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Virtual Reality Serious Game as an Assistive Technology to Support Pediatric Visual Perceptual Training

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Abstract

Amblyopia is a neurological impairment where children suffer from the insufficient visual gathering. Recent studies investigated the ability to improve amblyopic children's visual acuity. However, according to previous theories, visual acuity is the foundation for an excellent visual system, but more lies beyond acuity improvements, such as their visual cognition and perceptual skills. Virtual Reality acts as a serious game medium for active learning of virtual depth perceptions built after a solid improvement for visual acuity. This paper aims to provide a pediatric-centered practical approach for amblyopic children. We designed a game system in the form of a virtual depth hierarchical game pyramid based upon the classical visual perception hierarchical pyramid and standardized procedures for perceptual training. The bottom-up setup gradually trains for each level up the VR-designed hierarchy while building up a solid foundation.

CCS Concepts

• ***Human-centered computing*** → *Interaction design;* • ***Applied computing*** → *Life and medical sciences; Education;*

1. Introduction

Amblyopia is a neurodevelopment disease that the brain fails to provide stereoscopic vision and damages visual acuity. Depth perception impairments are visual cognitive symptoms of amblyopia, and it can cause difficulty in object interaction and judgments, which may even cause life-threatening problems. Depth perception problems become harder to cure as age progresses, and standard rehabilitation practice was considered dull and boring, so patients were unable to focus and comply with the task [HKT19]. Virtual reality provides an innovative approach to rehabilitation care.

The aim of this paper provides a VR serious game framework that defines a suitable fun and interactive treatment plan for amblyopic children to restore perceptual sensitivity and understand depth cues. We designed a VR hierarchical pyramid with respect to the Motor-Free Visual Perception Test–Fourth Edition (MVPT-4) [Pro15] and the hierarchical pyramid proposed by [War93]. This VR hierarchical pyramid follows a bottom-up process, where skills at lower layers build up the foundations for the successive layers as abilities advances to provide an alternative approach towards amblyopia depth perception pediatric training. We specifically designed the system for pediatric care to help children better understand the visual connections and interact with the world, especially for patients with an insufficient understanding of visual stimulation.

2. Related Works

Recent success in the VR amblyopia treatment provides a fun and interactive method [VC17, ZHH*17, BDT*18]. Many focused on conceptualized traditional rehabilitation methods to a VR medium, creating luminosity differences and asynchronous. Tasks performed in previous VR studies improved visual acuity, forcing the body to adapt and use the amblyopic eye [SNFV18, HKT19, ETT19]. State-of-the-art research for amblyopia eliminates interocular suppression and uses dicophotic training with both eyes to correct acuity [GDW*20, ZHH*17]. These studies are limited to completing the treatment for visual acuity but do not extend to problems to depth perceptual impairments that are hindered by poor visual acuity and amblyopia. A review on depth perception proposed that current research and commercial VR rehabilitation are left unexplored [BDT*18]. VR depth perception task investigated with the object's motion parallax in healthy participants [FJT*20]. However, even when the visual acuity is restored to an average level, amblyopic depth perception deficits can still impair one's welfare [Bri16]. The design is based upon previous VR research findings that suggest greater compliance, commitment and similar effects compared to traditional methods [VC17, GDW*20].

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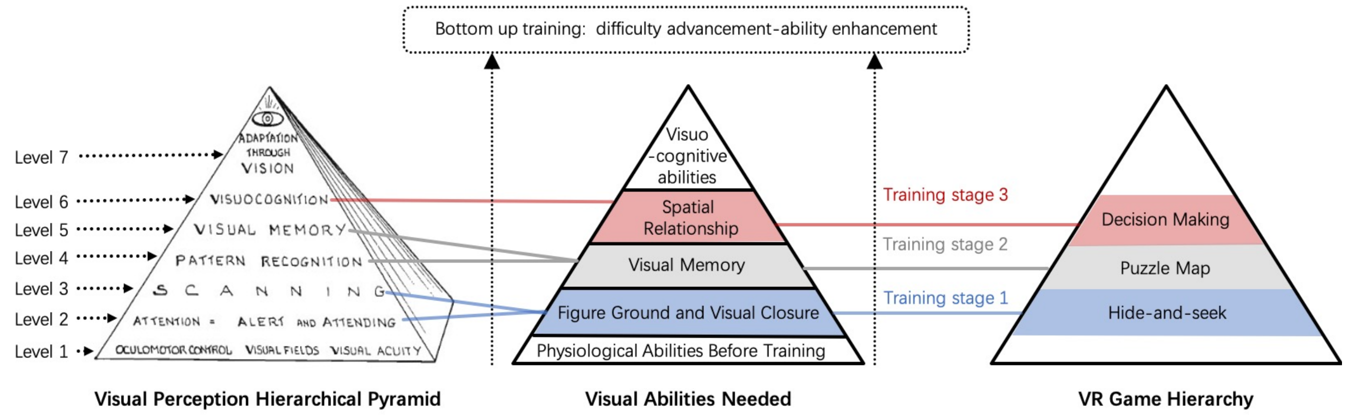

Figure 1: *Overview of the VR Depth Hierarchical Design. Pyramid on the left is designed by Mary Warren in 1993. [War93]*

3. VR Depth Perception Hierarchical Design

Virtual worlds mimic scenarios in the real world, elicit a stronger emotional sense of place illusion that leads to realistic behavior in the virtual world [CMGK20, Sla09]. Skills obtained in the virtual world will transfer to the real world to help players become sensitive towards the depth cues and interact correspondingly. The process of learning how to act and respond correctly builds up a robust foundation to generalize and perceive novel scenarios and cues. The virtual world's interaction can be easily performed and flexible for changes according to one's ability, maximizing the control of all the virtual things and minimizing any locomotive injuries or collisions that depth insensitivity may cause in the real world.

Our virtual serious game design is built upon the foundations of visual perception hierarchy to improve understanding for depth cues and re-establish necessary neurocognitive skills for amblyopic children. Similar to previous VR studies, the game design aims to motivate patient quality of care for enhancing depth perception abilities.

3.1. Depth Perception

Depth perception is the ability to perceive the three-dimension world visually. Depth cues are categorized into monocular cues and binocular cues about spatial information. An enhanced understanding of depth perception provides solid judgments for depth, size, and fit. Representativeness heuristic ensures cues are perceived correctly and estimates the distance for depth, leading to subjective constancy, a robust understanding of the different cues.

Monocular cues refer to the ability to understand depth cues with one eye. These variations are based on lines, shapes, and color intensity. Examples include optical flow, relative size, linear perspective, and monocular parallax [ZLLF19, CCG*19, MKMS20a]. Texture gradients, interposition, occlusion, known object sizes, light and shading, haze, defocus are widely acknowledged [ZLLF19, SL18]. An understanding of monocular cues can help develop temporal and spatial sensitivity about motion in actions. Binocular cues merge the three-dimensional aspects of a close object to perceive depth. Stereo cue relies on relative disparity to perceive slightly different visual image [CCG*19]. Both receptive fields are slightly different and are fuse together to produce a visual image with depth aspects.

3.2. Virtual Depth Hierarchy Pyramid

Mary Warren in 1993 laid the foundation for visual perception, and research has extended to conceptualize Warren's framework [SJH19]. We approach Warren's framework with a VR design for amblyopic pediatric care specifically. Our design, shown in Figure 1, focuses on rehabilitation after success with visual acuity (level one), as much research has shown success in laying down the foundation for visual acuity. The VR hierarchy design follows a bottom-up principle, building up each layer and show advancements in each corresponding stage while solidifying foundations prior to the layer.

The design focuses on training attention, visual scanning, pattern recognition, and visual memory within the broader hierarchy of level two to six. Bottom-up training through building the foundations can ultimately approach and train for the higher order of abstract perceptions of cognition and adaptation. Unlike the abstract levels, attention, scanning, pattern recognition, and visual memory can be quantified with quantitative data to explain the higher levels through Pico Neo 2 Eye VR headsets with eye-tracking, gaming response time, and achievements. These five levels are then broken down into the figure ground, visual closure, visual memory, spatial relationship, and visuo-cognitive abilities, as shown in the center pyramid in Figure 1 [Pro15]. The main challenge of designing this game is to find a proper way to restore visual perception deficits, including training of depth perception and providing monocular cues.

4. Practical Design

In order to make full use of VR technology, our design follows the principles below:

1. Provide a first-person perspective to immerse players into the interactive environment.
2. Manipulate with the asynchronous visual between differences in the left and right eyes to simulate the binocular vision.

3. In correspondence to MVPT-4, we eliminate motor, haptic feedback, and auditory cues that may provide unwanted hints. We rely on visual depth cues.
4. Looking into the distance can prevent ciliary muscle spasms and reduce extraocular muscle fatigue from VR [LSG*20].
5. Bullet time effect can reduce objects' movement speed in three-dimensional space; objects in motion often act too rapidly and dangerous to be perceived by those lacking monocular sensitivity. Supplemented with depth information prompts in observing the movement process for cognitive training to deal with the problem.

4.1. Training for Visual Discrimination

Concerning the standard procedures from MVPT-4, we design for figure ground, the ability to distinguish a prospective target from a complex background, and visual closure, the ability to use partial evidence to identify the object as a whole [CCGP*19, Pro15].

Figure 2: *Hide-and-seek (Training stage 1). Top: Instructions. Bottom left: Easy mode. Bottom right: Difficult mode.*

The purpose of the stage is set to attend and scan for the object of interest. In connection with photo-hunt [VC17] and Finding waldo, we set training stage 1 as a Hide-and-seek game. We create several scenes for players and three levels of difficulty into easy, medium, and difficult adjustments to correspond to the player's visual discrimination ability. For example, as shown in figure 2, the player needs to seek the correct star in the simple background. In the easy mode, they are supposed to find the objects with the color. Background object presents darker colors with the bright purple star distinguishable.

4.2. Training for Visual Memory

A lack of sensitivity in amblyopic children leads to poor visual working memory to retent an object or feature for tasks that follow [CCGP*19, Pro15]. Sequential memory and visual memory impairments can lead to poor task performance. The means of hypothesis testing, guess and check, reflect visual memory's ability to relocate objects in their corresponding spatial grounds and their abstract relationship.

Figure 3: *Puzzle map (Training stage 2). Top: Birds eye view. Bottom: First person view.*

A total of 16 objects are placed in the 4x4 grid. Players need to find two objects in the same color and shape to match successfully. Three styles of model and color design were used to separate the model's shape and make it more difficult to improve through color confusion. The puzzle map will let the player see the object once and present the same object in another view scenario, as shown in Figure 3. If the player recognizes successfully, the player will complete this puzzle map exploration.

4.3. Training for Spatial Relationship

A sense of spatial relationship helps determine the visual cognition of the VR hierarchy pyramid. Adaptation of the lower foundations and an overall understanding of the 'whole scenario' reflects an approach towards cognition. Spatial relationships provide information about how the self is positioned in the space, how the egocentric self should interact with the world, and how objects interact with each another [CCGP*19, Pro15]. The player needs to determine the spatial position relationship between objects and estimate the distance with the virtual self-using stereo vision or the cues. During the start of the stage, the player will attend to two objects of similar distances, and the player will judge the relative position of the two objects. After the player judges and concludes, the player needs to use nearby props to input their conclusion. At this time, the use of props is a close hand-eye coordination operation. In the closed-range operation process, the distant objects will continue to change accordingly with the operation, generate new attraction, forming a positive feedback loop.

There are three classifications of visual cues used in the game, shown in Table 1. These cues are flexible controls to help practitioners and adjust the aided depth perception.

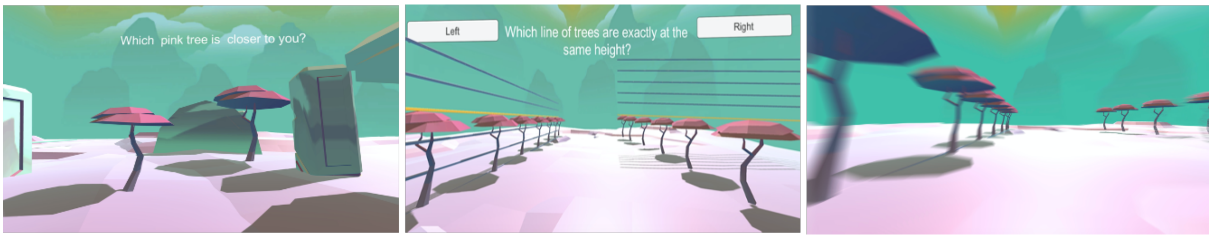

Figure 4: *Decision making (Training stage 3). Left: Interposition. Center: Perspective relationship . Right: Motion parallax*

Table 1: *Spatial relationship examples of different visual cues in the virtual world.*

	Cues	Interaction
Interposition	Shadow, Light, Distance	Optional Questions
Perspective Relation	Perspective Lines	Optional Questions
Motion Parallax	Blur, Distance	Eye Tracking with Pico Neo 2 Eye

Interposition is a form of monocular cue that humans are capable of understanding a scenario with limited or partial features with respect to object placements and relative size [MKMS20a]. In the first scenario displayed in Figure 4, we set different examples and practice and lead players to understand robust yet common knowledge. In the virtual scenario, we set progressive questions in the scene and ask players to judge the approximate depth and distance. Players need to evaluate the distance by combining interposition depth clues with the shadow of objects.

The linear perspective is a type of distance cues that creates the Ponzo illusion where features extending into the distance become smaller [YSKC19]. Every object present in the real world follows visual positioning principles both in two-dimensional and three-dimensional. Linear perspective is widely applied in drawing, which creates an illusion system of depth on a flat surface.

In this paper, we design to train the specific understanding for linear perspective and transfer knowledge for depth perception into advanced practice and thoughts. The system sets two different types of linear perspective scenes. In the second scenario displayed in Figure 4, all the trees are at the same height, but according to the linear perspective principle, though at a different distance, they share the same inclined line and 'shrinks' as it follows the lines. We set different views for players to position themselves into, where these point-of-views can provide a full understanding of the world itself. For example, players may feel a sense of visual cognitive dissonance based on viewing from different angles and positions.

Motion parallax provides an 'illusion' where objects at different distances will move at slightly different speeds due to human's sensitivity towards the monocular cue of object motion [MKMS20a]. Objects closer to the egocentric self tend to feel 'faster' to looking into the distance. Three-dimensional information can be presented as more realistic in the VR world and convey more information than a flat display. Michael maunder proposed that gaze-contingent depth of field can enhance subjective perceived realism and depth and contribute to the perception of ordering and distance between objects [ETT19].

Objects in motion are often too fast in real life, challenging yet dangerous to be perceived by people who lack stereo vision. In the third scenario displayed in Figure 4, we use the 'bullet time' concept to mediate the movement speed of objects in three-dimensional space, supplemented with depth information prompts in the observation of the movement process, for cognitive training.

5. Future Work

We plan to extend this work as a pilot clinical study to continue to work extensively with doctors at the ophthalmology and neurology department to investigate the positive effects and possible side-effects of VR games for amblyopic depth perception. Furthermore, we will adjust our VR system based on doctors, parents and children's feedback to not only suit children's interest but to standardize a pediatric clinical rehabilitation procedure with VR to promote telehealth during the pandemic.

6. Conclusion

The proposed VR serious game design provides a conceptualized and theoretical approach for clinical practice in pediatric rehabilitation care towards amblyopic children's visual understanding and perception. We exploit the advantages and functions of a VR display to achieve scenes concerning depth and looking into the distance. Our proposal can be further implemented in pilot clinical studies to investigate it as an alternative quality-of-care rehabilitation to fulfill children's perceptual sensitivity and abilities to interact with the world.

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