Using Cognitive Map Theory to Create a Serious Game Assessment for Cognitive Dysfunction Post-Brain Injury

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Abstract

There is a clinical need for ecologically valid neuropsychological testing for cognitive deficits post-traumatic brain injury. Serious games provide interactive, safe, and replicable virtual environments to assess real-world skills. This paper outlines how the theory of cognitive maps and landmarks were used to provide a methodological framework for the map and design of a novel serious game, the Comprehensive Assessment for Executive Function (CAED). The development process with descriptions of each iterative phase is outlined. Overall, three iterations of the map were designed utilizing both tier one and two landmarks to form the final version of the CAED interactive design.

1. Introduction

Traumatic brain injury (TBI) remains a primary global cause of chronic cognitive disability, yet current gold-standard neuropsychological assessments often lack the ecological validity required to predict real-world functional outcomes after such injuries (Gioia, Kenworthy, & Isquith, 2010; Suchy et al., 2024). Traditional diagnostic tools rely on static, abstracted tasks that isolate cognitive domains into highly controlled silos, thereby stripping away the environmental context essential for engaging cognitive behaviors such as executive functioning. To address this gap, recent advancements have shifted toward "serious games," research-focused virtual tasks that facilitate the measurement of "cognition-in-action," by providing a safe, replicable, and highly controlled environments, for assessing the complex integration of multi-sensory information and translatable skills underutilized in current clinical practice (O'Brien et al., 2025; Suchy et al., 2024).

A central theory of cognitive deficits following brain injury involves disruption of the central executive system, which supports organizing, planning, monitoring, and repairing goal-directed behaviour. One approach to examine this is to through the formation and utilization of cognitive maps, mental representations of one's environment that allow for flexible navigation and spatial reasoning (O'Keefe & Nadel, 1978). Successful navigation requires an individual to not only recognize specific visual markers (landmarks) but also to integrate these into a coherent, relational framework (Tolman, 1948). Consequently, the inability to navigate to a goal location serves as a critical proxy for broader executive dysfunction, as successful navigation relies on planning, working memory, monitoring, error correction, and cognitive flexibility. This makes cognitive map formation a practical means of evaluating executive functioning during realistic tasks.

This paper outlines the methods and iterative process of utilizing the theory of cognitive maps and landmarks to create an interactive serious game, the Comprehensive Assessment for Executive Dysfunction (CAED). The CAED is designed to examine higher-level cognitive deficits often missed by traditional neuropsychological assessments by presenting a complex, yet realistic environment that allows individuals to navigate real-life tasks, thus allowing a clinician to assess higher-level executive deficits in a safe, replicable, and controlled environment. To support this, a town environment was created that is familiar in structure yet novel in layout, requiring users to rely on landmarks to plan and navigate between multiple goal locations in a controlled and replicable manner.

2. Methods

2.1. Tools

2.1.1. Game engine and software tools

The CAED platform was developed using the Unity game engine to support rapid iteration and deployment to tablet-based hardware (i.e. an iPad) which are commonly used in clinical settings. To reduce installation requirements and facilitate updates throughout development cycles, the system was deployed using Unity's WebGL pipeline to run the game in a standard web browser (i.e., Safari). Unity allowed for the integration of behavioural logging and performance metrics directly into the game, which captured measures such as route travelled, time-to-completion, task completion accuracy, and the frequency of map and to-do list access. Upon completion of gameplay, the data is exported automatically to a Google Sheet for analysis and inspection to support the broader goal of quantifying executive function behaviours during functional navigation tasks. In addition to Unity, several tools were used to support asset design and development. Blender was used to create and animate a customizable 3D avatar model. Static meshes, including buildings, props, and items, were created using the Probuilder plugin in Unity. Textures and UI elements were created using GIMP, while the map layout was designed using Draw.IO.

2.2. Development

2.2.1. Project Members and Development Strategy

To support the development of this project, a multidisciplinary research and development team was established, integrating clinical expertise in TBI and cognitive rehabilitation with software engineering and game design. This collaborative framework was supported by a rotating cohort of graduate and undergraduate research assistants who filled specialized functional roles, including programmers, artists, and UI/UX designers. The development of the virtual environment was managed through a granular task-allocation strategy, wherein map and landmark designs were decomposed into discrete subcomponents and assigned to specific team members. Progress was coordinated through weekly plenary meetings, with project versions maintained on GitHub and supporting materials, including storyboards, sketches, and notes, stored in a shared Google Drive.

The design phase utilized iterative storyboarding to define the CAED layout, UI, and the mechanics of user-environment interaction. Once group consensus was reached for the storyboards, conceptual sketches were transitioned into a functional prototype within the Unity game engine to create the CAED world. The research team then play-tested the environment to evaluate the navigational feasibility of the virtual landscape. This testing occurred across both Windows and macOS platforms to ensure cross-functional stability. The final stage of development involved a validation check on an 11-inch iPad Pro (3rd Generation) to optimize the interface for mobile clinical delivery and confirm the platform-agnostic stability of the final application.

2.2.2. Design of the world map

The primary theory used as the foundation of the CAED design stemmed from the three-part "Parallel Map Theory" proposed by Jacobs (2003), which outlines two processes that combine to form the cognitive map: the bearing map and the sketch map. The bearing map serves as a grid of boundaries, providing rough estimates of a position, whereas the sketch map allows the individual to incorporate topographical markers (tier 2 landmarks described below) through an egocentric, first-person view. In combination, the two form the final cognitive map. Both the bearing and sketch maps provide directional and locational cues, albeit from different perspectives. The bearing map provides a bird's eye, allocentric view, whereas the sketch map provides the first-person, egocentric perspective that serves to scaffold the initial route details.

In addition to outlining the theory guiding the design of the serious game, it was important to establish the type of environment the CAED would present. While other serious games presented singular environments such as grocery stores, shopping lanes, libraries, and offices (Caglio et al., 2012; Jacoby et al., 2013; Knight et al., 2006; Krch et al., 2013; Renison et al., 2012), it was important to present a larger "world" which would allow for the assessment of diverse skills such as withdrawing funds from an ATM, buying a sandwich, delivering a food order, or organizing multiple errands. To accomplish this, a town comprised of a neighbourhood, an office building, a park, a grocery store, a bookstore, a restaurant, a gym, a coffee shop, and other locations traditionally found in a classic town centre was designed. Based Jacob's (2003) framework, an aerial map was included that could be referenced to plan a route, which would need to be easily accessible during gameplay to aid in the monitoring or repair of the route when needed. Three guidelines for the design of the map were established: 1) It needed to be sufficiently difficult and present multiple routes to navigate between locations; 2) It needed to include realistic landmarks that could be used to form and track a route; and 3) Each location needed to have a specific purpose for assessment. For example, a user may be instructed to withdraw money, purchase specific items, and deliver those items to another location, which require route planning, task sequencing, working memory, monitoring, and error correction while navigating between multiple destinations.

2.2.3. Landmark Incorporation

Landmarks describe physical markers in an environment that can be used to mark progress of a route and allow individuals to form their sketch map (Jacobs, 2003). They include signs, buildings, landscaping, decorative items, and anything that is fixed in its location. To meet the second guideline for the CAED map design, landmarks were designed and placed in two functional tiers. Tier 1 landmarks were defined as global, salient reference points, such as buildings, parking lots, or landscape fixtures (i.e. a fountain), that were visible from both the map UI as well the third-person view of the environment. These landmarks served as anchor points for large scale spatial orientation and support the formation of a mental cognitive map. In contrast, tier 2 landmarks consisted of localized cues such as smaller shop signs, environmental props (i.e. light poles, park benches, garbage cans), or street signs that assist with route formation at specific points in the map. Unlike tier 1 landmarks, tier 2 landmarks are not intended to aid in the initial planning of the route (these are not visible from the aerial map) but instead, support the formation of route memory and allow the player to retrace their steps when recalling their route. The diversification of the landmark tiers allowed for the assessment of different cognitive skills in the player's ability to initially plan and organize their route, monitor their progress, and in the case of errors, utilize tools to reverse their route, track their progress, and reroute when necessary.

3. Results

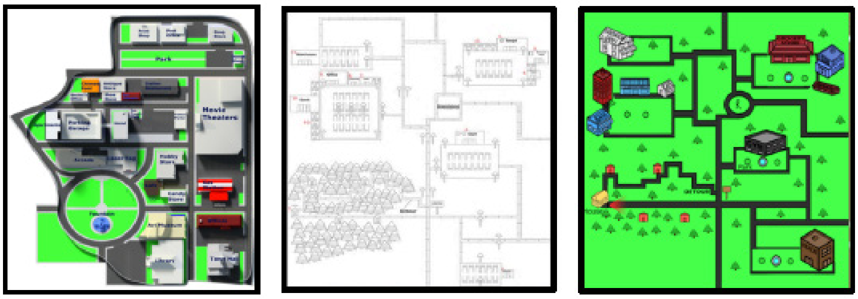

Figure 1: Map Versions 1, 2, and 3 (placed in order from left to right).

3.1. CAED Map

The spatial design of the CAED map evolved through three iterations which were driven by both the theoretical considerations of Jacobs (2003) and more practical usability constraints identified through feasibility tests run by the research team. The first iteration of the map was designed for navigation via a vehicle where users drove between locations. However, it was determined that this introduced excessive motor and attentional demands that would detract and overly complicate engagement with the CAED. To reduce this burden, the navigation was simplified to a walking-based model that utilized a single joystick for movement. To make the environment more ecologically plausible, the team designed a walkable town modelled after a New England municipality. This second iteration of the map emphasized pedestrian travel and featured clustered districts and parks spaced apart to ensure that travel distances remained realistic, yet feasible, for an average assessment session (>60 minutes). Traversal time between key locations (i.e. home to park, bank to café) was assessed through multiple testing sessions with the research team. This testing revealed satisfaction with the overall road layout, but issues with the spacing of the buildings and the density of the landmarks were raised. Multiple rounds of "playtesting" revealed that the buildings were clustered too closely which made it difficult to identify them individually, and that the density of the trees was distracting which made it difficult to see where the houses were located. It was also felt that the monochrome colouring of the map increased the difficulty of identifying locations. The third layout of the CAED map included brightly coloured and simplified districts, each connected by primary and secondary pedestrian streets, along with multiple routes to each district as well as significantly reduced tier 1 landmarks. To support orientation within the town and to reduce the working memory burden and minimize spatial disorientation, a player location marker was added to indicate the player's position on the map in real-time. Figure 1 showcases each iterative version of the map.

3.2. Landmarks

Tier 1 landmarks were incorporated into the first iteration of the CAED map, which consisted of a town environment designed for traversal by vehicle. Tier 1 landmarks included only roads, buildings, and a fountain. Since the modality of travel within the game was modified to walking, landmarks were not modified for this version of the map. In the second iteration of the map, tier 1 landmarks included buildings, parking lots, trees, and streetlamps. When discussing this map with the research team, it was determined that tier 1 landmarks were too dense and could unnecessarily distract the player. Additionally, the inclusion of parking lots, while realistic, was not purposeful (thus violating the third guideline) since there were no vehicles in the game. The third iteration of the map presented a more simplified design that included buildings, roads, trees, and landscape fixtures, but with less density so as to not distract the player. However, testing the third person view of the CAED world revealed that, although the minimalistic design of tier 1 landmarks may have been beneficial, tier two landmarks may had been oversimplified. During testing of the third-person view, players struggled to differentiate the roads to travel to and from locations because there were few salient landmarks to mark their path. To address this, additional features such as neighbourhood signs, park signs, and road signs were added to provide more realistic visual cues to aid in the formation of the cognitive map and allow for easier navigation to and from locations. This final phase of testing among the research team also resulted in a refined interface, as initial versions featured text labels too small for comfortable viewing on tablet devices. Additionally, the map interface elements such as the player location marker lacked sufficient contrasts, which made orientation difficult. Subsequent revisions increased the label size, enhanced contrast, and improved the visibility of the player location icon.

4. Conclusion

This work presented how we applied cognitive map theory to develop the framework for the CAED, an interactive serious game designed for individuals with traumatic brain injury (TBI). Through an iterative design and testing process, the team refined a "bearing map" – a minimalistic, aerial allocentric view using tier 1 landmarks – to provide essential directional and positional cues. To supplement this, tier 2 landmarks such as street signs and environmental features were integrated into a 360° first-person view, acting as a "sketch map" to help users build a detailed 3D mental representation of their environment. These changes provided the interactive framework for participants to perform daily tasks such as navigating to the grocery store, bookstore, or office building. Each respective location correlates with a set of realistic tasks such as buying food on a budget, ordering coffee in a distracting environment, finding an office location, and other daily tasks that are reliant on sequencing, cognitive flexibility, working memory, inhibition, planning/organizing, monitoring, and repair of behaviours. This final iteration is currently undergoing a feasibility study with speech-language pathologists and individuals with TBI to evaluate its effectiveness as a clinical tool for cognitive assessment.

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