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# Can't see the Forest for the Trees: Perceiving Realism of Procedural Generated Trees in First-Person Games

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## Abstract

This paper explores a bio-mimetic approach for procedurally generated trees and forests, emphasizing the need to deliver a unique gameplay experience. For this study a tree growth simulator was developed, based on a set of growth factors, and an ecological model used for the placement of the trees. The contribution of the proposed scheme is two-fold. In a micro level analyzes the user's perceived realism of a single tree, and on a macro level the user's experience in the context of navigation performance in a forest. Results of a user study indicate that the perceived appearance of the trees was mainly affected by the player's previous experience and expectations. The player's ability to navigate in a forest was affected both by growth factors of the trees and the distribution model used to generate the forest. Moreover, the participants reported the that distinct visual cues enhanced their navigation and orientation in the forest.

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**Keywords:** Procedural Content Generation, procedural trees, cognitive maps, Navigation in Virtual Environments, Ecological Simulator, self localization

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## 1. Introduction

Delivering vast and realistic game environments have become a huge undertaking for game developers, with users expecting high graphical fidelity and interesting, diverse worlds. This means that CG artists have to produce a nearly impossible amount of original assets, to meet up players' expectations, and at the same time developers need to employ a more efficient production process [26]. Procedural Content Generation (PCG) is a design process that use algorithms, in a non-linear system, to produce a nearly endless number of unique and unrepeatable results. The designers only provide a higher level description of the goal, along with parameters and constraints and then the generative system returns a list of solutions.

PCG poses the advantage of ease of implementation by moving parts of the graphical work flow from 3D artist to programmers and technical artists [30], but with the drawback of the loss of control over the end result. This in turn might lower the graphical and behavioral fidelity and thus the perceived realism of the assets. Another aspect of PCG is the requirement of an evaluation mechanism, guaranteeing that the outcome is of a logical kind and that the game is playable [4].

Many games use PCG approaches in the form of tools which are capable of producing game assets that look different, but, eventually players will recognize a pattern that is reused over and over again [27]. PCG might give the game improved re-playability, because of the uniqueness of solutions that can be generated. Among game assets vegetation plays an important role in making a natural and realistic looking game environment [5]. Outdoor scenery, and thus vegetation, takes a large portion of the screen space in the shape of grass, flowers, bushes and trees [7].

While a skilled artist can craft a realistic model of a tree, this will only represent a single instance. However, because biological, ecological and physical rules govern the appearance of single trees and the distributions of trees, PCG may offer an alternate approach to generating virtual forests.

Therefore, this research aims to investigate two inter-related themes: First, this work focuses on players' perceived realism of single trees. Secondly, the work explores the effects on players' navigation performance

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through the forest. This is based on the hypothesis that within a natural looking landscape there are more distinct visual cues that can act as landmarks, enhancing the player's way-finding efficiency. For these experiments an ecosystem simulation was developed, capable of 'growing' trees based on biological factors and generating forests based on an ecological distribution model.

## 2. Background

The definition of realism, from the player's perspective, is still debated. A lot of research has been directed into the graphical fidelity and what impact it has on the player's perceived realism [24], while others are investigating how the level of interaction and behavioural fidelity impacts the player's gaming experience [9]. It is difficult to state that perceived realism coincides with realism fidelity, because the level of perceived realism of an interactive environment depends on the player's previous experiences [19]. For example, the visual appearance (graphical fidelity) and growth factors (behavioural fidelity) of a modeled plant could for most people be realistic, but for a botanist might represent an unrealistic case. Perceived realism is solely a subjective phenomenon, and as Doyle [2] argues, a believable character is not necessarily a real character, but must be real in the context of the environment that it inhabits.

### 2.1. Perceived Realism vs Fidelity

While perceived realism is a subjective evaluation, fidelity has been defined as the objective expression of the degree of realism offered by the virtual environment [14]. Game players, while encountering realistic and fantastic elements in games, suspend their disbelief in order to become one with the game world [23]. The players are making subconscious contracts with the game to play on its premise which may lead the player to accept fantasy elements as reality [23]. There is evidence that realism can affect players' immersion but not all games benefit from improved graphics or gameplay mechanics [29].

Since the perceived realism is inherently subjective then an increase in fidelity might not scale linearly because players have different experiences and expectations. This is important for video games because high fidelity might not contribute to the highest perceived realism. The "Uncanny Valley" (figure 1) is a well known phenomenon, occurring because of high fidelity and thus higher performance cost, but with the drawback of unnatural appearance.

**PCG: Advantages and Disadvantages.** The greatest strength of PCG vegetation is the almost unlimited amount of content that can be produced; thus it is well suited for huge virtual worlds or large numbers of various levels. Because no two maps are the same the player has to adapt to a new situation for each new game. Noghani et al. [15] argue that PCG, such as vegetation and buildings, can enhance the realistic appearance and 'believability' of a game environment. This conclusion was also supported by Korn et al. [8] whose findings suggest that players are perceiving the game as more realistic and aesthetically pleasing when using procedural generated graphical props.

PCG can also be used to adapt the game world. This can include the simulation of weather phenomena such as packed snow behavior when it is stepped by a character [32] or realistic and detailed procedural destruction of objects. This is where the true power of generative design lies: Adjusting the environment to influence the player's emotion and experience [13], [].

One of the biggest weaknesses of PCG is the loss of control over the final result [25]. Current modeling and animation tools provides the designers with absolute control over the final result and for a single object this is a fast process for an experienced CG artist/animator. It can be hard for a designer or artist to handover the artistic style of a game to algorithms, because they know with their skill and dedication, that they can create virtually any object exactly the way they want with every detail needed [25].

In order to deliver high quality content a PCG system needs to integrate all the skills of a CG artist or level designer. This means adding in constraints and variables that ensures the algorithm obeys the theories and rules of good CG/game design which might end up with an extremely complex PCG system. Moreover, one size never actually fits all situations; hence PCG is rarely as powerful as carefully handcrafted content. But there is another important aspect of games, one that is largely unacknowledged, the game as an art form. Art fundamentally differs from design principles in the

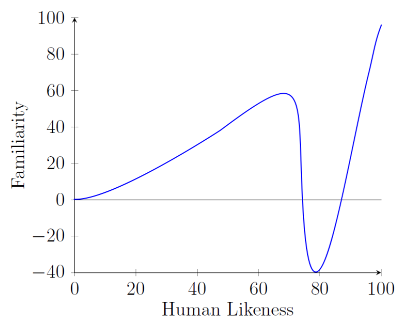


**Figure 1.** Uncanny Valley: When the human likeness of a character increases, so does the positive familiarity, until it reaches a point where the character looks like an unnatural human.

fact that it can bend, or even break, the rules of 'good design'.

## 2.2. Vegetation in Games

Current implementation approaches can be divided into image-based, geometric or hybrids of both approaches [5]. While many video games aims for photo-realism, some of the graphical fidelity depends on simplifications or approximations of equations instead of simulation-accurate models [6] because the most important criterion, for a player's experience, is the smoothness of the game playing. With a large amount of vegetation comes a large amount of polygons, and if the vegetation has to be interactive, this exponentially increases computational cost. Complex vegetation, such as bushes and trees, often use a hybrid of image-based billboards and geometric approaches, where the larger parts of the tree, like the trunk and branches, are represented as 3D models and the smaller branches and leaves are represented as billboards [5]. To improve performance, games make use of Level of Detail (LOD) systems, in which closer objects are rendered with more polygons than objects that are farther away, usually dictated by the game's system requirements. When used on complex geometry such as a tree, billboards might create perceptual artifacts because trees are not symmetric, and even with varying camera angles the tree always appears the same. This issue can be addressed with the use of impostors. These are collections of 2D representations for a set of pre-computed view-angles. By rendering out different billboards for different angles, the appearance of the tree becomes more natural [21].

However, recent research is focusing on the behavioural aspect of the vegetation [7], [18]. The behaviour of the vegetation can have a great impact on the player's perception of realism. In the case of vegetation, players expect that this would be affected by external forces such as wind and gravity [5]. Behavioral realism such as vegetation swaying in the wind is an important effect in outdoor scenes, because it makes the otherwise static scene look more alive [10]. In case of light vegetation, a player would expect this vegetation to move out of the way when colliding with it. The appearance and behaviour of the vegetation have to abide by the laws of physics; Gravity should influence the vegetation and the vegetation should interact with other objects in the same environment [18]. If every blade of grass is simulated at all time, then the game's performance will be negatively affected. That is why global effects like wind and local effects like collisions are being handled separately [3].

**Virtual Trees Adapting to Virtual Environments.** There are environmental factors that affect the growth of trees, such as water availability, soil quality, and climatic variation, but also the species ability to elongate its cells for each growing season, thereby growing in height. Trees are in constant competition with other vegetation for the limited resources in the ecosystem. The structure of the tree is optimized for photosynthesis and because the earth has many different climate zones many diverse tree species have evolved. Since trees are unable to move in search of resources, then they have to adapt to compete. Pirk et al. [18] proposed an approach of generating unique tree shapes in a 3D game environment through a simulation of a competition for resources, such as light. A tree's shape can also be changed by other factors like strong winds that can cause the tree to lean. A tree that has sustained damage will also try to right itself by changing it's growth direction upwards again or by growing it's crown out in one direction to balance out the stress in it's roots.

**Vegetation Distribution.** A wide range of techniques have been proposed for vegetation distribution. Noise algorithms have been used as an alternative to recursive functions, because they look more natural than white noise [8]. Onrust et al. [16] proposed a grid based ecological distribution that places different plant species according to geometrical variations of the terrain's relief.

## 2.3. Navigating in 3D Games

Humans form mental maps in order to determine the spatial character of a game environment [22]. These maps are compact topological representations of the environment [17] which contains many unique elements defined by Lynch [12] as a network of paths, edges, districts, nodes and landmarks. Game environments should provide the player with the necessary information for them to successfully reach the end destination. Vinson [28] has come up with a set of guidelines for placing visual cues in games in order to support players' navigation. If players are unfamiliar with an environment then they rely heavily on distinct visual cues from the surrounding environment [31]. Navigation might not be as easy in a forest as in a man-made environment, but many distinct visual cues are still present, such as glades or forest borders.

Thus, the appearance of a PCG forest might have a significant influence on the players ability to navigate. In the case of a forest consisting of similar trees in a completely random distribution, the player might not find any points of reference. If the distribution of the vegetation is based on ecological rules, then the game environment should form paths, forest borders and meadows, which can provide the player with essential landmarks. Moreover, the distinct appearance of individual trees might influence the player's ability to navigate. A tree with a unique shape could act as a natural local landmark.

**Figure 2.** Affected by wind. (left) not affected, (right) tree growth being influenced by the direction of the wind

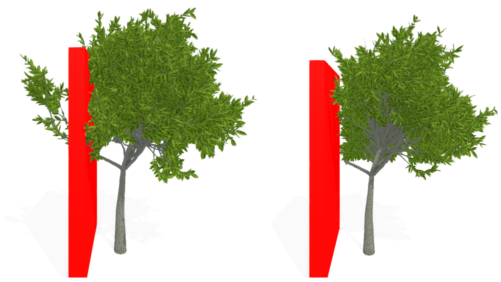

**Figure 3.** Check for Collision. (left) The tree is clipping into the obstacle, (right) the tree branches growth is being limited by the red wall

## 2.4. Simulating Growing Trees

The generation of the trees' shape was based on an L-system [11]. These systems have been used extensively to model the growth of organic systems such as plants and algae and can be used to generate both 2D and 3D artifacts. For this study a type of bracketed L-system was used to model realistic tree structures [27]. The main advantage of a bracketed L-system is that it can be modified, in real time, to adapt to a new set of environmental conditions. The trees are affected by the following set of limiting factors.

**Affected by Wind.** The wind affects the tree growth in two states. The trunk of the tree is not affected the same way as the individual branches because the trunk has more mass to bend. The branches are oriented in the direction of the wind which makes the crown bend over as seen in figure 2.

**Collision Detection.** To avoid that the tree's branches are growing through nearby objects a ray casting collision detection method was used to detect the presence of obstacles between the current branch segment and the next. If there is an obstacle then the branch tip will be capped off, as apparent from figure 3).

**Progressive Branching.** The progressive branching function controls the process of the growth of each individual branch and calculates the probability of generating a new branch. (figure 4).

**Figure 4.** Upward growth. (left) branches grow in random directions, (right) branches have a slight upward direction.

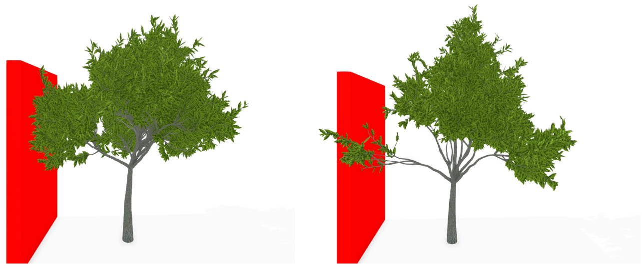

**Figure 5.** Check for shadow. (left) standard tree, (right) tree influenced from the shadow of the red wall. The tree has less branches and leaves.

**Check for Photosynthesis.** For this operation, a ray was cast from each leaf's and branch's position, following the opposite direction of the sun rays. In the absence of direct sunlight less branches and leafs were generated (figure 5).

## 2.5. The Leaves

Aiming at both graphical and behavioural realism, the wind effect was displacing each individual leaf. The leaves were represented through a point cloud where each point corresponded to the bud of each leaf. Based on the wind direction, a custom geometry shader was responsible for generating the leaves (figure 7).

## 2.6. Distribution of Trees

Two different distribution strategies have been implemented and considered in a comparative analysis. Each colored tile on the map (figure 6) represents a specific tree specie. Each tree specie has its own unique look and range. The spacing between trees was depended on a weight factor encoding the species' spatial needs:

(a) *Random Distribution:* A binary texture was generated, based on a 2D white noise function. The texture was smoothed out with a Gaussian kernel of size 5x5 to reduce noise sensitivity.

(a) *Ecological Distribution:* The smooth nature of Perlin noise is perfect for creating bio-inspired textures. Natural like textures consists of a set of scaled details, which can be achieved by combining 2D textures generated from different octaves of noise. Three octaves were used to synthesize a 2D Perlin noise texture.

The synthesized textures, from both approaches, were thresholded into five gray-scale ranges in order to generate bands of similar intensity. These bands were representing zones where individual tree species can exist.

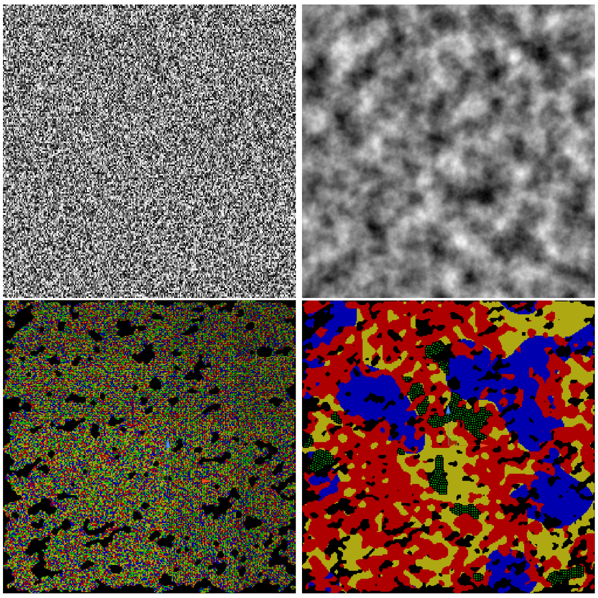

**Figure 6.** Distribution maps - (Left-Up) A random distribution based on white noise (Left-Down) Generated clustering patterns from white noise. (Right-Up) An ecological distribution based on Perlin noise (Right-Down) Generated clustering patterns from Perlin noise. Each one of the five colored bands represent an area where a tree specie can exist.

### 2.7. Level of Detail System

In order to improve performance a custom LOD system was built to reduce the amount of polygons on screen when objects were placed at longer distances. The LOD system selectively renders the largest branches at long distances and when the player moves closer to the trees more branches are being rendered (figure 8). The leaves use another custom LOD system where at long distances a single quad is used to represent a leaf while 3 quads are used when the player is up close (figure 8).

## 3. Methods and Materials

The primary aims of the study was to explore how the distribution and growth factors of virtual trees affect on perceived realism and navigation performance during exposure to a first-person game. Thus, the study relied on a within-subjects 2×2 factorial design, crossing two types of tree distribution (random distribution and ecological distribution) and two types of growth factors (with and without limiting factors).

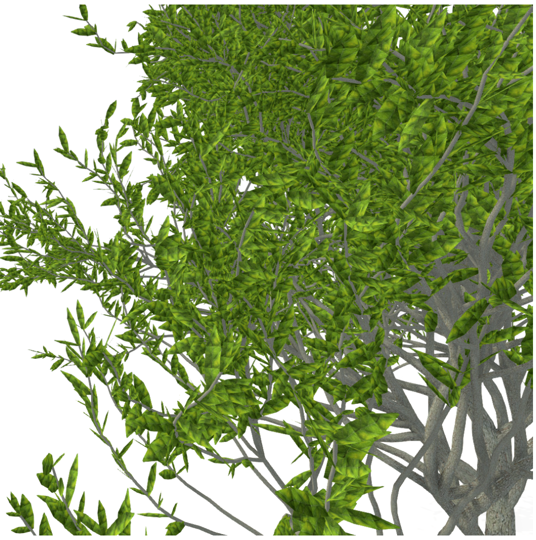

**Figure 7.** Close up of the leaves

### 3.1. Participants and Procedure

A total of 20 participants (16 males and 4 females), aged between 21 to 29 years (M=24.1, SD=2.4), took part in the study. The participants were recruited from the student body at anonymous university. All the participants reported having prior experience with playing video games and played between 0 to 19 hours a week (M =7.5, SD=6.1). When asked to indicate their level of experience with navigating forests on a 1-9 point scale, where 9 indicated a high level of experience, the answers ranged from 1-9 (M=5.1, SD=2.5). All participants gave written informed consent.

The presentation order of four conditions was counterbalanced based on Latin squares. After exposure to each condition the participants were asked to fill out a questionnaire pertaining to their experience of the virtual forest (see Section 3.4). Throughout the entire study all relevant comments made by the participants were noted.

### 3.2. Task and Environments

To increase the likelihood that the participants would focus on the visual appearance of the virtual forest, they were asked to perform a simple navigation task during each condition. Initially they were asked to follow a series of wooden signs forming a path through the virtual forest (figure 9). Once the participants reached the end destination, a camp site, they were returned to the starting position and asked to find their way to the camp site again by following the same path. However,

**Figure 8.** Level of detail system – The same tree shown with its three levels of detail. (top) with leaves, (bottom) without leaves.

this time the wooden signs were removed, and a time limit of two minutes was imposed. The time limit was introduced to ensure that participants that wandered off the path would not do so indefinitely.

## 3.3. Setup

All participants were exposed to the conditions using the same setup. That is, the application ran on a Windows 10 computer equipped with an Intel i7-7700k CPU, 32GB DDR4 RAM, and a GeForce GTX 1080ti graphics card. The visuals were displayed on a 32" QLED Curved Gaming Monitor CHG70 and the participants wore open circum-aural headphones (Steel series Siberia v2). The setting for brightness, contrast, volume and mouse sensitivity were identical for all participants.

## 3.4. Measures

Because the study sought to explore the effects of tree distribution and growth factors on perceived realism and navigation performance, the study relied on a combination of self-reported and performance measures.

**Self-reported measures:** The questionnaire administered after exposure to each condition included six items answered on 9-point Likert scales (see Table 1). Two items asked the participants to rate the perceived realism of the trees' appearance (a,b); two items related to the perceived realism of the tree's distribution (c,d); and the final two items related to how easily the participants found it to navigate the forest (e,f). The items pertaining to perceived realism were adapted from an existing questionnaire designed to evaluate video game realism [20].

**Table 1.** The six questionnaire items. Each item was answered using 9-point ranging from 1-9 (1 indicated strong disagreement and 9 indicated strong agreement).

| Questions | |
|---|---|
| 1. | The trees looked realistic |
| 2. | The trees' shape looked realistic |
| 3. | The trees' placement looked realistic |
| 4. | The forest looked realistic |
| 5. | It was easy to find my way in the forest |
| 6. | The trees were easy to use as landmarks |

**Figure 9.** Two game environments (T) Growing trees without limitations using the random distribution for the tree placement. (Down) Growing trees with limitations using the Perlin noise distribution, where it becomes apparent that more variation in growth behavior and tree distribution exists.

**Performance measures:** The participants' navigation performance was assessed by logging time stamped virtual positions during each condition. Based on this information the following measures were derived:

(a) *Completion time:* The time it took the player to get from the starting position to the target destination.

(b) *Time off path:* The time the player spent navigating off the path presented prior to starting the trial.

(c) *Distance travelled off path:* The total virtual distance travelled off the path during each trial.

(d) *Mean distance to path:* The mean distance to the path during each trial.

## 4. Results

This section details the results obtained from the self-reported measures of perceived realism, perceived performance, and the objective measures of navigation performance.

### 4.1. Self-reported measures:

The data obtained from the individual rating scales were treated as ordinal data and Friedman tests were run to determine if there were statistically significant differences in scores between conditions. Post hoc pairwise comparisons were performed using Dunn-Bonferroni tests. Figure 13 visualizes the corresponding results.

**Perceived realism of the trees' appearance:** The Friedman test found no significant difference between scores with respect to item (a) asking the participants to rate how realistic the trees looked, $X^2(3) = 2.727, p =$ .436 (Figure 13a)

Conversely, a significant difference was found in regard to item (b) asking the participants to rate how realistic the the trees' shape looked, $X^2(3) = 8.847, p =$

.031 (Figure 13b). However, the pairwise comparisons did not reveal any significant differences between conditions. Nevertheless it is worth noting that the two conditions involving limiting factors yielded the highest median scores: That is random and ecological distribution with limiting factors had median scores of 6.0 and 6.5, respectively, whereas random and ecological distribution without limiting factors had median scores of 4.5 and 4.0, respectively.

**Perceived realism of the trees' distribution:** No differences were found in terms of how realistic the different distributions of trees were perceived. That is, no significant differences were found with respect to item (c) asking how realist the placement of the trees was, $X^2(3) = 2.287, p = .515$ (Figure 13c), or item (d) asking how realistic the forest looked, $X^2(3) = 0.705, p = .872$ (Figure 13d).

**Perceived ease of navigating:** Turning to the two items related to perceived performance, a significant difference was found with respect to item (e) asking how easy the participants found it to navigate the forest, $X^2(3) = 10.571, p = .014$ (Figure 13e), and the pairwise comparisons revealed a significant difference between ecological distribution without limiting factors (Mdn = 3.5) and ecological distribution with limiting factors (Mdn = 7). While no other significant differences were found, it is worth noting that the medians scores for the two conditions with limiting factors scored the highest.

The results pertaining to question (f) asking whether the trees easily could be used as landmarks paints a similar picture. The Friedman test found a significant difference in scores, $X^2(3) = 9.000, p = .029$ (Figure 13f). While the pairwise comparisons yielded no significant differences the two conditions with limiting factors had higher median scores than the two conditions without limiting factors.

## 4.2. Navigation Performance:

The data obtained from the measures of navigation performance were treated as ratio data, two-way repeated measures analyses of variance (ANOVAs) were run to determine if the performance measures varied between conditions. Figure 14 visualizes the corresponding results. While the assumption of normality was violated in regard to all four measures, we proceeded to carry out the analysis as ANOVAs are fairly robust to normality violations. Moreover, we ran non-parametric tests (i.e., Friedman tests) showing that there were statistically significant differences between conditions in case of all four measures.

**Completion time:** The analysis revealed that there was no statistically significant two-way interaction between distribution and growth factors, $F(1, 19) = 0.583, p = 0.454$, and no significant main effect of tree distribution was found, $F(1, 19) = 1.359, p = 0.258$. However, a signficant effect of growth factor on completion time was identified, $F(1, 19) = 12.315, p = 0.002$. Post hoc tests using Bonferroni correction revealed that the participants completed the task faster when the growth factor involved limiting factors (M = 37.3, SD = 15.4) as opposed to no limiting factors (M = 59.9, SD = 30.9).

**Time off path:** Similarly, no significant two-way interaction was found between distribution and growth factors with respect to time off path, $F(1,19) = 0.122, p = 0.730$, and no main effect of tree distribution was found with respect to this measure $F(1, 19) = 0.328, p = 0.573$. However, a significant main effect growth factors was found, $F(1, 19) = 11.997, p = 0.003$. Post hoc tests using the Bonferroni correction indicated that participants performed the best when exposed to limiting factors (M = 20.0, SD = 12.7) compared to no limiting factors (M = 45.0, SD = 31.0).

**Distance travelled off path:** The same was the case with respect to distance travelled off path. No significant two-way interaction between distribution

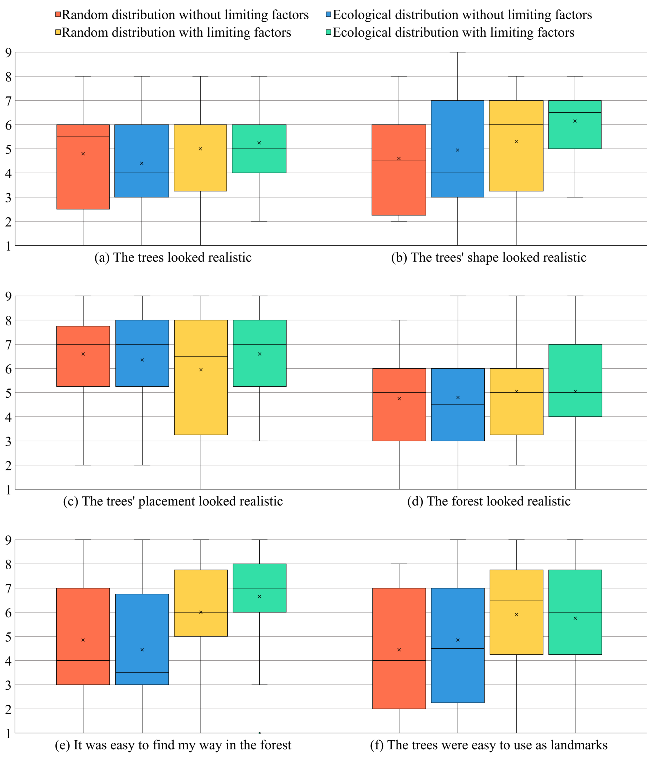


**Figure 10.** Box-plots visualizing the results of the six 9-point rating scales (1-9) in items in terms of medians (-), means (x),inter-quartile ranges, and minimum and maximum ratings.

and growth factors was found, $F(1, 19) = 0.347, p = 0.563$, and no significant main effect of distribution was identified, $F(1, 19) = 0.990, p = 0.332$. Again, the tests indicated that there was a significant main effect of growth factor, $F(1, 19) = 11.434, p = 0.003$, and post hoc tests using Bonferroni correction revealed that participants walked off the path for shorter distances when limiting factors were present (M = 148.981, SD = 68.607) compared to when they were no (M = 341.784, SD = 245.722).

**Mean distance to path:** Finally, the same pattern was apparent with respect to mean distance to path. No significant two-way interaction was found, $F(1, 19) = 0.137, p = 0.716$ and the main effect of distribution was not statistically significant, $F(1, 19) = 0.132, p = 0.720$. However, a significant main effect of growth factor was identified, $F(1, 19) = 16.888, p = 0.001$, and post hoc tests using Bonferroni correction revealed that participants on average walked closer to the path when limiting factor were presented (M = 12.176, SD = 3.985) compared to when they were not (M = 27.663, SD = 17.361)

**Path visualization** Figure 15 visualizes the paths paths chosen by the participants during the initial walk where they were guided by signs and during the navigation task for each of the four conditions. Optimal performance would result in the two paths being identical. These visualizations corroborate the findings of the four performance measures indicating that tree growth with limiting factors yielded the best performance. Moreover, it is worth noting that the participants performed poorly even during the initial walk when exposed to ecological distribution without limiting factors.

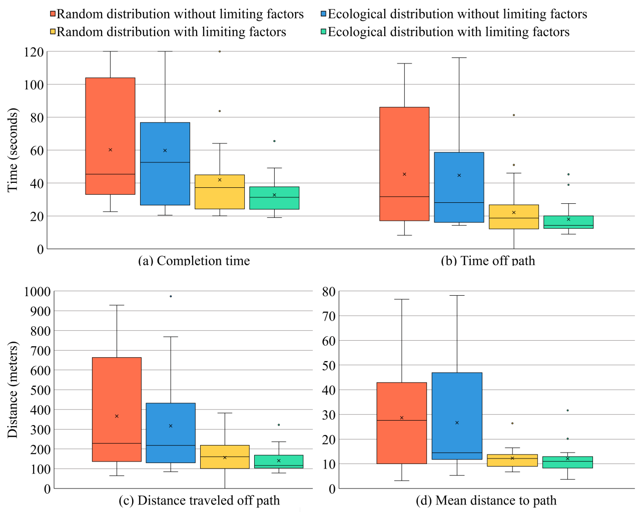


**Figure 11.** Box-plots showing the results of the performance measures in items in terms of medians (-), means (x), inter-quartile ranges, minimum and maximum ratings, and outliers.

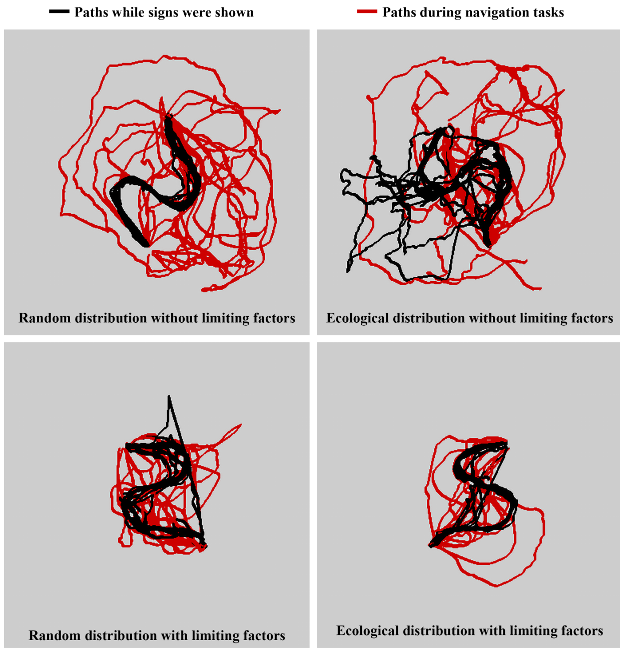


**Figure 12.** Visualization of the virtual paths taken by the participants during the initial walk where they were guided by signs (black lines) and during the navigation task (red lines) for each of the four conditions.

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## 5.2. Navigation Performance:

The data obtained from the measures of navigation performance were treated as ratio data, two-way repeated measures analyses of variance (ANOVAs) were run to determine if the performance measures varied between conditions. Figure 14 visualizes the corresponding results. While the assumption of normality was violated in regard to all four measures, we proceeded to carry out the analysis as ANOVAs are fairly robust to normality violations. Moreover, we ran non-parametric tests (i.e., Friedman tests) showing that there were statistically significant differences between conditions in case of all four measures.

**Completion time:** The analysis revealed that there was no statistically significant two-way interaction between distribution and growth factors, $F(1, 19) = 0.583, p = 0.454$, and no significant main effect of tree distribution was found, $F(1, 19) = 1.359, p = 0.258$. However, a signficant effect of growth factor on completion time was identified, $F(1, 19) = 12.315, p = 0.002$. Post hoc tests using Bonferroni correction revealed that the participants completed the task faster when the growth factor involved limiting factors (M = 37.3, SD = 15.4) as opposed to no limiting factors (M = 59.9, SD = 30.9).

**Time off path:** Similarly, no significant two-way interaction was found between distribution and growth factors with respect to time off path, $F(1, 19) = 0.122, p = 0.730$, and no main effect of tree distribution was found with respect to this measure $F(1, 19) = 0.328, p = 0.573$. However, a significant main effect growth factors was found, $F(1, 19) = 11.997, p = 0.003$. Post hoc tests using the Bonferroni correction indicated that participants performed the best when exposed to limiting factors (M = 20.0, SD = 12.7) compared to no limiting factors (M = 45.0, SD = 31.0).

**Distance travelled off path:** The same was the case with respect to distance travelled off path. No significant two-way interaction between distribution and growth factors was found, $F(1, 19) = 0.347, p =$

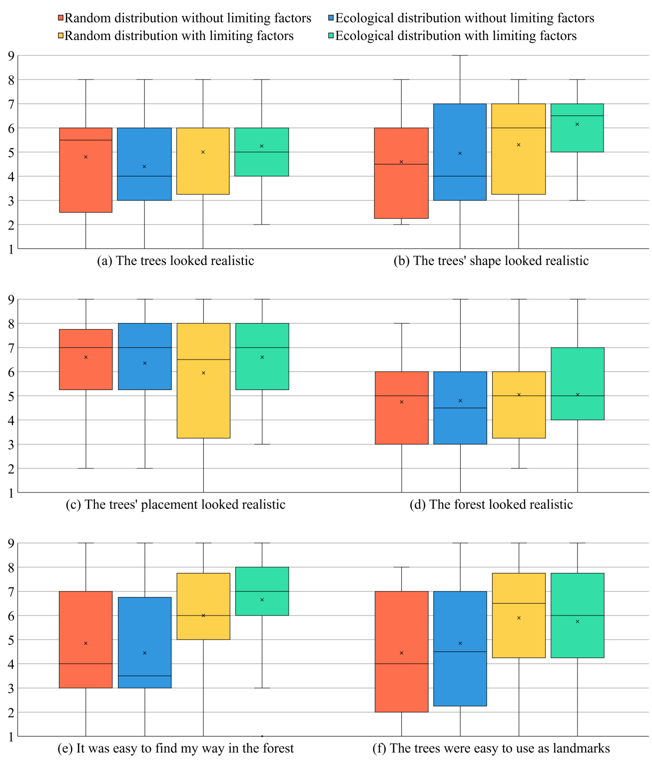


**Figure 13.** Box-plots visualizing the results of the six 9-point rating scales (1-9) in items in terms of medians (-), means (x),inter-quartile ranges, and minimum and maximum ratings.

0.563, and no significant main effect of distribution was identified, $F(1, 19) = 0.990, p = 0.332$. Again, the tests indicated that there was a significant main effect of growth factor, $F(1, 19) = 11.434, p = 0.003$, and post hoc tests using Bonferroni correction revealed that participants walked off the path for shorter distances when limiting factors were present (M = 148.981, SD = 68.607) compared to when they were no (M = 341.784, SD = 245.722).

**Mean distance to path:** Finally, the same pattern was apparent with respect to mean distance to path. No significant two-way interaction was found, $F(1, 19) = 0.137, p = 0.716$ and the main effect of distribution was not statistically significant, $F(1, 19) = 0.132, p = 0.720$. However, a significant main effect of growth factor was identified, $F(1, 19) = 16.888, p = 0.001$, and post hoc tests using Bonferroni correction revealed that participants on average walked closer to the path when limiting factor were presented (M = 12.176, SD = 3.985) compared to when they were not (M = 27.663, SD = 17.361)

**Path visualization** Figure 15 visualizes the paths paths chosen by the participants during the initial walk where they were guided by signs and during the navigation task for each of the four conditions. Optimal performance would result in the two paths being identical. These visualizations corroborate the findings of the four performance measures indicating that tree growth with limiting factors yielded the best performance. Moreover, it is worth noting that the participants performed poorly even during the initial walk when exposed to ecological distribution without limiting factors.

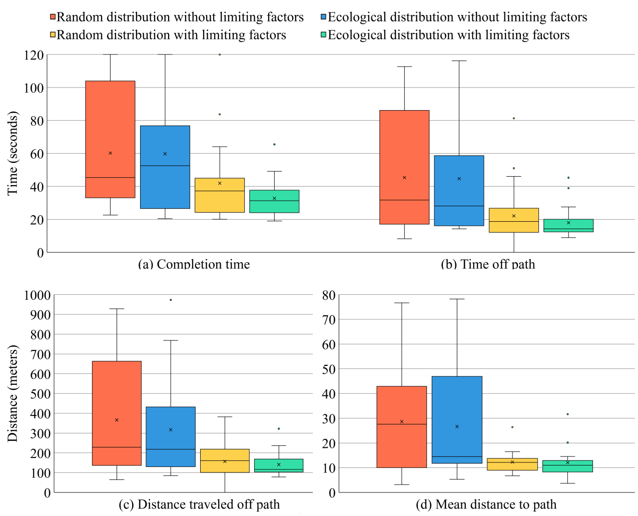


**Figure 14.** Box-plots showing the results of the performance measures in items in terms of medians (-), means (x), inter-quartile ranges, minimum and maximum ratings, and outliers.

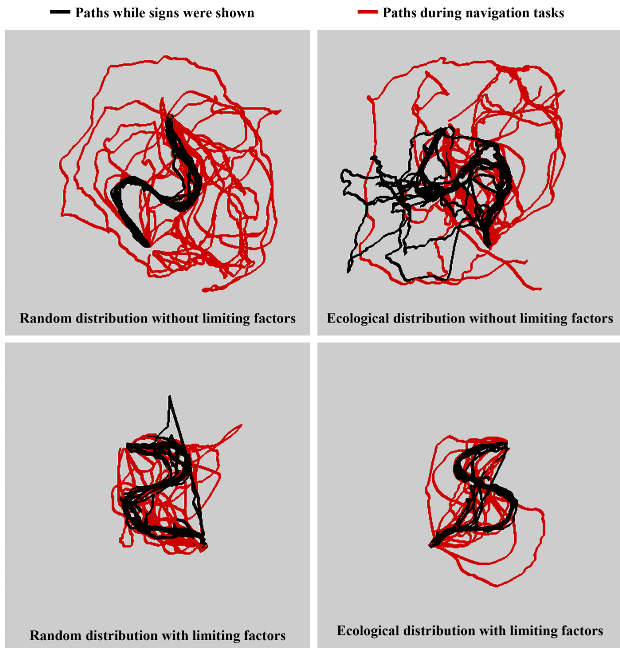


**Figure 15.** Visualization of the virtual paths taken by the participants during the initial walk where they were guided by signs (black lines) and during the navigation task (red lines) for each of the four conditions.

## 6. Conclusions

An advanced ecological simulator was presented capable to procedurally generate trees and forests for games. The simulator use a set of bio-inspired rules as growth factors, and an ecological model for the distribution of different tree species. In addition, the simulator has been evaluated in terms of user experience and performance in a user study. The evaluation was two-fold. At first, the simulator was examined into whether it can deliver realistic 3D trees. Results indicates that in this micro level the perceived appearance and behavioral fidelity of the trees is mainly affected by subjective factors such as the player's previous experiences and expectations. On a macro level, the user experience evaluated in the context of navigation performance through a forest. A total of 20 participants were tested in a way-finding task during exposure to a first-person game. The study relied on a 2x2 factorial design, crossing two types of distribution (random and ecological) and two types of growth factors (with and without limiting factors). The results indicate that the player's ability to navigate in a forest was affected both by growth factors of the trees and the distribution model used to generate the forest. Moreover, the users reported that the presence of distinct visual cues enhanced their navigation and orientation in the forest.

While PCG has the potential to deliver high quality content, when there is a dependence on cost and time factors, without adding in constraints and variable factors it is unsure if it can produce a satisfying tailor-played experience. An important factor for improving the applicability of PCG is to focus on the quality of the diversity instead of the quantity, and this requires a rigorous and designer-friendly environment.

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