BrainBuilder: A Virtual Reality Serious Game for Insect Neuroanatomy Education

Anonymous Submission for Blind Review

Abstract—**This paper introduces *BrainBuilder*, a Virtual Reality (VR) serious game designed to support learning about insect neuroanatomy as part of an undergraduate neurobiology curriculum. Leveraging a cognition-oriented design, we used the revised Bloom's taxonomy to translate complex learning objectives into specific cognitive instructions, subsequently implemented through various engaging game mechanics. The learning scenarios include a shooting game for brain structure identification, a whack-a-mole game for naming brain parts, a throwing game for understanding brain regions, and a puzzle game for assembling brain components. The development of *BrainBuilder* follows a user-centered approach, incorporating formative evaluations to refine gameplay and instructional content.**

Index Terms—**VR, serious game, instructional design, insect neuroanatomy, spatial learning**

I. BACKGROUND

Like other brains, the brains of insects are highly complex structures organized into spatially segregated substructures, so-called neuropils. These are often highly complex in their three-dimensional shape and spatial arrangement. Mentally assembling these structures into a complete brain requires substantial spatial visualization ability, a skill integral to many domains [1]. Technological progress is reshaping how we comprehend and teach complex subjects. Virtual Reality (VR) is particularly effective for teaching intricate structures, providing learners an intuitive grasp of spatial relationships by immersing them in 3D spaces [2]. Serious games leverage gameplay to communicate complex information, transforming difficult subjects into interactive learning experiences [3], [4].

In this paper, we introduce *BrainBuilder*, a VR-based serious game for learning insect neuroanatomy through tailored scenarios. It is designed to support an undergraduate course in integrated behavioral biology, using standalone VR technology for an immersive educational experience. We detail our design approach, rooted in cognition-oriented instructional principles derived from the revised Bloom's Taxonomy [5], to translate learning objectives into clear cognitive tasks integrated into engaging game mechanics. Adhering to a user-centered development process, we employed formative evaluations to refine educational content and gameplay. We present insights from these evaluations, demonstrating the game's efficacy in meeting educational goals and student engagement, alongside iterative improvements based on this feedback.

In Section II, we examine spatial learning in VR and related applications in fields similar to insect neuroanatomy. Section III details our game design process. Section IV covers playtesting outcomes and improvements. We conclude in Section V and suggest future enhancements in Section VI.

II. RELATED WORK

Spatial ability is the skill to process and mentally visualize objects and their spatial relationships [3], [6], essential for developing mental models, i.e. cognitive representations needed for comprehending both physical and hypothetical scenarios [7]. Traditional learning resources can overload learners by requiring the mental conversion of 2D to 3D, especially challenging for those with lower spatial abilities, underscoring the need for tools that reduce cognitive strain to enhance learning [6]. Anatomy education has increasingly adopted 3D models to effectively convey spatial and factual knowledge without using cadavers [1], [2]. Using confocal imaging or micro-computed tomography, neurobiologists capture data stacks, from which 3D models can be reconstructed (For example see *InsectBrainDB* [8]). Interacting with 3D models in VR allows dynamic, hands-on exploration [1], boosting learners' spatial awareness and 3D stimulus processing compared to traditional 2D displays [9]. Enhancing VR learning with gameplay can improve active participation and sustained interest [3]. Serious games, grounded in educational frameworks like the revised Bloom's Taxonomy, match gameplay with learning goals for optimal educational impact [3], [10]. The revised Bloom's Taxonomy categorizes learning objectives into cognitive levels of complexity: knowledge, comprehension, application, analysis, synthesis, and evaluation [5]. Aligning game elements with learning objectives bridges the gap between entertainment (the game dimension) and education (the serious dimension) [4].

Our review of VR applications revealed no specific tools for the specialized field of insect neuroanatomy, though similar features are common in applications for understanding complex structures in other domains. For example, *EntomonVR* [11] focuses on insect external morphology, allowing users to manipulate and scale models for interactive learning, though it lacks instructive and gamified elements. *VRNeuroGame* [10] targets human neuroanatomy, using a puzzle format where players assemble a virtual brain from annotated parts. Another example is a VR puzzle game that aids medical students in learning anatomical terms and spatial relations [12]. Checa et al. [13] showed that VR serious games could outperform traditional methods in improving user satisfaction and educational outcomes for learning computer hardware assembly.

III. METHODOLOGY

As in preceding works[1], we follow a process that infers concrete design elements from pedagogically recommended

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[1] References omitted for the double-blind review process.

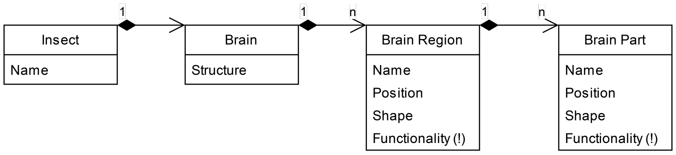

Fig. 1. The diagram illustrates a knowledge graph for insect neuroanatomy.

instructions, which, in turn, are inferred from the targeted learning goals. These learning goals capture the result of a process in which a domain expert organizes all relevant information for achieving mastery. Using the revised Bloom's Taxonomy [5], we translate these goals into a learning process that details why and how certain cognitive skills need to be prompted. We then identify game design elements, particularly gameplay mechanics, that meet these cognitive needs.

A. Knowledge Design

The targeted knowledge includes the neuroanatomy of various insect species starting with the bumble bee (*Bombus terrestris*) due to its course relevance, expanding to include other species to enrich the learning scope. We source our neuroanatomical data and models from *InsectBrainDB* [8], a comprehensive public-domain database, ensuring our material is accurate and up-to-date. Our content is restricted to the neuropil-level and does not include individual neurons. To ensure accuracy, we exclude uncertain details, like the relationship between brain parts and their functionalities, which are still under investigation. The structured knowledge is depicted in a hierarchical knowledge graph shown in Fig. 1. In the graph, the first node represents an 'Insect' identified by 'Name'. It is linked to its 'Brain' identifiable by its 'Structure', the result of its composition. The 'Brain' is broken down into 'Brain Regions', specified by 'Name', 'Position', 'Shape', and 'Functionality', with the latter marked by "!" to highlight potential incompleteness due to research gaps. 'Brain Regions' are further composed of 'Brain Parts', sharing the same attributes, indicating a modular approach and suggesting the potential for additional subpart complexity.

B. Instructional Design

The knowledge graph describes the knowledge items and their relationships. It helps to derive concrete learning objectives and, using the revised Bloom's taxonomy [5], according to instructional elements listed below.

- **(1) Identify/Recognize Brain**: Learners identify insect brains by recognizing shapes, drawing on visual cues and prior knowledge to meet the "remembering" level of the revised Bloom's Taxonomy [5].
- **(2) Identify Region/Part by Name**: Learners develop the ability to name and identify brain regions or parts by associating names with the shapes of brain structures, targeting the "remembering" level [5].
- **(3) Matching Regions to Parts**: Learners memorize and associate different brain parts with their respective regions, engaging the "remembering" level [5].
- **(4) Assemble the Brain**: Learners build their spatial understanding by constructing a brain from various parts, tapping into the "applying" level [5].

C. Game Design

Implementing the instructional design in engaging experiences, we created four arcade-style minigames embedded in a low-poly, nature-themed amusement park. This same setting, including the same minigames, hosts different levels, each focusing on a specific insect species. Players approach challenges in any order, enhancing exploration and autonomy. Each minigame allows difficulty adjustments — easy, medium, hard, plus a learning mode, with higher difficulties offering increased challenges and greater rewards through score multipliers. The learning mode supports beginners by offering guidance and corrections to teach correct actions. In regular mode, players receive feedback solely on action correctness through visual and auditory cues and scores.

1) Minigame 1: Shoot-a-Brain: We implemented the 'Identify Brain' instruction with a shooting game. At the booth, shown in Fig. 2, players grab a toy gun to play and select a difficulty by shooting at a target. During gameplay, insect brain models advance towards the player one at a time. The task is to determine whether the insect brain in front of them corresponds to the displayed species. Players shoot at "agree" or "disagree" targets next to the model based on whether they decide the brain belongs to the specified insect, as shown in Fig. 2. Correct identifications accrue points, whereas errors result in point deductions, with bonus points for fast correct responses. The difficulty setting affects the speed at which the models appear and the positioning of the targets. Assisting tools include a laser pointer for aiming. The game ends after a specified number of targets have passed.

2) Minigame 2: Whack-a-Part: To teach the identification of brain parts by name, we designed a "whack-a-mole" style game shown in Fig. 3. Players grab a hammer to hit targets, with initial targets setting the game's difficulty level. During gameplay, they must identify and strike the brain part named on the screen. Parts appear randomly for brief intervals, prompting quick associations. With each successful hit, the game promptly cues up the next target for identification. The scoring system rewards speed and consecutive correct hits, while errors reset the scoring streak. Difficulty settings vary the duration, number, and complexity of parts displayed. The game ends once all the brain parts are correctly identified.

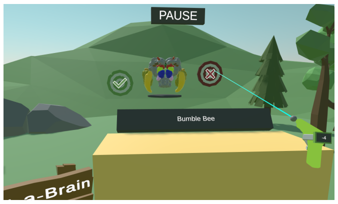

Fig. 2. Shooting Game: Precision in identifying brains.

Fig. 3. Whack-a-Part: Quick identification of brain parts.

3) Minigame 3: Brain-Part-Darts: The instruction of associating brain regions with their parts is realized in a dart-throwing challenge, shown in Fig. 4. Players pick up darts and throw them at targets on a wall. They begin by hitting a difficulty indicator, which then populates the wall with parts. The darts are color-coded to represent different brain regions, and players aim to hit the matching parts. Successful hits score points and burst the target, while misses deduct points and cause the dart to bounce off. Quick decisions are rewarded, with a timer influencing scores. Difficulty settings vary the targets' size and complexity, demanding more precise identification at higher levels. A trajectory assists in aiming, making the game more accessible. The game ends if there are no more brain parts left.

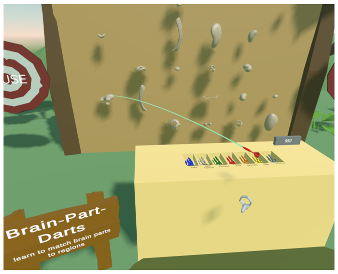

Fig. 4. Brain-Part-Darts: brain region matching game.

Fig. 5. Brain Puzzle: Assemble the insect brain.

4) Minigame 4: Brain Puzzle: For the assembly task, we use a puzzle game depicted in Fig.5. Players can examine a complete brain before selecting a difficulty level. Upon start, the brain "explodes" and its parts are scattered within a holographic sphere, ready for reassembly. Players pick up and join brain parts. Each part has multiple invisible connection points. Holding one over another, a ghost image [12] appears at a connection point nearby, if available. Releasing the part secures the connection. Players can detach parts when necessary and manipulate or examine individual and assembled parts from any angle. The game pauses when players exit the sphere and resumes upon re-entry. Completion is marked by hitting a stop buzzer, causing the sphere to light up green for success or red for errors. Points are given for correct connections and faster completion, revealed at the end to prevent guessing. Again, with rising difficulty, the complexity of the brain parts' geometry rises.

IV. EVALUATION

BrainBuilder has been refined through a continuous formative evaluation process, enhancing usability, engagement, and educational impact to meet both serious and gaming aspects [4]. This section details insights from playtests with 46 volunteers across five sessions. Participants aged 19 to 52 years (27 on average), including 25 females and 21 males. They self-reported their proficiency: 32 as novices, 8 as intermediates, and 6 as experts. Participants were briefed on the game's goals, VR equipment basics, and motion sickness prevention and then guided through the controls and minigames. The average playtime was 14.5 minutes, with an instructor offering hints and support as needed. Post-session, participants completed a questionnaire assessing usability, engagement, and educational effectiveness. The heterogeneity of test environments and situations made detailed questionnaires impractical. To fit our informal setup, we merged elements from standard questionnaires [14], [15] into more flexible questions, similar to other studies [10], [12]. Blending Likert scales and open-ended questions, we collected quantitative and qualitative feedback essential for iterative development.

A. *Iterative Design Improvements from Formative Feedback*

The initial testing phase aimed to refine game mechanics. The first prototype, featuring early versions of shooting and puzzle minigames, was improved based on participant feedback. We held two sessions with 12 biology students as part of the targeted course on neurobiology. In between, we tested at an educational exhibition with 10 participants, including students and educators from various fields. After resolving many minor interaction issues, we concluded the prototype feedback by consulting 5 neurobiology researchers.

Qualitative feedback from the initial tests showed that left-handed users struggled with the shooting game, which we quickly resolved. In the second session, we observed accidental teleportation, which prompted us to establish fixed teleport zones. We also replaced 2D brain images with 3D models in the shooting game for visual clarity. During later sessions, issues in puzzle interactions were pointed out; parts that were visually close to each other were often mistaken for being truly connected, which led to confusion. We refined the snap and release mechanics and integrated clear feedback for all interactions and outcomes. Participants also requested aiming assistance, for which we added a laser pointer for both distance-based games later on. Taking inspiration from an expert's recommendation to provide visual guidance on correct or incorrect connections in the puzzle game, we implemented a learning mode across all games. Consistently, users called for clearer instructions and a tutorial. While we added basic instructions, more comprehensive tutorials are planned to improve user guidance and gameplay understanding.

B. *Evaluating the Vertical Slice*

Concluding our series of studies, we gathered feedback from 8 students enrolled in the target course on a finalized prototype containing all minigames. Participants scored the usability as follows: ease of use and intuitiveness of the interactions at 4.4, ease of navigation at 4.0, and engagement at 4.1. Perceived educational effectiveness ratings were 3.5 on the shooting game for learning brain recognition, 3.75 for the puzzle game in aiding in the understanding of brain structures, and 3.0 for both the dart game and the whack-a-mole game. The overall recommendation of the game as a learning tool scored 3.75. In open-ended responses, a participant recommended including an overview of each brain part with names and functions.

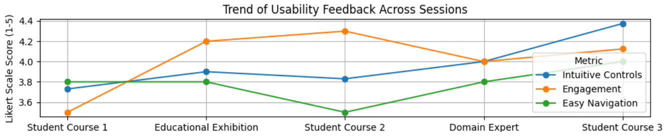

Fig. 6. This graph illustrates the trend of usability metrics across sessions.

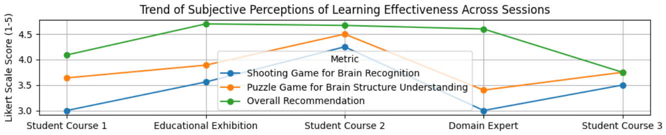

Fig. 7. This graph shows perceived educational effectiveness ratings for the shooting game, puzzle game, and overall game across sessions.

C. *Quantitative Results Over Time*

In analyzing quantitative data across sessions, variations in settings, participant diversity, and numbers complicate interpretation and comparability, yet some trends were noticeable. As depicted in Fig. 6, the trajectory of usability metrics is on an incline, underscoring that the game has become increasingly user-friendly and engaging through the process. These metrics reflect that the enhancements made were positively received, affirming the effectiveness of the user-centered development approach. The educational metrics, visualized in Fig. 7, reveal a more nuanced picture. Initial interventions, such as integrating 3D models and more precise feedback mechanisms, seem to have positively affected learning ratings associated with each game, evidenced by the improved effectiveness scores from the first to the second biology course. However, a notable downturn in the final session signals that the game did not meet the users' expectations or educational needs as effectively as in previous sessions. Feedback variances between the initial sessions, using similar prototypes, underscore how participant backgrounds and educational contexts, such as educational innovation exhibitions, affect perceptions. Intermediate users typically provided more positive feedback, suggesting that prior knowledge enhances the game's educational value. This highlights the need to adapt the game for different knowledge levels, which we plan to address with new learning modes. While most feedback concentrated on two minigames, the results are promising for the game's educational use, but also point to necessary improvements in user interface design and support for new VR users.

V. CONCLUSION

BrainBuilder is designed to enhance the educational experience of insect neuroanatomy by transforming the challenging task of understanding minuscule, complex brain structures, typically viewed on a computer screen, into an engaging VR game. Following a cognition-oriented design approach, we tailored multiple learning scenarios specifically for acquiring comprehensive knowledge on insect neuroanatomy, based on the revised Bloom's Taxonomy [5]. This strategy ensures that the educational material is not only engaging but also scientifically sound, thus improving learning outcomes. The development of Brain Builder followed a user-centered methodology, incorporating continuous formative evaluations to refine the game mechanics and educational content. This process proved essential, with user feedback playing a crucial role in iterative improvements to enhance both the user experience and the educational effectiveness of the game.

VI. FUTURE WORK

We plan to improve how players encounter new knowledge in-game by introducing a dissectable insect brain, providing detailed information on each part upon interaction. Additionally, we plan to develop a tool for educators to customize the presented VR game design easily by integrating subject-specific content like knowledge graphs and 3D models. This simplifies adaptation, enabling cross-disciplinary use for teaching spatial concepts in various domains, from human anatomy to mechanical systems.

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