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Manufactory: Promoting 3D Spatial Skills with Productive Failure and Educational Games

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Abstract
This research study investigated an innovative teaching and learning framework that incorporated educational games utilizing the proven concept of Productive Failure (PF). The aim of the research study was to enhance students' learning experience and improve their understanding in the threshold concepts of product design, manufacturing and assembly. As a measure to promote active learning, an educational game was introduced in the problem-solving phase of PF. A 3D puzzle game titled "Manufactory" was designed, developed and implemented to assist students in improving their 3D spatial abilities. In order to test the presented framework, an experiment was conducted where students were allocated to either a Productive Failure (PF) or Direct Learning (DL) group. For the PF group, students were first required to solve problems in the puzzle game independently during the problem-solving phase, before instructions were given in the second delayed instruction phase. A conventional teaching approach was conducted for the DL group. Results from the experiment reflected that students in the PF group achieved a distinctive improvement, raising their average score by 40 percent and outperforming students in the DL group with 22 percent greater progression during the post-test. The experiment displayed evidence that the 3D educational game design provided an engaging environment for the problem-solving phase, which served as the primary motivation for effective absorption of the concepts in the delayed instruction phase.

Keywords: Productive failure, 3D spatial skills, Educational games, Game based learning.

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Introduction

Cultivating and improving 3D spatial skills is crucial for students studying in the fields of product design/ industrial design/ mechanical engineering and is the most fundamental determinant of future success (Sorby & S.A., 2009). 3D spatial ability is one of the most important factors that can influence a students' design performance (Liao & L.H., 2017). In product design, the ability can be represented as the capacity to imagine 3D models or shapes in the mind (Martín-Gutiérrez, J., Saorín, Contero, Alcañiz, Pérez-López & Ortega, 2010). Specifically, spatial conversion ability (Liao & L.H., 2017), reflecting transformation between 3D perspective and 2D perspective, is claimed to be the most critical among the spatial abilities.

However, students often have trouble visualizing a two-dimensional blueprint drawing of a three-dimensional object, which severely affects their understanding on how features of a product like case walls, bosses, snap fits and ribs are drawn. Additionally, students may overlook including one or many of these features in their drawings, which is detrimental to designing high-quality products.

Conventional instruction for creating two-dimensional blueprint drawings did not necessarily bridge the gap between students' academic backgrounds and the subject matter and principles. These gaps can be reduced by first creating a cognitive connection between the academic content and the student's ability, the method proposed for this project was to transform the learning content into a playful medium to attract students' attention. A second method of giving detailed instructions was also employed to help students to consolidate knowledge and develop their learning abilities. This learning design was inspired by a scientifically proven theory called "*Productive Failure*" (Kapur, 2008).

Productive failure (PF) is a recently proposed learning design that encourages students to get involved in searching and generating original solutions to complex and ill-structured problems before the instructional course (Jasper, 2013). PF has been applied and tested in the British Advanced level (A-Level) curriculum; therefore the same benefits are expected when integrating PF design in tertiary education. Since failure is an integral and unpleasant part of both learning and playing video games (Jasper, 2013), there is a prospect for mapping failure in games and failure in productive failure from a psychological perspective. What is relevant for this research project is that the approach to a product design consists of the abilities to address ill-defined problems, apply solution centered strategies, use productive thinking and adopt spatial modelling techniques (Cross, 1990).

Previous research has identified the importance of 3D spatial skills for product design students, along with the demand to figure out the relationship between 3D spatial ability and design performance in 3D product design (Liao & K.H., 2017). With this is mind, an educational game combined with productive failure learning design titled *Manufactory* was developed with an aim to help students in improving their skills in orthographic projection, sectioning visualization and spatial awareness.

To answer those assumptions, we listed the following three pertinent research questions:

- *Can the concept of Productive Failure be successfully translated to tertiary education?*
- *To what extent can tertiary educational content be transformed into educational games?*
- *Can educational games serve and function as ill-structured problems in the productive failure design phase?*

The methodology involves three key constructs: The first challenge is to translate the key learning contents of product design into an attractive game that could foster cognitive absorption and comprehensive understanding. The second consideration is to use the game as an ill-structured mediator nested in the productive failure design structure. Finally, in the third phase of the project, an evaluation is carefully planned to test the overall effect of the game and productive failure.

Related work

With the rapid development of multimedia technology, educators have developed creative solutions and training approaches to help students develop their spatial visualization skills.

Jorge Martin and his research group developed a book based three dimensional visualization tool using Augmented Reality (Martín-Gutiérrez et al, 2010) where fiducial markers on the book were captured by webcams and 3D models were displayed through the markers. Students could observe different perspectives of virtual models by turning or rotating the book, this tool was perceived positively by students. However, the system lacked interaction, and the indirect interaction could cause a disconnection between what was seen and what could be manipulated. The system mainly relied on camera detection, which could have lighting issues and distortion problems. Furthermore, vision was constrained to limited areas (marker size) and could cause strain on eyes (Van Krevelen, D. W. F., & Poelman, 2010).

Ahmad Rafi (Rafi, Anuar, Samad, Hayati, & Mahadzir, 2005) introduced a web-based virtual environment, which was designed to provide an immersive learning system and improve students' spatial ability. The students could involve themselves in interactions like rotating virtual objects to identify orientations or folding and unfolding 2D surfaces that could be transformed into 3D models. Overall, learning with web-based virtual environment turned out to be more efficient than the traditional learning practices. However, the system offered very limited interactions. It is hard to conclude that the operations are intriguing and engaging from a long-term perspective.

Apparently, learning games have gained widespread popularity in educational fields. Stephen W. Crown (Crown & S.W., 2001) developed a well-received web-based game to help students improve their visualization skills through instant feedback and instructional puzzles. It shared mixed features of a puzzle game and a visualized quiz and had gradually increasing levels of difficulty. It could be noted that the challenges in puzzle formats had motivated students to develop a more profound understanding of difficult concepts.

Manufactory: The game design

The game includes many features and interactions that are familiar to students studying product design and provides a controlled environment where they can explore elements of the game on their own and use different strategies to complete the game. In such a controlled environment, students can fail and have a chance to learn from their failures and discover what is needed to succeed. Students are encouraged to refer to their learning materials based on hints that the game provides and find solutions to areas in which they are unsuccessful.

Technology

The game was developed in Unity, a popular game engine among the independent game developer community. Unity was chosen due to its low learning curve, powerful scripting engine and asset store containing many useful scripts and game assets, a good community and reliable answers-solution forum. The engine allows quick prototyping and has helped during the development of the game where design results can be seen rather quickly and be iterated.

Mechanics

Manufactory contains 11 levels, arranged in ascending order of difficulty, where each level is a product, which students must assemble from pre-built parts by selecting appropriate blueprint images on the left, as seen in Figure 1 below.

Figure 1: A level being played in the game.

The images are rendered in 2D orthographic views, in both cross-sectional and orthogonal views, ranging from bad quality to good quality, which can be seen in Figure 2 below. The goal of the player is to identify blueprints drawn in the highest quality and selecting them to fabricate the parts and assembling them into a set of electronic components to create the product, an example of which can be seen in

Figure 3 below. A sound cue is played when parts are correctly assembled in place. In an event of a misjudgment or carelessness, players can detach and or delete parts.
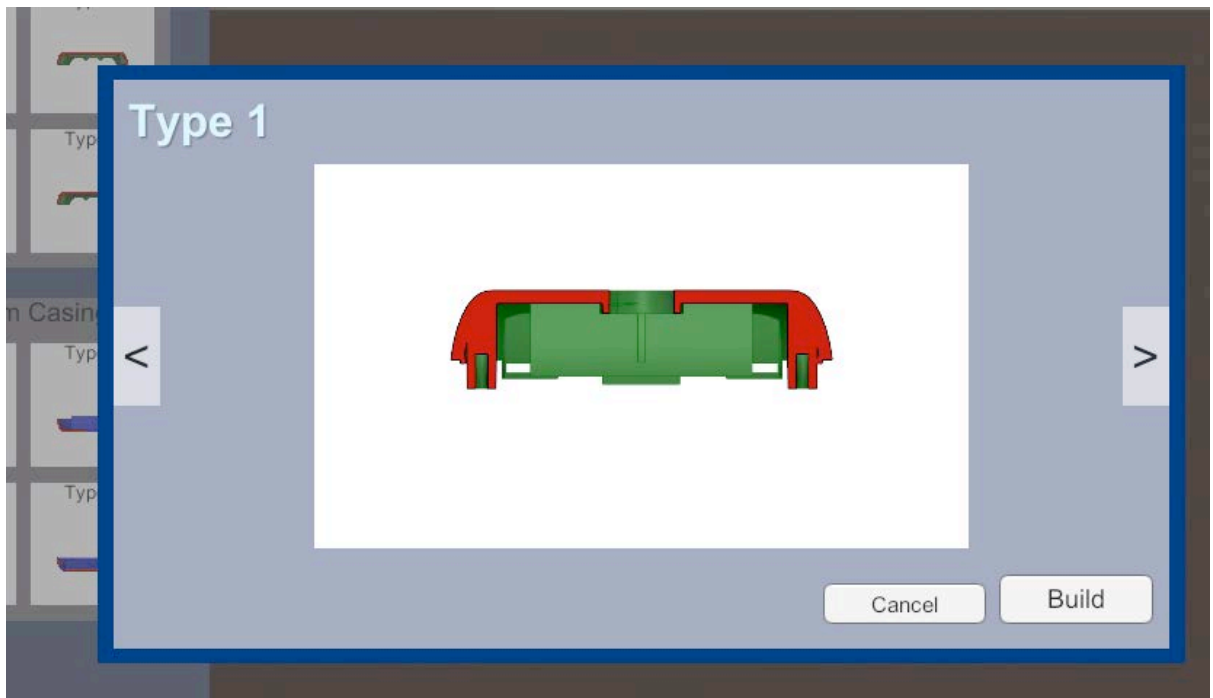

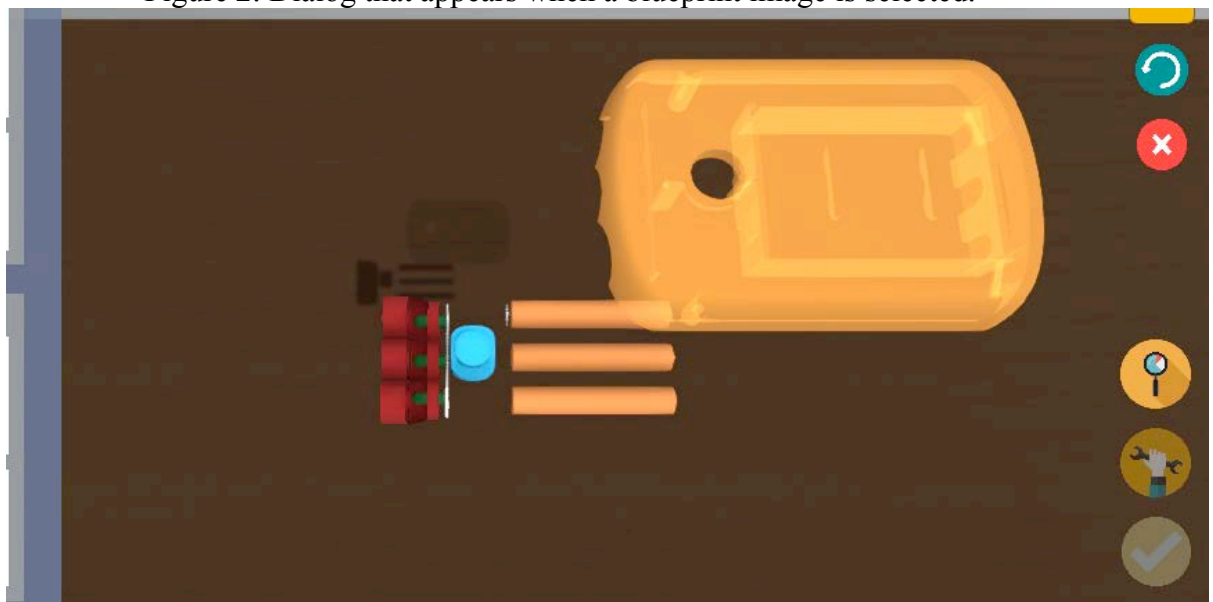Figure 2: Dialog that appears when a blueprint image is selected.

Figure 3: Assembling fabricated part onto electric components.

A button to complete the level will reveal once the product is assembled and clicking on the button will reveal a result screen displaying the completion time, score, and mistakes. The result screen as seen below serves as a form of feedback from the game and the consequence of their actions in the game.

Figure 4: Feedback window after players complete the level.

The students are familiar with 3D computer-aided design programs such as Rhinoceros, Keyshot, and Solidworks for modelling and creating renderings, thus the game's control scheme operates in a similar fashion to those programs. Controls include:

1. Viewport navigation controls such as zoom, dolly, and rotation using the mouse buttons.
2. To move objects around, common controls found in such 3D programs like the transform gizmos, object translation and rotation are provided. This creates familiarity and reduces the learning curve for the game.

A manual as seen in Figures 5 to 7 is included in the game to guide players who are new to the game. It introduces all the interactive elements in the game, the controls, rules and objectives of the game. The manual presents itself in a book like manner, introducing each element in a guided, progressive way.

Objective

The objective of the game is to correctly determine if the sectioning images of a part is correct and assemble the product carefully with the selected part. Selecting the correct part will yield a higher score, while selecting a wrong part will yield a lower score or no score at all.
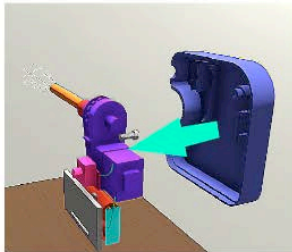
Assemble by moving the casing part towards the electronic components.

If the product is not complete, you cannot complete the level as seen with this greyed out checkmark.

Once the proudct is done assembling, the checkmark will be enabled. This allows you to complete the level.

Right click to go back

Left click to continue

Figure 5: User's manual showing the objectives of the game.

Buttons

Inspect Mode
Used to inspect parts. Click on a part to focus on them and look around them. Parts cannot be moved in Inspect Mode.

Build Mode
Build mode will display the parts drawer on the left of the screen. Click on a desired part to build them onto the world.

Right click to go back

Left click to continue

Figure 6: The manual showing the game's interactive elements.
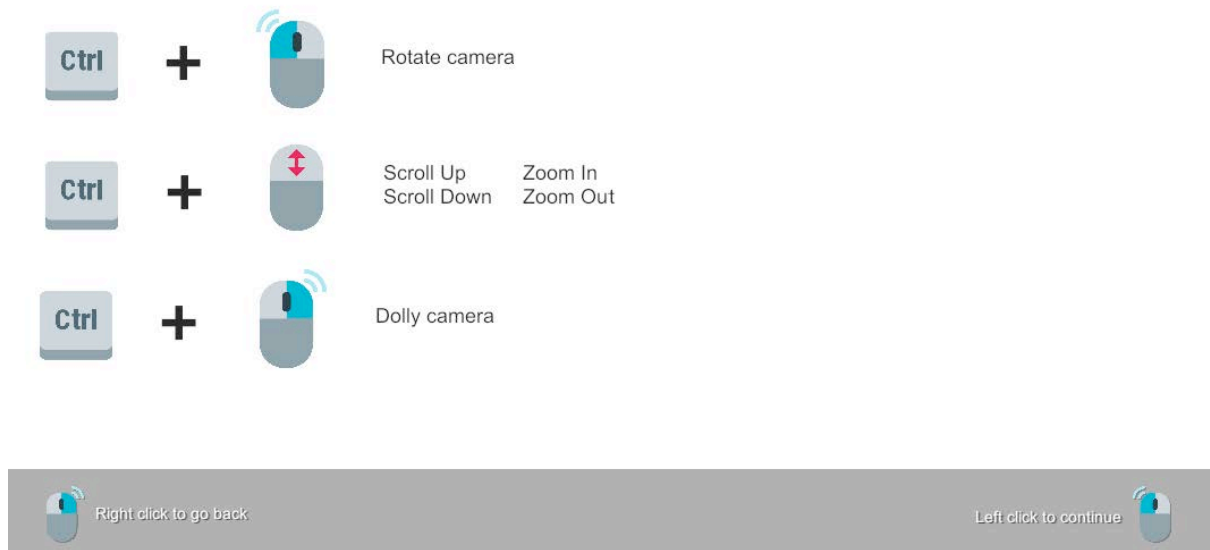
Camera Controls

Figure 7: Camera controls in the manual.

The mechanics were designed in such a way to cultivate the improvement on three-dimensional spatial skills and projection skills of students. The game contains similar control schemes to Rafi's (Rafi et al, 2005) work. However, in contrast to Rafi's solution, ours comes with added interactions like the puzzles and providing players with goals that create better long-term engagement. Our game includes roughly the similar kind of mechanics in Crown's solution (Crown & S.W., 2001) including puzzle-based levels, increasing level of difficulty and instant feedback. However, there was no emphasis on making failure of students as part of the motivation required to further understand the subject on a deeper level. Our solution highlights this, so that students can create a more profound understanding of their subject and become better at their craft in the long term.

Aesthetics

Creating immersion and suspension of disbelief among players is important as it creates the perception and illusion among players that they are involved in the game world, which can further increase motivation to complete the goals in the game (Schell, 2014).

With the target audience being product design students, the game needs to fulfill their expectations of what a product design game should look and feel like. With that in mind, the game world is set in a modern product design studio environment. The game intends to emulate elements of a product design studio, primarily the interior design, lighting and color scheme and feel.

As a result, the game uses a simple color palette filled with whites, greys, subtle yellows, subtle blues and purple tints and is littered with things that can be typically found in a design studio.

By creating an environment, which the target audience can relate to, they can feel more connected and involved in the world. Combined with the standard 3D program-like controls, which should be familiar with the target audience, as well as the mechanics where players' goals are to assemble the product from parts through a thorough selection of sectioning images further amplify the immersion because players can interact with the world in a meaningful way.
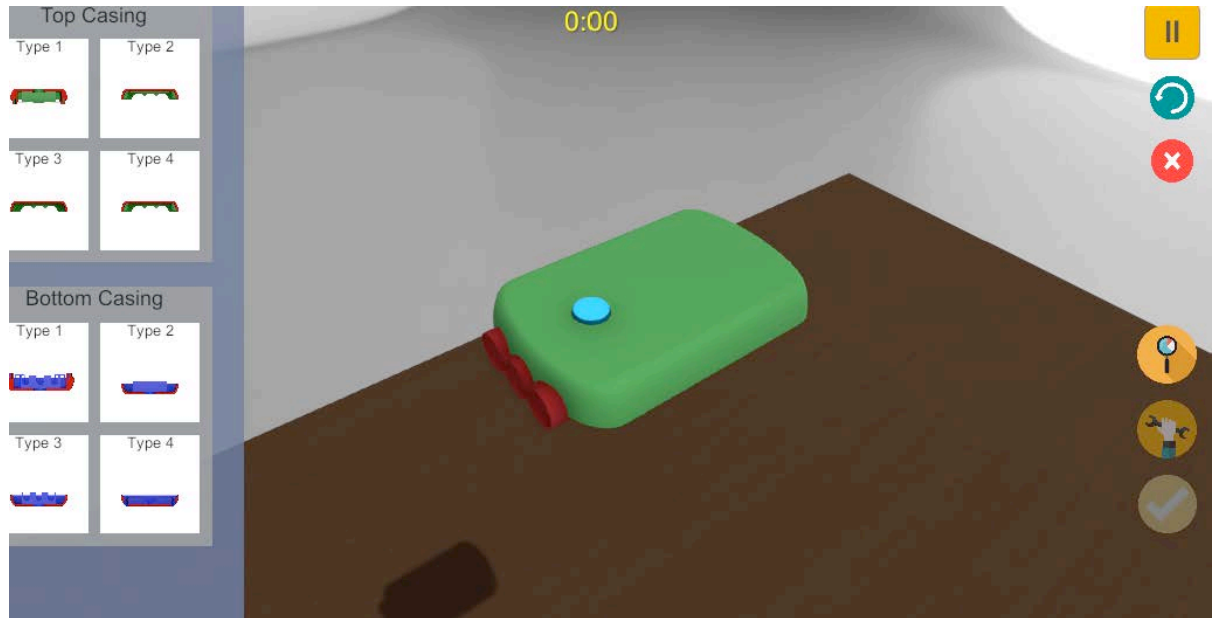

Figure 8: The main game screen.

In the figure above, the game utilizes the minimalist approach in its aesthetic to reduce clutter, be in the game world or its user interface. Animations and sound contribute to the overall aesthetic in a meaningful manner as well. An animation of an injection molding machine included in the game is played along with sounds the machine makes when players construct a part from selection of a blueprint image. Since many product designers will be working with such a machine in their industry, resulting in an even more relatable environment to the target audience.
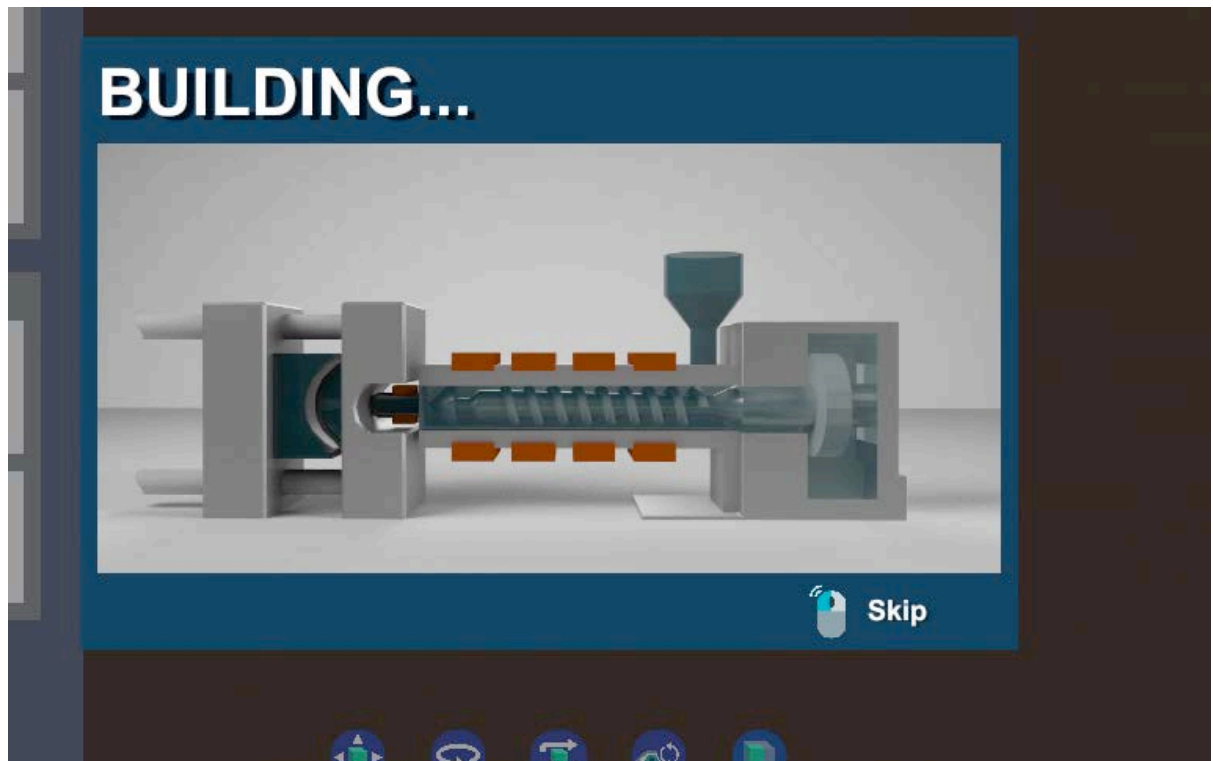
Figure 9: Building animation showing the injection molding machine.

Many of the solutions mentioned do not seem to have a world or space specifically crafted to create additional immersion to create engagement among players. For example, with Martin's AR solution (Martín-Gutiérrez et al, 2010), there was the issue of disconnection between the interaction and visuals on the screen where parameters and variables of the real world can affect how the players perceive themselves in the game. They may not feel part of the game as the digital and physical realms are clearly divided in AR. Other solutions such as Rafi's (Rafi et al, 2005) and Crown's (Crown & S.W., 2001) also do not offer a world but just the learning content, which can be fine on their own but may not offer the long-term engagement that can be beneficial in the goal of making students learn and understand the subject at a deeper level.

Experiment design

Theoretically, it looks promising that educational games and productive failure are somehow compatible with each other, practically however, there is no precedent, this experiment design presents an attempt to assess their compatibility.

Participants

The experiment was conducted in a product design classroom with an experienced tutor. Due to limits in class size, there were 14 participants in the entire experiment. Students aged from 20 to 27 who were enrolled in the course voluntarily took part in the experiment. The participants were naturally divided into two groups based on different schedules. The control group consisted of 6 students (67% of all the attendees) were given the traditional instruction by the tutor. Meanwhile, the experimental group consisting of 8 students (67% of all the attendees) followed the

new learning design.

Process

It was very difficult and challenging to come up with a solid experimental scheme especially when we need to embody the duality of the game associated with productive failure along with the students' schedules. Students in the experimental group were only available on Tuesday, and students in the control group were only avialable on Thursday. The conceptual experiment procedure is illustrated in Figure 10. The learning time for both groups is balanced so that their performance can be measured fairly.
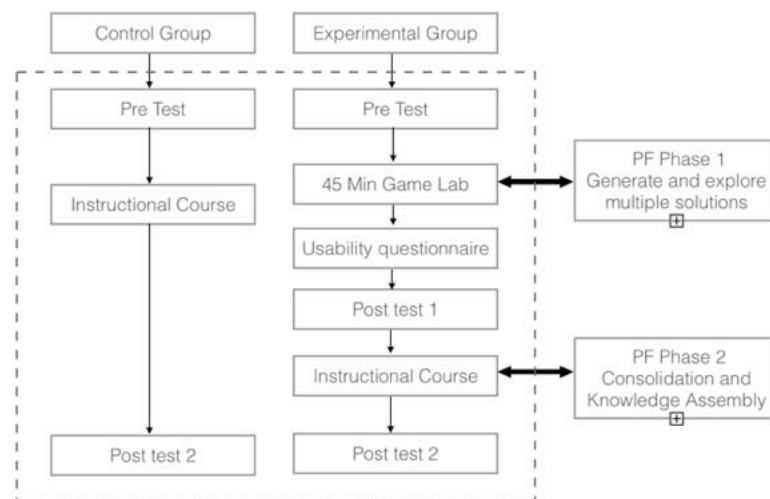

Figure 10. The experiment flow of two groups. PF phases (Kapur & Bielaczyc, 2012)

At the beginning of the experiment, both groups were notified of the upcoming process. A pre-test was conducted for both the experimental and control groups to examine the innate spatial ability and related prior knowledge of the students.

In the following week, the experimental group was asked to partake in playing the *Manufactory* game. They were given 45 minutes to play while there were no instructions related to the learning concepts or game provided during the play. The students were expected to navigate through the game using the tutorial provided within. There was also no assistance from the tutor or experiment designers. The students played in isolation and silence, such that no external factors would cause disturbance or affect their performance. If the students were stuck on a level, they were expected to analyze their mistakes by reading the level report and re-attempting the levels. The students were also free to stop playing whenever they wanted if they felt tired, frustrated or bored. Once they finished playing, they were asked to fill out a user experience survey. Meanwhile, the control group did not engage in the game and had their regular classes for the same time interval as the experiment group.

After this, the experimental group is given an examination as post-test 1. This is to understand how the learning game and resulting occurrence of failures could help students to understand concepts like visualizing sectioned views of object/models without explaining it using traditional textbook or slides in classrooms.

Following this test, the experimental group is given an instructional study by the tutor. Equally, the control group shares the same amount of instructional time. Finally, both groups participated in post-test 2 to test their knowledge from the instructional study. The scores of these tests are tabulated and compared for discussion and results.

Data collection

Game Data
Score - A performance metric for a level the players have played in. It can be used to measure the understanding of players when making choices in the level.

Completion Time - Used to measure how fast a player completes the level. It is used in conjunction with the score to assess player behavior in the game.
High Score - The overall performance of players in the game. It is the cumulative score of all levels that players have played.

Drawing Test Scores
The drawing tests were scored on a scale of 1 to 10, with a good drawing reflecting a higher score.

As described in the experiment design, for the pre-test (Figure 11), both experimental and control groups were given a series of tasks to create 2D section sketches of an existing product. Students' performance in the exam can sufficiently reveals their 3D spatial ability. Scores for the pre-test were given based on the orientation of the drawings in relation to the joining of parts in either a top/bottom or left/right configuration, and on the line-work representing where the parts were cut in section view.
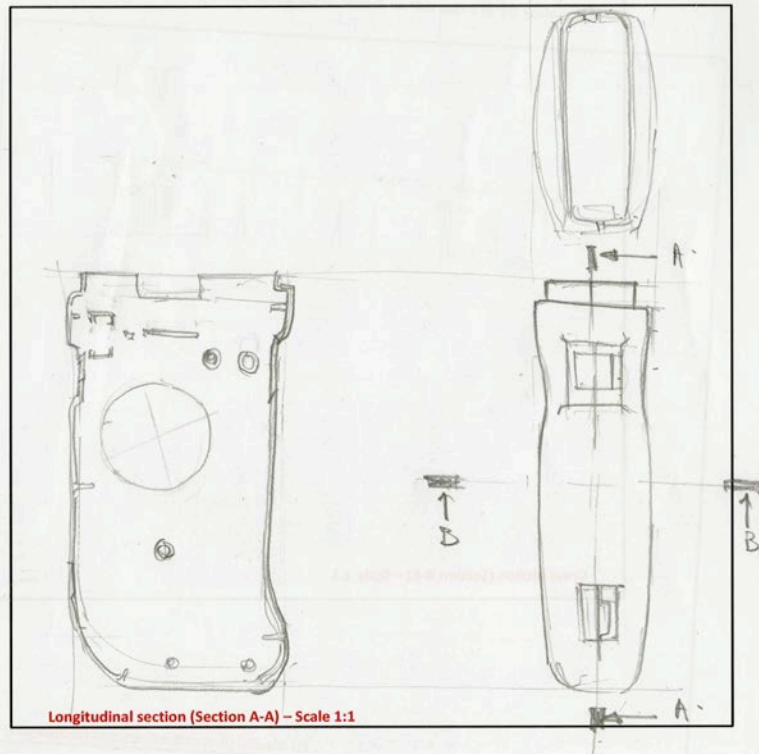
Figure 11: Sample pre-test Drawing

For post-test 1, after playing Manufactory, the experimental group was given a series of tasks to create 2D section sketches of the similar existing product used in the pre-test. Scores for post-test 1 were given based on the same criteria as the pre-test.

For post-test 2 (Figure 12), both experimental and control groups were given a series of tasks to create 2D section sketches of a different existing product than that used in the pre-test.
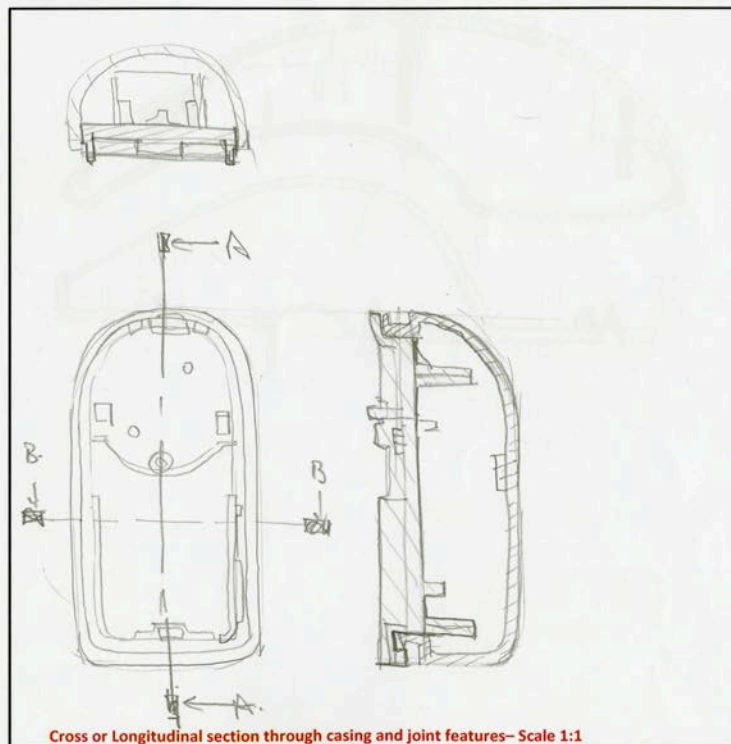
Figure 12: Sample post-test 2 drawing

Questionnaires

Game experience is vital as it determines user engagement and learning efficiency. Thus, through questionnaires, we can better understand users' subjective feelings during the gameplay and reflect on the answers of their learning outcome. Functionality, usability and aesthetics are three essential properties defining the quality of game experience (Calvillo-Gámez, E. H., Cairns & Cox, 2015). Since our game resembles a puzzle, the questions have more focus on usability, engagement and aesthetics.

In this study, we designed two questionnaires to collect user information and feedback after each learning phase.

The first questionnaire presented to the experimental group immediately after the 45-minutes gameplay was the usability questionnaire. It consists of four sections; the first

section was used to collect basic user information like age, gender, and their previous game experiences. The questionnaire was modified from a Game Engagement Questionnaire from a journal article in the Journal of Experimental Social Psychology (Brockmyer, Fox, Curtiss, McBroom, Burkhart & Pidruzny, 2009). The second and third section was designed to evaluate the usability and aesthetics from the Human Computer Interaction perspective. The questions in these two sections are referenced from papers in the Proceedings of the 2016 CHI Conference Extended Abstracts on Human Factors in Computing Systems (Bernhaupt & Mueller, 2016) and Computers in Human Behavior (Aldemir, Celik & Kaplan, 2018) and adjusted accordingly. Finally, there's a fourth section including questions associated with the learning effect. The second questionnaire is used for an overall study of the learning experiences after the instructional phase. Questions were selected and modified from the paper (Bernhaupt & Mueller, 2016).

Results

We carried out a systematic analysis after collecting all the data from the experiment. Since the study involves with-subject and between-subject design, the statistics and analysis methods, therefore, include the average values, paired t-test, and One-way ANOVA. Paired t-test was used to compare the before and after game performance of the experimental group. One-way ANOVA was performed to understand whether exam scores statistically differed between groups. The statistical analysis was conducted with IBM SPSS.

Results of Experimental Group

The results are presented in the following tables. The examination scores measured the mastery of the procedural knowledge of 3D spatial visualization. And the questionnaires are designed to reveal the usability of the game and quantify students' attitude toward such learning experiences.

Experimental Group	Pre test	Post test	Post test 2
Mean	5.50	6.13	7.75
SD	1.92	1.88	0.71

Table 1. The average scores of three paper exams

Exam score	N	Mean	P-Value
Pre-test	8	5.50	0.33>0.05
Post test1	8	6.13	

Table 2. Paired t-test result of Pre-test and post-test 1

Exam score	N	Mean	P-Value
Post test1	8	6.13	0.042<0.05
Post test2	8	7.75	

Table 3. Paired t-test result of post-test 1 and post-test 2

Exam score	N	Mean	P-Value
Pre-test	8	5.50	0.005<0.05
Post test 2	8	7.75	

Table 4. Paired t-test results of pre-test and post-test 2

Table 1 shows all the learning outcomes in sequential order. The results indicate a gradual improvement on the average scores of the students, and show significant improvement after they played the game with an average difference of 0.63 points. The performance continues progressing with an average difference of 1.62 points. Paired t-test results in Table 2 shows that in comparison with the pre-test, statistically, there is no enhancement on the learning outcome right after they experienced the game. Interestingly, the p-value in table 3 and 4 indicates statistical improvements after they complete the follow-up instructional courses.

Results of Control Group

Control Group	Pre test	Post test 1	Post test 2
Mean	4.83	_	5.67
SD	1.72	_	2.76

Table 5. The average score of two paper exams

Exam score	N	Mean	P-Value
Pre-test	6	4.83	0.54>0.05
Post test 2	6	5.67	

Table 6. The paired t- test of pre-test and post-test 2

The result shows that the improvement of the average score with traditional learning structure is limited (0.84). Meanwhile, the p-value further indicates that average scores of the pre-test and post test 2 were not significantly different.

Comparing two groups

We also conducted a between-group study to layout the difference after they've experienced the different learning strategies.

Pre test	N	Mean	P-Value
Experimental Group	8	5.50	0.52>0.05
Control Group	6	4.83	

Table 7. One-way ANOVA of pre-tests

Post test 2	N	Mean	P-Value
Experimental Group	8	7.75	0.02<0.05
Control Group	6	5.67	

Table 8. One-way ANOVA of post-tests 2

Although we can observe a small difference (0.67) between the pre-test means of two groups, the p-value shows statistically, there's no difference. A greater variation could be observed with a difference of 2.08 points. The p-value of the two post tests results is seen as a strong indicator of the experimental group outperforming the control group.

Results from the questionnaires

Detailed results collected from the questionnaire are presented as follows:
1. Basic user information: Among all the eight test subjects, three of them are male and five of them are female. Two of them often play games and 3/8 students consider themselves good at playing games and five of them prefer puzzle games. Although we have a very small sample size, it is interesting to find that there's gender difference in the favorite game genre.
2. Engagement and usability: The answers imply a more neutralizing attitude. Although the game is not as appealing to the students as we expected, 7/8 students have confidence in complete the whole gameplay. Six of them believed that their ability enhanced through the gameplay. Additionally, all of them agreed that the game objectives are very clear.
3. Learning Effect
All of the eight students agreed that through the gameplay, they could comprehend the importance of 3D spatial ability in practical application. And six of them thought that they could learn 3D sectioning ability more efficiently with the game. Six of them could correlate the virtual sectioning diagrams and 3D models with their visualization ability.

Discussion

Study within the experimental group
The significant differences in the results confirm the positive effect of our learning design. The progress of learning outcome is incremental. Although superficially, the potential impact of the game is limited from the test result, students shared positive comments on the intriguing game experience compared to the traditional experiences. The immersive gameplay activated players' inherent nature to investigate new knowledge and to keep pursuing correct answers. The challenges and levels of difficulty in the game established the proper atmosphere to engage students continuously. Game score points and level reports displaying mistakes and instructions served as efficient feedback for the students to maintain their focus on the game objective. The role of different designs of 2D sectioning images is not only applicable to puzzles or traps in the game, but also an indirect instruction of product design. Students agreed that the transformation from 2D section views to 3D models deepened their knowledge of 3D visualization. The game is designed as a medium to activate the notion of key learning concepts in developing 3D visualization skills. More importantly, students also shared feedback that the interactive learning experiences in the game had contributed to a reflection of the relation between 2D sectioning view and 3D perspective view. As shown in the results, students had achieved a much higher score after they received the instructions from the tutor. Such significant improvement implies a positive effect of productive failure learning design. The follow-up instructions were perceived by students as a reinforcement strategy to consolidate and enhance their 3D spatial ability.

Though the students could not directly master the entire concepts through the game, the impact of the game on developing the interest of 3D visualization could leverage knowledge and skills in the instruction phase. The correct solutions given by the tutor after post-test 2 further helped to redefine and enrich students' comprehension of 3D spatial skills.

On the one hand, students displayed relatively positive attitudes to the educational quality of the game. Yet, students also criticized that the game experience was comparatively boring. Students suggested that the game design needs further improvement to make it more appealing. One issue with the game design is that the levels were exposed to players at once. The paradox is that such design allows more freedom of choice, but the game appeared to be less mysterious and challenging. Different solutions could be attempted to address this issue. We could either unlock the levels by increasing difficulty or group the levels by difficulty and make players choose the difficulty while starting the game. As the game is structured as a puzzle, the number of solutions is limited and the best/ correct answer can always be found through several trials. As there is little narrative content in the game, it is a potential area to explore to maximize the potential power of narrative to immerse students more in the game.

Contrast between experimental group and control group

We also compared performances between two groups. Since there is no significant difference in the pre-test, it is reasonable to conclude that students in both groups had the same level of knowledge before the experiment. Thus, the significant difference in post-test is strong evidence indicating that the *Manufactory* game is effective in learning key concepts in university classrooms.

The positive feedback from the final questionnaire also indicated that students' learning experience was augmented with the game.

Furthermore, despite the opinions from some participants that failure in the game is frustrating, the students still appreciated the challenges and were motivated to find the best solution. Ultimately, the result demonstrated that game technology has potential to provide problem-solving contexts in PF phase while enhancing user engagement. It suggests that the medium to deliver the questions in PF was no longer constrained to plain text, as it could be more dynamic or interactive like a game.

Due to the limitation of data collection from games, we cannot statistically correlate the game performance with the learning outcome. Meanwhile, it is arguable that whether success could be allowed in the problem-solving phase of productive failure. Theoretically, playing a game is often a continuous process of alternating failure and success; it is difficult to capture the exact moment when a player fails and to keep tracking the performance after the failure. The team was unable to collect such detailed level of data and provide more precise analysis based on objective figures from the failure perspective. The results are limited to subjective opinions from students.

Conclusion

The purpose of the study was to explore the potential of a unique learning design incorporating educational game to enhance students' mental faculties, including abstract 3D visualization and learning ability. The study is a compound learning design. To weigh the impacts of game and PF, further study is recommended to obtain more detailed data collection relating to game elements and failures in games. The

study also needs a bigger sample size, for better comparison and analysis. In addition, we can observe different behaviors between male and female students during gameplay. The answer from the usability questionnaire implies gender preference. Thus, a reliable survey on user gender or player type will be interesting. The game design can be further improved to make it more appealing by maximizing the narrative component of the game; increasing challenges and difficulty in levels and improving the aesthetics and UI design. For this study, game technology was nested within the productive failure learning phases. Further studies could consider investigating the possibility of including productive failure mechanisms in games.

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