* to increase the likelihood the game would help train players' spatial skills.

A New Mapping for Spatial Game Features

In our earlier work, we proposed a mapping between game features and spatial operations that enabled us to identify which features from commercial games shown to train spatial skills contribute to their training effectiveness. These features were then incorporated into *Homeworld Bound* and separated from each other across different game levels and modes to enable them to be tested for spatial training effectiveness in isolation [31]. However, as our research progressed, we realized that this previous mapping had only weak ties to the body of research on categorizing types of spatial operations. One of the first steps we took as we began modifying and improving *Homeworld Bound* was to reconsider our mapping and improve its grounding in the relevant literature.

Our new mapping is grounded in Uttal et al.'s taxonomy of spatial skills, which is based on a meta-analysis of spatial skill training literature. While there is disagreement in the research literature about the best way to classify spatial skills into subskills, Uttal et al. draw from the general consensus of the literature and propose that spatial skills can be broken down into a 2x2 taxonomy along two axes: *intrinsic-extrinsic* (information about a specific object versus information about the relations between a group of objects) and *static-dynamic* (fixed information versus information about how something is changing over time) [28].

While the design of *Homeworld Bound* drew inspiration from several commercial games shown to train spatial skills, we focused on two in particular for our redesign: *Tetris* [18] (Figure 1) and *Portal 2* [29] (Figure 2), since they best exemplified the use of the three spatial skill types in Uttal et al.'s taxonomy with the highest relevancy to STEM proficiency: *intrinsic-dynamic*, *extrinsic-static*, and *extrinsic-dynamic*. *Tetris* has been shown to improve *mental rotation*

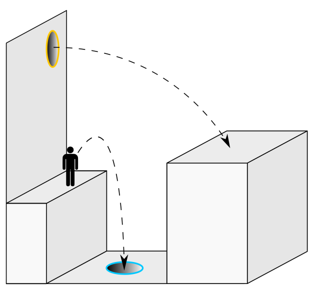

Figure 3: An illustration of how players can use portals to navigate through otherwise inaccessible areas in *Portal 2*. The player chooses the location of both the orange and blue portals using the Portal Gun and then jumps through one of them, flying out the other with the same momentum with which they entered the first portal.

skills, an *intrinsic-dynamic* spatial subskill that measures the ability to imagine how the appearance of an object would change as it is rotated in various ways [21, 28]. However, this performance improvement is generally limited to near transfer: mental rotation tasks where the objects to be rotated look similar to the blocks the player must manipulate in *Tetris* [3, 23].

Portal 2, in contrast, is a physics-based first person puzzle game requiring the player to decide how to walk, climb, and jump their way through the environment using a small set of tools. Despite the substantially different gameplay, training with *Portal 2* has also been shown to improve players' mental rotation ability and performance on an additional spatial subskill in the *extrinsic-dynamic* category called *environmental spatial skill* [15, 16, 22], demonstrating the far transfer potential of training with this game.

While *Tetris* does not afford the same far transfer benefits as *Portal 2*, it is a much simpler game, and therefore it is easier to determine which of its features might play a role in improving players' spatial skills. In *Tetris*, players have two tasks: rotating falling blocks quickly, and moving those blocks into the most dense configuration possible. We will refer to these two features as *object rotation* and *object alignment*.

It is more difficult to determine which features of *Portal 2* gameplay might be contributing to its effectiveness at training spatial skills. However, the game's emphasis on its central mechanic of *portals* (see Figure 3 for an explanation) suggests that players may be using landmark cues to decide where to place a portal and then visualizing how their character would move from one end of the portal through the other in order to evaluate whether their portal was placed in the correct location. We will refer to these two features of the gameplay as *landmark orientation* and *navigation visualization*.

Game Feature	*Spatial Operation*
Object Rotation	Intrinsic-Dynamic
Object Alignment	Intrinsic-Dynamic
Landmark Orientation	Extrinsic-Static
Navigation Visualization	Extrinsic-Dynamic

Table 1: Game feature to spatial operation mappings used to inform the design of *Homeworld Bound: Redux*.

In our new mapping, the *object rotation* and *object alignment* operations required in *Tetris* correspond to the *intrinsic-dynamic* quadrant in Uttal's 2x2 taxonomy of spatial skills, while the *landmark orientation* and *navigation visualization* required of *Portal 2* players correspond to the *extrinsic-static* and *extrinsic-dynamic* quadrants in the taxonomy, respectively (Table 1) [28].

Spatial Feature Game Revisions

The revision of our spatial operation to game feature mapping, in turn, provoked us to revise *Homeworld Bound* to emphasize the four spatially relevant game features it highlighted. Construction Mode naturally incorporated *object rotation* and *object alignment* into gameplay as players attempted to determine how each part should be placed and rotated to fit in with the others and build the desired structure, similar to a 3D version of *Tetris*. And navigating through a virtual world to a specified destination, as was done in the original version of Exploration Mode, naturally requires the player to orient themselves in the environment relative to specific landmarks via *landmark orientation*.

However, to further align the game's features with those in our new mapping, we incorporated a few key changes. First, we increased the navigational complexity of environments in Exploration Mode while making landmarks more distinctive through the use of distinct color variations to encourage players to use landmarks to navigate. Second, we added a map to certain Exploration Mode levels (See Figure 4) to prompt players to plan out their route more strategically, tapping into their *navigation visualization* skills rather than engaging in the nonstrategic wandering we observed during playtests with the original game. Third, we limited the number of rotation operations a player could use to a fixed amount per Construction Mode level to encourage the player to plan their rotations more carefully and imagine how they would play out, engaging their *intrinsic-dynamic* spatial skills more fully in the form of *object rotation* and *object alignment*. Finally, we added time limits to certain levels in both Exploration Mode and Construction Mode to force players to work out spatial problems more quickly, as is required in *Tetris* and in most standardized tests of spatial skill.

Player Experience Game Revisions

In addition to enhancing the spatial features of *Homeworld Bound*, we modified the game to be more in line with recent guidelines we and our colleagues proposed for designing spatial skill training games that are appealing to the population that stands the most to benefit from them: those with low spatial skill [30]. All of the following changes were based on the following recommendations from [30]:

- Facilitate Short Gameplay Sessions
- Promote Simple Fun and Thrill
- Get Creative with Adventure and Puzzle Genres

One of our alterations was to make levels playable in just a few minutes in both Exploration and Construction Mode to allow for shorter gameplay sessions that still feel satisfying. The time limit we introduced in certain levels to challenge players' spatial skills more throughly, coupled with suspenseful music to match, also served the goal of increasing players' sense of thrill. Finally, we added a more of a narrative to the game to give players a sense of purpose to what they were doing, supporting one of low spatial skill players' stronger motivations for playing games.

Future Plans

In the future, our immediate goal is to evaluate the effectiveness of the feature set we have chosen for *Homeworld Bound: Redux* as well as analyze the player experience of the game for low spatial skill students. We are planning a series of studies conducted within the context of introductory level engineering and computer science courses that will analyze the training effects of the game relative to a more traditional spatial skill training program consisting of workbook exercises. Working together with the teachers of each course, we will integrate opportunities to play through the game into the course schedule.

Our plan is to conduct a pretest of spatial skills, randomly assign students to the treatment group (playing a few hours of *Homeworld Bound: Redux*) or the control group (completing several sets of workbook exercises of approximately equal length). A final post-test of spatial skills after the intervention is complete will then allow us to analyze how favorably the game compares to the more traditional training methods, particularly among those who begin the course with a low level of spatial skill. Doing this study across multiple classes will also allow us to gather a large enough sample of player performance data to conduct a correlation analysis assessing the relationship between performance

Figure 4: In *Homeworld Bound: Redux*, the player navigates the a 3D environment to collect scrap parts in Exploration Mode, in some levels with the assistance of a map (left) and then uses the collected parts to construct useful items by aligning them correctly with rotations and then attaching them together in Construction Mode (right). Shown here are levels with time limits, but most levels do not have time limits.

in the game and pre-existing spatial skill (as measured by pretest score). If the game fails to improve players' spatial skill test scores, this correlation analysis could serve as a useful diagnostic tool for identifying the levels in Exploration Mode and Construction Mode that are not tapping into players' spatial skills enough to produce a training effect.

Comparing the player experience among low spatial skill students between *Homeworld Bound: Redux* and the more traditional workbook exercises will help us determine to what extent the game meets its goal of being a more fun way for this target audience to train their spatial skills. This analysis will be conducted via post-game surveys using standard, validated questionnaires for assessing enjoyment and player experience, such as the IMI [20, 14, 26] and PENS [19, 8]. The results of this analysis will identify opportunities for improving the player experience for future experiments using the game. Once the game has been iterated on enough times to produce an effective training intervention with good player experience for low spatial skill players, it will have the potential to help students who might otherwise drop out of STEM courses and majors achieve the necessary spatial proficiency to succeed.

Finally, we make our game available in open source form at https://github.com/hwauck/homeworld-bound in the hope that other researchers may find *Homeworld Bound: Redux* useful for their future studies and customize the game as needed, enabling a larger, more diverse set of studies on the nature of spatial skill training with video games.

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