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SPECIALIZATION - COMPUTER SCIENCE IN ENGLISH

DIPLOMA THESIS

Subconscious behavioral patterns and decision-making in three-dimensional virtual environments

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ABSTRACT

The decisions that individuals choose to take when navigating unfamiliar environments in daily life are biased, being inherently dependent on various characteristics of the surrounding context, whether the individuals in question consciously acknowledge this or not. In spite of this broad topic and the sizeable body of psychological academic articles addressing it, little research has been conducted regarding the degree to which these base preferences translate to virtual environments, such as those depicted in three-dimensional video games or interactive panorama applications like Google Street View. This paper attempts to study the aforementioned subject at a base level from the perspective of human-computer interaction by measuring potential biases in test subjects within a simulated environment. To this end, 15 students from the Faculty of Mathematics and Computer Science of our university were presented with three distinct virtual labyrinths, constructed in such a way as to highlight certain fundamental environmental features, namely color, texture and brightness. Basic features were depicted in order to extrapolate general behavioral patterns, as well as to ensure a degree of consistency between the subjects' understanding of the testing environment. The results of this research show that, even in a simulated, simplified rendition of an unfamiliar three-dimensional space, the choices made by individuals are influenced by subconscious biases. As such, these findings indicate the possibility of further examination of the topic bearing fruit. Moreover, deliberately leveraging these preferences when designing 3D applications could improve accessibility or otherwise favorably influence user behavior.

Contents

Chapter 1

Introduction

The core preoccupation of human-computer interaction (HCI) is the study and analysis of the relationship between users and systems, as well as the development of interfaces which facilitates the interplay between users and systems.[Car97] HCI is an interdisciplinary field, integrating concepts and theories originating from cognitive psychology, social studies, communication theory et alia with applied computer science. In spite of its relative recency when compared to other fields of computer science, its principles are leveraged in a variety of areas, such as user interface design, affective computing, game design, and software engineering. From Licklider (2021), the discussion of a symbiosis between the user and the system has developed out of psychological roots, drifting into discussion about the influences of technologies on human dependency, decision making, and evaluation.[Lic21] From these origins, the use of cognitive psychology persisted throughout the 1980s in what Bødker (2006) dubs the ”first wave” of HCI, [Bød06] characterized by cognitive science a la Rumelhart (1984)[Rum84]. The relevance of psychology to software design and computer science as a whole became apparent as automated systems became more widespread and accessible to consumers.[Dou01] From this point, HCI has developed from cognitive factors to ergonomic concerns and to human actors only to shift again into what Sod and Palen (2018) call the ”fourth wave” of HCI,[SP18] which is characterized by social justice and awareness movements, relationships, and broadening the definition of HCI into surrounding and influential fields.

Despite the great strides that have been made in HCI since its indistinct inception post-World War II, the fact remains that there are yet many unexplored — or sparsely studied — aspects of the ways in which users choose to interact with software. One such aspect concerns users' intuitive behaviors and innate tendencies when interfacing with applications depicting three-dimensional environments. While the matter of human navigation in real three-dimensional spaces is an amply explored topic in the field of psychology,[KMB+08] its virtual equivalent is largely neglected, likely due to the fact that such software is most frequently of a recreational nature and has a significant performance cost, making it less widespread in commercial contexts. On the occasions in which HCI has studies 3D virtual environments, it has been primarily from the perspective of control and input translation. For example, Zeleznik and Forsberg (1999)[ZF99] proposed an alternative mapping for camera controls in three-dimensional environments that only requires a single button on the input device (mouse or stylus), referred to as the UniCam. Another relevant mention are Ghosh et al. (2010),[GZC+10] who researched and implemented a fully markerless hand-detection system based on computer vision, making it orientation-agnostic. While these studies are very important to paving the way for further developments in accessibility and human-oriented software design, they do not analyze the matter of three-dimensional virtual environments from a behavioral, output-reactive point of view.

From the perspective of psychology, the subject at hand has been given much attention over several decades, with a variety of academic articles examining its different facets. These articles vary from those arguing the importance of environmental geometry in maintaining spatial orientation,[KMB+08] to those analyzing subjects' ability to determine the shortest route to an object in a non-euclidean virtual environment,[MG21] to those attempting to assess the effectiveness of virtual reality environments for spatial orientation testing[AH03] (although the assessment was not extended to conventional 3D software), among others. Given the breadth of research done on spatial navigation from the perspective of psychology, its scarcity from the perspective of human-computer interaction becomes much more pronounced.

This paper attempts to inspect this less-explored topic in computer science, observing possible subconscious biases in the route selection and pathway navigation of virtual environments. To this end, it utilizes and highlights relevant articles from the field of psychology to provide a structural basis for the experimentation and analysis, following traditions of early HCI. Afterwards, it provides a section detailing the testing methodology employed, the rules and constraints set to ensure consistent empirical data, and the environment facilitated for test subjects. Following this, it describes the structure, design and features of the software that was written for and used during the experiment. Additionally, the software design section also contains relevant application and use case diagrams. The study concludes with the results and analysis section, providing graphical representations for the data derived from testing.

The results are conclusive in illustrating that there are, in fact, collective underlying biases in user behavior when navigating three-dimensional virtual environments that manifest in a similar way as when navigating real environments, as far as the chosen test subjects exhibit. This is especially relevant when considering that the interaction between the testing environment and the subjects was facilitated by conventional input and output devices i.e., a computer mouse, keyboard and monitor, a detail which implies that the heightened level of abstraction did not prevent the subjects from interfacing with the space in a natural way.

Chapter 2

Previous Works

This section showcases and describes previous works, primarily taken from the body of knowledge belonging to psychology, with some articles also originating from user interface and game design, that are relevant to the subject of this paper, whether through testing methodology, experiment structure, concrete results or analytical method.

2.1 Game Design

In the realm of game development and design, there are numerous avenues by which game developers may interact with game design in a user behavior-aware way. Of these avenues, that of applications concerned with critical design[Dun08] — a research-centric practice meant to leverage software designs in order to make users more critical about the assumptions they make in their everyday lives — is especially relevant. Another such venue is found in the cyclical development process of tinkering and critical play, popularized by Flanagan (2013),[Fla13] which addresses the ways in which developers should engage with audiences and audience desires in order to continue development in a way conducive to providing rich experiences across gaming. Through these studies comes an appreciation and a study for how three-dimensional games and applications function as virtual environments in connection with psychological principles, although there are several other articles leveraging this relation.

One such work[AD12] states the importance of designing three-dimensional applications with coherent and suggestive virtual environments, in order to effectively communicate intent and direction to the user, ensuring that they interact with the program in ways intended by the designer. The onus is placed on manipulating the user's actions through the use of interactable, visually distinct objects and a space that is easily readable as well as open. Given the direction of this analysis, it should come as no surprise that it belongs to the practice of level design, a body of methods emphasizing the need for mindful environmental design in video games.

In the same vein, Feil and Scattergood (2005)[FS05] detail the significance of awareness in three-dimensional video game environment design in their book focusing on game level design. They argue for the importance of considering user feedback, either from reviews or tester input, as a building block to providing appealing and engaging experiences. In this sense, they recommend a social studies-oriented approach to environment design. Additionally, they leverage behavioral analysis in their provided examples as a tool to further improve level design and maximize user satisfaction, studying the results of playtesters in order to determine the most — and least — captivating sections of given environments.

2.2 User Interface Design

With regards to the field of user interface (UI) design, the onus lies on providing intuitive and natural experiences for users at the input level - ensuring that a piece of software's functionalities are easily understood and quickly accessed by the intended actors, for the intended use cases. As a natural consequence of this, a majority of its focus lies in the study of two-dimensional environments in applications. In spite of this, there are a number of works which consider the problem of categorizing and translating inputs to three-dimensional environments, providing a variety of solutions that are in line with psychological and behavioral methodology.

A notable work treating this subject comes from Bowman et al. (2001)[BKLP01] provide a comprehensive, if somewhat antiquated, synthesis of specifically 3D software interfacing, defining several aspects of 3DUI, from the peripheral devices used to facilitate input and output to the different classifications and taxonomy of three-dimensional virtual environments. The article strongly argues in favor of accessible design, drawing awareness to the difficulties that a user may experience when first navigating a 3D application. Due to this, it emphasizes that researchers need to continue performing evaluations of application usability, and that more comprehensive guidelines for the development of effective 3D interfaces will be critical for expediting this process. Moreover, it asserts that three-dimensional interaction research will become increasingly relevant in the future, a statement proven correct by the passage of time.

Another noteworthy study for the purposes of this paper comes from another 3D user interface design research effort led, once again, by Bowman et al. (2012),[BMR12] who address the matter of naturalism in 3D user interfaces. Naturalism, in this context, refers to interfacing devices' ability to provide very accurate input and output to and from a three-dimensional virtual environment. Interfacing devices with a relatively high level of naturalism include virtual reality head-mounted displays, remotes containing accelerometers and infrared motion-tracking dot projectors, among others. The methodology employed in this article is thorough and based on clear empirical analysis, and the conclusions are quite valuable for the current study. While it was found that a very high level of naturalism in design and interfacing provided a more immersive and engaging experience to a sizeable subset of subjects, it also proved an unpleasant experience for some of those completely unfamiliar with the technology. Additionally, all subjects exhibited lowered input precision and, if the level of naturalism was moderate as opposed to high, the benefits quickly became minimal for all users. By comparison, traditional interfacing devices, such as keyboards, mice and standard visual displays provided consistent results with good performance across all test subjects, even if the level of immersion was slightly reduced.

2.3 Psychology

The field of psychology, due to the nature of its subject of study, is unfathomably vast, carefully researching topics related to the human mind's behavioral tendencies and cognitive apparatus. A significant sub-section of it studies concern the broad matter of spatial cognition, the subject most relevant to our needs. A number of highlighted works are instrumental in detailing the internal structures and tendencies referred to in our paper's analyses, while other highlighted works showcase the usage of three-dimensional virtual environments through the interface of virtual reality as experimentation environments, further cementing the existing connection between 3D virtual environments in HCI and psychology.

A relevant study from Meilinger et al.(2016),[MSB16] which leveraged the potential of virtual environments in spatial navigation (albeit in virtual reality) explored the topic of the memorization process with regards to objects and how it manifested in a local versus global space. It found that the memorization of object states in local spaces was highly dependent on visual configuration i.e., layout structure and ordering schemes. By contrast, memorization in global spaces was much more dependent on distance traveled and the order that objects were found in during this phase of travel. As such, it was concluded that borders of visibility play a strong role in determining the mental updating of object locations. Namely, locations beyond the currently visible local space are less likely to be updated compared to locations within the same vista space. This study is noteworthy for its robust testing methodology centered around its virtual reality apparatus, which contributed to further contouring the methods utilized in the current work.

Additionally, we have a newer article from Muryy et al.(2021),[MG21] exploring the subconscious mechanisms individuals employ when selecting the shortest route to a target, facilitated once again through experimentation in virtual reality, this time using non-euclidean environments. The environments are contained in a single maze whose internal structure shifts through the use of rendering portals, created in the Unity 3D engine. The shifts are utilized to test the nature of observers' internal representations of 3D space — the related analysis extrapolates that the physically logical maze structure allowed subjects to best take advantage of shortest distance based navigation, while the non-euclidean structure caused them to "fall back" on memory based navigation, otherwise known as the prioritization of paths which have already been confirmed as successfully leading to the target object. Another example of thorough applied methodology that leverages virtual reality environments, it determined that successful navigation of a three-dimensional environment hinges on the mental representation of the scene.

As a more general psychological analysis on the emergent patterns of spatial cognition, Mallot and Basten (2009)[MB09] argue that an important detail to keep in mind when analyzing spatial behavioral patterns is that the cognitive apparatus of biological organisms is not a universal computer, but rather a collection of partially-isolated, interconnected adaptations to various, relevant problems to the organism's life. The framework for spatial cognition specified in the study starts from the nervous stimulus-response schemata and fundamental representations of the perception-action cycle. In order to represent topological navigation, graph-like structures are utilized, with nodes representing junctions or rest areas and edges representing paths or movement areas. This representation is especially notable for the purposes of the current study, as it provides a simple avenue for quantifying decision-making. The researchers also choose to represent an organism's interconnected spatial cognition systems using graph-like structures, a choice which has a degree of overlap with the previous two articles' perspectives on cognitive structure, although it is not quite as relevant to the current study. This article assesses, then, that the core tasks in spatial recognition are "place recognition" — the ability to recall previously encountered areas after being separated from them for an amount of time — and "homing" — the ability to return to the aforementioned areas after being separated from them for an amount of time.

The dichotomy of local and global spaces mentioned earlier is explored with greater amplitude in Meilinger et al. (2014),[MRB14] which asserts that local (vista) spaces are those physical locations that can be experienced and recognized from a single point of view, such as rooms, open squares, small valleys et alia, while global (environmental) spaces are those that must be navigated in order to be properly comprehended. It is worth noting that most research pertaining to spatial recognition before the year 2015 was focused on either local spaces or figural spaces, such as maps, pictures, plaintext information on computer screens et alia. This was due to the fact that, in order for a testing environment to be recognized as a valid representation of a global space, it had to not possess any global landmarks that would be visible from multiple locations (such as recognizable outdoor scenery), as well as be completely foreign to the test subjects, and provide consistent conditions for every test run. As such, before the advent of virtual reality as an experimentation assistance tool, there was no feasible way to represent global spaces in the context of a controlled laboratory experiment, outside of very well-funded, sprawling research compounds. It is for this reason that the dichotomy between local and global spaces is most clearly defined in this paper, as it was one of the earliest to leverage the full potential of virtual reality in psychological studies. In leveraging this, the research team chose to explore the impact that different angular alignments to the local and global reference frames would have on orientation performance.

Another psychology article[GWM08] attempts to shine light on how landmarks are categorized by humans by analyzing how test subjects are able to return to certain areas in these markers' absence. In doing so, it more clearly contours the spatial cognition concept of the landmark. In colloquial speech, the term "landmark" is generally used in reference to an object whose scale and visual characteristics makes it easily recognizable from a distance. As such, the problem of landmark recognition as a topic of psychology becomes a special case of the general object recognition problem. The testing methodology concerned the matter of visual "homing" in humans, the selfsame concept defined earlier, in a virtual reality environment devoid of any distinct objects and easily discernible visual features. The environment consisted of a circular room, whose floor and ceiling was of a dark, unobtrusive shade of grey, while the room's circular wall was covered in a homogeneous color gradient. Under these conditions, test subjects were asked to take note of their current position, after which they were teleported to another, random area of the virtual room and asked to return to their original positions. Subjects were consistently able to approach their previously identified positions when treating the movement and recognition as their primary task. Additionally, in order to more adequately determine the effect of the environment's geocentric lines — or the lines defining the edges where the wall meets the floor and the ceiling, respectively — on landmark definition, more sets of experiments were performed, with either a variability in the color gradient's contrast, and, therefore, detail, or a variability in the room's size. Both the act of decreasing the gradient's contrast and increasing the room's size had a negative effect on the subjects' precision, suggesting that geocentric lines are, in fact, used as landmarks when no other distinguishing features are available.

This suggests some commonality with the snapshot model of spatial recognition, where a simple mental image of a location is used to recognize it, rather than assigning it a conceptual value or mentally processing it further. The study postulates that humans have not pruned this apparatus, a claim that contrasts Siegel and White (1975),[SW75] who suggest that landmark knowledge should be entirely conscious. This was a widely accepted claim until the turn of the century, originating from naming experiments where verbal recall is used to identify landmarks out of "non-landmark" objects. In spite of this, it's exceedingly clear that structures with no such verbal association are also utilized for navigation tasks in a similar manner. Additionally, depth signatures were also considered in the study, wherein the environment is evaluated based on the depth in geometry. It's been shown that humans engaging in a secondary, cognitively distracting task besides their navigation tend to confuse diagonally opposing or symmetrical corners in a rectangular room, indicating their preference for geometric layout as an information source in this case.

Chrastil and Warren (2015)[CW15] prove, using a virtual "hedge maze" environment, that decision-making during environmental exploration has a significant role in assisting with learning its associated abstract graph structure. This result seems to be consistent with the exploration-specific learning hypothesis that making decisions helps to link paths and places together in graph knowledge, forming strong associations between learned locations and the possibility to more easily connect these locations together. By contrast, this process does not contribute to the acquisition of survey knowledge, or more precise metric knowledge of the environment. It is also possible that the role of decision making is enhanced by the presence of idiothetic information — self-motion cues — suggesting that the association of a choice with a specific motion, whether it be simple locomotion or gesticulation, can assist in learning.

The final notable work for the synthesis of this paper comes from Valdez et al. (1994),[VM94] who effectively taxonomized and categorized emotional responses to different hues of color using robust methodology, while also remaining aware of the limitations imposed by the topic of study, and the ways in which it was improperly handled in the past in order to better facilitate reliable and accurate results. They tackled color as an environmental stimulant from the perspective of saturation, as well as hue. In order to quantify emotional responses effectively, they utilized the pleasure-arousal-dominance emotion model, which was the most comprehensive and consistent at the time. Due to the article, amplitude, not all of its results and conclusions are relevant to the current paper. However, it was a pivotal work in the psychology of color, and some of its results are, in fact, used by us. At the same time, the procedures they employed to achieve their results and the scale of experimentation was truly staggering at the time, and is still impressive today.

2.4 Reflection on Aggregated Theory

In this section, we have considered eleven of the most relevant articles to the topic of our paper, as well as highlighted and synthesized the information most useful to the study. Given these precedents from several related fields, it can be stated with a good degree of confidence that the structure, methodology and data provided in the current study follow established disciplinary convention and contribute to the existing body of work belonging to human-computer interaction.

Chapter 3

Testing Methodology

3.1 Participants

Fifteen students of Babeș-Bolyai University's Faculty of Mathematics and Computer Science participated in the experiment. Before they were selected for the experiment, it was verbally confirmed that all of them were familiar with the control scheme utilized for interfacing with the application. Of the participants, nine of them were male and six of them were female, with ages ranging from 20 to 22. Subjects all presented either normal or corrected eyesight — those with corrected eyesight wore their glasses during the experiment — and fully functional motor skills, faculty confirmed by asking that they snap their fingers with both hands. Additionally, the subjects were allowed to briefly familiarize themselves with the interfacing devices (mouse, keyboard, display) before the test by using them on the system's desktop menu until they felt comfortable.

3.2 Instructions

The participants were not informed of the experiment's purpose ahead of time, such as to not influence the testing results. However, they were given a set of clear instructions to abide by and guidelines to keep in mind. They were instructed to not leave the testing area for the duration of the test, as that would invalidate their results and remove them from the experiment. Additionally, they had to ensure they would not be at risk of external distraction through devices such as smartphones or smartwatches, and that they could be in a relaxed, neutral state for the test's duration. These instructions were chosen to guarantee the subjects made decisions in a calm and attentive manner. As for relevant guidelines, they were only told that they would be navigating three labyrinths with no given entrance or exit, and that they could explore at their own leisure, for a duration of sixty seconds per maze.

3.3 External Environmental Configuration

The different trials of the experiment took place, intermittently, in vacant classrooms on the third floor of the Faculty of Economics and Business Administration's building. Empty classrooms were chosen specifically to reduce noise pollution and keep distractions to a minimum. In terms of hardware, the tests were conducted on a Lenovo laptop with a 17" TN panel LED display and a refresh rate of 120Hz, equipped with a GTX 1650 Ti graphics card. This configuration proved more than sufficient for the test's graphical rendering needs.

The three-dimensional virtual environment was designed and implemented in the Unity 3D engine. The field of view of the application's first person camera, through which participants interpreted visual data, was 90 degrees and the visuals were rendered at 120 frames per second. The frame rate output was consistent and coincided with the display's refresh rate, leading to a smooth and responsive visual experience for the subjects. The test was run in full-screen mode and any extraneous background applications running on the system were terminated before starting. Participants utilized the WASD keys on the keyboard to control the movement in three-dimensional space (W - move forward, A - strafe left, S - move backward, D - strafe right) and the mouse to control the movement of the camera. The control scheme was comfortable for all subjects, bearing close resemblance to those typical of first-person video games. As such, the subjects were allowed sufficient freedom to explore the testing environment.

3.4 Virtual Environment and Stimuli

Three different layouts were designed and implemented for this experiment, correlating to the different fundamental environmental features that we sought to evaluate the impact of — color, texture and brightness. The labyrinths did not possess any entry or exit points, nor were they designed in such a way as to imply the existence of any, as the testing environments are meant to be freely explored and self-contained. Similarly, while the external dimensions of the labyrinths remained consistent over the three tests (having identical heights, widths and depths), their internal structure varied arbitrarily, such as to not have participants recognize paths from previous maze tests and rely on their memory in decision-making. Additionally, the black floor and white ceiling textures were identical and solid between the three courses, while the lighting was a simple, top-down global spotlight. These design choices ensured that the most prominent trait, as well as the only variable of each labyrinth was the trait whose impact was being evaluated. The sixty second time limit was also imposed for consistency.

Each maze showcased contrasting implementations of their respective visual feature. For the first test,3.1 which considered how color might subconsciously impact participants' decision-making process, four different colors were chosen: red, green, blue and magenta. These colors were selected for the simplicity and contrast of their hues, as well as for the widespread psychological connotations[VM94] that they carry: red is typically associated with danger and innately causes anxiety, green is usually associated with safety and reassurance, blue is generally associated with calm and tranquility, and magenta is, while not a color encountered naturally, still an innate source of anxiety. The second test3.1 considered how textures could impact subconscious decision-making, making use of three distinct tiled textures: circles, triangles and squares. These geometric shapes were chosen for their simple unique visual identities, being unmistakable from a distance. Bar et al. (2006)[BN06] manage to synthesize intuitive knowledge of shape-emotion relations using empirical data and confirm the hypothesis that curvatures lead to positive emotions and that jagged contours usually trigger a negative bias. For the final test,3.1 differences in brightness were chosen as the variable — four different levels of monochrome glow were selected in order to discriminate between the routes, in a similar fashion to the previous tests. Here, Wilms et al. (2018)[WO18] analyze emotional responses to color, accounting for hue as well as for brightness. From their findings, it can be extrapolated that brighter monochrome glows should incite greater valence, or positive emotion in subjects.

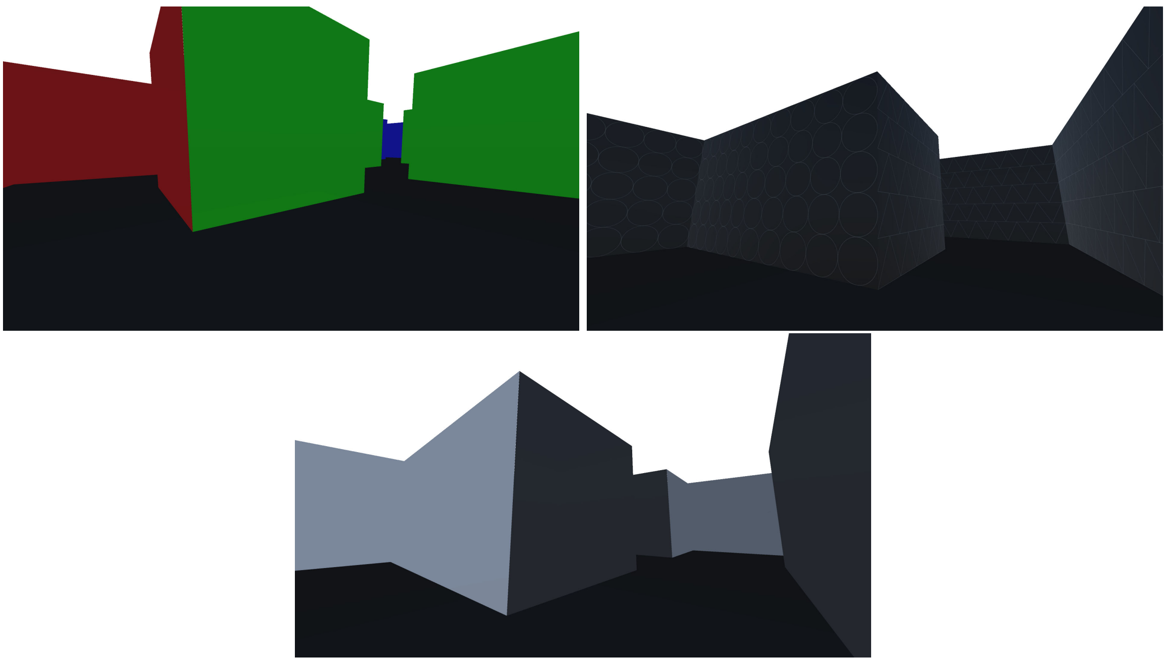

Figure 3.1: The mazes emphasizing the features of color, texture and brightness.

Chapter 4

Application

4.1 Design

The testing application was designed following the principles of the event-driven software architecture pattern. ”Events” in the context of this pattern consist of changes in the state of the application. An event-driven application generally contains event emitters, event consumers and event channels. Emitters are used solely in order to detect, aggregate and broadcast events. As such, emitters do not carry innate knowledge of the state of event consumers — whether they exist, are reachable, or any have consumed its emitted event. However, consumers have the responsibility of reacting as soon as an event reaches them, in which case they do broadcast their existence, through the state-change they initiated. It is worth noting that the event-driven architecture bears a strong resemblance to the message-driven architecture. This was considered the ideal architecture pattern to follow for implementation, given this application's specific usage and unique structural requirements. This choice was further simplified by the fact that it loosely resembles a video game, which is an archetype of consumer software that also utilizes the event-driven architecture pattern, for the most part.

The main points of interaction through which the user can trigger events are the Player and Camera objects, both controllable entities, analogous to our ”emitters”. The Player entity helps facilitate the ”movement” event through the environment, bound by the collision boxes assigned to the Wall and Floor entities, which play the role of ”consumers” and, in turn, present the reaction of preventing the Player entity from falling through them, allowing it to continue moving. At the same time, the Camera entity helps facilitate interaction through natural, first-person perspective visual exploration of the environment. In this case, the emitted event would be the user's request to look around the virtual environment, and the consumers would be the floor and walls' shaders, reacting by rendering their related objects.4.1.

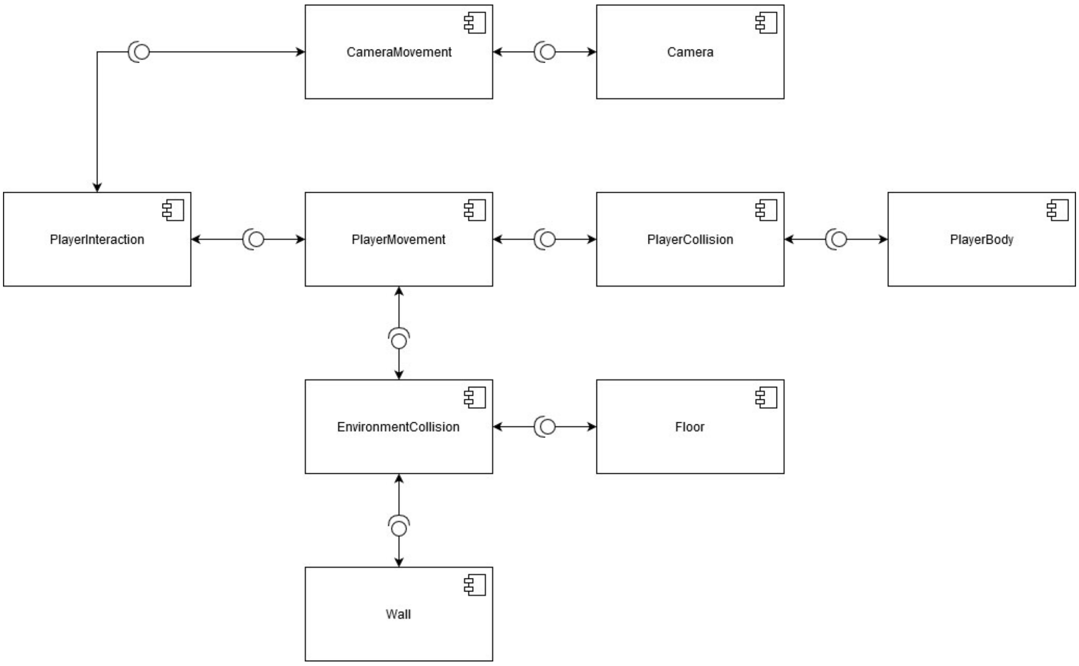

Figure 4.1: Component diagram emphasizing the relations between the different interactable entities.

4.2 Program Structure

The structure of the application adheres to the event-driven paradigm characteristic of user reactive-type programs, being constructed over several "scenes" — a term specific to the Unity 3D engine, which refers to isolated environments, usually shown to the user sequentially. The order in which they are shown is determined at application compile time, defined either programmatically or manually by the developer. The degree to which Unity scenes are isolated from one another is not dissimilar to the degree to which distinct objects maintain identity in conventional object-oriented programming. Scenes act as containers, encompassing entities, objects and semantic associations, such as scripts, that are relevant to that specific environment. While it is possible to pass variables and objects between scenes, it is usually not necessary.

The application consists of seven such scenes, where four of them are simple, two-dimensional user interface containers to inform the subject of the coming trial, while three of them are the mazes themselves, with all of the implementation elements necessary to facilitate testing. As such, the maze scenes are equally interspersed with the UI scenes, providing a linear flow from the start to the end of execution.

4.3 Implementation

The application was implemented in the Unity 3D engine, which allows for a large degree of modularity and flexibility in the development process, due to its accessible interface and robust built-in systems. These systems provide an accessible way to define complex mechanisms such as object physics and scene rendering. Meanwhile, the interface facilitates the easy modification of existing testing environments and their elements, or the addition of new ones. The player object's physical characteristics are abstracted in three-dimensional space through the use of a capsule-shaped mesh and associated Rigidbody component — used to signal that an object should be taken into consideration by the built-in physics engine — with attached scripts to provide interactibility to the user, namely spatial and camera movement. Meanwhile, the environment-related objects (floor, walls, ceiling) are cuboid three-dimensional objects with simple, static collision4.2.

At the same time, the overarching structure and flow of the program is defined by scripts attached to scene-exit entities, namely the UI elements and labyrinth timers. To expand on Unity's scripts, they are miniature packages written in C# which are essential for interactibility, functioning by hooking into a given scene at runtime, monitoring the input (if applicable) or scene variables, and using them to determine state changes — otherwise known as events. Many of the scripts utilized in the testing application take advantage of Unity's frame-checking framework, which permits them to listen for value changes on every frame that is output to the user.

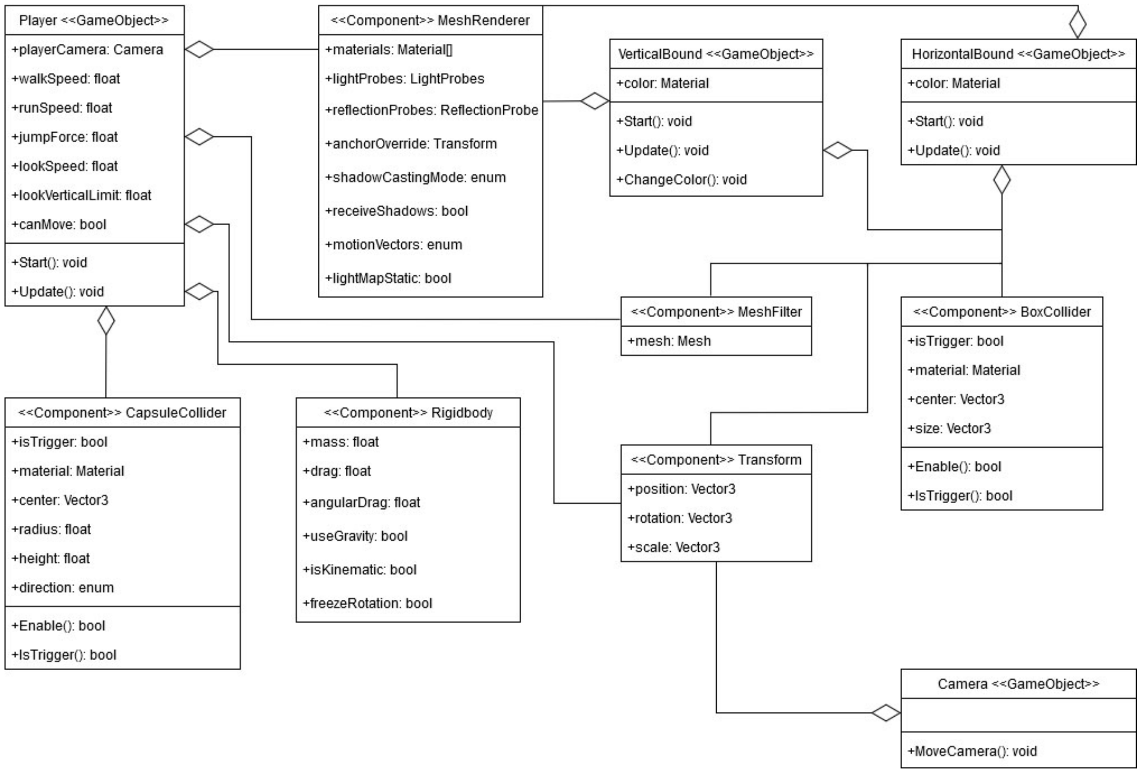

Figure 4.2: Class diagram illustrating the construction of various application objects.

4.4 Use Cases

The application is meant to be primarily used by two types of actors. The first type is the test subject, around whom a large part of the application's structure, features and general flow was designed. The test subject will enter the main menu of the application, and click the start button in order to begin the experiment proper. The color labyrinth test will last sixty seconds, in which they will be able to move and look around freely. After the duration of the first test has expired, the scene will change to a UI, which briefly informs the subject of the next labyrinth's primary feature. They can choose to continue to the next test at any point by clicking the related button. This pattern continues for the rest of the tests, with the final UI thanking the subject for their participation and providing them with a "quit" button.

The second actor is the researcher, who will mainly interact with the application through the data it stores on the machine, once the test is completed and application execution has ended. Under these circumstances, the application will have saved the movement data of the aforementioned participant, represented as periodically recorded location coordinate strings, under three different text files — one for each type of labyrinth4.3.

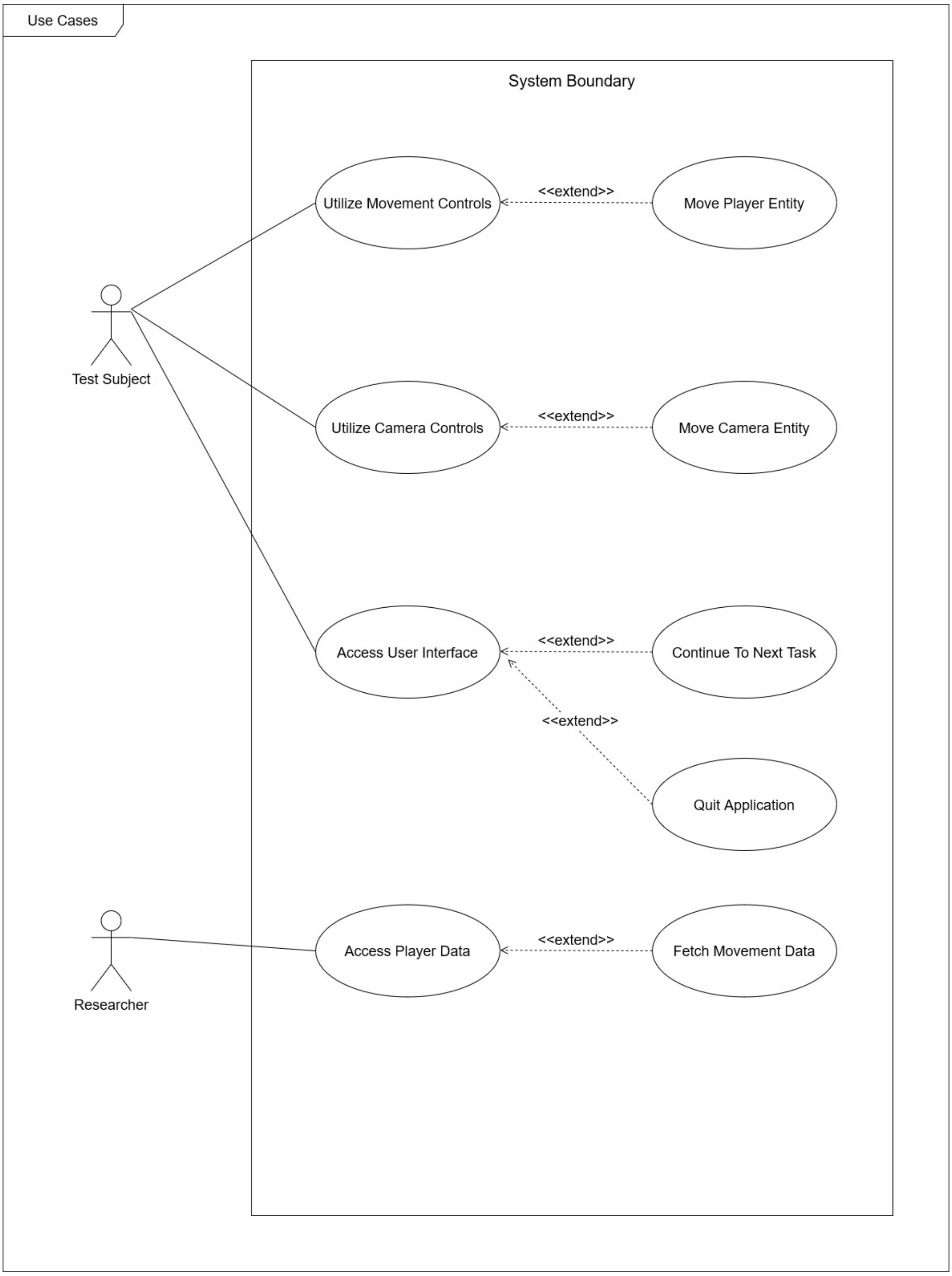

Figure 4.3: Use case diagram showing the primary types of actors and the extent of interactibility that the application provides for each.

Chapter 5

Results

5.1 Data Acquisition

After concluding the testing phase with every selected subject, the raw movement data was extracted from the application and anonymized, such as to provide a general conclusion on emergent behavioral patterns, without dividing by demographic subgroups. This data consisted of three .txt files per user, each containing the user's X and Y coordinates in the reference frame of each respective labyrinth, updated every 500 milliseconds. As such, every user has 120 lines of positional readings for a given maze, or two per second for a duration of sixty seconds. Per total, this resulted in 360 lines of coordinate pairs per test subject. Once the data was verified as valid (no missing, corrupt or incorrectly written files), it was ready to be used in modeling and analysis.

5.2 Modeling

As the study permitted test subjects to move freely around the testing environments, it can be somewhat challenging to extract and compile their data in constructive ways. In order to successfully resolve this issue, we chose to adopt a graph-like approach to defining the labyrinths' topological features, wherein any given corridor represents an "edge" or "path", while any intersection of two corridors with different characteristics represents a "node" or "junction". Whenever a test subject approaches a junction and decides to explore a previously undiscovered path, the path's unique characteristic will receive a "score" equal to the number of unexplored paths at that junction minus one. This ensures that, if there are several unknown paths at a node and a participant returns to visit all of them, their value will be quantified based on their priority. To illustrate this rule with a hypothetical example — a subject approaches a junction that branches into a red path, a green path and a blue path, all undiscovered to them. They revisit this intersection multiple times, in order to explore all of the paths, and do so in the order: green, red, blue. Given the imposed scoring condition, green's favorability would increment by two points, red's by one, and blue's by none. The reasoning behind the subtraction by one from the count of available paths is that, when devoid of any other unexplored possibilities, the last remaining path ceases to be a truly "free" choice.

For the sake of accuracy and visual clarity, we have decided to plot the raw movement data of each subject using Python's matplotlib and numpy libraries. These plots are then individually overlaid onto a proportionally accurate top-down depiction of each labyrinth, which is used to evaluate each subject's preferences, following the scoring rule highlighted in the previous paragraph.5.15.25.3 It is worth noting that, in the labyrinths' depictions, the symbol "X" represents an inaccessible area (not belonging to any path), while the symbol "J" represents a junction.

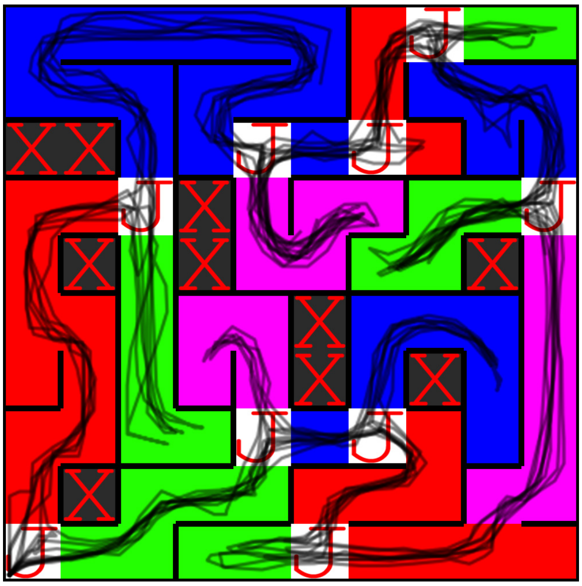

Figure 5.1: Color maze depiction, with the 15 subjects' plotted paths overlaid.

Red	Green	Blue	Magenta
19	33	20	13

Table 5.1: Total favorability score for each color attribute.

Figure 5.2: Texture maze depiction, with the 15 subjects' plotted paths overlaid.

Circle	Triangle	Square
37	18	14

Table 5.2: Total favorability score for each texture attribute.

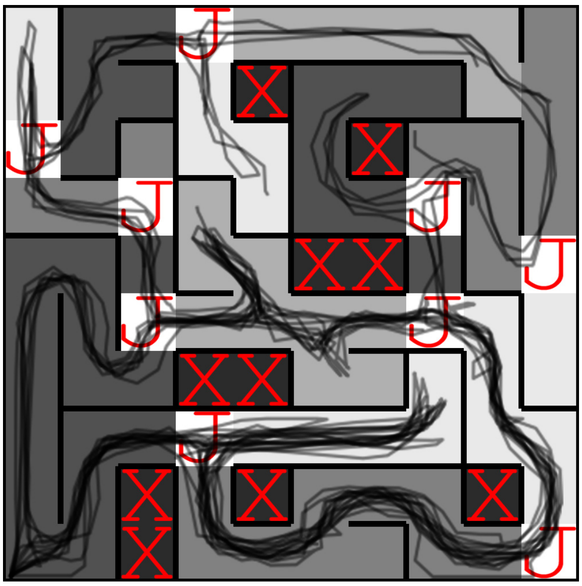

Figure 5.3: Brightness maze depiction, with the 15 subjects' plotted paths overlaid.

Bright	Dim	Dimmer	Dark
24	15	11	12

Table 5.3: Total favorability score for each brightness attribute.

5.3 Analysis

The analysis of the results carries on from the completion of the data modeling step, and seeks to highlight emergent patterns in the modeled data, which can be used to outline and characterize the subjects' behavior in the provided testing environments. In the case of this study, the modeled data consists of the "favorability score" of each trait in a labyrinth, for each participant. Due to the inherently isolated nature of the three provided testing environments, we will be analyzing findings pertaining to them in different subsections.

5.3.1 Color Labyrinth Analysis

From the perspective of color as an influencing factor to the decision-making process, the quantitative results show several degrees of bias between the available traits.

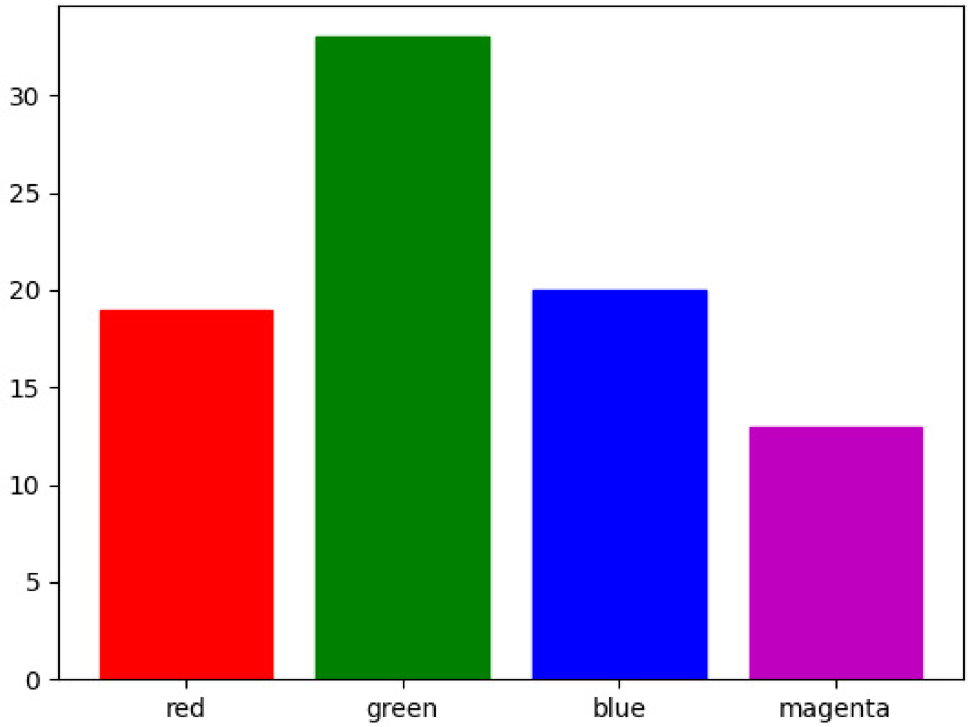

Figure 5.4: Bar chart for color bias.

From the bar chart5.4 representing the color-related quantitative data it can be observed that, over all the test runs, green (33 score) paths were chosen with much greater frequency than red (19 score) or blue (20 score) paths, while magenta (13 score) paths were generally the least favorite. Additionally, blue and red paths were chosen almost the same amount of times, within one point of difference.

Of course, quantitative data representations only provide an overview of the entire testing group's tendencies, without accounting for the possible skew caused by outliers. Given that we want to assess whether certain shared behavioral patterns occur for each individual, it would be much more appropriate to note the spread of results between subjects using the five-number summary:

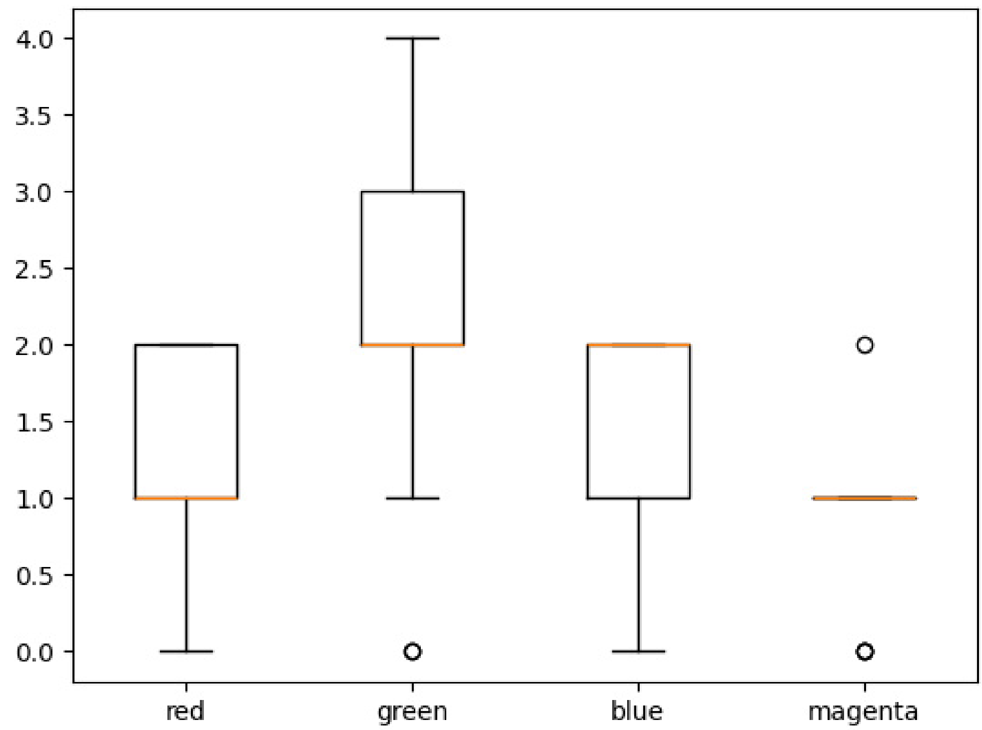

Figure 5.5: Box plot for color bias.

Studying the box plot5.5 for color-related data, we can see other patterns emerge. Despite green paths having by far the most points in the quantitative representation, their median value is identical to the median value for blue paths. Observing the quartiles of the two, we notice that most of green's minority individuals tend towards higher values, while blue's minority individuals tend towards lower values, explaining the difference in favorability score. The same can be said of red and magenta — while a greater number of red's non-median values tend upward, magenta's non-median values are extremely sparse, with the largest majority of people choosing to explore magenta paths exactly once.

From this analysis, we can extrapolate that there is an inherent positive navigational bias towards green and blue paths, while red and magenta paths have an over-all neutral to negative bias. These findings are consistent with Valdez et al. (1994),[VM94] who successfully mapped the perception of colors to emotional and psychological stimulus and whose conclusions we leveraged to select the testing environment's color set, with the assumption that the green and blue paths would be more calming and reassuring — resulting in positive bias, while the red and magenta paths would cause more anxiety — resulting in negative bias.

5.3.2 Texture Labyrinth Analysis

When taking into account texture as an influencing factor to the decision-making process, the quantitative results show several degrees of bias between the available traits.

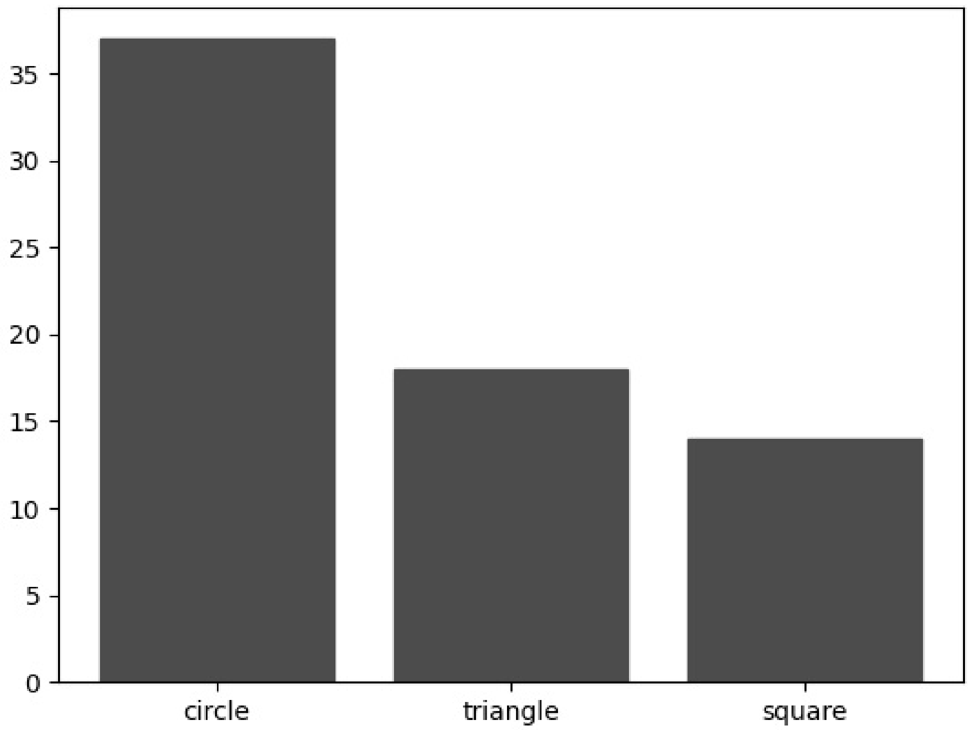

Figure 5.6: Bar chart for texture bias.

From the bar chart5.6 representing the texture-related quantitative data, we can surmise that circle-patterned (37 score) paths were chosen much more often, per total, than either triangle-patterned (18 score) or square-patterned (14 score) paths. In the same vein, both triangle-patterned and square-patterned paths seem to have been chosen with a similar frequency.

In spite of these results, quantitative data aggregation is not sufficient for our purposes, providing only a general overview of the entire testing sample's tendencies, without accounting for the possible skew caused by outliers. Since we want to assess whether certain shared behavioral patterns occur for each individual, it would be much more appropriate to once again note the spread of results between subjects using the five-number summary:

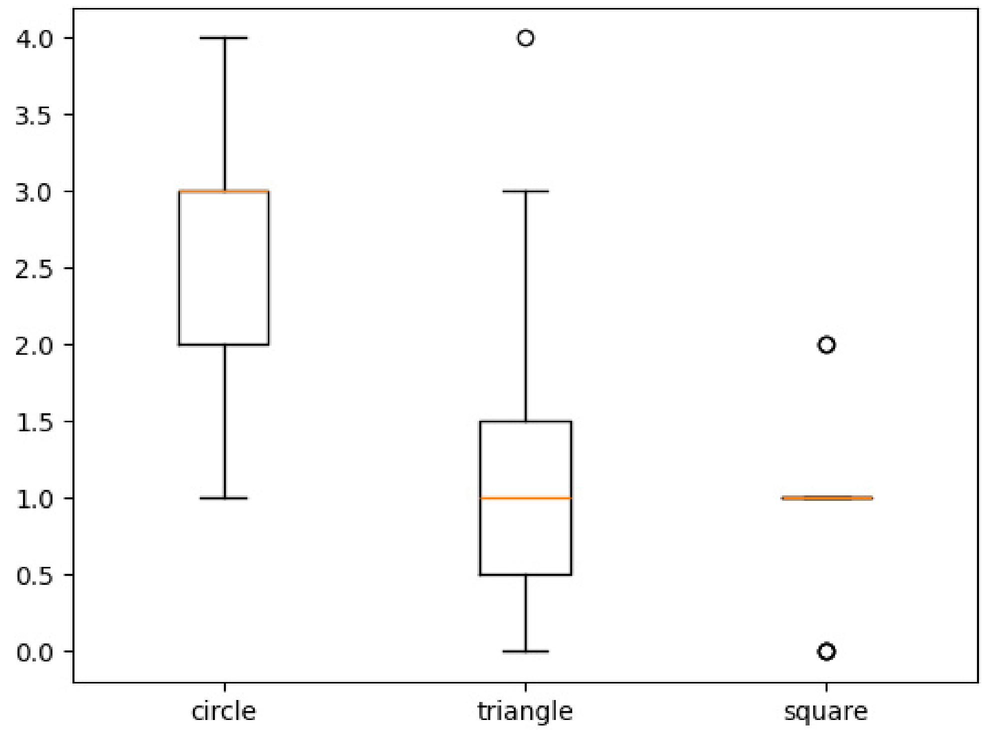

Figure 5.7: Box plot for texture bias.

Observing the box plot5.7 for texture-related data, we can see some complementary patterns emerge, not too dissimilar to those which we gleaned from the quantitative aggregate. In this test, circle-patterned paths were very clearly favored, having the highest median out of all textures. The quartile distribution suggests that a non-negligible amount of individuals were not as positively biased towards circles, but the entire distribution set remains above the median value for triangles and squares. Concerning triangle-patterned and square-patterned paths, triangles remain more explored over-all, with squares exhibiting a phenomenon similar to the magenta paths from the color analysis subsection, namely being explored once and only once by the overwhelming majority of test subjects.

From this analysis, we can extrapolate that there is a significant positive bias towards circle-patterned paths, while triangle-patterned and square-patterned paths have mildly negative bias. These findings are consistent with Bar et al. (2006),[BN06] who confirmed the hypothesis that curved shapes elicit positive emotions from humans, while jagged shapes elicit negative ones.

5.3.3 Brightness Labyrinth Analysis

With regards to the property of brightness as an influencing factor to the decision-making process, the quantitative results show several degrees of bias between the available traits.

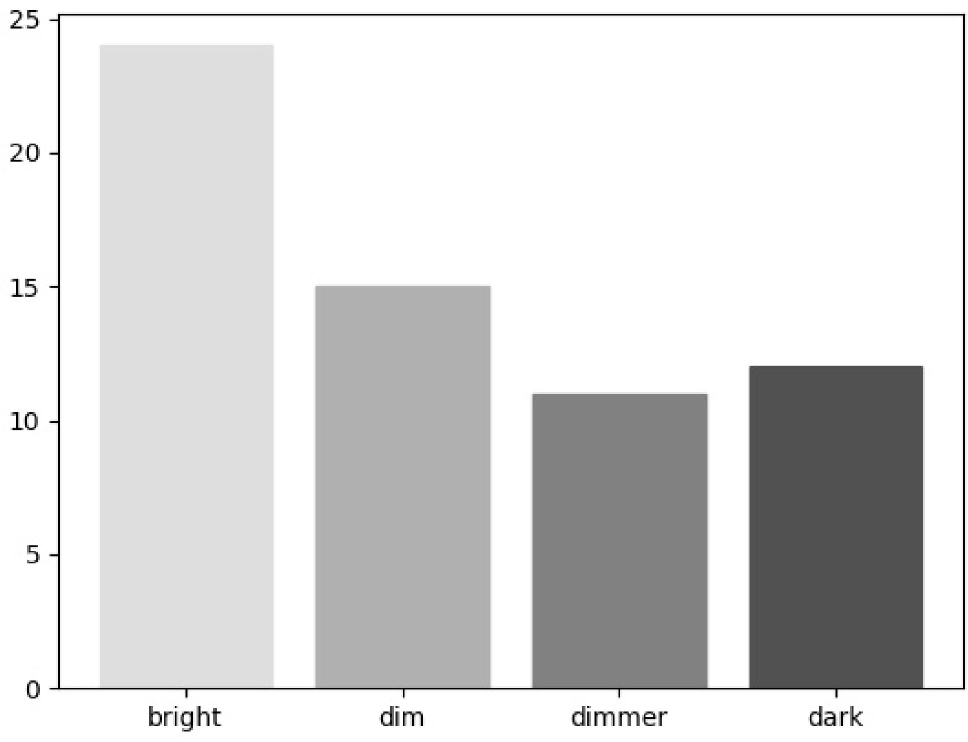

Figure 5.8: Bar chart for brightness bias.

From the bar chart5.8 representing the brightness-related quantitative data it can be observed that, over all the test runs, bright (24 score) paths were chosen much more frequently than dimmer (11 score) or dark (12 score) paths, while dim (15 score) paths achieved an intermediary favorability score. Similarly to blue and red paths in the color analysis subsection, dimmer and dark paths were chosen almost the same amount of times, within one point of difference.

Yet again, in spite of these results, quantitative data aggregation is insufficient for our purposes, providing only a general overview of the entire testing sample's tendencies. It is fundamentally unable to account for the possible skews caused by outliers or distribution density. Seeing as we want to assess whether certain shared behavioral patterns occur for each individual, it would be much more appropriate to quantify the spread of results between subjects using the five-number summary:

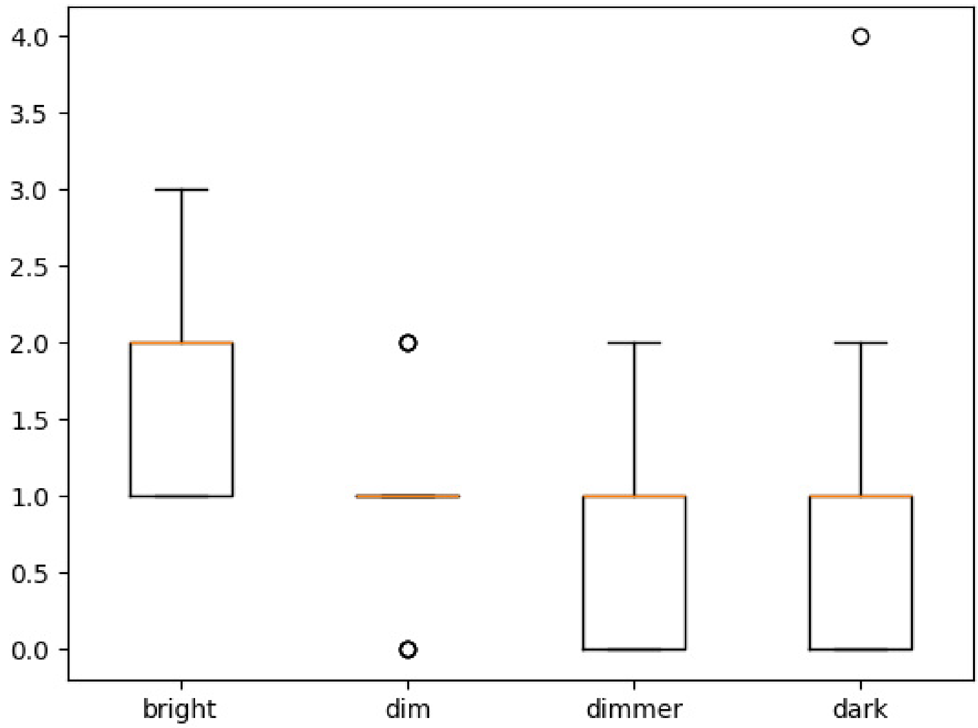

Figure 5.9: Box plot for brightness bias.

The box plot5.9 for brightness-related data shows some interesting relations between the different paths. While it follows as a matter of course that the bright paths would have the highest median score, it is the associations between the non-bright paths that are most fascinating. Dimmer and dark paths seem to be nearly identical in distribution, with the only difference being a very high outlier (occupying the single highest value in the graph). Thus, it is safe to assume that the difference in quantitative value between the two traits is caused by this outlier. By contrast, the dim path value distribution is formed of a well-established median body and some very sparse outliers, not unlike some other traits from the other analysis subsections. Still, all three non-bright paths present the same median value.

Given this analysis, we can conclude that there is an inherent positive navigational bias towards bright paths, while the other light intensities are likely neutral, within a certain margin of error. Unsurprisingly, the findings of Wilms et al. (2018)[WO18] concurred with our results, illustrating that while brighter monochrome glow might cause greater valence — or the positivity of emotional responses — it does not particularly influence arousal — or the intensity of emotional responses. As such, it is very likely that the positive bias towards bright paths was simply because they presented increased visibility compared to the other three types.

5.3.4 Synthesis of Analyses

Through breaking down the modeled data and re-structuring it into more relevant representations, we were able to extrapolate multiple relations between our defined testing characteristics and the way in which they are perceived by individuals. However, the most important observation from these isolated analysis subsections is that their results consistently coincided with psychological articles' statements and conclusions, which is very relevant to the topic of this paper, and will be discussed further in the conclusion.

Chapter 6

Conclusions

The scope of this paper was to explore the biases found in the navigation of three-dimensional environments from the perspective of human-computer interaction since, in the context of this field, the topic is much less explored than in psychology. While other avenues of interfacing and their psychological implications have been researched to a greater extent in HCI, 3D interfacing has been largely ignored, due to the fact that such software is most frequently of a recreational nature and has a significant performance cost. To expand upon this lackluster area of the field, we sought to analyze and quantify test subjects' decision-making patterns in neutral, controlled three-dimensional virtual environments, in order to prove that underlying navigational biases do, in fact, manifest in a similar way as they do in real environments. Our findings were compelling — not only did we effectively leverage graph-like topological representation, like the one detailed by Mallot & Basten (2009)[MB09] and several others psychological articles in order to achieve meaningful results in our field of study, we were also able to empirically demonstrate that the navigation of virtual environments with the help of traditional interfacing devices can arouse the same subconscious behavior in humans as a real environment. This concurrence was present in all three of our testing environments — the results of color labyrinth testing coincided with the work of Valdez et al. (1994),[VM94] the results of texture labyrinth testing coincided with the studies established by Bar et al. (2006),[BN06] and the results of brightness and glow testing coincided with the somewhat recent discoveries made by Wilms et al. (2018).[WO18]

While it is true that our study was limited its scope and selection of test subjects, and may, as such, present incomplete or skewed findings, the close correlation is nevertheless fascinating, and warrants further investigation. We have approached this study as an introductory case study, as such. If such fundamental navigational biases as those pertaining to color, texture and brightness can translate from real spaces to abstracted virtual spaces without great issue or change, then the analysis of other psychological tendencies in three-dimensional environments could be valuable for the field of human-computer interaction, for academic, as well as economic reasons. The economic motivator is becoming increasingly relevant nowadays, as three-dimensional applications are becoming more widespread, not only for entertainment, but also for commercial use. Additionally, system hardware has advanced greatly over the last decade, permitting most computers and automated devices presently in use to run at least rudimentary 3D applications. Most important, however, is the fact that the core preoccupation of human-computer interaction is the study and analysis of the relationship between users and systems, and, as long as an academic field exists, it must progress.

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