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Article

Safety, Acceptability, and Usability of Immersive Gamification System for Use in Rehabilitation Management of Pediatric Patients with Cerebral Palsy and with Mobility Limitations (Phase 1 Trial)

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Abstract

Virtual reality (VR) is increasingly integrated into the rehabilitation of children with cerebral palsy (CP). However, evidence to substantiate its potential as part of standard care remains limited. This Phase 1 study aimed to evaluate a VR-based immersive gamification technology system (ImGTS) for use in CP rehabilitation based on its safety, acceptability, and usability in healthy children. The system included software and hardware designs informed by discussions with CP rehabilitation and VR development experts (e.g., developmental pediatricians, physical therapists) and tailored to the local context, tested with two setups: the head-mounted display (HMD) and the semi-cave automatic virtual environment (semi-CAVE). We describe the experience of 30 healthy children aged 6–12 years using the ImGTS (Mission to Planet Axel version 1.0) using either the HMD (n = 15) or semi-CAVE (n = 15) setup. Descriptive and thematic analyses of data from semi-structured interviews based on questionnaires for safety and acceptability, as well as observations of behaviors for the usability dimensions of effectiveness, efficiency, and satisfaction, indicated that participants were engaged and motivated with the ImGTS, with low incidence and severity of VR-related symptoms for both setups and high acceptance of the ImGTS, based on perceptions of the environment and feelings of presence. Usability was also high. These findings suggest that the ImGTS is safe, acceptable, and usable for healthy children. This trial provides initial evidence to guide the methods of subsequent trials testing the safety, acceptability, usability, and clinical effectiveness of the ImGTS in children with cerebral palsy, and, eventually, to guide its deployment.

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1. Introduction

Cerebral palsy (CP) is a group of permanent and non-progressive disorders that affect movement, motor coordination, and posture, occurring due to malformation or damage to one or more parts of the developing fetal or infant brain [1,2]. As a result, children with CP may experience disabilities in cognition, sensation, communication, and behavior [2]. Interventions for CP address body structure, function, and activity, and include medications (anticonvulsants, botulinum toxin), fitness training, and goal-directed training, among others [3,4]. However, only a few have consistently shown effectiveness with strong and high-quality evidence.

Virtual reality (VR) is one such novel approach that could address gaps in traditional rehabilitation strategies. VR uses hardware and software to create a simulated virtual environment (VE) where the user is fully immersed. The computer-generated VE allows the creation of entertaining, engaging scenarios that might otherwise be impossible or unsafe in the real world [5]. In this VE, users experience a sensation of being in a different physical place [6]. VR also uses interactive simulations that respond to a user's movement, such that a user can interact with virtual objects within the VE while performing functional activities. This interaction, coupled with multiple sensory stimulations, further enhances the immersive experience. When VR is used during rehabilitation, the therapist ensures that the environment and the experience support safe practice of skills, are responsive to the needs of the patient, and are tailored to the patient's abilities. Skills learned in the VE are then further trained to ensure their transfer to daily life activities in the real world [7]. Thus, the role of a therapist is important in guiding the patient while practicing the skill in the VE and ensuring the effective application of the skill in the real world. Notably, young children were found to report higher levels of presence and "realness" of the VE when engaging with VR compared to adults 19–65 years of age. This heightened immersion among young children makes them more likely to be influenced by the content [8]. However, it is important to note that children respond differently to VR compared to traditional media [9]. Therefore, the content should be safe and should not raise any ethical concerns [10]. Fortunately, most VR-based therapeutic content focuses on playful designs and child-centric activities, such as make-believe actions [11,12], and is deemed safer, as opposed to traditional online gaming with war as a theme [13].

There are unexplored gaps to be filled in CP management in the Philippines. In a profile study on CP conducted at the Philippine General Hospital [1], 55% of patients diagnosed with CP were younger than 5 years old and were usually functioning at levels equivalent to Gross Motor Function Classification System (GMFCS) Level III (i.e., able to walk with adaptive equipment or move over long distances using a wheelchair) and Manual Ability Classification System (MACS) II (able to handle most objects with impaired speed or quality). These children employ a variety of rehabilitation interventions, including physical therapy (64%) and occupational therapy (29%), while 7% were unreported [1]. However, these traditional therapy treatments are often long and require a rigorous amount of work [14], which can lead to decreased motivation when performing repetitive and demanding exercises [14,15]. This lack of motivation and sustained participation is a challenge in long-term pediatric rehabilitation. Given these challenges, rehabilitation professionals seeking to contribute to improved mobility in children with CP will benefit from novel approaches to rehabilitation that reduce the monotony of traditional therapy and the complexity of delivering personalized sessions that are goal-specific, safe, engaging,

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and adaptive. Such therapeutic strategies must be acceptable, usable, and flexible for a variety of settings, including clinics, homes, schools, or community environments. In this context, ImGTS may be an innovative approach to CP rehabilitation therapy by providing an engaging environment where the children can perform these activities [16]. Gamification provides a complementary design approach to VR to support the motivation and sustained participation of children during rehabilitation [17]. Gamification incorporates game design elements into non-game contexts, such as rehabilitation, in a manner consistent with principles of motor learning and pediatric rehabilitation, including repetition with variation, task-specific practice, timely feedback, "just right" and progressive challenges, and engagement [18]. The combination of gamification elements and therapeutic activities is taken a step further by being set within an immersive virtual environment, thus enhancing user interaction, imagination, and engagement [19]. This combination of approaches is presented as an immersive gamification technology system (ImGTS), specifically integrating immersive technology using virtual reality and gamified therapeutic activities designed to improve motivation, engagement, and rehabilitation outcomes [16]. Commercially available games have been used in rehabilitation [20], but these games are limited in their responsiveness to therapeutic goals, their ability to adapt in difficulty based on the real-time performance of the user, their mechanisms for transferring the learned tasks to real-life scenarios, and their features that would allow clinicians to modify the sessions [21–23]. These limitations highlight the need for a novel ImGTS that considers the therapeutic goals, the input of the therapist, and the needs and abilities of the user.

Thus, this Phase 1 trial aimed to determine the safety, acceptability, and usability of an ImGTS using two setups designed for the rehabilitation of children with CP with mobility limitations, tested among healthy children as a critical initial step in developing an effective VR-based system that could ultimately be integrated into the rehabilitation of children with CP.

This paper evaluates the safety, acceptability, and usability of an ImGTS for use in CP rehabilitation. First, the details of the software and hardware components of the ImGTS are described, along with the recruitment process of the healthy children included in the clinical trial. The study results are then organized by intervention: the head-mounted display (HMD) and the semi-cave automatic virtual environment (semi-CAVE). For each intervention, the findings are subdivided into the characteristics of the participants who used the intervention, the scores of the Virtual Reality Sickness Questionnaire, observations using the BENOGO place probe, and ratings from the usability assessment. Finally, the results of this Phase 1 trial are analyzed, indicating that the ImGTS is safe, acceptable, and usable for mobility rehabilitation of children with cerebral palsy.

2. State of the Art

Management of the motor-associated symptoms of CP includes a variety of approaches, from pharmacologic therapy to physical rehabilitation [24], which aim to maximize the motor functionality of children with CP by improving coordination, balance, and mobility. This section presents key findings from the latest literature on the existing approaches for CP management via VR, which specifically focuses on assessing its effectiveness through improvements in motor functionality, motivation, engagement, cost, and mode of implementation.

Current findings support the use of VR therapy for CP as an assistive technology [25], which demonstrates favorable clinical outcomes and cost-effectiveness, especially in resource-limited settings, particularly when used in combination with standard therapy [26]. Virtual reality for children with CP generally has non-inferior effects compared to traditional therapy across motor and cognitive domains, specifically when using an immersive environment such as the GRAIL, Oculus Rift, CAREN, horse-riding simulators, and treadmill systems. A systematic review that summarizes the effects of these interventions demonstrates that these immersive systems can support improvements in gross motor skills while maintaining motivation in performing the rehabilitation exercises [27]. Additionally, the effect of VR is significant in specific cognitive areas such as attention ($p = 0.026$) and decision-making ($p = 0.01$) [28].

Other studies provide evidence concentrated on benefits to lower-limb function. Treadmill-based training using VR significantly improved the gait of children with CP based on the 6MWT ($p = 0.005$), SSWS ($p < 0.001$), and FAQ-WS ($p = 0.059$) [29]. Aside from gait, VR can also improve balance in children with CP. A meta-analysis of 11 randomized controlled trials conducted between 2010 and 2019 demonstrated significant overall improvement in balance for children with CP (Hedge's g = 0.29, 95% CI 0.10–0.48, $p < 0.05$) who were exposed to VR-based games. These studies assessed balance using different indicators such as the M-ABC, PBS, BBS, Nintendo Wii Fit Balance Board Score, TUG, and PBM. Moreover, this positive effect may not be attributable to the duration and frequency of VR game administration. Given that most of the included studies used VR in combination with conventional therapy, these findings suggest that VR can be an effective adjunct to traditional rehabilitation exercises for children with CP [30]. Another paper also demonstrated the same effect of VR on balance (SMD = 0.89, 95% CI 0.14–1.63, $p = 0.02$), which was examined across static, dynamic, and combined static–dynamic balance [31].

VR therapy for upper motor function in children with CP remains elusive. An earlier study demonstrated a positive effect of using an 8-week home-based VR intervention. This pilot implementation showed initial promising results in improving fine motor skills by observing changes using BOT-2 and PMAL [32]. These findings were inconsistent with a meta-analysis of four randomized control trials that revealed a small (SMD = 0.39, 95% CI 0.01–0.76, $p = 0.04$) magnitude of effect favoring VR over traditional therapy in the improvement of upper motor skills in these children [33]. However, a recent attempt at describing the effect of VR on upper extremity movements through a randomized control trial of 30 children with spastic hemiplegic CP revealed significant changes in grip strength ($p = 0.011$) detected via a dynamometer when VR-based exercises for task-oriented training were used alongside neurological developmental therapy [34].

These improvements are linked to broader effects in QoL and ADL, which have been observed by different studies and may be affected by different factors related to the implementation of the VR interventions. A meta-analysis of 41 RCTs focusing on the use of VR intervention for children and adolescents with CP revealed great effects (SMD = 1.46, 95% CI 0.71–2.2, $p = 0.0001$) on ADLs, which may have affected several aspects of the intervention, where a duration of 4–6 weeks with 3–4 sessions/week using the Xbox 360 Kinect (Microsoft, Redmond, WA, USA) in a non-immersive VR showed particular improvement in ADLs [35]. Meanwhile, another study recommends a dosage of 101–200 min/week over $\leq$6 weeks (SMD = 0.44, 95% CI 0.11–0.57, $p = 0.08$) to provide optimal results [36]. In addition, a systematic review of 10 studies showed benefits to overall quality of life in terms of level of participation, motivation, and the Childhood Health Assessment Questionnaire [16].

Not only do these studies support the use of VR therapy for CP in terms of physical, cognitive, and functional benefits, but they also show the potential of using the system for home-based therapy, allowing continuity of care beyond clinic hours [20], while maintaining effectiveness in motor and postural improvements [37,38]. Access to conventional physical therapy and rehabilitation in the Philippines is constrained by poverty, archipelagic geography, inequitable distribution of healthcare infrastructure and professionals, and heterogeneous political priorities in the country [39]. As a result, there is a strong need for suitable therapeutic options that can be delivered even in areas where healthcare professionals may not be regularly available. Home-based VR therapies may also lessen the usual cost of physical rehabilitation due to the commercial availability of VR hardware [40] and reduced transportation expenses, especially when using semi-immersive platforms [41,42].

Given the expected benefits of VR technology as a more accessible and effective modality for physical rehabilitation, robust real-world evidence is necessary to substantiate this claim. This Phase 1 clinical trial would provide preliminary evidence on the safety, usability, and accessibility of the ImGTS system in resource-limited settings such as in the Philippines. The data generated by this study can be used to justify the application of this technology to actual patients with CP for the Phase 2 clinical trial. Moreover, the game-specific observations and findings from this trial can also inform future refinements of VR game design.

3. Materials and Methods

This study was approved by the University of the Philippines Manila Research Ethics Board (UPMREB 2021-0371-01). The two components of the ImGTS (software and hardware components) were conceptualized prior to the conduct of this study [43–49]. The software component was finalized after a focus group discussion with relevant stakeholders, among whom were IT or game development experts and those who have extensive experience with care for CP patients, including developmental pediatricians, physical therapists, and other healthcare providers. They provided various practice-informed insights focusing on the feasibility of VR therapy in the Philippine setting, design considerations, and potential challenges in implementing the VR therapy for children with CP. The participants proposed task-based and goal-oriented activities for the VR games in the first FGD. Furthermore, these insights provided impetus for the development of a relatable game storyline for children. All these elements were incorporated in the prototype games, which were tested by the panel of experts. From this, they provided descriptions of their immersive experience, which further fueled refinements of the games. The refined game was then tested in a second FGD. Feedback from this second FGD was considered and integrated into the game design, such as in the improvement of the game environment (e.g., color and lighting considerations) and the virtual companion (e.g., expanding the role of the character to become an extension of the therapist), which would generate a safer and more engaging environment for the patient. The finalized game design (Mission to Planet Axel version 1.0) consisted of three games: 'Alien invasion,' 'Lock 'em up,' and 'Walkey Moley.' 'Alien invasion' is a bowling-type game that targets the improvement of balance by letting the participants reach for balls beyond their arm's reach. It also aims to exercise arm swing. 'Lock 'em up' targets the patient's limb muscles during the exercise. This strengthens the user's limbs through squats. The activity's goal is to close all the doors to lock out approaching aliens. A door will close halfway when the user performs a successful squat while bringing the lever in front of them up and down. Performing 10 successful squats closes all five doors. This also marks the success of the activity. 'Walkey Moley' tests the endurance of the user walking long distances at a specific speed. To keep score in the activity, the user is asked to count the tiles and any flying object that pass them. The success of the activity is determined when the desired distance has been covered. As the tests progress, the difficulty level is also increased, either by adjusting the distances between the need-to-reach objects or the speed following the system architecture framework (Figure S1). These games embody gamification elements that enhance motivation within therapeutic activities [50]. The three games, taken together, present a narrative where the user assists the space captain with a mission to go back to their home planet, creating meaning and purpose for the user. Other gamification elements include opportunities for creativity through avatar customization, accomplishment and ownership through earning points and trophies, awareness of the results of their actions through feedback from the virtual companion, and unpredictability and curiosity through the aliens and other objects that appear throughout the games, keeping the user engaged. The participants also receive a trophy every time they finish a game, which they display in a trophy case, symbolizing their achievements. A robot virtual companion called Captain Max assists them throughout the intervention. Captain Max has encouraging voice lines that the therapist can play around with freely during the games. The rewards, like trophies, and the encouraging voice lines reinforce a positive feedback loop to the participants. These gamification elements (progression, rewards and achievements, and feedback loops) were incorporated into the software (Figures S2–S6).

The hardware component includes the HMD and the semi-CAVE setups. The HMD is a commercially available device that uses handheld controllers in addition to the head-mounted apparatus to control movement while in the VE. The semi-CAVE uses three screens positioned at two corners of the room, each with a ceiling-mounted short-throw projector in front. The users sit in the middle of the area, giving them a viewing angle of roughly 180 degrees. The users interact with the system through motion sensors positioned at the corners of the area. To one side of the area is a sufficiently powerful computer running the software.

The study was conducted in the UP College of Allied Medical Professions Clinic for Therapy Services, where one part of the clinic, measuring about 26.5 square meters, was dedicated to the VR experience. Five people (i.e., the participant, caregiver, technical team member, physical therapist, and physician) at most were in the room during testing.

In this parallel randomized trial, the study population involved healthy children recruited indirectly through advertisements in large-group emails for employees and staff of the University of the Philippines. Volunteers were included if they were 6 to 12 years old and demonstrated fine and gross motor abilities within the norm for the child's age, as measured by the BOT-2. Volunteers were excluded if they were previously diagnosed with any developmental disorder including CP, had had episodes of seizures or been previously diagnosed as having epilepsy, had a history of motion sickness, or were unable to follow one-step instructions.

Eligible participants were then randomized to receive the ImGTS intervention using one of two setups: HMD or semi-CAVE. The randomization was computer-generated. The recruitment of participants continued until 15 participants had completed the experience with the HMD, and a separate 15 participants had completed the experience with the semi-CAVE.

The appropriate verbal assent and informed consent were obtained from each child and their respective parents or legal guardians during the recruitment phase (Files S1 and S2). All participants and their legal guardians received a brief explanation of the study's purpose and procedures, as well as information about their rights, responsibilities, and the confidential handling of their data. Once legal guardians consented and children of age assented, the children took part in four testing sessions using one of the two setups based on their random allocation to the group. For each testing session, the ImGTS was used for 10 to 20 min at a time, with 5 to 20 min of rest in between each use. The therapist provided guidance to the participants, providing supervision, contact guarding, or assistance as necessary, throughout the sessions. A medical doctor was on standby in case adverse events arose.

The use of the ImGTS was followed by a semi-structured interview using questions from the Virtual Reality Sickness Questionnaire (VRSQ) [51] to assess safety; and the BENOGO Place Probe questionnaire [52] and the Measurements, Effects, Conditions Spatial

Presence Questionnaire (MEC-SPQ) [53] to assess acceptability in terms of perceptions of the virtual environment and the experience, and the feeling of presence, respectively. To further assess the feeling of presence of the children while in the virtual environment, the children were also asked to do a sketch map, a component of the BENOGO Place Probe, to elicit what they considered to be the key or most memorable features of the virtual environment [54]. In addition, the usability of the ImGTS was assessed across the dimensions of effectiveness, efficiency, and satisfaction by observing behaviors indicating the children's ability to complete the tasks without interruption or resetting and within the given time limits (effectiveness), the children's ability to perform the tasks without needing any assistance or showing any difficulty (efficiency), and their satisfaction for each task (File S3).

Descriptive statistics were used to analyze quantitative data from the VRSQ, BENOGO Place Probe, and MEC-SPQ. Demographic information was also analyzed using descriptive statistics. Specifically, age and prior VR experience were analyzed using mean and standard deviation, while sex was analyzed using frequency and percentage. VRSQ scores for safety are reported as the means (standard deviation) of the total VRQQ score, oculomotor score, and disorientation score. The scores for perceptions of the virtual environment for acceptability using the BENOGO Place Probe are reported as frequencies. The scores for feelings of presence for acceptability using the MEC-SPQ are reported as means and standard deviations. The effectiveness and efficiency dimensions of usability were scored as frequencies and percentages, while the satisfaction dimension of usability was analyzed as means and standard deviations.

Thematic analysis was employed for qualitative data from questions from the BENOGO Place Probe, specifically about the experiences of the children while in the virtual environment [52]. One researcher initially coded the responses, including grouping the responses as positive or negative impressions of the experience. Two other researchers reviewed and confirmed the themes from the coded responses. Moreover, scoring of sketch maps was done by two independent reviewers as to map goodness (rates the usability of the map; maximum of three points), object classes (measures completeness; the higher the number of object classes correctly identified, the higher the completeness), and relative object positioning (measures accuracy; maximum of two points). Disagreements in qualitative analyses were resolved through consensus.

Analyses were based on all available data, and missing data for given variables were excluded from analyses involving those variables. This approach minimized data loss and ensured that no participant was excluded due to missing data.

4. Results

4.1. Head-Mounted Display System

The participants who used the HMD were mostly female, with a mean (SD) age of 10.07 (1.81) years (Table 1). The majority are currently in elementary school and in the care of their parents. The participants were all well at the time of the testing, and only one participant reported taking medications (vitamins). The most common hobby of the participants was physical activity, such as running, swimming, and playground or street games (80%), and this was followed by playing computer or cellphone games (53.33%). Only five out of the fifteen participants had prior experience with VR games, specifically with using HMDs.

Table 1. Demographic characteristics of participants who used head-mounted display system (n = 15).

Characteristic	Value
Age in years, M (SD)	10.07 (1.81)
Sex, n (%)	
Male	7 (46.67)
Female	8 (53.33)
Educational attainment, n (%)	
No grade completed	1 (6.67)
Elementary undergraduate	12 (80)
Elementary graduate	2 (13.33)
Primary caregiver, n (%)	
Parent	11 (73.33)
Relative	4 (26.67)
Current illness (if any), n (%)	0
Current medications (if any), n (%)	1 (6.67)
Hobbies, n (%) [a]	
Outdoor physical activities	12 (80)
Computer or cellphone games	8 (53.33)
Watching TV or videos	4 (26.67)
Using a cellphone	4 (26.67)
Musical instruments	2 (13.33)
Drawing	2 (13.33)
Toys	2 (13.33)
VR experience, n (%)	
Yes, an HMD	5 (33.33)
No	10 (66.67)

[a] participants could give more than 1 response.

4.2. HMD: BENOGO Place Probe

4.2.1. Descriptions

Thematic analysis of the descriptions used by the participants to describe the VR experience revealed three themes: objective descriptions of the activities, subjective descriptions of the VR experience, and physical reactions to the game (Appendix A.1). The most frequent theme was objective descriptions of the activities (‘Bowling Game’ [n = 14], ‘Walkey Moley’ [n = 13], and ‘Lock ‘Em Up’ [n = 12]) (Box 1). Of these three games, ‘Bowling Game’ was most often mentioned by the participants across the four sessions. Other activities that were described were the counting part of ‘Walkey Moley’ (n = 7), initializer activities such as traditional bowling and piano playing (n = 7), riding the elevator (n = 4), receiving rewards (n = 3), and customizing their avatar (n = 2). Although it accompanied the walking game, less than half of the participants mentioned counting the mini spaceships.

Box 1. Objective description of games after using the head-mounted display system.

“Bowling, squat”
“Throwing the ball, walking for 10 steps”
“Threw the ball towards cockroach, walking, counted the spaceships, squatted, door closing”
“Bowling, there’s an alien who talks and gives instructions, close the doors so the aliens won’t come in, walking and seeing spaceships in the sky”
“Defeat aliens with guidance of Capt Max the robot Bowling, walking around, particles appear (teddy bear, stars, candies)”
“There’s a robot, an alien, a ball, spaceship, elevator”
“Threw the ball at the aliens, got a trophy after the first game. pulling the lever so aliens won’t come in, walking to find birds.”

Subjective descriptions of the VR experience were mostly positive responses (“Very fun, amusing”, “enjoyed, relaxed”, “fun”, “exciting”) (Box 2). Negative responses included

"Too easy", "Boring", and "Scared". Three participants expressed tiredness ("A little tiring from squatting and walking").

Box 2. Overall subjective reaction/description after using the head-mounted display system.

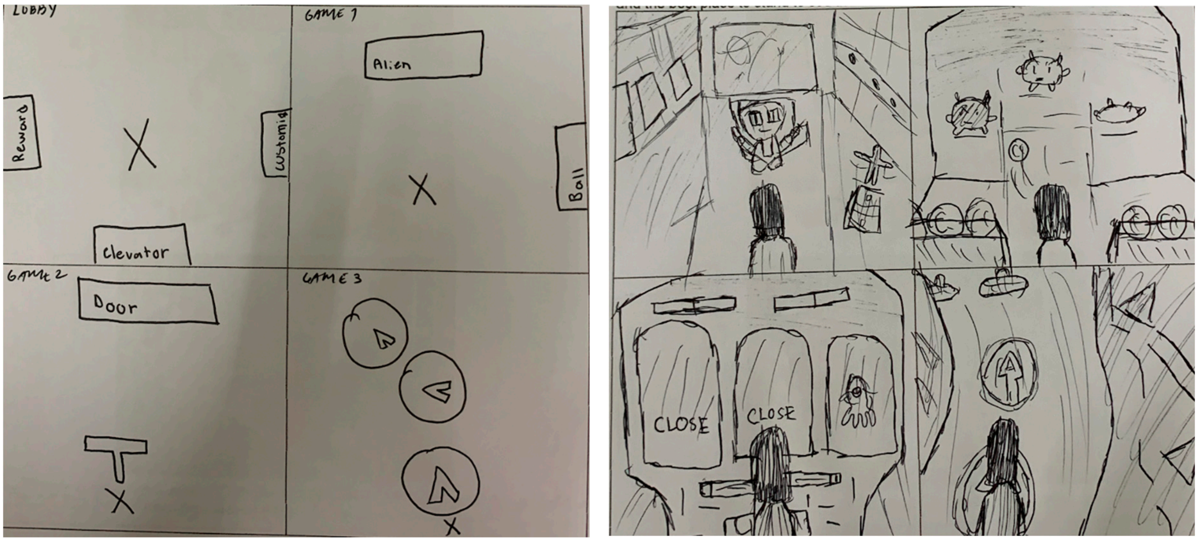
Positive	**Negative**
"Very fun. Amusing"	"Scared of aliens"
"Enjoyed. Excited"	"Vision is a little blurry but can see them if bigger"
"Fun experience. Sad that it's the last session."	"Bored"
"Interesting. Wonderful to play the game"	"Too easy"

4.2.2. Map Drawn After Using the Head-Mounted Display System

The average scores of the sketch maps are indicated in Table 2. There is an average score of 1.71 for map goodness, which indicates moderate representation in the maps drawn by the participants. About four to five objects were drawn in each map, and about three to four objects were correctly placed per map across the four testing sessions. Figure 1A,B illustrate some examples of the maps drawn by the participants.

Table 2. Sketch map scoring per test using the head-mounted display system.

Components, M (SD)	Test 1	Test 2	Test 3	Test 4
Map goodness	1.43 (0.86)	1.70 (0.70)	1.80 (0.66)	1.9 (0.66)
Object classes	4.13 (2.05)	4.57 (1.65)	4.87 (1.63)	4.73 (1.78)
Relative object positioning	1.83 (0.99)	2.20 (0.61)	2.37 (0.61)	2.23 (0.63)



(A) (B)

Figure 1. Representative sketch maps drawn by participants who used the head-mounted display. Notable to one participant (**A**) was the orientation of themself, symbolized by the letter X, and specific objects in the lobby and each of the three games. Another participant (**B**) found the characters (e.g., themself, Captain Max, and the alien) memorable.

4.2.3. Features of the Virtual Environment Recalled After Using Head-Mounted Display System

The most prominent features are those related to the Setting (n = 57), which includes the elevator, the trophy, and the lobby; the Guide (n = 44), which was the robot or Captain Max; and Alien Invasion (n = 33), which includes responses such as "Aliens," "Throwing ball at aliens," and "Kill aliens." There was an increasing prominence of the Guide as a feature as tests progressed. Other, less prominent features are listed in Table 3. The Walkey Moley Game includes features such as "walking" or "running," "spaceship," or "birds." The Initiator Game, which includes regular bowling and Avatar customization, was less frequently mentioned. The Lock 'Em Up Game includes "Closing the door." Affective descriptions ("Amusing," "Effective," and "Simple") were not reported across all tests.

Table 3. Number of features under different categories per test using the head-mounted display system.

Categories, *n* (%)	Test 1 (*n* = 45)	Test 2 (*n* = 45)	Test 3 (*n* = 43)	Test 4 (*n* = 44)
Setting	10 (22.22)	19 (42.22)	13 (30.23)	15 (34.09)
Guide	9 (20)	11 (24.44)	12 (27.91)	12 (27.27)
'Alien Invasion'	7 (15.56)	10 (22.22)	9 (20.93)	7 (15.91)
'Walkey Moley'	10 (22.22)	2 (4.44)	3 (6.98)	3 (6.82)
Initiator	2 (4.44)	4 (8.89)	4 (9.30)	4 (9.09)
Avatar customization	2 (4.44)	2 (4.44)	2 (4.65)	1 (2.27)
'Lock 'Em Up'	2 (4.44)	0	0	2 (4.55)
Affective	3 (6.67)	0	0	0

4.2.4. Pictures Selected to Represent the VR Experience After Using the Head-Mounted Display System

Most of the participants chose a photo of a boy with an alien to be the most representative of their VR experience. The most frequent reason for this across all tests is the similarity between the object/character and the object/character in the VE, and includes responses such as "Outer space, galactic," presence of "Aliens," "Looks like the robot" and "alien and spaceship" (Table 4). Similarity in action includes responses such as "Alien and it wont let me go," "robot talking and aliens," and "Alien, robot helping to finish the game." Responses that impact feelings/mood include "Made me interact with beings from space," "Things in the VE are interesting," and "I got curious with the things in the VE."

Table 4. Thematic analysis of responses describing the most preferred photo using the head-mounted display system.

Themes, *n* (%)	Test 1 (*n* = 9)	Test 2 (*n* = 11)	Test 3 (*n* = 12)	Test 4 (*n* = 9)
Similarity in character/object	7 (77.78)	9 (81.82)	7 (58.33)	5 (55.56)
Similarity of action	2 (22.22)	1 (9.09)	4 (33.33)	3 (33.33)
Impact on feelings/mood	0	1 (9.09)	1 (8.33)	1 (9.09)

4.2.5. Sounds

For all tests, the most frequently remembered sound was the voice of the robot guide. Most of the participants described the robot voice as calming and easily understandable. Other sounds mentioned are indicated in Table 5. Sound effects include the sound of the elevator door, spaceship, piano, and bouncing ball. Other characters identified that the created sounds are the aliens.

Table 5. Number of responses for prominent sounds per test using the head-mounted display system ($n = 15$).

Categories, *n* (%)	Test 1	Test 2	Test 3	Test 4
Guide	13 (86.67)	10 (66.67)	12 (80)	13 (86.67)
Background music	3 (20)	0	2 (13.33)	2 (13.33)
Sound effects	5 (33.33)	4 (26.67)	5 (33.33)	4 (26.67)
Other characters	2 (13.33)	2 (13.33)	1 (6.67)	1 (6.67)

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4.2.6. Words

The six most frequently mentioned words that described the overall VR experience are illustrated in Figure 2. These include 'fun' (n = 33, 36.67%), 'exciting' (n = 32, 35.56%), 'bowling' (n = 19, 21.11%), 'beautiful' and 'happy' (n = 18, 20%), 'robot' (n = 15, 16.67%), and 'relaxing' (n = 11, 12.22%). Most of these words are positive affective differentials describing the virtual experience (fun, exciting, beautiful and happy, relaxing), while the others were features of the VR (bowling, robot). Negative affective words were also found. For Test 1, the word 'scary' was one of the top six most mentioned words, and the word 'nervous' was identified in Tests 2 and 4.

(**a**) Test 1

(**b**) Test 2

(**c**) Test 3

(**d**) Test 4

Figure 2. Word cloud illustrations of the six most common descriptors of virtual reality experience using the head-mounted display system across the four test sessions. The descriptions were obtained for Tests 1–4 pertaining to each of the testing sessions.

4.2.7. Semantic Differentials

Tables 6–9 summarize the participants' responses for the semantic differentials. Highlighted in the tables are the response categories with the highest frequencies.

The participants who used the HMD rated the technological quality of the VE positively (Table 6). The graphics depicted in the VE were said to be 'clear,' 'realistic,' and 'accurate.' Although opinions varied regarding the believability of the images, the responses for most of the sessions leaned towards 'believable.' The movement of the images in the

VE was described as being 'smooth,' 'unbroken,' and 'consistent,' with variable results for 'fast/slow.' When rating the activities performed in the VE, the majority of participants said that they felt 'active,' 'free,' 'oriented,' 'inside,' and 'mobile' (Table 7).

Table 6. Frequency of HMD users' ratings for the technology differentials under the BENOGO Place Probe across four testing sessions (*n* = 15).

	Test 1					Test 2					Test 3					Test 4					
	V	**Q**	**N**	**Q**	**V**	**V**	**Q**	**N**	**Q**	**V**	**V**	**Q**	**N**	**Q**	**V**	**V**	**Q**	**N**	**Q**	**V**	
Grainy	0	3	1	2	9	0	2	1	4	8	0	3	0	3	9	0	0	1	5	9	Clear
Realistic	9	2	2	1	1	6	5	1	2	1	6	4	2	2	1	6	4	1	4	0	Unrealistic
Unbelievable	2	1	3	4	5	2	6	0	2	5	1	4	1	3	6	0	2	1	4	8	Believable
Distorted	0	0	1	5	9	0	0	2	3	10	0	2	1	4	8	0	1	1	4	9	Accurate
Smooth	11	3	0	1	0	9	5	0	0	1	9	5	0	1	0	10	2	1	1	1	Jerky
Broken	0	1	1	2	11	1	3	1	0	10	1	1	0	3	10	0	2	0	4	9	Unbroken
Slow	2	2	5	2	4	1	5	4	2	3	1	3	3	2	6	0	3	5	2	5	Fast
Consistent	9	0	2	2	2	11	4	0	0	0	9	2	3	1	0	8	1	3	2	1	Erratic

Color legend: green—highest frequency for Test 1; blue—highest frequency for Test 2; orange—highest frequency for Test 3; yellow—highest frequency for Test 4. V very, Q quite, N neither.

Table 7. Frequency of HMD users' ratings for the activity differentials under the BENOGO Place Probe across four testing sessions (*n* = 15).

	Test 1					Test 2					Test 3					Test 4					
	V	**Q**	**N**	**Q**	**V**	**V**	**Q**	**N**	**Q**	**V**	**V**	**Q**	**N**	**Q**	**V**	**V**	**Q**	**N**	**Q**	**V**	
Passive	0	0	1	2	12	0	2	0	4	9	0	0	1	2	12	0	1	0	3	11	Active
Free	10	1	2	1	1	5	6	2	2	0	8	4	1	2	0	8	3	1	3	0	Restricted
Disoriented	1	4	2	2	6	1	0	0	6	8	0	1	1	4	9	0	1	1	3	10	Oriented
Inside	12	2	0	1	0	11	1	1	1	1	12	1	2	0	0	10	3	2	0	0	Outside
Mobile	10	3	1	0	1	10	2	1	0	2	11	2	2	0	0	9	4	1	1	0	Immobile

Color legend: green—highest frequency for Test 1; blue—highest frequency for Test 2; orange—highest frequency for Test 3; yellow—highest frequency for Test 4. V very, Q quite, N neither.

Table 8. Frequency of HMD users' ratings for the physical differentials under the BENOGO Place Probe across four testing sessions (*n* = 15).

	Test 1					Test 2					Test 3					Test 4					
	V	**Q**	**N**	**Q**	**V**	**V**	**Q**	**N**	**Q**	**V**	**V**	**Q**	**N**	**Q**	**V**	**V**	**Q**	**N**	**Q**	**V**	
Small	1	3	2	5	4	1	1	2	5	6	0	3	3	3	6	1	2	2	2	8	Big
Empty	0	1	1	7	6	1	1	0	9	4	0	1	2	5	7	0	0	3	1	11	Full
Light	8	5	1	1	0	7	6	0	2	0	7	6	1	0	1	10	4	1	0	0	Dark
Enclosed	3	0	2	6	4	4	3	2	3	3	5	4	0	3	3	1	4	1	3	5	Open
Permanent	6	1	2	1	5	5	1	1	1	7	3	1	0	4	7	2	2	0	3	8	Temporary
Colorless	0	1	1	5	8	0	0	1	6	8	0	0	1	5	9	0	0	1	3	11	Colorful
Static	3	1	1	2	8	3	3	1	1	7	3	0	1	4	7	2	1	0	4	8	Moving
Responsive	8	4	1	0	2	8	2	1	1	3	11	2	1	0	1	10	2	2	1	0	Inert
Far	2	1	3	3	6	1	3	2	4	6	1	1	3	4	6	1	1	3	2	8	Near
Untouchable	1	2	1	2	9	2	3	2	1	7	2	1	3	2	7	0	1	1	3	10	Touchable

Color legend: green—highest frequency for Test 1; blue—highest frequency for Test 2; orange—highest frequency for Test 3; yellow—highest frequency for Test 4. V very, Q quite, N neither.

The VE itself was rated as being 'big' and 'full,' with variable responses for 'open/enclosed.' The environment was also described as being 'light' and 'colorful,' and its appearance made the participants feel that it was 'moving,' 'responsive,' 'near,' and 'touchable.' There was an inconsistency in the responses related to the environment's feeling of permanence, but most responses favored 'temporary' over 'permanent.' A summary of these responses is in Table 8. The appearance of the virtual environment had a positive effect on the mood of the participants who used the HMD (Table 9). The environment was rated as 'beautiful,' 'pleasant,' 'relaxing,' 'harmless,' 'exciting,' 'interesting,' 'memorable,' 'meaningful,' 'understandable,' and 'significant.'

Table 9. Frequency of HMD users' ratings for the affective differentials under the BENOGO Place Probe across four testing sessions (n = 15).

	Test 1					Test 2					Test 3					Test 4					
	V	**Q**	**N**	**Q**	**V**	**V**	**Q**	**N**	**Q**	**V**	**V**	**Q**	**N**	**Q**	**V**	**V**	**Q**	**N**	**Q**	**V**	
Ugly	0	0	1	3	11	0	0	1	1	13	0	0	1	3	11	0	1	1	1	12	Beautiful
Pleasant	10	3	1	1	0	9	5	0	1	0	9	4	0	1	1	10	4	1	0	0	Unpleasant
Stressful	0	0	1	3	11	0	1	1	3	10	0	3	1	2	9	0	0	1	4	10	Relaxing
Harmful	1	0	2	1	11	0	0	0	3	12	0	0	1	0	14	0	0	0	1	14	Harmless
Exciting	12	0	0	2	1	10	4	1	0	0	11	3	1	0	0	11	2	2	0	0	Boring
Interesting	11	2	0	1	1	9	3	1	2	0	11	2	2	0	0	11	2	1	0	1	Uninteresting
Memorable	8	4	1	1	1	7	3	2	3	0	10	2	2	1	0	10	4	1	0	0	Forgettable
Meaningful	9	4	2	0	0	8	2	3	2	0	10	2	2	1	0	11	1	2	0	1	Meaningless
Confusing	0	3	3	0	9	1	1	1	3	9	0	0	2	2	11	1	1	0	3	10	Understandable
Significant	8	4	1	1	1	6	6	2	1	0	9	2	3	0	1	12	1	2	0	0	Insignificant

Color legend: green—highest frequency for Test 1; blue—highest frequency for Test 2; orange—highest frequency for Test 3; yellow—highest frequency for Test 4. V very, Q quite, N neither.

4.2.8. Feelings of Presence

The participants who used the HMD had average scores during the first two sessions for most of the subscales of the MEC-SPQ, but these scores generally improved (i.e., higher mean scores or smaller standard deviations) by the last session (Table 10). The top three highest-scoring subscales varied per testing session. For the first testing session, these were spatial presence: self-location (M = 4.02 $\pm$ 1.05), visual spatial imagery (M = 3.95 $\pm$ 1.07), and domain-specific interest (M = 3.93 $\pm$ 1.17). The subscales with the highest scores during the second testing session were attention allocation (M = 4.53 $\pm$ 0.65), spatial presence: self-location (M = 4.12 $\pm$ 0.92), and spatial situation model (M = 4.07 $\pm$ 0.90). By the third and fourth testing sessions, the highest-scoring subscales were attention allocation (M = 4.45 $\pm$ 0.65), domain-specific interest (M = 4.37 $\pm$ 0.82), and spatial presence: self-location (M = 4.32 $\pm$ 0.77). The subscale with the lowest score across the four testing sessions using the HMD was suspension of disbelief. The scores under this subscale were also the most variable, resulting in a wider standard deviation.

Table 10. Mean scores for the MEC spatial presence questionnaire across four testing sessions after using the head-mounted display system (n = 15).

Subscale, M (SD) [a]	**Test 1** [b]	**Test 2**	**Test 3**	**Test 4**
Attention allocation	3.86 (1.07)	4.53 (0.65)	4.45 (0.65)	4.52 (0.72)
Spatial situation model	3.88 (1.10)	4.07 (0.90)	4.27 (0.90)	4.13 (1.03)
Spatial presence: self-location	4.02 (1.05)	4.12 (0.92)	4.32 (0.77)	4.35 (0.88)
Spatial presence: possible actions	3.63 (1.32)	3.93 (1.19)	4.05 (1.02)	4.08 (1.12)
Higher cognitive involvement	3.39 (1.33)	3.43 (1.27)	3.98 (0.95)	3.78 (1.19)
Suspension of disbelief	2.95 (1.61)	2.93 (1.59)	3.40 (1.44)	3.38 (1.47)
Domain-specific interest	3.93 (1.17)	3.80 (1.12)	4.37 (0.82)	4.30 (1.08)
Visual spatial imagery	3.95 (1.07)	3.97 (1.13)	4.20 (0.97)	4.13 (1.14)

[a] score out of 5, [b] 1 missing response.

4.3. Usability Assessment

The participants were able to demonstrate high effectiveness, high efficiency, and high satisfaction with the VR experience. The majority of participants were able to complete the experience within the allotted time (Table 11). A small number of non-completers were observed from Test 1 to Test 3, but all participants were able to complete the activities by Test 4. Slight differences were noted in the times spent on each of the three games, but due to the small sample size, it is difficult to determine if these differences are significant.

Table 11. Frequency distribution of participants who completed specific components of the virtual reality experience using head-mounted display.

Component	Test 1 (n = 15)		Test 2 (n = 14)		Test 3 (n = 15)		Test 4 (n = 15)	
	C, n (%)	t, M (SD)	C, n (%)	t, M (SD)	C, n (%)	t, M (SD)	C, n (%)	t, M (SD)
Initiator	15 (100)	-	14 (100)	-	15 (100)	-	15 (100)	-
Avatar room	15 (100)	-	13 (92.86)	-	15 (100)	-	15 (100)	-
Lobby and elevator	15 (100)	-	13 (92.86) [a]	-	15 (100)	-	15 (100)	-
Alien bowling	13 (86.67)	1.15 (0.27) [a]	13 (92.86)	1.02 (0.3) [a]	14 (93.33)	1.22 (0.38) [a]	15 (100)	1.43 (0.67)
Lock 'Em Up	14 (93.33)	1 (1.07) [a]	12 (85.71)	1.13 (0.85) [a]	15 (100)	1.03 (0.98) [a]	15 (100)	0.88 (1.17)
Walkey Moley	14 (93.33)	2.25 (0.87) [a]	12 (85.71)	1.75 (0.57) [a]	15 (100)	2.33 (0.53) [a]	15 (100)	3.1 (1.3)
Mean effectiveness	95.55	-	91.67	-	98.89	-	100	-

C task completion, t time in minutes. [a] missing responses.

The participants predominantly did not demonstrate having difficulty with any of the key tasks listed in Table 12. When comparing the four testing sessions, an increase in ease of use could be observed as the sessions progressed. Difficulties were most often encountered during customization of the participant's avatar.

Table 12. Frequency distribution of participants who did not experience difficulties while using the head-mounted display system across four testing sessions (n = 15).

Task (%)	Test 1 (n = 15)	Test 2 (n = 14)	Test 3 (n = 15)	Test 4 (n = 15)
Select leg	100	92.86	100	100
Do T-pose	100	100	100	100
Stand still until scanning is complete	100	92.86	100	100
Click 'Customize' button	100	100	100 [a]	100
Select suit parts	86.67	78.57	85.71 [a]	93.33
Select suit variant	80	78.57	85.71 [a]	93.33
Click 'Confirm' button	100	100	100 [a]	100
Respond to robot companion prompts	93.33	100	100	100
Locate and click the elevator button to open it.	93.33	100	100	100
Locate and click the button for Game 1	100	100	93.33	100
Locate and click the button for Game 2	100	100	100	100
Locate and click the button for Game 3	100	92.86	100	100
Take the trophy and place it on the appropriate podium	93.33	92.86	100	100
Place foot on the platform	100	92.86	93.33	100
Confirm understanding of Game 1 instructions	100	92.86	93.33	100
Click 'Start Game' button for Game 1	100	92.86	93.33	100
Pick up a ball	100	92.86	93.33	100
Aim and release the ball correctly	93.33	92.86	93.33	100
Confirm understanding of Game 2 instructions	93.33	100	100	100
Click 'Start Game' button for Game 2	93.33	100	100	100
Bend and pull the lever	93.33	100	100	100
Confirm understanding of Game 3 instructions	93.33	92.86	100	100
Click 'Start Game' button for Game 3	93.33	92.86	100	100
Count the number of the mini-spaceships	93.33	92.86	100	100
Step on the tiles	100	92.86	100	100
Mean efficiency	96	94.57	97.26	99.47

[a] missing responses. Satisfaction ratings were consistently high across the four testing sessions (Table 13). Of the three games, 'Walkey Moley' had the highest rating (M = 4.85 ± 0.12).

Table 13. The mean satisfaction ratings of participants for each component of the virtual reality experience using the head-mounted display system.

Task, M [a]	Test 1 (*n* = 15)	Test 2 (*n* = 14)	Test 3 (*n* = 15)	Test 4 (*n* = 15)
Initiator	4.87	4.93	5 [b]	5
Avatar room	4.87	4.92 [b]	5 [b]	5
Lobby	4.87	4.93	5 [b]	5
'Alien Bowling'	4.67	4.71	5 [b]	4.8
'Lock 'Em Up'	4.6	4.79	4.93	5
'Walkey Moley'	4.67	4.86	4.93	4.93
Mean efficiency	4.76	4.86	4.98	4.96

[a] score out of 5, [b] missing response.

4.4. Virtual Reality Sickness Questionnaire

The mean VR sickness scores of the participants who used the HMD were generally low across the four testing sessions (Table 14). Out of the fifteen participants, seven (46.67%) experienced at least one oculomotor or disorientation symptom after Test 1, eight (53.33%) after Test 2, three (20%) after Test 3, and five (33.33%) after Test 4 (Appendix A.1). The majority of these symptoms were 'slight' in intensity, except for one instance of 'moderate' fatigue and fullness of head during Test 1 and one instance of 'moderate' fatigue during Test 4. Among the nine symptoms, the most common symptom that the participants reported was fatigue, which is also the only symptom consistently reported across the four testing sessions.

Table 14. A frequency distribution of participants who experienced oculomotor and/or disorientation symptoms before and after the virtual reality experience using the HMD system (*n* = 15).

Symptom, *n* (%)	Test 1		Test 2		Test 3		Test 4	
	Before	After	Before	After	Before	After	Before	After
General discomfort	1 (6.67)	1 (6.67)	0	2 (13.33)	0	0	0	0
Fatigue	1 (6.67)	5 (33.33) [a]	2 (13.33)	4 (26.67) [c]	1 (6.67)	2 (13.33) [b]	2 (13.33)	5 (33.33) [b]
Eye strain	1 (6.67)	0	0	1 (6.67)	0	0	0	0
Difficulty focusing	1 (6.67)	2 (13.33) [b]	0	0	0	0	0	0
Headache	1 (6.67)	1 (6.67)	1 (6.67)	1 (6.67)	0	0	0	0
Fullness of head	1 (6.67)	1 (6.67)	0	1 (6.67)	0	0	0	1 (6.67)
Blurring of vision	1 (6.67)	2 (13.33)	0	1 (6.67)	0	1 (6.67)	0	0
Dizzy (eyes closed)	1 (6.67)	1 (6.67)	1 (6.67)	2 (13.33)	1 (6.67)	0	1 (6.67)	0
Vertigo	0	1 (6.67)	0	1 (6.67)	0	0	0	0
Participants with ≥1 symptom, *n* (%)	4 (26.67)	7 (46.67)	4 (26.67)	8 (53.33)	2 (13.33)	3 (20)	3 (20)	5 (33.33)
Total score, M (SD)	-	4.06 (6.44)	-	3.28 (4.35)	-	0.78 (1.62)	-	1.89 (3.30)

[a] 1 prevalent case with increased intensity, [b] 1 prevalent case with unchanged intensity, [c] 2 prevalent cases with unchanged intensity.

A decreasing trend in symptoms reported could be observed across the four testing sessions. By Test 3 and Test 4, only two out of the nine symptoms were reported by the participants, but an increase in frequency for 'fatigue' was noted. These patterns were reflected in the resulting total VR sickness scores, where a decreasing trend was observed from Test 1 to Test 3, followed by a slight increase during Test 4 (Table 14).

There were 13 instances among seven participants where an oculomotor or disorientation symptom was present before using the VR application. In the majority of these instances, the symptoms recorded prior to the test were either resolved or persisted with the same intensity after the test.

4.5. Semi-CAVE

The participants who used the semi-CAVE were mostly male with a mean (SD) age of 8.33 (2.92) years (Table 15). All participants were in elementary school, and 80% were in the care of their parents. One participant had a cough and cold at the time of the testing, and one participant was taking vitamins. The most common hobbies among these participants were playing computer or cellphone games (80%) and playing outdoor games (73.33%), such as basketball, swimming, biking, and playground or street games. Four out of the fifteen participants had prior experience with VR games, and they had used an HMD during these experiences.

Table 15. Demographic characteristics of participants who used the semi-CAVE (n = 15).

Characteristic	Value
Age in years, M (SD)	8.33 (2.92)
Sex, n (%)	
Male	8 (53.33)
Female	7 (46.67)
Educational attainment, n (%)	
Elementary undergraduate	15 (100)
Primary caregiver, n (%)	
Parent	12 (80)
Relative	3 (20)
Current illness (if any) (n = 1), n (%)	
Cough and colds	1 (100)
Current medications (if any) (n = 2), n (%)	
Vitamins	2 (100)
Hobbies, n (%) [a]	
Computer or cellphone games	12 (80)
Outdoor physical activities	11 (73.33)
Drawing	3 (20)
Toys	3 (20)
Reading	2 (13.33)
Watching TV or videos	1 (6.67)
Dancing	1 (6.67)
VR experience, n (%)	
Yes, an HMD	4 (26.67)
No	11 (73.33)

[a] participants could give more than 1 response; HMD head-mounted display.

4.6. Semi-CAVE: BENOGO Place Probe

4.6.1. Descriptions

Four themes describing the VR experience were found: overall subjective description (divided into positive, negative, and neutral), objective description of the VR features and/or activities, physical reaction to the games, and semblance of reality (Appendix A.2).

Representative responses under each theme in each test are enumerated in Boxes 3–6. There were no physical reactions to the activity in Test 4.

Box 3. Overall subjective descriptions from participants who used the semi-CAVE.

Positive	Negative	Neutral
"Enjoyed the experience" "Enjoyed playing the game. Cute robot and hands" "Excited to play" "Fun to play" "Game was easy"	"Game was boring" "Bowling was difficult. "Difficult to do bowling game, but I was able to finish."	"Treadmill was okay"

Box 4. Objective description of games from participants who used the semi-CAVE.

"Played with a ball and a piano" "Pick up ball and throw during bowling" "Ball thrown toward alien" "Played while holding something, had something attached to forehead"	"Stars, bears, and candies appeared" "Hit zombies during bowling game, finished quickly to get trophy"

Box 5. Physical reaction to games from participants who used the semi-CAVE.

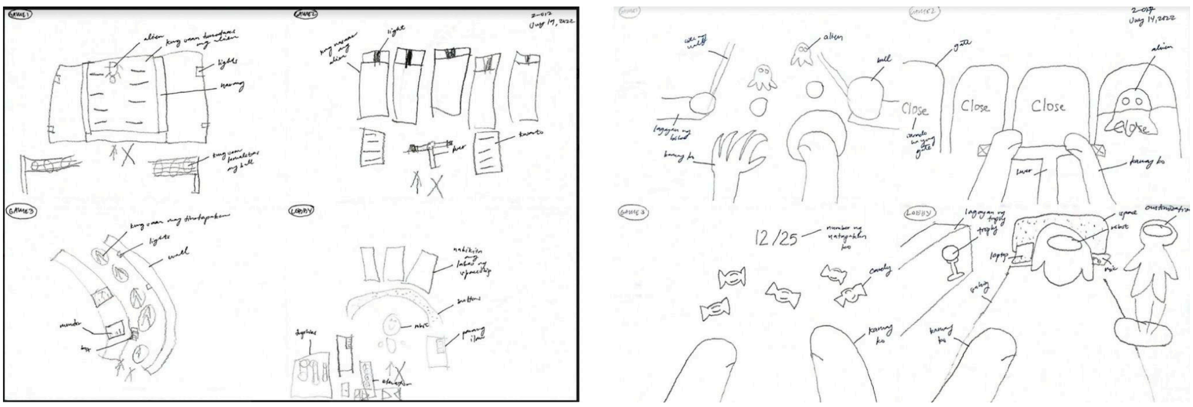
"Felt dizzy to move in VR"	"Got tired"

Box 6. Semblance of reality from participants who used the semi-CAVE.

"Felt like they could touch the ball. Felt like they were walking inside. Felt like they could hold the trophy" "Items felt touchable."	"Things they saw felt real. Felt like they were on a spaceship."

4.6.2. Map Drawn After Using Semi-CAVE

The average scores of the sketch maps are indicated in Table 16. There was an average score of 2 (1.70) for map goodness, which indicates moderate representation. There were about four to six objects drawn across all tests, and there was an average score of 2.07 for the relative placement, meaning about three to four objects were usually placed correctly for the maps drawn. Representative sketch maps can be seen in Figure 3.



(**a**) (**b**)

Figure 3. Representative sketch maps. The text, hand-drawn by the participants, are variably legible (some are too small for the naked eye), but seem to be object labels. The interpretation of these sketch maps were done by distinguishing objects from one another. In the first participant (**a**), they represented themselves as the symbol X. Objects that were notable were the alien, the lever, lights, and

Captain Max (smiley face). For the second participant (**b**), they represented themself as hands. Objects that were notable were the rewards/feedback (e.g., numerical score, candy, and trophy), other inanimate objects (e.g., ball, lever, and gates), and characters (e.g., aliens and robot).

Table 16. Sketch map scoring per test using semi-CAVE.

Components, M (SD)	Test 1	Test 2	Test 3	Test 4
Map goodness	1.70 (0.65)	1.43 (0.63)	1.83 (0.65)	1.83 (0.59)
Object classes	4.13 (1.70)	4.43 (2.19)	5.07 (2.38)	5.70 (2.20)
Relative Object positioning	1.90 (0.61)	1.90 (0.66)	2.17 (0.79)	2.30 (0.65)

4.6.3. Features of the Virtual Environment Recalled After Using Semi-CAVE

There was variation in the top three most prominent features among the tests, but overall, the most frequently mentioned features are part of the Walkey Moley Game (n = 45) and include 'Walking,' 'Treadmill,' 'Stars,' and 'Spaceship' (Table 17). This is followed by features of the virtual setting, including 'Trophy,' 'Elevator,' 'Sounds,' and 'Chair,' and features of the Initiator Game (n = 33) such as 'Bowling ball' and 'Piano.' There was an increasing prominence of the features of the virtual setting as tests progressed. Avatar customization was not a prominent feature in Test 3, and features of the Lock 'Em Up Game were not prominent in Test 4. There was no mention of any affective differential as a prominent feature of the VR.

Table 17. Frequently mentioned VR features in semi-CAVE (n = 45).

Categories, n (%)	Test 1	Test 2	Test 3	Test 4
Walkey Moley Game	12 (26.67)	9 (20)	13 (28.89)	11 (24.44)
Setting	5 (11.11)	8 (17.78)	11 (24.44)	14 (31.11)
Initiator Game	11 (24.44)	7 (15.56)	8 (17.78)	7 (15.56)
Guide	6 (13.33)	8 (17.78)	4 (8.89)	9 (20)
Bowling Game	8 (17.78)	10 (22.22)	8 (17.78)	3 (6.67)
Avatar customization	1 (2.22)	1 (2.22)	0	1 (2.22)
Lock 'Em Up Game	2 (4.44)	2 (4.44)	1 (2.22)	0

4.6.4. Pictures Selected to Represent the VR Experience After Using Semi-CAVE

The majority of the participants chose the photo of children playing in a soccer field to represent their experience. The most common reason is under the theme of "similarity of action" (Table 18). Examples of responses under this theme are "Because they are playing in the photo" and "They are playing ball".

Table 18. Thematic analysis of responses describing the most preferred photo in semi-CAVE (n = 8).

Theme	Test 1 [a]	Test 2	Test 3	Test 4
Similarity of action	6 (85.71)	6 (75)	5 (62.5)	6 (75)
Similarity in character/object	1 (14.29)	1 (12.5)	1 (12.5)	1 (12.5)
Impact on feelings/mood	0	1 (12.5)	2 (25)	1 (12.5)

[a] 1 missing response.

4.6.5. Sounds

Across all tests, the voice of the robot guide (Captain Max) was the most notable sound (n = 53) (Table 19). This is followed by other sound effects (n = 17) and background music (n = 9). Most of the participants described the robot guide's sound as clear but quite fast. Some participants repeated the dialogue of the robot ("Good job, success!") while some narrated the instructions given to them by the guide. Most descriptions for other sound effects and the background music were "Just right." Sounds from other characters included alien sounds (Test 1) and the participant's voice (Test 2).

Table 19. Number of responses for prominent sounds per test in semi-CAVE.

Categories	Test 1	Test 2	Test 3	Test 4
Guide	11	14	15	13
Sound effects	4	5	3	5
Background music	2	0	5	2
Other characters	2	1	0	0

4.6.6. Words

The six most frequently mentioned words that participants used to describe their VR experience are illustrated in Figure 4. These include 'fun' (n = 34, 37.78%), 'exciting' (n = 32, 35.56%); 'happy,' 'bowling,' and 'beautiful' (n = 18, 20%), 'robot' (n = 15, 16.67%), 'relaxing' (n = 11, 12.22%), and 'alien' (n = 10, 11.11%). Most of the words mentioned were positive affective differentials ('fun,' 'exciting,' 'happy,' 'beautiful,' 'relaxing'), while some of them were features in the VE ('robot,' 'alien'). In Test 1, 'not tiring' and 'not scary' were prominent phrases, while negative attributes were also mentioned at least once in Test 2 ('dizzy,' 'boring').

(**a**) Test 1

(**b**) Test 2

(**c**) Test 3

(**d**) Test 4

Figure 4. Word cloud illustrations of the 6 most common descriptions of VR experience in semi-CAVE. The descriptions were obtained for Tests 1–4 pertaining to each of the testing sessions.

4.6.7. Semantic Differentials

The graphics of the virtual environment were 'clear,' 'realistic,' 'believable,' and 'accurate' across the four testing sessions (Table 20). Movement of these images was also similarly rated across sessions as 'smooth,' 'unbroken,' 'consistent,' and 'neither slow nor fast.' When the participants were asked to rate the activities, these were described as being 'active,' 'free,' 'oriented,' 'inside,' and 'mobile' across the four testing sessions (Table 21). The participants who used the semi-CAVE described the virtual space as being 'big' and 'full' (Table 22). The results were mixed regarding the openness of the space, but the ratings slightly favored 'open' over 'enclosed'. The environment was also rated as being 'colorful' and 'neither light nor dark.' To the participants, the environment appeared 'permanent,' 'moving,' 'responsive,' 'touchable,' and 'neither far nor near.' The environment was rated as 'beautiful,' 'pleasant,' 'relaxing,' 'harmless,' 'exciting,' 'interesting,' 'memorable,' 'meaningful,' 'understandable,' and 'significant' (Table 23).

Table 20. Participants' ratings for technology differentials across four testing sessions using the semi-CAVE (*n* = 15).

	Test 1					**Test 2**					**Test 3**					**Test 4**					
	V	**Q**	**N**	**Q**	**V**	**V**	**Q**	**N**	**Q**	**V**	**V**	**Q**	**N**	**Q**	**V**	**V**	**Q**	**N**	**Q**	**V**	
Grainy	0	0	4	3	8	0	0	4	0	11	0	0	3	1	11	0	0	4	2	9	Clear
Realistic	8	1	3	0	0	6	3	5	0	1	9	1	2	0	1	10	4	1	0	0	Unrealistic
Unbelievable	0	2	4	3	6	1	0	5	4	5	0	1	2	1	11	1	0	4	2	8	Believable
Distorted	0	0	2	5	8	0	0	2	0	13	0	0	2	1	12	1	0	2	1	11	Accurate
Smooth	9	5	1	0	0	12	2	1	0	0	11	0	3	1	0	11	3	0	0	1	Jerky
Broken	0	0	1	3	11	0	0	5	1	9	0	1	3	0	11	0	0	2	1	12	Unbroken
Slow	1	1	9	3	1	0	3	8	3	1	0	1	8	5	1	1	2	8	3	1	Fast
Consistent	10	3	0	2	0	5	3	5	0	2	9	3	2	1	0	8	1	5	1	0	Erratic

Color legend: green—highest frequency for Test 1; blue—highest frequency for Test 2; orange—highest frequency for Test 3; yellow—highest frequency for Test 4. V very, Q quite, N neither.

Table 21. Participants' ratings for activity differentials across four testing sessions using the semi-CAVE (*n* = 15).

	Test 1					**Test 2**					**Test 3**					**Test 4**					
	V	**Q**	**N**	**Q**	**V**	**V**	**Q**	**N**	**Q**	**V**	**V**	**Q**	**N**	**Q**	**V**	**V**	**Q**	**N**	**Q**	**V**	
Passive	0	0	1	5	9	0	1	2	2	10	1	0	1	3	10	0	0	1	1	13	Active
Free	10	2	1	1	1	6	3	5	1	0	8	4	2	0	1	10	3	2	0	0	Restricted
Disoriented	0	0	1	6	8	1	0	3	0	11	1	0	1	1	12	1	0	3	1	10	Oriented
Inside	7	4	2	2	0	6	2	4	1	2	9	4	1	0	1	9	2	1	1	2	Outside
Mobile	11	4	0	0	0	10	3	2	0	0	11	3	1	0	0	11	2	1	1	0	Immobile

Color legend: green—highest frequency for Test 1; blue—highest frequency for Test 2; orange—highest frequency for Test 3; yellow—highest frequency for Test 4. V very, Q quite, N neither.

Table 22. Participants' ratings for physical differentials across four testing sessions using the semi-CAVE (*n* = 15).

	Test 1					**Test 2**					**Test 3**					**Test 4**					
	V	**Q**	**N**	**Q**	**V**	**V**	**Q**	**N**	**Q**	**V**	**V**	**Q**	**N**	**Q**	**V**	**V**	**Q**	**N**	**Q**	**V**	
Small	0	1	5	2	7	1	0	6	2	6	0	1	7	2	5	0	1	6	3	5	Big
Empty	0	0	7	4	4	0	0	4	4	7	0	0	5	4	6	0	0	4	1	10	Full
Light	4	4	6	1	0	4	3	6	2	0	3	2	7	3	0	3	3	7	2	0	Dark
Enclosed	2	3	2	4	4	3	2	6	0	4	3	1	4	1	6	2	1	2	4	6	Open
Permanent	7	4	2	1	1	5	1	6	0	3	8	3	4	0	0	9	2	4	0	0	Temporary
Colorless	0	0	2	5	8	0	1	3	2	9	0	0	3	1	11	0	0	1	4	10	Colorful
Static	1	0	4	5	5	0	0	3	3	9	2	0	3	2	8	2	1	2	3	7	Moving
Responsive	8	5	1	1	0	8	3	2	1	1	9	2	4	0	0	10	1	3	0	1	Inert
Far	0	0	5	7	3	0	1	7	4	3	2	0	7	3	3	0	0	8	3	4	Near
Untouchable	1	1	2	4	7	1	3	3	1	7	2	0	4	2	7	0	0	3	2	10	Touchable

Color legend: green—highest frequency for Test 1; blue—highest frequency for Test 2; orange—highest frequency for Test 3; yellow—highest frequency for Test 4. V very, Q quite, N neither.

Table 23. Participants' ratings for affective differentials across four testing sessions using the semi-CAVE (n = 15).

	Test 1					Test 2					Test 3					Test 4					
	V	**Q**	**N**	**Q**	**V**	**V**	**Q**	**N**	**Q**	**V**	**V**	**Q**	**N**	**Q**	**V**	**V**	**Q**	**N**	**Q**	**V**	
Ugly	0	0	1	1	13	0	0	2	3	10	0	0	3	0	12	0	0	0	1	14	Beautiful
Pleasant	14	1	0	0	0	14	0	1	0	0	12	2	1	0	0	12	0	2	1	0	Unpleasant
Stressful	1	0	2	4	8	0	0	1	4	10	0	0	0	3	12	0	0	0	3	12	Relaxing
Harmful	0	0	0	3	12	0	0	1	2	12	0	0	3	1	11	0	0	2	1	12	Harmless
Exciting	15	0	0	0	0	12	1	2	0	0	13	1	0	1	0	13	1	1	0	0	Boring
Interesting	12	2	1	0	0	10	1	3	1	0	11	2	2	0	0	13	0	2	0	0	Uninteresting
Memorable	9	4	2	0	0	9	0	5	0	1	9	3	3	0	0	12	1	2	0	0	Forgettable
Meaningful	8	3	3	1	0	10	2	2	0	1	9	2	4	0	0	13	1	1	0	0	Meaningless
Confusing	0	2	2	3	8	0	0	3	1	11	0	0	2	1	12	1	0	4	1	9	Understandable
Significant	8	3	3	0	1	6	3	5	0	1	12	1	2	0	0	12	0	3	0	0	Insignificant

Color legend: green—highest frequency for Test 1; blue—highest frequency for Test 2; orange—highest frequency for Test 3; yellow—highest frequency for Test 4. V very, Q quite, N neither.

4.6.8. Feelings of Presence

Participants who used the semi-CAVE had high scores for most of the subscales of the MEC-SPQ across the four testing sessions (Table 24). The scores also generally improved (i.e., higher mean scores or smaller standard deviations) by the last session. The subscale with the highest score varied per session: domain-specific interest (M = 4.65 ± 0.68) for the first session, spatial situation model (M = 4.65 ± 0.58) for the second session, attention allocation (M = 4.75 ± 0.54) for the third session, and attention allocation (M = 4.83 ± 0.49) and spatial situation model (M = 4.83 ± 0.42) for the fourth session. Aside from suspension of disbelief and domain-specific interest, the mean scores of the subscales also generally increased as the sessions continued. The subscale with the lowest score across the four testing sessions using the semi-CAVE was suspension of disbelief. The scores under this subscale were also the most variable, resulting in a wider standard deviation.

Table 24. Mean scores for the MEC spatial presence questionnaire across four testing sessions among semi-CAVE users (n = 15).

Subscale, M (SD) [a]	**Test 1**	**Test 2**	**Test 3**	**Test 4**
Attention allocation	4.62 (0.69)	4.55 (0.75)	4.75 (0.54) [b]	4.83 (0.49) [b]
Spatial situation model	4.47 (0.83)	4.65 (0.58) [b]	4.63 (0.66)	4.83 (0.42) [b]
Spatial presence: self-location	4.37 (0.88)	4.57 (0.77)	4.35 (1.09)	4.50 (0.95)
Spatial presence: possible actions	4.40 (1.03)	4.30 (0.96)	4.40 (1.01)	4.60 (0.83)
Higher cognitive involvement	4.52 (0.70)	4.27 (1.10)	4.43 (0.89)	4.58 (0.81)
Suspension of disbelief	3.62 (1.51) [c]	3.65 (1.53) [c]	3.85 (1.59) [c]	3.57 (1.71) [c]
Domain-specific interest	4.65 (0.68) [b]	4.17 (1.12)	4.28 (1.17)	4.42 (1.12)
Visual spatial imagery	4.38 (0.90)	4.52 (0.81)	4.70 (0.56)	4.81 (0.47)

[a] score out of 5, [b] highest score, [c] lowest score.

4.7. Usability Assessment

The participants demonstrated high effectiveness, high efficiency, and high satisfaction with the VR experience. The majority of participants were able to complete the experience within the allotted time (Table 25). Slight differences were noted in the times spent on each of the three games, but due to the small sample size, it is difficult to determine if these differences are statistically significant.

The participants did not demonstrate having difficulty with any of the key tasks listed in the usability checklist. Satisfaction ratings were consistently high across the four testing sessions (Table 26). Of the three games, 'Walkey Moley' had the highest rating (M = 4.98 ± 0.04).

Table 25. Frequency distribution of participants who completed specific components of the virtual reality experience.

Component	Test 1 (*n* = 15)		Test 2 (*n* = 14)		Test 3 (*n* = 15)		Test 4 (*n* = 15)	
	C, *n* (%)	t, M (SD)	C, *n* (%)	t, M (SD)	C, *n* (%)	t, M (SD)	C, *n* (%)	t, M (SD)
Initiator	15 (100)	-	14 (100) [a]	-	15 (100)	-	15 (100)	-
Avatar room	14 (100) [a]	-	15 (100)	-	15 (100)	-	15 (100)	-
Lobby and elevator	15 (100)	-	15 (100)	-	15 (100)	-	15 (100)	-
Alien bowling	12 (80)	2.37 (0.7) [a]	15 (100)	1.73 (0.27)	15 (100)	1.85 (0.32)	14 (93.33)	1.92 (0.58)
Lock 'Em Up	14 (93.33)	1.01 (0.93) [a]	15 (100)	0.82 (0.4)	15 (100)	0.83 (0.42)	15 (100)	0.85 (0.78)
Walkey Moley	15 (100)	1.47 (0.3) [a]	15 (100)	1.35 (0.15)	15 (100)	1.62 (0.12)	15 (100)	1.67 (0.17)
Mean effectiveness	95.56	-	100	-	100	-	98.89	-

C task completion, t time in minutes. [a] missing responses.

Table 26. Mean satisfaction ratings of participants for each component of the virtual reality experience (*n* = 15).

Task, M [a]	Test 1	Test 2	Test 3	Test 4
Initiator	5	5	5	5
Avatar room	5	5	5	5
Lobby	5	5	5	5
'Alien Bowling'	4.77	5	5	5
'Lock 'Em Up'	4.69	5	4.93	5
'Walkey Moley'	4.92	5	5	5
Mean satisfaction	4.9	5	4.99	5

[a] score out of 5.

4.8. Virtual Reality Sickness Questionnaire

The participants who used the semi-CAVE yielded low mean VR sickness scores across the four testing sessions (Table 27). Twelve participants (80%) had an oculomotor- or disorientation-related symptom for at least one testing session after trying out the VR application (Appendix A.2). All of the symptoms that the participants reported were 'slight' in intensity, and the most common symptom reported was fatigue.

Table 27. Frequency distribution of participants who experienced oculomotor and/or disorientation symptoms before and after the virtual reality experience using the semi-CAVE system (*n* = 15).

Symptom, *n* (%)	Test 1		Test 2		Test 3		Test 4	
	Before [a]	After	Before	After	Before [a]	After	Before	After [b]
General discomfort	1 (7.14)	0	1 (6.67)	1 (6.67) [c]	0	0	1 (6.67)	1 (7.69)
Fatigue	0	5 (33.33)	1 (6.67)	1 (6.67)	3 (21.43)	1 (6.67)	1 (6.67)	1 (7.69)
Eye strain	0	1 (6.67)	0	1 (6.67)	0	1 (6.67)	0	0
Difficulty focusing	2 (14.29)	1 (6.67) [c]	1 (6.67)	1 (6.67)	0	0	0	0
Headache	0	1 (6.67)	2 (13.33)	2 (13.33) [d]	1 (7.14)	0	0	0
Fullness of head	0	1 (6.67)	1 (6.67)	1 (6.67) [c]	0	0	0	0
Blurring of vision	1 (7.14)	0	1 (6.67)	1 (6.67)	1 (7.14)	1 (6.67)	1 (6.67)	0

Table 27. *Cont.*

Symptom, *n* (%)	**Test 1**		**Test 2**		**Test 3**		**Test 4**	
	Before [a]	**After**	**Before**	**After**	**Before [a]**	**After**	**Before**	**After [b]**
Dizzy (eyes closed)	1 (7.14)	1 (6.67)	4 (26.67)	1 (6.67) [d]	1 (7.14)	1 (6.67)	0	1 (7.69)
Vertigo	1 (7.14)	0	0	0	0	1 (6.67)	0	0
Participants with at least 1 symptom, *n* (%)	5 (35.71)	6 (40)	6 (40)	4 (26.67)	4 (28.57)	4 (26.67)	3 (20)	3 (21/43)
Total score, M (SD)	-	2.61 (4.27)	-	2.22 (4.60)	-	0.78 (2.20)	-	0.90 (1.72)

[a] 1 missing response, [b] 2 missing responses, [c] 1 prevalent case with unchanged intensity, [d] 1 prevalent case with decreased intensity.

The majority of the reported symptoms were noted during Test 1 and Test 2, and this was succeeded by a decrease in reports during Test 3 and Test 4. The total VR sickness scores similarly demonstrated a decreasing trend as the testing sessions progressed.

At least seven participants (46.67%) reported having an oculomotor- or disorientation-related symptom before using the VR application. In the majority of these instances, the symptoms recorded prior to the test were either resolved or persisted with the same intensity after the test.

5. Discussion

This Phase 1 trial provides initial evidence for the safety, acceptability, and usability of an ImGTS that combines gamification elements and therapeutic activities for children with CP with mobility limitations, set within an immersive virtual environment. Specifically, the results indicate that the ImGTS was well-received by healthy children aged 6 to 12 years who tested it, with participants experiencing minimal to no oculomotor or disorientation symptoms typically associated with virtual reality sickness. Participants reported high ratings for feelings of presence, implying high acceptability of the virtual environment. Participants also obtained high scores for effectiveness, efficiency, and satisfaction in using the ImGTS, indicating high usability of the ImGTS. These results, taken together, suggest the potential of the ImGTS as an engaging rehabilitation tool for children with CP, and as a promising solution for delivering goal-specific, adaptive, simple, fun yet challenging, and customizable strategies to improve their mobility.

By providing initial evidence for the safety, acceptability, and usability of the ImGTS, this study lays the groundwork for future clinical trials that will ultimately lead to an optimized design and clinical use of the ImGTS. As such, this study contributes to addressing the gap in standardized protocols for the use of VR in the rehabilitation of mobility limitations in children with CP [55].

As regards safety, the study showed that oculomotor and disorientation symptoms were not common and were slight, if present. The low incidence and severity of symptoms experienced by the participants were consistent with the results of pilot studies among children or pediatric patients with small sample sizes [56,57]. Fatigue, considered an oculomotor symptom using the VRSQ, was the most common symptom reported by participants of either the HMD or semi-CAVE group after the VR experience. In contrast, higher VR sickness scores were noted for disorientation symptoms in previous work that used HMD [58]. It is possible that the slightly higher rates of fatigue observed in this present study were due to the amount of visual stimulation experienced by the participants while playing the game [58], the active nature of the VR application, and the increasing level of difficulty in the third and fourth sessions. Further, participants who used the HMD and those who used the semi-CAVE both showed a decreasing trend of new symptoms reported as the testing sessions progressed. This finding suggests that continued exposure to VR could help healthy children become accustomed to the virtual environment and reduce the likelihood of VR sickness over time.

As regards acceptability, the findings indicated that participants generally had positive perceptions of the virtual environment and their experience. Many responses highlighted physical attributes of the environment as being important to their experience. The participants for both HMD and semi-CAVE setups gave positive ratings for most of the physical attributes of the environment, such as its size ('big'), use of space ('full'), color ('colorful'), and perceived interactability ('moving,' 'responsive,' and 'touchable'). The responses for brightness, depth, and permanence may be due to inherent properties of the technology. For example, the majority of HMD users may have perceived the environment as being 'light' and 'near' due to the closeness of the screen to their eyes, while most semi-CAVE users felt the VE was 'permanent' due to the fixed nature of the screens around them. It is notable that most participants for both setups rated the VE as being 'open' despite the enclosed nature of the spaceship depicted.

Further analysis of the perceptions of the physical features of the VE revealed that the participants generally had a good recollection of the VE, based on the sketch maps they produced. Similarly, both the HMD and semi-CAVE groups clearly recalled most of the actions associated with each of the three games, and these were often coupled with the items associated with each action (i.e., throwing a ball, pulling a lever, stepping on arrows, and counting spaceships), based on their responses to the interview questions. However, the level of detail and quantity of responses varied among participants, likely reflecting individual differences in attention, engagement, or experience with the VE. These observations are consistent with the rich responses provided by children aged 12 to 16 who participated in the early development of the BENOGO Place Probe [52].

The participants also gave positive responses on the technological quality of the environment. Slight differences in rating were noted when participants were asked to evaluate the speed of the images, but these ratings may have been influenced by personal preferences and the inherent characteristics of the technology used. These differences in rating did not appear to detract from the emotional responses to the VE.

Participants in both the HMD and semi-CAVE groups characterized the VE using the following affective characteristics: 'beautiful,' 'pleasant,' 'relaxing,' 'harmless,' 'exciting,' 'interesting,' 'memorable,' 'meaningful,' 'understandable,' and 'significant.' Participants often mentioned feeling enjoyment, excitement, happiness, or relaxation while they were in the VE. In addition, some participants reported wanting to repeat the experience or feeling sadness that the experience was over. These characterizations are consistent with previous research that showed children or pediatric patients demonstrating high enjoyment during VR experiences [56,59]. Other qualitative methodologies that have evaluated the impact of VEs on children [60] also described these environments as being 'engaging' and 'fun' alternatives to their real-world counterparts [61–63], which is consistent with qualitative responses in our study where the words 'fun' and 'exciting' were repeatedly seen.

When assessing feelings of presence, participants in both the HMD and semi-CAVE groups yielded moderately high scores for most of the dimensions of presence (MEC-SPQ subscales). While this study did not aim to compare the experiences of users between HMD and semi-CAVE, it is interesting to note that scores for feeling of presence were higher for the semi-CAVE group across all dimensions of presence. For HMD users, participants were able to concentrate on the VE and the activities, as shown by their giving the highest scores for attention allocation items. The same is true for semi-CAVE users. Equally high for semi-CAVE users were their scores for spatial situational model and visual spatial imagery, indicating that they could imagine the space clearly. Both the HMD and semi-CAVE groups were conscious of how their "body" was oriented in the virtual space and felt as though they were physically present in the VE, as shown by their high scores on self-location. Both groups were also interested in the themes presented in the VE, based on their high scores for domain-specific interest. Suspension of disbelief scored lowest for both groups (neither agreed nor disagreed), suggesting that participants noticed some errors and inconsistencies while in the virtual environment. Some participants may have been more analytical of the VE, knowing they would be asked to evaluate their experience afterward, while others may have been more focused on completing the activities in the VE during their sessions. Future research could probe factors that account for feelings of presence. Still, this finding could be a point of design enhancement for the ImGTS.

As regards usability, participants in both the HMD and semi-CAVE groups completed the experience within a reasonable time, with minimal to no difficulty, and with high satisfaction. These observations on usability were consistent across the four testing sessions for both the HMD users and semi-CAVE users, suggesting that the activities offer a "just right" challenge and that the positive user experience remains stable over time. Effectiveness and efficiency are critical in maintaining the engagement of children in therapy sessions. Similarly, the very high satisfaction scores indicate the potential of the ImGTS in sustaining the participation of children in therapeutic activities over the long term, making it a promising tool for the rehabilitation of children with CP.

A descriptive synthesis of user experiences for the two setups suggests comparable safety, acceptability, and usability, with some nuances that are specific to the setups. For example, total VRSQ scores were descriptively higher in the HMD group than in the semi-CAVE group, driven primarily by oculomotor symptoms. Despite this descriptive difference, VR sickness symptoms were infrequent and mild for both groups, indicating overall safety of the ImGTS using either setup when tested among healthy children. Beyond safety, the acceptability of the ImGTS based on perceptions of the VE was comparable between groups, with both groups selecting generally similar descriptors in the technical, activity, and affective differentials. Most participants of both groups rated the images as very clear, realistic, believable, and accurate. Most participants of both groups also perceived the motion of these images as very smooth, unbroken, and consistent, and neither slow nor fast. Most participants of both groups felt that they were very active, free, oriented, inside, and mobile while in the VE. Most participants of both groups perceived the virtual environment as very beautiful, pleasant, relaxing, harmless, exciting, interesting, memorable, meaningful, understandable, and significant. These similar perceptions between groups suggest that the design of the ImGTS preserved the immersive gamification experience regardless of the setup. This observation further implies the potential use of the two setups as comparable alternatives for deployment based on characteristics of the VE, with their suitability determined by user needs and context rather than by the nature of the setup [48,49,64] (Table 28).

Some setup-specific nuances emerged in the perceptions of the physical characteristics of the VE. Most participants of the HMD group described the VE as very big, light, temporary, and near, while most participants in the semi-CAVE group described the environment as neither small nor big, neither light nor dark, very permanent, and neither far nor near.

Feelings of presence were higher for the semi-CAVE group compared to the HMD group. This difference may be related to reduced encumbrance, compared to what may be experienced when wearing a headset for the HMD setup, or the immersion afforded by the larger walled space in the semi-CAVE setup. Correspondingly, usability ratings, although high for both setups, were higher for semi-CAVE, with no participant encountering difficulty in any of the key tasks and participants reporting a higher satisfaction rate. The magnitude of these differences was small.

Table 28. Observed differences in the HMD and semi-CAVE setups for rehabilitation therapy of children with CP.

Characteristics	HMD	Semi-CAVE
Technical Requirements	• VR headset capable of outside-in and inside-out tracking • 3 × 3 area	• Three (3) short-throw projectors • Three (3) walls along the edges of a 3 × 3 area • HTC Vive Base Stations • HTC Vive Trackers
Outcomes		
Safety	• Low incidence and severity of oculomotor and disorientation symptoms • Decreasing incidence of new symptoms across time	
Acceptability	• Positive ratings for the physical attributes of the environment • Good recollection of the VE and associated activities • Moderately high score across all dimensions of presence	
	Environment perceived as "light and near"	Environment perceived as "permanent"
Usability	• Completed within reasonable time • Minimal to no difficulty • High satisfaction	
Limitations	None	Only on 3 fixed screens, where additional functionalities were added for movement (i.e., turning and changing places) in the VE
Cost	USD 2200	USD 6600 (economized)

It must be emphasized that these observations on safety, acceptability, and usability between the HMD and semi-CAVE setups are descriptive and should not be interpreted as inferential. These observations inform further design refinement, for example, mitigating oculomotor symptoms using HMD. These comparisons might be worth formally exploring in subsequent phases of this research project, with larger sample sizes. Such future comparisons must consider other factors not explored in this current study, such as portability, simplicity in setup, training demands, and cost, among others.

The findings of this study may not necessarily be applicable to actual patients with CP, since the findings may not account for the perceptual differences that may be encountered by CP patients. One major factor that may contribute substantially to differences between a healthy cohort and children with CP is the presence of visual impairments such as strabismus, which affects about 49.8% of individuals with CP in high-income countries and 39.8% in lower-income countries [65]. While the safety evaluation in the healthy cohort characterizes the effects of the VR intervention on cybersickness and fatigue, it may not fully capture the fall risk, postural instability, or mobility limitations experienced by many children with CP, for whom VR may introduce distinct safety concerns. Visual impairments may also mask perceptions that shape the acceptability and usability of VR therapy, as patients with reduced visual acuity can experience altered perception of depth and contrast of game elements [66], which may, in turn, affect overall user performance [67]. Although some of these visual challenges may be mitigated through auditory cues for in-game activities, a subset of children with CP will also present with hearing impairments [68], which may further complicate the sensory demands of VR-based interventions. Nonetheless, future game designs may better accommodate patients with audiovisual impairments by enabling customization of game elements according to user needs and by incorporating multi-sensory feedback mechanisms that provide alternative options in delivering sensory cues [69].

On the whole, the results of this study must be interpreted considering several study limitations. First, the small sample size, although typical for Phase 1 trials, limits the generalizability of the results. Second, the short duration of the intervention may not have fully captured the VR experience over longer periods. Third, the newness of the ImGTS for the participants and their experience may have influenced engagement and the positive perceptions. Fourth, individual differences in attention span, ability to recall visual and auditory information, and comprehension of instructions and questions exist in children aged 6 to 12. For instance, younger children may be more satisfied with the visuospatial aspects of augmented realities than older children [70]. The influence of such age-related variability on the results was not explored in this study. Fifth, repetition of exposure to VEs over the four sessions may also be a limitation, as each participant may base subsequent answers on previous experiences. However, such repetition could also ensure intrapersonal consistency of responses and, therefore, contribute to a clearer picture of how children engage with the ImGTS over time. Finally, while there were similarities and differences in the safety, acceptability, and usability of the HMD and semi-CAVE setups, these differences should be interpreted as contextual considerations for deployment rather than comparative evidence, as this Phase 1 trial was not designed to evaluate differences between the two setups.

Still, this Phase 1 trial indicated the potential of the ImGTS as a safe, acceptable, and usable tool for the rehabilitation of children with cerebral palsy. These findings need to be confirmed in a Phase 2 clinical trial with children with cerebral palsy as participants. This Phase 2 trial will evaluate the clinical effectiveness of the ImGTS in addition to its safety, acceptability, and usability over six sessions spanning three weeks. The therapist's role and safety protocols will include the use of a harness for the third task, when the participants walk, and the presence of a physician for each session. Considering the usability of the ImGTS and the potential benefits of alternative rehabilitation strategies for children with less severe impairments receiving significantly fewer hours of therapy and demonstrating less self-initiated physical activity [42], the Phase 2 testing is envisioned to involve children with CP who can walk without a mobility device with limited speed, balance, and/or coordination (equivalent to Gross Motor Function Classification System-Expanded and Revised Level I or II) and who can handle objects easily and successfully (equivalent to Manual Ability Classification System Level I). The selection criteria will be reassessed and modified, if necessary, during pilot testing with children with CP in the Phase 2 trial. The Phase 2 trial could also evaluate the usability of the ImGTS using standardized questionnaires such as the System Usability Scale [71], adapted as needed for children with cerebral palsy, to complement qualitative information from interviews. Using the ImGTS with the target clinical population in Phase 2 could provide useful insights on further design enhancements to optimize the ImGTS for clinical use. Following Phase 2, a Phase 3 randomized controlled trial could involve a sample large enough to allow comparison of clinical outcomes between the ImGTS combined with traditional rehabilitation and traditional rehabilitation alone, and possibly compare outcomes between the HMD and semi-CAVE setups.

6. Conclusions

This report described the development of an ImGTS, designed as a possible tool for the rehabilitation of children with cerebral palsy with mobility limitations. The results of this Phase 1 trial provide preliminary evidence for the safety, acceptability, and usability of the ImGTS using either an HMD or a semi-CAVE setup, tested among healthy children aged 6 to 12 years. The results showed low incidence and severity of oculomotor or disorientation symptoms, high ratings for feelings of presence and, therefore, acceptability of the design, and high scores for usability across the dimensions of effectiveness, efficiency, and satisfaction. The therapeutic activities and the virtual environment were positively regarded, with participants describing their experience as fun, exciting, beautiful, and relaxing, among others, which are desirable features of an engaging and innovative rehabilitation tool for children. A Phase 2 trial that will test the ImGTS with children with cerebral palsy with mobility limitations is necessary to confirm the safety, acceptability, and usability of the ImGTS, and ultimately, its clinical effectiveness, for this target clinical population. This future trial could also point to further refinements in the design of the ImGTS to optimize it for clinical use with children with cerebral palsy.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/info17020206/s1, Figure S1: High-level overview of the System Architecture; Figure S2: Standard intervention interaction flow; Figure S3: Screenshot of the Space Lobby; Figure S4: Screenshot of the Alien Invasion mini-game; Figure S5: Screenshot of the Lock Em' Up mini-game; Figure S6: Screenshot of the Walkey Moley mini-game; File S1: Informed Consent Form; File S2: Verbal Assent Script; File S3: Data Collection Forms.

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Institutional Review Board Statement: All materials and procedures for this study were approved by the University of the Philippines Manila Research Ethics Board (UPMREB 2021-0371-01).

Informed Consent Statement: Verbal assent and informed consent were obtained from each child and their respective parents or legal guardians involved in the study.

Data Availability Statement: The original contributions presented in this study are included in the article/Supplementary Materials. Further inquiries can be directed to the corresponding author.

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Abbreviations

The following abbreviations are used in this manuscript:

6MWT	Six-minute walk test
ADL	Activities of Daily Living
BBS	Berg Balance Scale
BOT-2	Bruininks–Oseretsky Test of Motor Proficiency second edition
CP	Cerebral palsy
BENOGO	BEing there, NO need to GO
FAQ-WS	Functional assessment questionnaire-walking scale
GMFCS	Gross Motor Function Classification System
HMD	Head-mounted display
ImGTS	Immersive gamification technology system
M-ABC	Movement Assessment Battery for Children
MACS	Manual Ability Classification System
MEC	Measurement, Effects, Conditions
MEC-SPQ	Measurements, Effects, Conditions Spatial Presence Questionnaire
PBM	Pediatric Balance Measurement
PBS	Pediatric Balance Scale
PMAL	Pediatric Motor Activity Log
QoL	Quality of Life
Semi-CAVE	Semi-Cave automatic virtual environment
SD	Standard deviation
SSWS	Self-selected walking speed
TUG	Timed Up and Go
UP	University of the Philippines
UPMREB	University of the Philippines Manila Research Ethics Board
VE	Virtual environments
VR	Virtual reality
VRSQ	Virtual Reality Sickness Questionnaire

Appendix A

Appendix A.1. Head-Mounted Display

Table A1. Frequency distribution of participants who experienced oculomotor and/or disorientation symptoms according to the severity of symptoms felt before and after the virtual reality experience using the head-mounted display system (n = 15).

Symptoms, n	Test 1								Test 2								Test 3								Test 4							
	Before				After				Before				After				Before				After				Before				After			
	N	Sl	M	Sv	N	Sl	M	Sv	N	Sl	M	Sv	N	Sl	M	Sv	N	Sl	M	Sv	N	Sl	M	Sv	N	Sl	M	Sv	N	Sl	M	Sv
General discomfort	14	1	0	0	14	1	0	0	15	0	0	0	13	2	0	0	15	0	0	0	15	0	0	0	15	0	0	0	15	0	0	0
Fatigue	14	1	0	0	10	4	1	0	13	2	0	0	11	4	0	0	14	1	0	0	13	2	0	0	13	2	0	0	13	1	1	0
Eye strain	14	1	0	0	15	0	0	0	15	0	0	0	14	1	0	0	15	0	0	0	15	0	0	0	15	0	0	0	15	0	0	0
Difficulty focusing	14	1	0	0	13	2	0	0	15	0	0	0	15	0	0	0	15	0	0	0	15	0	0	0	15	0	0	0	15	0	0	0
Headache	14	0	1	0	14	1	0	0	14	1	0	0	14	1	0	0	15	0	0	0	15	0	0	0	15	0	0	0	15	0	0	0
Fullness of head	14	1	0	0	14	0	1	0	15	0	0	0	14	1	0	0	15	0	0	0	15	0	0	0	15	0	0	0	14	1	0	0
Blurring of vision	14	1	0	0	13	2	0	0	15	0	0	0	14	1	0	0	15	0	0	0	14	1	0	0	15	0	0	0	15	0	0	0
Dizziness	14	1	0	0	14	1	0	0	14	1	0	0	13	2	0	0	14	1	0	0	15	0	0	0	14	1	0	0	15	0	0	0
Vertigo	15	0	0	0	14	1	0	0	15	0	0	0	14	1	0	0	15	0	0	0	15	0	0	0	15	0	0	0	15	0	0	0

N none, Sl slight, M moderate, Sv severe.

Table A2. Thematic analysis of descriptions and representative responses of the virtual reality experience using the head-mounted display system.

Themes	Test 1	Test 2	Test 3	Test 4
Objective description of games	"Bowling, squat" "Throwing the ball, walking for 10 steps"	"Defeat aliens Little bowling, walking around, squatting" "Threw the ball towards cockroach, walking, counted the spaceships, squatted, door closing"	"Bowling, there's an alien who talks and gives instructions, close the doors so the aliens won't come in, walking and seeing spaceships in the sky" "Defeat aliens with guidance of Capt Max the robot Bowling, walking around, particles appear (teddy bear, stars, candies)"	"There's a robot, an alien, a ball, spaceship, elevator" "Threw the ball at the aliens, got a trophy after the first game. pulling the lever so aliens won't come in, walking to find birds."
Overall subjective reaction/description	"Very fun. Amusing" "Too easy" "Bored to stay long" "Vision is a little blurry but can see them if bigger"	"Enjoyed. Excited" "There's a lot to do, there were 3 games, beautiful"	"Exciting. Enjoyed the game"	"Fun experience. Sad that it's the last session." "Scared of aliens" "Interesting. Wonderful to play the game"
Physical reaction to games	none	none	"Got tired" "A little tiring from squatting and walking"	"Got tired"

Appendix A.2. Semi-CAVE

Table A3. Frequency distribution of participants who experienced oculomotor and/or disorientation symptoms according to the severity of symptoms felt before and after the virtual reality experience using the semi-CAVE (n = 15).

Symptoms, n	Test 1								Test 2								Test 3								Test 4							
	Before [a]				After				Before				After				Before [a]				After				Before				After [b]			
	N	Sl	M	Sv	N	Sl	M	Sv	N	Sl	M	Sv	N	Sl	M	Sv	N	Sl	M	Sv	N	Sl	M	Sv	N	Sl	M	Sv	N	Sl	M	Sv
General discomfort	13	1	0	0	15	0	0	0	14	1	0	0	14	1	0	0	14	0	0	0	15	0	0	0	14	1	0	0	12	1	0	0
Fatigue	14	0	0	0	10	5	0	0	14	0	0	1	14	1	0	0	11	3	0	0	14	1	0	0	14	1	0	0	12	1	0	0
Eye strain	14	0	0	0	14	1	0	0	15	0	0	0	14	1	0	0	14	0	0	0	14	1	0	0	15	0	0	0	13	0	0	0
Difficulty focusing	12	2	0	0	14	1	0	0	14	1	0	0	14	1	0	0	14	0	0	0	15	0	0	0	15	0	0	0	13	0	0	0
Headache	14	0	0	0	14	1	0	0	13	1	0	1	13	2	0	0	13	0	0	1	15	0	0	0	15	0	0	0	13	0	0	0
Fullness of head	14	0	0	0	14	1	0	0	14	1	0	0	14	1	0	0	14	0	0	0	15	0	0	0	15	0	0	0	13	0	0	0
Blurring of vision	13	1	0	0	15	0	0	0	14	1	0	0	14	1	0	0	13	1	0	0	14	1	0	0	14	1	0	0	13	0	0	0
Dizziness	13	1	0	0	14	1	0	0	11	3	0	1	14	1	0	0	13	0	1	0	14	1	0	0	15	0	0	0	12	1	0	0
Vertigo	13	1	0	0	15	0	0	0	15	0	0	0	15	0	0	0	14	0	0	0	14	1	0	0	15	0	0	0	13	0	0	0

N none, Sl slight, M moderate, Sv severe. [a] 1 response missing, [b] 2 responses missing.

Table A4. Thematic analysis of descriptions and representative responses of the virtual reality experience using the semi-CAVE.

Themes	Test 1	Test 2	Test 3	Test 4
Overall subjective description	Positive "Enjoyed the experience" "Excited to play" "Game was difficult" "Game was easy" Negative "Game was boring"	Positive "Squatting game and treadmill were easy" "Easier and faster because second time" Negative "Bowling was difficult.	Positive "Enjoyed playing the game. Cute robot and hands" "Good experience" "Not boring"	Positive "Bowling and squatting games were fun." "Fun to play even if not real." Negative "Difficult to do bowling game, but was able to finish." Neutral "Treadmill was okay"
Objective description of games	"Played with a ball and a piano" "Pick up ball and throw during bowling"	"Played while holding something, had something attached to forehead" "Ball thrown toward alien"	"Stars, bears, and candies appeared" "Threw at aliens. Locked gates" "Threw balls to knock down pins"	"Hit zombies during bowling game, finished quickly to get trophy"
Physical reaction to games	"Felt dizzy to move in VR"	"Felt slightly dizzy and tired"	"Got tired"	none
Semblance of reality	none	"Felt like they could touch the ball. Felt like they were walking inside. Felt like they could hold the trophy"	"Things they saw felt real. Felt like they were on a spaceship."	"Items felt touchable."

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