

STANFORD UNIVERSITY

**MACHINES OF PERCEPTION**  
**Sensory Physiology through Interactive 3D**

Learning, Design and Technology  
Stanford University School of Education

Catherine Harrell  
August 9, 2010  
Master's Degree Candidate 2010

**CONTENTS**

<b>LEARNING PROBLEM.....</b>	<b>3</b>
<b>LEARNING GOALS .....</b>	<b>4</b>
<b>THEORY AND RATIONALE .....</b>	<b>4</b>
Existing Solutions .....	4
Educational Theory.....	5
Design Principles .....	6
<b>DESIGN PROCESS .....</b>	<b>7</b>
Research.....	7
Ideation.....	7
Alternative Solutions .....	9
User Studies.....	10
Prototypes.....	10
<b>THE SOLUTION .....</b>	<b>13</b>
Overview .....	13
Prototype .....	14
<b>LEARNER ASSESSMENT.....</b>	<b>14</b>

## LEARNING PROBLEM

---

Biology is filled with complex systems. From the human circulatory system to the structure of eukaryotic cells, students of life science face countless elaborate systems and interconnected parts. Students often struggle to understand systems on a basic, intuitive level [1], particularly when they must imagine structures in three dimensions [2]. In the majority of cases, students learn about structure by memorizing written definitions [1], and they may fail to learn about the system “as a united whole with parts whose functions interact with and influence each other” [1].

The importance of system learning has been emphasized by researchers and educators in recent years, including Harvard’s Understandings of Consequence project [3] and recent reports on systems biology:

Because a system is not just an assembly of genes and proteins, its properties cannot be fully understood merely by drawing diagrams of their interconnections. Although such a diagram represents an important first step, it is analogous to a static roadmap, whereas what we really seek to know are the traffic patterns, why such traffic patterns emerge, and how we can control them [4].

Without understanding how systems work dynamically and interactively, students struggle to make predictions and determine sequences. These issues are especially important for high school students as they embark on studies of complex anatomy and physiology.

Science education involves a suite of core skills: in addition to the scientific method, science students learn logical reasoning, cause and effect, and systems understanding. However, “most science curricula found in schools today are descriptive, focused on the laws, theories, and concepts,” [5] and even advanced science students may focus on facts while failing to understand cause and effect [6]. Learning to interact with systems and visualize complex structures could greatly enhance understanding of STEM topics [2].

In recent years, the practice of science has become increasingly important in American education, as the United States strives to remain competitive in science, technology, engineering and math, collectively known as STEM. Recent science initiatives, including the multimillion dollar “Educate to Innovate” campaign, aim to increase interest and subsequent involvement in scientific disciplines [7]. Without a solid foundation of structural and functional knowledge, students may have trouble understanding advanced science topics, and may lose interest in the field at an early age.

## **LEARNING GOALS**

---

The goal of “Machines of Perception” is to provide biology students with an interactive learning tool for visualizing complex structures. The human eye was chosen as a model system, due to its relative familiarity and suite of easily identifiable parts. The project was shaped by the following goals:

*Interactivity:* Students must be able to actively manipulate and explore. Rather than being passively instructed, students will have the opportunity to experiment with the system and shape their own outcomes.

*Ease of use:* The interface and mechanics must be intuitive enough that students can immediately begin to play with the structure, without being distracted by the technology.

*Engagement:* Students should find the experience interesting and enjoyable. Ideally, playing with the application will prompt them to find out more about the system on their own.

## **THEORY AND RATIONALE**

---

### **Existing Solutions**

Medical illustration has a rich history, from ancient Egypt to the Renaissance to modern digital media. Traditionally, anatomical systems are described through static diagrams and illustrations. Such representations include textbook diagrams [8] and sophisticated medical graphics [9]. For example, the Visible Body project allows users to view digital renderings of the human body in great detail [10].

The Bodies Exhibition, an international museum exhibit of real human bodies, brought anatomical illustrations into real-life 3D [11]. The use of 3D has the potential to enhance understanding and visualization of anatomical structures. Building physical puzzles has become widespread in classrooms: high school courses may use plastic molecules for chemistry or cell models for biology. Learning by actively designing a structure can have a positive impact on learning: for instance, a group of sixth graders improved their understanding of systems by building a model respiratory system [1].

Systems learning has also crept into the world of games. Relevant examples include Fantastic Contraption and Crayon Physics Deluxe, both physics-based puzzle games that incorporate system design. Although both of these examples are two-dimensional, there are a number of popular 3D computerized puzzles designed to enhance spatial reasoning [12]. 3D volumetric displays, while still in development, also have the potential to improve spatial visualization and visual reasoning in STEM research [2].

Machines of Perception takes advantage of the power of 3D graphics to represent physiological systems. Existing game design and usability heuristics were used to make the interactivity as simple and intuitive as possible. The design process also drew from existing best practices for using games in classrooms, such as allowing students to produce and not just consume, staying focused on learning, and incorporating interdisciplinary skills [13].

## **Educational Theory**

The project is based on a theoretical framework of interactive education. Research indicates that games and other interactive play experiences can enhance learning and

memory [14], especially when the activities engage multiple senses. The role of sensory perception in learning is well documented. Indeed, discussions of play, interactivity, and sensory development can be found in many influential learning theories, including the works of Montessori and Piaget [15, 16].

Montessori describes physical interaction as a precursor to higher cognition, with a special focus on sensory development [15]. According to Montessori, interacting with an object and attending to detail can lead to more powerful discernment and observation skills, both of which are useful in science education. The proposed project will encourage interactive manipulation of objects on the screen, and the game will include multimodal feedback such as visual and auditory cues. In order to solve the puzzles, students will attend to visual characteristics, observe changes, and classify objects, all of which require active sensory engagement.

Though Piaget's work deals specifically with children, his principles of play can be applied to people of all ages. "There are individual actions such as throwing, pushing, touching, rubbing," he writes. "It is these individual actions that give rise most of the time to abstraction from objects" [17]. Like Montessori, Piaget emphasizes active experimentation as a crucial foundation of learning. Instead of being taught about physiology through a book or a diagram, students will have the opportunity to play with the objects themselves. Science students in particular will benefit from manipulating the pieces and generating ideas about what will happen next.

## **Design Principles**

Machines of Perception was produced through iterative design. Simple prototypes were tested and revised, beginning with storyboards and "paper prototypes" and gradually advancing to 2D puzzles and eventually complete 3D systems. Establishing the basic mechanics at an early stage allowed the project to stay focused on its learning goals, without being sidetracked by features or technical details along the way. User-centered design also played a vital role in the project: user feedback drove a variety of interface changes and learning approaches.

## DESIGN PROCESS

---

### Research

The senses are tangible and accessible, since nearly everyone has experienced sight, sound, smell, touch and taste. All five sensory systems were examined as possible candidates for the project. The visual system was selected due to several desirable features: a localized system with easily distinguishable parts and a widely recognizable shape. Many people are familiar with the basic structure of the eye, whereas the structural appearance of olfactory and gustatory systems (taste buds, chemoreceptors) are unfamiliar to a general audience. The ear was a promising second choice, due to its mechanical nature and Rube Goldberg-like transfer of energy, and the somatosensory system offered the unique challenge of representing a distributed system.

Once the selection had been made, the human eye was investigated in great detail. Special attention was paid to structural elements such as the iris, lens, and retina. Textbook descriptions, diagrams, and websites all contributed to a foundational understanding of the eye, which was then translated into simplified components for the puzzle version. Some details and smaller pieces were omitted in order to achieve an easily accessible representation.

### Ideation

Sketches and storyboards were used to visualize the structure and articulate the sequence of events. Due to the visual nature of the finished product, the ideation process took place almost entirely through drawings and diagrams. Index cards were useful tools for sketching interface ideas and working out the layout of the puzzle screen.

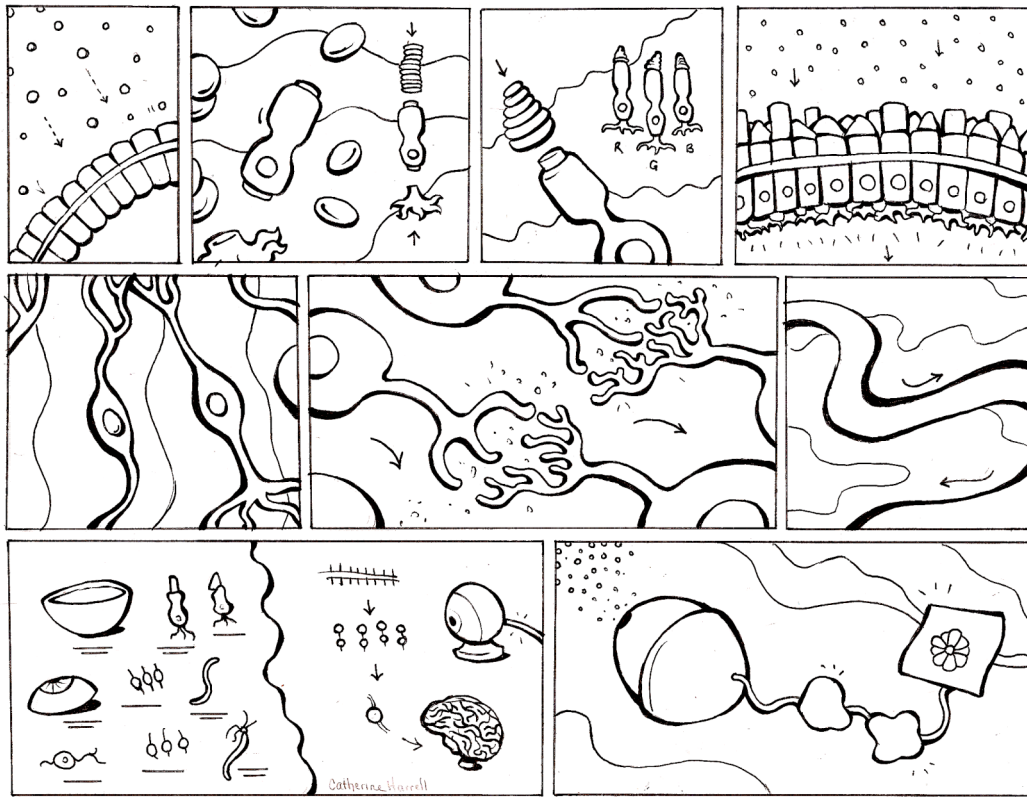


FIGURE 1: Storyboard of how light enters the eye.

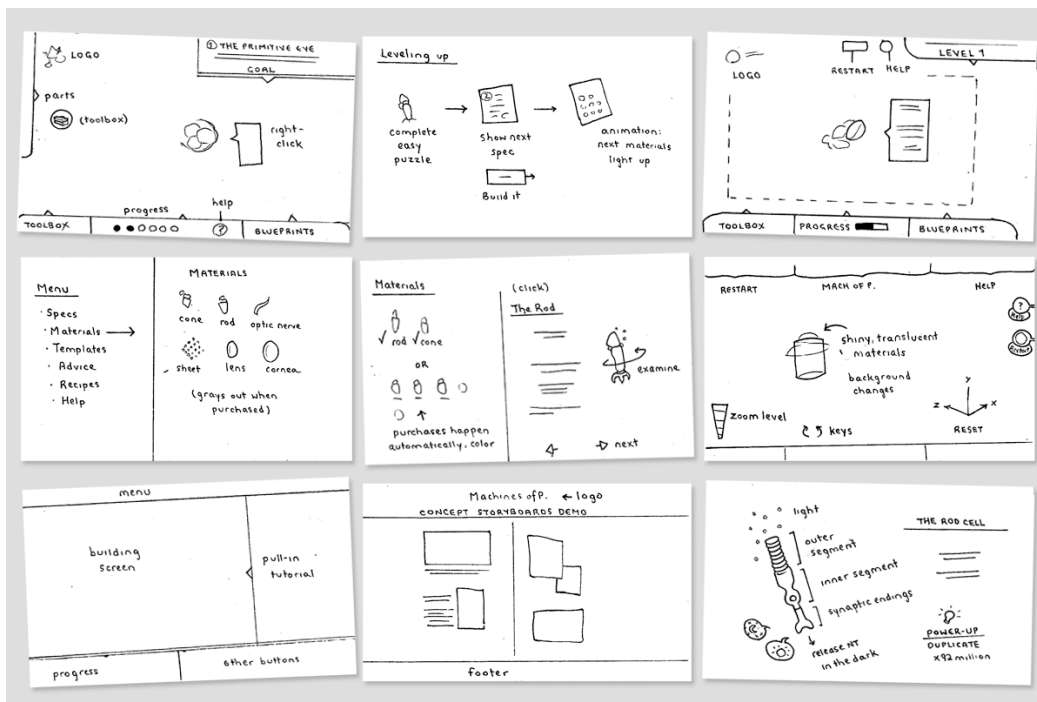


FIGURE 2: Index card diagrams of interface elements.

## Alternative Solutions

Machines of Perception was implemented as an easy, accessible 3D puzzle with click-and-drag mechanics and a gradual difficulty ramp. An alternate approach would be to create a “game” in the traditional sense, with scores, timing, advanced controls, and player competition. The current implementation was designed to give players a safe space to explore, providing an open-ended, low-pressure experience without too many gaming elements. However, it would be interesting to reimagine the project as a fast-paced video game. Either approach could contribute to learning, and it would be intriguing to see what kind of differences would emerge in player understanding.

Realism was another design element that was carefully considered. Medical representations may exhibit varying degrees of detail, and the human eye in particular can be broken down into incredibly elaborate sub-structures. For the current prototype, a soft, cartoonish style was chosen to make the game more approachable to casual players. Players can get a feel for the basic elements without being over-burdened by details. Future iterations may incorporate more details for better medical accuracy.

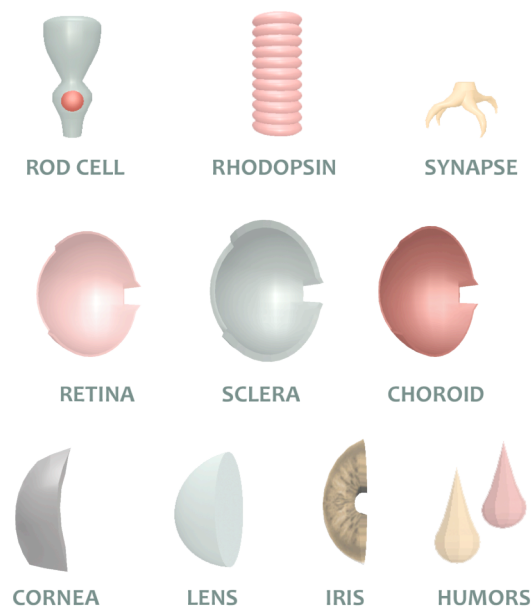


FIGURE 3: Inventory of pieces in a cartoonish visual style.

## **User Studies**

Users played a vital role in refining and improving the design. At the earliest stages, the idea was described to a group of graduate students at the Stanford University School of Education Conference. The students offered ideas for similar games to explore, including *Dr. Brain* and *Invisible Anatomy*, and asked questions about scope and feasibility. Preliminary user studies with storyboards and small-scale paper prototypes raised important questions about the learning goals: for example, would the puzzle focus more on information or skills? One user suggested that the game would be most useful for kids who already have a preliminary interest in science, or who are already somewhat motivated and interested in school. The puzzle could take their interest to the next level, teaching them the specifics about biological systems while also enhancing skills they will need further down the road.

One of the key takeaways from the informal user discussions was the importance of designing and testing multiple versions of the game, adjusting certain variables along the way. These variables included level of visual detail, amount of specialized vocabulary, and level of difficulty. Informal user tests were performed frequently as functional prototypes were created, allowing for user-centered changes to the puzzle and rapid feedback from users.

## **Prototypes**

Implementations of increasing complexity and functionality were built and tested over the course of the design process. The interface underwent various user-directed changes, initially through static storyboards and wireframes, and later through testing with working prototypes.

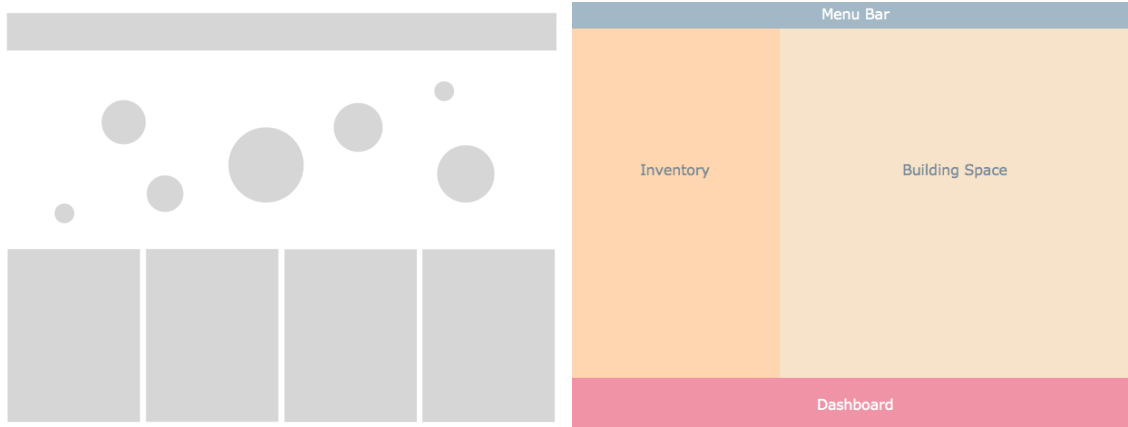


Figure 4: Wireframes of the interface prior to functional implementation.

Early versions were built in Unity 3D using primitive shapes like cubes and spheres. These functional prototypes allowed for testing of the mechanics before introducing more complex models.

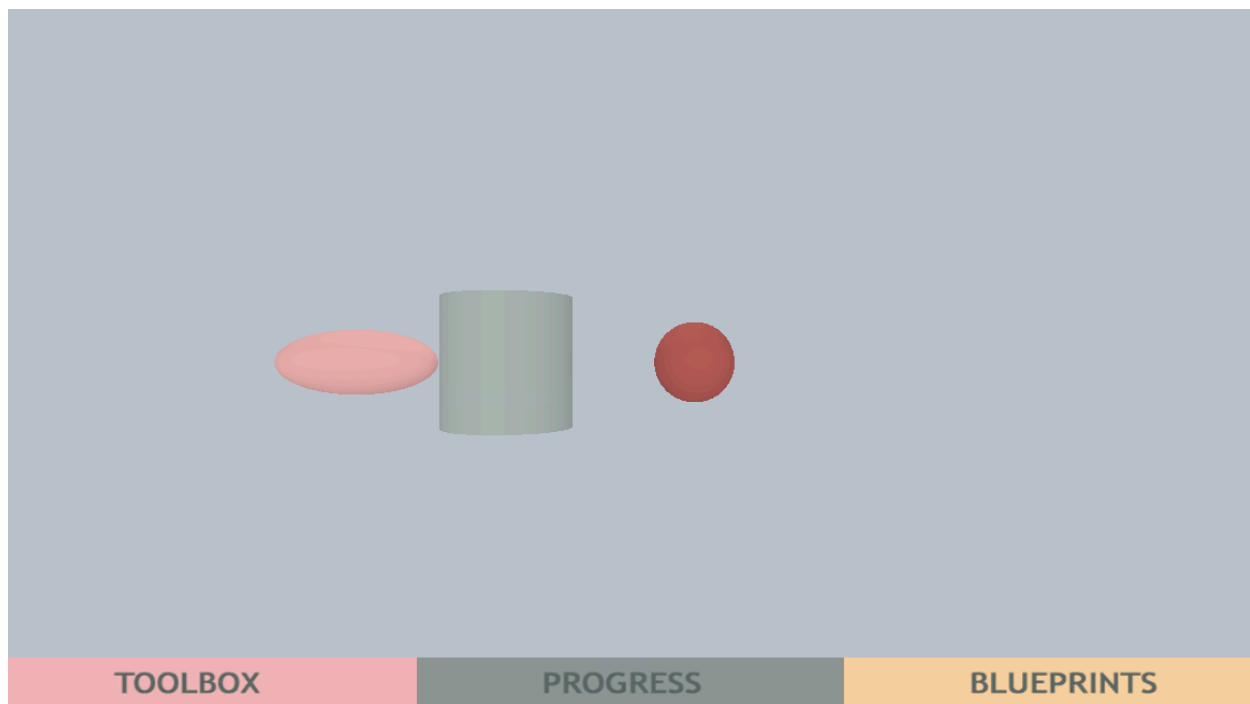


Figure 5: Functional prototype using primitive shapes.

The final version was implemented with Autodesk Maya and Unity 3D. Shapes were sculpted in Maya to resemble pieces of the eye, and Javascript was used to add

interactivity and click-drag mechanics. Menus, toolbars, and extra features were also added to the final prototype.



Figure 6: Screenshot from the finished puzzle, with all of the features implemented.

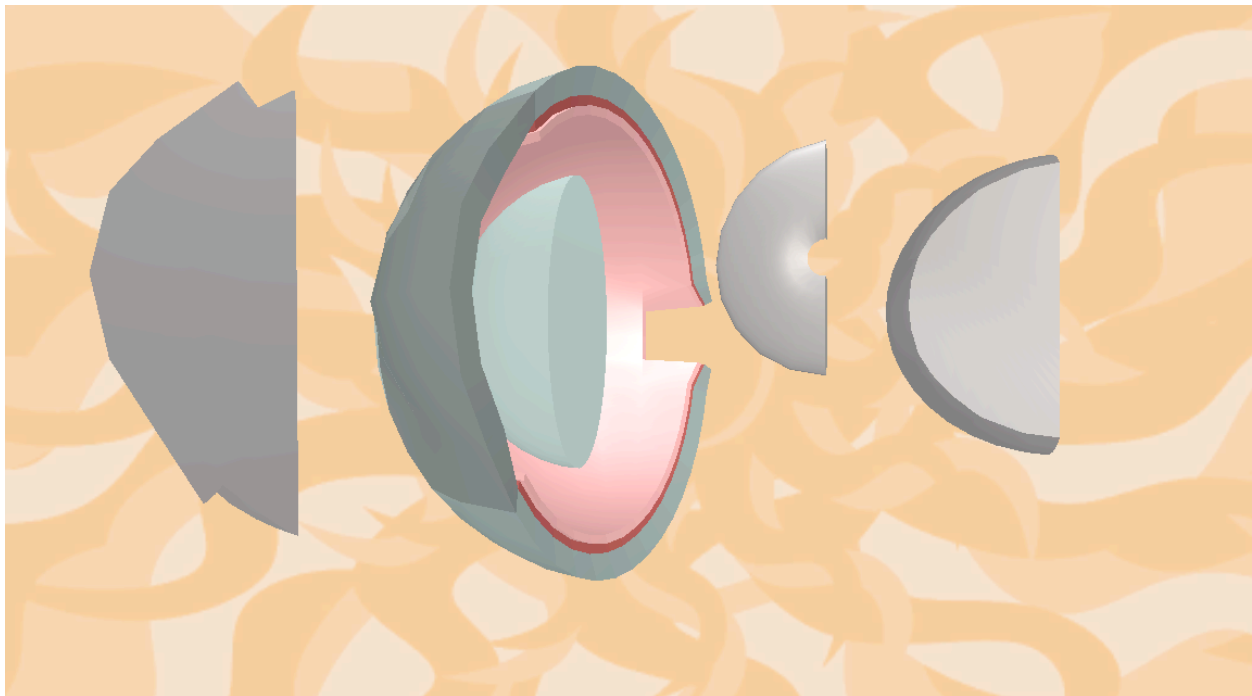


FIGURE 7: Another screenshot from the final prototype.

## THE SOLUTION

---

### Overview

Machines of Perception includes the following elements:

*3D Puzzle:* Models of perceptual systems and their constituent parts were constructed in Maya and added to an interactive puzzle. The pieces were stylized as colorful, cartoony parts, simple and easy to manipulate. The models allowed easy understanding and a clear intuition of how the parts fit together, while maintaining enough scientific accuracy to avoid introducing misconceptions.

*Interface:* Players interacted with the models through an intuitive user interface, which included the ability to advance to harder levels and seek additional help. A clean interface allowed the players to focus on the objective of the game, rather than struggling to understand the mechanics. Designing an effective interface was a high priority for the project.

*Levels:* The player begins with an easy puzzle in order to learn the mechanics of the game (dragging and dropping, clicking on pieces, attending to feedback cues). The difficulty gradually increases over the course of the puzzle, allowing players greater independence to make choices and think critically. Level numbers were indicated at the top of the screen, so players were able to note their progress.

*Resources:* In addition to the main puzzle screen, Machines of Perception also includes ways for the player to seek out more information. For example, players can click to find out more about the retina, and the information they learn may guide their building strategy. They may also look at diagrams of the finished eye. These resources reinforce the game's grounding in real science, and they also allow students to practice seeking information and making logical predictions.

## **Prototype**

The working model demonstrates possible mechanics and visual approaches for creating a manipulable 3D system. The product is intended to be a prototype for possible future iterations. Expansions to the current prototype may include exploring more sensory systems, incorporating functional understanding and cause/effect reasoning, and adding brand new gaming elements.

## **LEARNER ASSESSMENT**

---

Informal learning assessments were performed with 5 university students in order to gauge the learning potential of the puzzle. During evaluation sessions, players were asked to play freely through the levels and describe what was going on. The self-description approach was similar to the assessment used in Hmelo's study of students assembling a model respiratory system, in which they were asked to build a model and explain themselves [1]. Players were asked about what the pieces represented, and how they knew where to put each one.

Three key learning benefits were observed: first, players exhibited a new awareness of the complexity of the eye, saying things like, "I didn't know there was all that stuff in my eye!" and expressing surprise that there were so many odd-looking shapes involved in vision. Even if without biological facts or specialized vocabulary, players gained a sense of the elaborate nature of the visual system.

Second, players expressed some basic structural understanding, using location-based language to describe relationships, such as "Ok, so the lens must go behind the pupil," and "Oh, I see there's a space between these two parts." Self-explanation can be a valuable tool for learning [19], as well as a useful indication of how much the player has understood. Further testing would be needed in order to determine the exact degree of structural knowledge gained from the puzzle, but the use of descriptive self-explanations indicates that the model has some potential in this area.

Third, players gained a newfound interest in the structure and function of the eye. While playing with the puzzle, they often expressed a desire to know more, asked questions about the parts. Players tried to orient themselves, asking questions about scale and relationships. Interest can be a powerful motivator for further learning, and hopefully the puzzle will encourage players to find out more.

The Learning, Design and Technology Expo presented further opportunities for user feedback. Visitors who played the demo expressed similar sentiments as those tested during learning assessments, often seeking additional information and expressing a desire to find out more. They also offered suggestions for new features, interface adjustments, and new learning ideas, all of which could contribute to future iterations of the puzzle. With more user feedback and a series of new prototypes, Machines of Perception could transition from an interaction design demo to a fully-realized, marketable interactive learning tool.

## References

- [1] Hmelo, C. E., Holton, D. L. and Kolodner, J. L. Designing to learn about complex systems. *Journal of the Learning Sciences*, 9, 3 (2000), 247-298.
- [2] Eisenberg, M. and Pea, R. *Three dimensions within our hands: Toward the creation of handheld volumetric displays*. Stanford University, City, 2008.
- [3] Grotzer, T. A. and Bell, B. Negotiating the funnel: Guiding students toward understanding elusive generative concepts. *The Project Zero Classroom: Views on Understanding*. Cambridge, MA: Fellows and Trustees of Harvard College (1999).
- [4] Kitano, H. Systems biology: a brief overview. *Science*, 295, 5560 (2002), 1662.
- [5] Hurd, P. D. H. Scientific literacy: New minds for a changing world. *Science Education*, 82, 3 (1998), 407-416.
- [6] Perkins, D. N. and Grotzer, T. A. Models and Moves The Role of Causal and Epistemic Complexity in Students' Understanding of Science. *Relation*, 10, 1.78 (2001), 1309.
- [7] Chang, K. *White House pushes science and math education*. City, 2009.
- [8] Kandel, E. R., Schwartz, J. H. and Jessell, T. M. *Principles of neural science*. McGraw-Hill, Health Professions Division, New York, 2000.
- [9] AMI *The Association of Medical Illustrators*. City, 2010.
- [10] *Visible Body: 3D Human Anatomy*. Argosy Publishing, Inc., City, 2007-2010.
- [11] *Premier Bodies: The Exhibition*. Dalian Medical University Plastination Co., City, 2008.
- [12] Ritter, F., Preim, B., Deussen, O. and Strothotte, T. *Using a 3d puzzle as a metaphor for learning spatial relations*. Citeseer, City, 2000.
- [13] McDaniel, R. and Telep, P. Best Practices for Integrating Game-Based Learning into Online Teaching. *Journal of Online Learning and Teaching*, 5, 2 (June 2009).
- [14] Gee, J. P. *What video games have to teach us about learning and literacy*. Palgrave Macmillan, New York, 2007.
- [15] Montessori, M. and George, A. E. *Montessori method*. Barnes & Noble Publishing, 1992.
- [16] Piaget, J. Play, dreams and imitation. *Play, dreams and imitation*, 103, 4 (1962).
- [17] Piaget, J. Genetic epistemology. *American Behavioral Scientist*, 13, 3 (1970), 459.
- [18] Sharpe, J., Lumsden, C. J. and Woolridge, N. *In silico: 3D animation and simulation of cell biology with Maya and MEL*. Morgan Kaufmann, 2008.
- [19] Chi, M. T. H., De Leeuw, N., Chiu, M. H. and LaVancher, C. Eliciting self-explanations improves understanding. *Cognitive Science*, 18, 3 (1994), 439-477.