Shining Light on Colors

Using a Puzzle Game to Teach Additive Color Theory

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Abstract. Game-based learning is rapidly transforming the educational landscape by providing engaging supplementary tools to students around the world. A problem area where game-based learning has not been empirically studied is the subject of additive color theory. Can a puzzle video game increase players' knowledge of additive color theory? This paper describes how a puzzle game can be designed in order to teach this topic. The puzzle game prototype *Temple of Starlight* was developed, and an evaluation of its effectiveness at teaching was performed. The evaluation was done online following a within-subjects study design, where the participants answered questions about additive color theory before, immediately after, and a week after playing through the game prototype. Two analyses were performed: first one comparing the amount of correct answers from before playing the game and right after playing; and the second one comparing answers from before playing and a week after playing. Results showed a significant increase in knowledge of additive color theory, both right after (N = 37, $p = <.001$) and a week after (N = 30, $p = <.001$) playing through the game prototype. This suggests that the game prototype could be used as valuable supplementary material for teaching additive color theory in learning environments.

1. Introduction

In recent years, digital games have increased in popularity, especially for teens and young adults [1]. Consequentially, there has been fast growth in the educational games industry as well [2; 3]. The idea of using games in an educational setting is not a novel concept, and it has long been acknowledged that games are excellent at increasing and retaining motivation – something traditional teaching approaches often lack [4]. Additionally, games add to the effort of transferring learning to a more sustainable digital structure, where updates or changes to the learning content can be implemented and distributed smoothly.

Among existing educational games, science is one of the more popular topics [5]. This may be explained by a growing need for more active instructional methods to be used particularly for science teaching [6]. Furthermore, game-based learning appears especially beneficial in this area, as games can create interactive virtual environments where students can freely get hands-on experience with the learning topics.

One science topic that could benefit from a more interactive and contextualized teaching method is the additive color property of light. This topic is also becoming increasingly important in today's highly digitalized world, where most things are presented and designed for light based displays, in the form of screens. A study by Martini et al. [7] shows that students often struggle with gaining intuitive understanding of this theory, and indicates that this struggle may stem from misconceptions or lack of knowledge about the differences between additive color theory and the subtractive color theory, as the latter is commonly taught early on in kindergarten art classes relating to the mixing of various pigments. Such a misconception may create a barrier for many and ultimately demotivating them when learning about lighting design or light related art. Expanding the understanding of additive color theory will therefore be the basis of this study, with an investigation of whether game-based learning can prove useful for mediating knowledge on this topic. This raises our research question:

To what extent can learners' knowledge of additive color theory be increased by a video game?

2. Background

2.1. Color Mixing

What humans recognize as various colors are different wavelengths of light from a part of the electromagnetic spectrum called the visible spectrum, which covers the interval of wavelengths that are perceivable to the human eye [8].

The visible spectrum stems from the types of photoreceptors in the eyes [9]. Our main color perception is based on one type of photoreceptors called cones, which come in three variations, each sensitive to a specific wavelength range. These three wavelength ranges define what we consider to be the primary colors of light: red, green, and blue.

When humans perceive non-primary colors, it is the brain interpreting the combinations of different cones' signals. This serves as the basis of additive color mixing [8], seen on the left side of Fig. 1. Additive color theory is mainly applied when working with digital screens, since these display color by emitting red, green and blue light in different combinations. It is otherwise useful in the art, design and digital industries as it teaches about color perception and formation.

The other type of color mixing concerns subtractive colors. Subtractive color theory is often taught in relation to mixing paints, and refers to how physical objects absorb and reflect different wavelengths of light [8].

From the model of subtractive color mixing (Fig. 1), the primary and secondary colors have been switched compared to the additive colors. This is because the subtractive color model focuses on which of the three primary light colors are being absorbed, and therefore not perceived. For example, if we perceive a box to be red, this means that its surface material is reflecting the red light that is hitting it back at our eyes, while any potential green and blue light is being absorbed. As such, if said red box were to be lit only by a cyan light, then we would perceive it

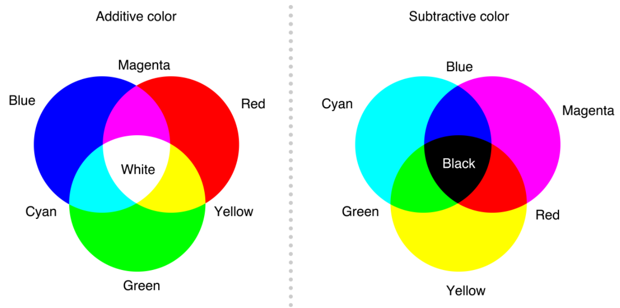

Figure 1. Model showcasing additive and subtractive color mixing [10].

as black, as no light would be reflected off of it [8].

2.2. Transformational Games

Transformational games are experiences that change the player by modifying behavior or improving a personal skill [11]. For a game to be effective at transforming players, the desired change has to both transfer and persist. For example, if the player becomes skilled at a game's mechanic that requires color mixing, it cannot be inferred that a successful transformation has taken place. Transfer requires the player to be able to apply color mixing outside the game's context. Moreover, persistence requires the player to be able to blend colors even some time after the game experience has ended.

2.3. Game-based Learning

The transformational framework suggests that educational games or learning games can be considered a part of the umbrella term "transformational" [11]. In related research, various terms have been used to describe the application of games or game elements in an educational context. While some terms may be used to describe a varying focus on the educational part compared to the game part, all terms are usually used to refer to learning in a game-like manner [12]. In this paper we will be using the terms "game-based learning" and "educational games" interchangeably to refer to games that are designed as learning tools.

It has long been accepted that the activity of play is important for a child's development [12], and the psychologist Vygotsky expressed the importance of play as a leading activity determining children's volitional, emotional and cognitive development [13]. Currently, the use of games in an educational context is a well-known and established concept [14]. The significance of play in early education has also been addressed [15], as well as the usefulness of games in primary education [16]. Nevertheless, educational games are seldom used as a learning tool in higher education, although there seems to be no evidence of any natural decrease in the desire for playing or the benefits hereof as we get older [12].

Game-based learning is rarely thought to be a substitute for traditional formal education but rather a supplement [12]. Educational games are often developed to teach only a limited set of learning goals. Nevertheless, there are multiple arguments for including game-based learning in an educational context, and it could prove useful in conjunction with other teaching methods or as a starting point for discussion [17]. There have already been a number of successful implementations of educational games and studies have indicated a promising use of games for learning purposes [18].

One important argument for game-based learning is its ability to motivate students due to their inherent entertainment factor [19; 12]. For example, games that are used for entertainment purposes are able to motivate players through rewards (points, trophies etc.), or interesting and enjoyable game mechanics and activities that would contribute towards high situational interest [20]. Similarly, enjoyment has been shown to be a large influential factor for learning effectiveness [21; 22; 23], as well as for motivation [24; 25]. This aligns with more general learning theory, stating that if a learning activity is enjoyable it will have a positive affect on performance and competences [26]. The motivational factor is also closely related to players' engagement, which can be facilitated in educational games, for instance, by interactions, visuals, narratives, mechanics or by having the game adapt to player's individual capabilities [12]. The capability of games to engage players is very useful, as engagement in an educational game can have a positive effect on learning [27].

Another benefit of game-based learning is that with digital games it is possible to have a safe environment, where players are allowed to make mistakes without having large negative consequences [12]. This also makes it possible to situate a student in a simulated position that would not be possible for them in reality. Investigations by Barab et al. showed that students who interacted with a game were much more motivated to participate in the classroom activities than those who learned in a traditional classroom [28].

2.4. State of the Art

Following one of the pillars from the transformational framework (section 2.2), this section will investigate prior works related to additive color theory and games.

Looking at games aimed specifically at teaching either or both additive and subtractive color theory, there are *True Colors* [29] and *Color Mixing* [30]. These games are structured very similarly; they both present a palette of available colors and specify a color that must be mixed. This same structure of teaching is offered by the *RGBox* [31], a physical device illustrating the mixing of additive colors using a line of LEDs.

All three examples serve their purpose of providing a space for potentially learning and/ or practicing how to mix different colors using either additive or subtractive color theory. However, it could be argued that the entertainment value they provide is low, as they do not offer much variation in gameplay or difficulty. This could be because development teams for educational games often lack resources to make the game engaging. As such, these games likely struggle to keep the players' attention for long enough to properly teach the theory they present [32].

3. Prototype Design

The transformational framework was used to establish different aspects of the transformational factor of the game in pre-production (see section 2.2).

We developed a prototype in the game engine Unity [33], which is a first-person puzzle game called *Temple of Starlight* that uses additive color mixing as the core of its light-focused mechanics.

The game has the player go through 19 levels, in which each level has a puzzle for them to solve in order to proceed to the next. These puzzles are constructed from two core mechanics based on colored light:

- Colored objects become visible and gain physical properties only when they are lit up by a color of light that would be reflected by the object. E.g. a magenta box would be visible under blue and/or red light, but not under green or no light (see Fig. 2).
- Power nodes can be activated by shining a combination of lights on them to match the node's color. E.g. a cyan power node will be activated when hit by both green and blue light simultaneously (see Fig. 3).

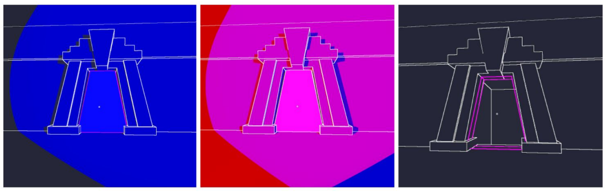

Figure 2. Screenshots of a magenta door under blue light (left), under a combination of red and blue light (center), and while unlit (right).

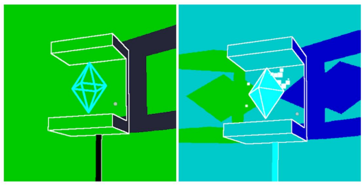

Figure 3. Screenshots of a cyan power node when it is inactive under green light (left) and when active under a combination of blue and green light (right).

3.1. Game Progression
All levels are designed so that the exit starts out blocked by a solid colored door (as seen in Fig. 2). The player then moves around in each level, activating and deactivating various lights, and changing their color in order to solve the puzzles, resulting in the door being unblocked.

While progressing through the levels, the player is gradually introduced to the different mechanics, providing a smooth learning curve. It is important to create an optimal experience, where the difficulty of the task (in this case, a level of the game) relates to the player's skill [34]. Optimal experiences increase the enjoyment when playing educational games, which in turn can positively affect learning [27].

3.2. Game Visuals
The game's visual style was designed around the core focus that the light and its colors should be clearly visible and stand out from the environment. As a result of this, the environment itself is kept in a single darker color. Since one of the game's core mechanics is based on making colored objects appear and disappear using the lights, the various ornamental objects in the levels were kept the same dark color as the environment itself to prevent the players from being confused about which objects were important for the puzzles. To ensure that the environment and objects were still identifiable, white wireframe-like outlines were added along all edges. All of this can be seen in Fig. 4.

Deliberate changes were also made to the visual appearance and physical behavior of the lights. The light modifications were done to ensure that the lit areas were clearly defined, and that the color mixing was kept to clean secondary colors and white only (as seen in Fig. 4). This means that if two red lights and one green light are all shining at the same area, the color will still be yellow instead of orange. This was mainly done to limit our domain concepts (section 2.2) to reach a more realistic scope.

4. Methods
After iterating on the game prototype for this study, it could then be used in an attempt to answer the research question:

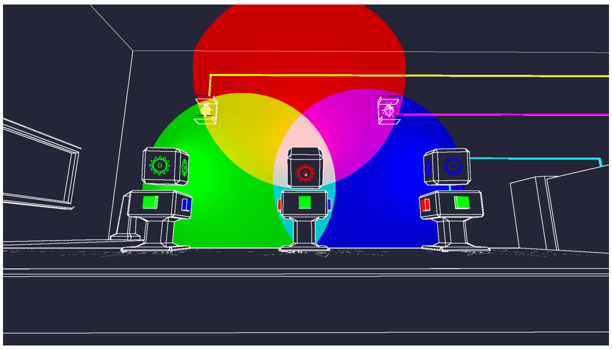

Figure 4. Screenshot showing off what color mixing looks like in the game.

To what extent can learners' knowledge of additive color theory be increased by a video game?

Following the transformational framework (section 2.2) we established the player transformation *"the player intuitively knows what color an object reflects based on what color it is and what light is shining,"* and we could conduct scientific experiments as part of our assessment plan. This also suggested the hypotheses:

H0: The puzzle video game prototype does not increase the players' knowledge of additive color theory.

H1: The puzzle video game prototype increases the players' knowledge of additive color theory.

To evaluate the player transformation, we did a repeated measures experimental design with the following experimental variables:

- **Independent variable** – time since completing the game.
- **Dependent variable** – level of knowledge of additive color theory.

4.1. Design of Experiment

Based on the variables, we defined three different conditions:

(i) Answered questions about additive color theory without (or before) playing through the game (later referred to as pre-gameplay).

(ii) Answered questions about additive color theory shortly after playing through the game (later referred to as post-gameplay).

(iii) Answered questions about additive color theory a week after playing through the game (later referred to as follow-up).

To better distinguish the change in additive color theory knowledge, the same participants should both play through the game and answer all of the questions. This suggests that ideally, a within-subjects study design should be followed, where each participant produces one result for each condition [35]. Within-subjects study design also allows to minimize confounding variables, as the baseline of knowledge of additive theory is captured when the participant fills out the questionnaire prior to playing the game. It can then be compared to the results of the questionnaire after the play-through.

In this study's case, the 'carry-over' effect [35] is minimized by ensuring that the participants do not get feedback on their questionnaire answers. We also avoid giving questions that could suggest answers or provide hints to upcoming questions.

4.2. Participants
Audience & context is one of the pillars in designing a transformational game (section 2.2), and it is essential in any experimental design. The most important aspect of the target group for the project was to distinguish colorblind participants (the prototype was not adapted for colorblind accessibility). These characteristics could impact the outcome of the study and serve as additional confounding variables; colorblindness could act as a barrier (section 2.2). This information, however, was gathered via some additional questions during the test procedure.

Participants for the test procedure were recruited online in several ways:

- Contacted personally, following convenience and snowball sampling methods.
- Invited to participate in the study via various websites and social media sites.
- Distributed to students through the help of teachers.

As part of the participant gathering effort, a chance to win different video games was advertised.

4.3. Measures
A questionnaire was prepared for the purpose of getting an understanding of the participant's level of knowledge about additive color theory. The questionnaire begins with demographic questions, asking about age, gender, nationality, and if they were colorblind. A follow-up questionnaire was required to evaluate if the game is able to fulfill the transfer and persistence aspects of transformational games (as discussed in section 2.2).

After the demographic questions, the core of the questionnaire consisted of nine questions of varying difficulty regarding additive color theory.

- All of the theory questions had the same eight answer options (Red, Green, Blue, Yellow, Magenta, Cyan, Black, White).
- Images were used to present the questions and make them more understandable without giving away the answers.
- The participants did not receive feedback as to whether their answers are correct or incorrect.

Three sets of the additive color theory questions were used that had the same amount of questions and the same structure and phrasing, but described different colors instead. For counterbalancing, each time a participant was doing a questionnaire, one of the three sets was randomly assigned.

4.4. Procedure
The whole procedure was performed online. The participants were directed to a website. There, all of the information and materials (questionnaire, consent form and a link to the video game prototype) were presented. If needed, the researchers could be contacted via provided e-mail address.

The starting page of the website provides information about the study, data handling, instructions regarding withdrawal from the study, and requirements to participate. The procedure then went as follows:

(i) The questionnaire was presented (described in section 4.3), where the participants first filled out demographic information and e-mail address.
(ii) Participants proceeded to the first additive color theory questionnaire set.
(iii) Game prototype link was provided. Participants were instructed to play through it and continue with the questionnaire once the game was finished.
(iv) The second additive color theory questionnaire was presented.

(v) Participants were presented with open-ended questions related to additional usability feedback (visuals, audio, and gameplay), their continuation desire, and issue reports.

If the participants agreed to answer the follow-up questionnaire, they were then contacted via their provided e-mail address after a week. The follow-up questionnaire only consisted of additive color theory questions. Those participants also received an opportunity to enter a video game key giveaway.

5. Results

Two separate data analyses were performed, since fewer participants responded to the follow-up questionnaire seven to nine days after their initial participation in the study.

5.1. Experiment 1

For Experiment 1, the first two conditions were compared (see section 4.1). The two conditions have the same number of participants, since they were completed one after the other. The responses to the questionnaires were treated as ordinal data. Each participant had a score from 0 to 9, based on whether they correctly answered each of the nine questions; a correct answer increased their score by 1, and an incorrect or partial answer did not increase the score at all. The study had a total of 43 participants. Some of the data had to be discarded, since several participants did not fully play through the game. Data from one colorblind participant was separated, and was not used in the results analysis. Among the 37 valid participants, there were 27 males and 10 females, aged 16-30 ($M = 22.78$, $SD = 3.19$). Participant nationalities were Lithuanian ($N = 11$), Danish ($N = 10$), Polish ($N = 9$), and 6 other. The average of the scores was found for each condition: The average pre-gameplay questionnaire score was 4.32 ($SD = 1.84$). The average post-gameplay questionnaire score was 5.73 ($SD = 1.56$). The one-tailed Wilcoxon signed-rank test indicated that the increase in questionnaire scores was statistically significant, $T = 452$, $p = <.001$, with a large effect size (CLES = .73).

5.2. Experiment 2

Experiment 2 was performed on a portion of the participants (out of the initial 37) which had successfully gone through all three of the conditions. Experiment 2 analysis was performed to compare the first and third condition. Valid data used for the results analysis was gathered from 30 participants (out of the 37 participants from Experiment 1). Among 30 valid participants, there were 21 males and 9 females, aged 16-30 ($M = 23.07$, $SD = 3.16$). Participant nationalities were Lithuanian ($N = 9$), Danish ($N = 9$), Polish ($N = 6$) and 6 other. The average of the scores was found for each condition: The average pre-gameplay questionnaire score was 4.57 ($SD = 1.77$). The average follow-up questionnaire score was 5.77 ($SD = 1.65$). One-tailed Wilcoxon signed-rank test for the longer-term effect indicated that there was a statistically significant increase of additive color theory questionnaire scores, $T = 33$, $p = <.001$, with a large effect size (CLES = .70).

6. Discussion

6.1. Findings

The results showed a statistically significant increase in the participants' measured knowledge. With this, the null hypothesis can be rejected. This greatly increases our confidence that the game could serve as supplementary educational material to teach individual about additive color theory. Having only a week between the gameplay and the follow-up questionnaire is a relatively shorter time in relation to educational topics. However, the results suggest that the game is capable of fulfilling the two main purposes outlined by the transformational framework (section 2.2); change to both transfer and persist.

6.2. Subtractive Color Theory

As shortly described in the Color Mixing section 2.1, people tend to confuse additive and subtractive color theory since they are usually taught to mix pigment at a younger age. Upon deeper inspection of the data, we noticed a tendency in pre-gameplay responses, as 12 participants answered that either **red, blue and yellow** or **cyan, magenta and yellow** are the primary colors, and 12 participants answered that mixing all the colors together would result in black. These two sets of 12 participants partially overlap.

One possible concern from teaching additive color theory through our game, is whether it is communicated clearly enough that this color mixing specifically applies to light. This concern stems from the notion that if it is not clear that light mixes differently than pigments, the game might cause players to merge their color mixing knowledge together; potentially causing more confusion later on.

6.3. Real-world Application

In order to be fully beneficial in an educational context, the game should be a supplement of lectures on this topic. By itself, the game lacks theoretical explanation of why the colors of light mix in such manner, and does not provide a theoretical explanation of the physical properties of light. As such, the game mainly serves to create an intuitive understanding of how additive colors mix, but needs to be played alongside additional teaching of the theory, in order to convey the full scope of knowledge needed for use in real-world applications. Although our solution is very limited in what it teaches, it can be used to break a barrier many may experience when learning about colors of light, which is a fundamental concept in lighting design and visual art.

Conclusion

Game-based learning has shown to be a promising supplement to traditional learning methods, and especially within the field of science, educational games may be beneficial for providing students with hands-on experimentation with the learning topics. This paper set out to investigate if game-based learning can be used as an effective learning approach for additive color theory – a topic of which students often appear to lack intuitive understanding. Transformational games and color mixing were researched in order to find a way of designing such an educational game. Based on the research, we developed a prototype of a first-person puzzle game.

An evaluation was conducted online on 37 participants. 30 of the participants also took part in a follow-up study a week after, where their knowledge of additive color theory was assessed once more. The results showed that a significant increase in the knowledge of additive color theory was found both immediately after playing the game and after a week had passed since playing it. The game was well-received by the majority of the participants, showing that such a game could potentially be used as supplementary material when teaching the topic of additive color theory.

Finally, we hope to inspire other game developers to make games that have some kind of transformational value. It is a general issue within the field that there is a lack of established methods to evaluate transformational games [36], and only by coming together and making a stronger community around it can we hope to achieve advancements and further knowledge in the field.

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