Remapping and replay in generative spaces

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Abstract

The space we inhabit influences our perception, constrains our thoughts, and shapes our behaviour. In psychology experiments, larger spaces facilitate creative use of everyday objects, while arrangement of furniture affects the use of those spaces, for example for discussion vs. presentation. In these times of physical isolation, confined spaces are detrimental to mental health. How do we perceive space in these confining times, and overcome these restrictions to open our minds to a wider, more expressive environment?

We examine the human cognitive map that evolves with generative spaces, as humans enter virtual contexts and experience different functional spaces. Neuroscientists have found neurons called place cells in the hippocampus part of the brain that fires whenever humans enter a particular location. These cells remap when humans passage to different contexts, and rescale when they enter the same room but at a different scale. In between these transitions, place cells also replay their own prior activity as humans learn from their own navigation in space. These neuroscience insights are captured by abstract models of place cell networks as humans traverse virtual spaces that generate complex open structures depending on audience interaction within their boundaries.

The web experience takes the audience through procedurally generated spaces generated from player interaction. As the player moves virtually in space, a cognitive map of shape architectures representing place cells are shown above the player activated when stepping into a particular space. New spaces lead to remapping of the shapes to new locations, and trigger them to replay their activity when players remain stationary. When players visit certain areas, the confined spaces become wider and the shapes become more expressive, generating patterns that reflect the larger spaces and diverse sensory inputs they listen to. Finally the audience can begin to see the connection between the complexity of spaces they inhabit and their own evolving neural coding for these spaces.

1. Introduction

We are becoming increasingly isolated due to health and safety measures that serve as a double edge sword: protecting us physically from infection of each other, but causing mental issues by isolating us from each other psychologically, inducing depression, anxiety [15], trauma [9], emotional instability , and higher rates of suicide [34]. Indeed, space is the medium of our interactions, and when confined in restricted spaces for prolonged periods such as explorers in Antarctica or astronauts in space, humans experience social avoidance and physical incapacity analogous to the hikokomori syndrome in Japan, where people don't go out of their rooms for weeks at a time [19].

To narrate countering the effects of confinement by exploration, we created an interactive artistic intervention that allows people to control a character as it wanders beyond their isolated environments and discover the surrounding playground of a generative space. In the process we discovered how human minds process spatial interactions and used this insight to show audiences how their own cognitive maps react when they encounter generative spaces that change with audience interaction.

2. Background

2.1 Psychology of Space

The spaces we interact in defines our perception and actions within that space. Studies have shown that traits like creativity in the use of novel objects is reduced when subjects are enclosed in spaces like small rooms and corridors, and higher when located in larger spaces like auditoriums [7]. Meanwhile, the arrangement of space using instruments like furniture determines our interaction with it. For example, chairs in a circle imply discussion and communication while the same chairs in a column designate presentation [24]. Different seating arrangements can even affect how favourably subjects evaluate ads oriented towards individuals or towards families [42].

To use spatial arrangements for the benefit of those within it, we would need to generate spaces that take audiences from a state of confinement to a state of openness. Moreover the generative process should be meaningful in the social context of the interaction. A case in point is a study of social dining, wherein lighting (dim vs. bright) affected the way subjects assessed the situation (romantic or non-romantic) [40], indicating that the properties of the space can provide social hints for the interaction. What's more, these influences of space can work at an implicit, subconscious level without explicit evaluation from subjects. These "implicit interactions" can drive the design of everyday instruments [17] from the arrangement of door handles to traffic markings on the street. One of our goals is to tease apart the effect of these subtle changes in spatial interactions on how people perceive confined or open spaces.

2.2 Neuroscience of Space

In the original experiment that gave rise to the idea of a cognitive map, Edward Tolman gave rats a reward on successfully navigating a maze. Over time the rats get better at remembering where the reward was. In a surprising result, his group found that rats not given rewards could catch up to those given rewards after just a few trials of rewards, indicating that during the non-reward trials, the animals were actually learning something intrinsic about the maze itself, rather than being motivated by the reward [39].

This fundamental insight in neuroscience is instantiated today in the work in the hippocampus, where physiological analogues of the cognitive map have been localized as place cells of the CA1 and CA3 regions, and grid cells of the Entorhinal Cortex [28]. Place cells respond whenever humans and animals are in some specific location in a room, while grid cells [10] respond in a spatial frequency manner whenever they are in some area of a grid in the room (Figure 1). In addition, there are cells like head direction cells and boundary vector cells that code for other properties of space like current direction of travel and the boundaries in a room [23] (Figure 2).

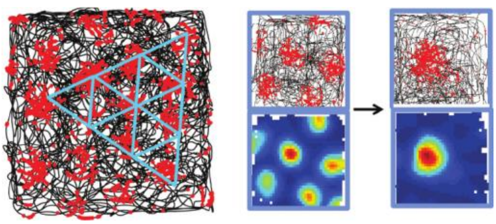

Figure 1: Heat maps of activity in grid cells (left) and place cells (right). High activity for a single cell indicated in red, low activity in blue. (From Moser et al, 2015 [27])

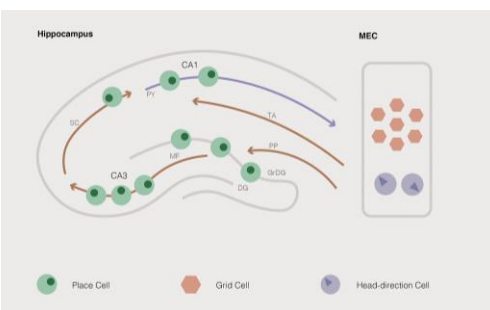

Figure 2: Diagram of locations of place cells, grid cells, and head-directions in a visual representation of the hippocampus.

Three properties of place cells are particularly relevant in the context of generative spaces:

(1) Place cells are **scale** invariant, i.e. if the room is enlarged 2x, then the place cell will fire in the same location scaled by 2x [21].
(2) Place cells adapted to a particular space can **remap** to fire to different locations when a new space is encountered [16] or remap by changing their firing rates [1].
(3) Place cells can **replay** the sequence of their recent activity when encountering rewards [2], and the “replay” can even take place before decision points in an attempt at prediction via “vicarious trial and error” [32].

These three properties of place cells suggest that generative spaces would produce neural firing that correspond to particular functions when people navigate in fenced-in spaces, revisit landmarks, encounter new environments, and learn to predict new contexts or consolidate recent spatial memory. Everyday functions like the use of tools (a light-pen in the study) can remap the structure of space [4], while replaying the insights gleaned from previous exploration can help predict optimal decision-making [33].

While the effect of confinement on human brain circuits have not been well-established, evidence has suggested that isolation leads to abnormality in the usually inhibitory circuits in the amygdala, causing persistent activation to other areas of the brain [13]. Work with humans even shows changes in EEG frequency bands with solitary confinement [11]. Interesting, social isolation makes deficits in spatial memory even worse in particular animal models [14:1], suggesting that confinement in space affects spatial learning.

These ideas are consistent with recent general findings suggesting that hippocampal circuits like place and grid cells code more than only for spatial location. In particular, place cells can respond to locations of others in a room in addition to one's own [8], and even respond independently while watching a conspecific's demonstrated navigation [31], suggesting a role for place cells not only in navigation but also social foraging. Hippocampal signals have been found that facilitate learning in place cells that code for social memory, such as recognition of conspecifics [30]. Thus, a spatial-social system exists in the brain that helps us identify location and socially relevant rewards in these locations. Spatial interaction and social rewards appear to be intimately tied to each other. After all, humans are social creatures that navigate in space. When we move to a new city, we look up where the closest basketball court is, or the public library or symphony, or where to meet people integrated in the community. Navigating in space and social behaviour are paramount to our success in changing environments.

2.3 Computation of Space

If indeed spatial navigation is intimately tied to social rewards, how can we compute these spatial reward interactions in a virtual space during navigation? Computational models for rewards and spatial interactions have centred on work in reinforcement learning (RL) [36,38].

Two general types of reinforcement learning strategies are model-based and model-free methods. Model-based methods build state and structure representations that capture knowledge - based learning, while model-free methods use prediction errors to update a simpler heuristics-based learning [12].

A frequently applied model-free RL method is Q-learning, which involves learning the values of actions that lead to optimal rewards [41]. At each location of the interaction, we can associate a value with moving right, left, forward, or backward. Given reward at a particular location, Q-learning iterated over many trials can find the optimal path to the reward in the navigation process. Audiences engaged in the specific task can generate many trials that are used to train the parameters of Q-learning, and the learned parameters capture a model for how humans forage for reward interactions to remap the space they are in. More complex models versions of Q-learning like Dyna-Q can also account for replay of previously encountered activity and remapping of cognitive maps in new spaces [26]. These ideas serve as a possible extension of our work to show how learning occurs in the spatial interaction paradigm.

3 Methodology

3.1 3D Modelling

The cognitive map is an intricate network of neurons that communicate with each other to provide environmental, contextual, and social information to humans and animals. New stimuli that take place in space, like scenery, spatial sounds, and physical activities can cause activation of these neurons, signalling spatial information, and forming a network for navigation. We wanted to illustrate the neuronal network of cells in the cognitive map by highlighting its spatial coding properties, and to bring elements of architectural space into the visual design. In the first generation of the model, based on the morphology of the pyramidal cell, we explore possible forms of the place cell, from concrete to abstract. We then extend the place cell into 3D, producing a modular model using an architectural approach.

3.1.1 Place Cell Visualization

We started from single place cells, which have pyramidal (triangular) morphology, with the apical dendrite of the cell extending vertically above the soma and the basal dendrites radiating laterally from the base of the cell body. From the morphology of the pyramidal cell, we made some sketches of realistic-looking pyramidal cells based on work from two-photon imaging of these hippocampal cells [20] (Figure 3, left).

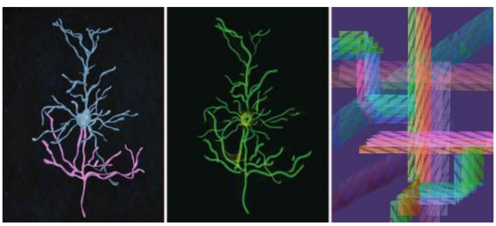

Figure 3: Sketch of the place cell (Left). Abstract representation of the place cell (Middle). Tubular synapses as sites of info exchange for a place cell (Right).

Next, we show the cells in a more abstract way by extracting their structure based on connectivity and function, (Figure. 3, middle), which further enables people's spatial imagination. Here, the central element no longer looks like a cell, but rather an information processor.

Finally, we discarded the canonical template of what cells should look like in our minds to show the information and connectivity inherent in single cells. Noting that visual representations of cells are only metaphors for the cells themselves, we chose to represent instead the importance of connectivity and information exchange in what cells do. Thus we used tubes to build "a world of information exchange." (Figure 3, right).

3.1.2 Network Architecture

Next, we move on to the design of systems of cells. Along with our abstract tube-shaped representation of single cells, we want to visualize how the connectivity of cells themselves evokes architectural space. This is inspired by work examining how architecture of human surroundings is related to the way our brain functions in space [3]. Instead of showing cells as biological entities, we decide to portray them as spatial entities, in so much as they are active in the processing of spatial information. Thus we provided a sense of architecture in characterizing the place cell (Figure 4). Instead of using morphology of cells under the microscope, we use functions of the cell as processors of spatial info to define the visual representation.

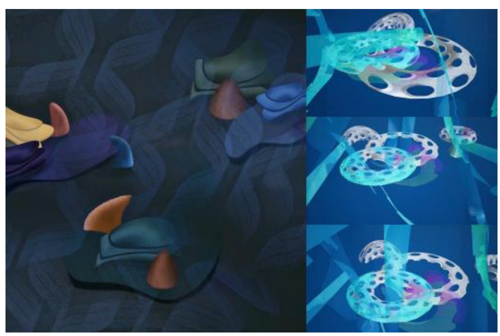

Figure 4: Sketch of the system (Left). 3D model of network architecture (right).

3.1.3 3D Model Realization

To instantiate the architectural ideas concretely for interactivity, we first have to create 3D models to represent cell systems that process spatial information.

We realized that different cells in the brain are like modular buildings with the same components that can be built in different ways in the short run [35]. The synapses, dendrites, and other cell components are like windows and doors that can be adapted to any form and specialized for function. Thus we introduced the modular model into the design of cells. On one hand, modular models provide a system that allows for the randomized configuration necessary in the generative process. On the other hand, each model of the modular system shares the same general structure, but has its own specific instantiation, mirroring the diversity of cell morphology in the brain.

In the first iteration (3-1 in Figure 5), we use various twisted tubes to represent cells, which end up looking like symbolic graphics and mysterious ancient text that conveys unspecified information. However, it is too abstract for players to identify the models as the cells, and tend to lose touch with the idea of information processing.

Next we used the shape of rings to represent a diversity of cell types, much as they would occur biologically in diversification of an evolutionary template (3-2 in Figure 5). They evoke a systems perspective to the design like the way different bacteria can be classified in a biology class. We took a more abstract approach to replace the tubes, which represent the connections between cells, with cells that potentially can be innervated by tubes.

Next we wanted to combine the cell diversification in 3-2 with connectivity. We realized that connectivity requires the presence of processes: an input and an output end. First we combined the elegance of 3-1 with the diversity of 3-2 to produce a line that also has processes that would serve as connectors (3-3 in Figure 5). Next we refined that design to make the entities more sculptural, three-dimensional, and hence more capable of representing the diversity of shapes and sizes in a hippocampal cell line (3-4 in Figure 5). By modifying the cell bodies to adapt for processes that allow for information exchange in the interaction, we created a morphologically more functional version of the cell system.

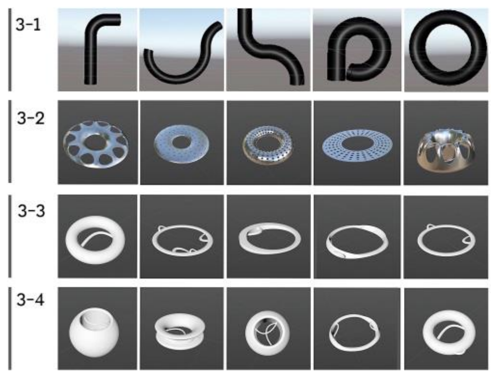

Figure 5: Catalogue of the modular models. Iterations of the modular models from the 1st generation to 4th generation.

3.2 Interaction

3.2.1 Spatial Representation

The existing research has suggested that mammalian spatial navigation ability relies on a neuronal representation of space provided by cells in the hippocampus [22]. Additionally, grid cells are thought to provide a hexagonal spatial frequency-dependent input to unitary place cell firing [6]. Inspired by this, we applied the hexagonal grid cell receptive fields to our design as a way to visualize the spatial cognitive map that players wander in. They can also play a triggering role that reveals and subserves place cell activities. This is consistent with modelling and physiology studies showing Entorhinal grid cell input into pyramidal place cell outputs [37].

The first step is to form the hexagonal tiles that can be used as a cognitive map for player navigation. Inspired by the organization of place cells in hippocampal formation as a coordinate coding system that fire at regular lattice intervals [25], we experimented with arrangements of the hexagonal system in both fully supported and randomly supported forms (Figure 6).

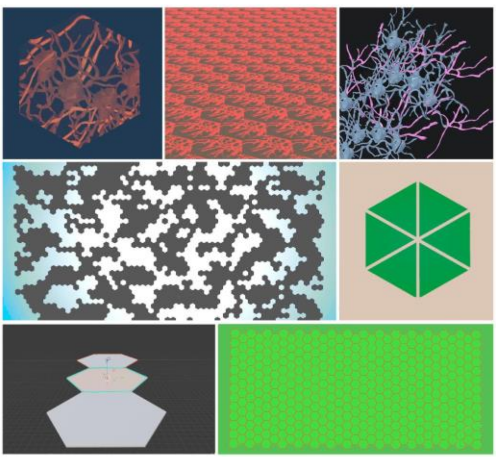

Figure 6: A texture of neural circuitry for a hexagonal place fields (Above). Simpler hexagonal tiles procedurally generated in the environment (Middle left). Grid model (Middle right) and grid combination, including fully connected spaces in perspective and overview (Below).

Next, we explored the effects of different shaders in a single grid and in a grid combination. First, we assigned a complex neural circuit texture as texture on the grid in order to highlight the context of the biological inspiration. As the design evolved, we realized that the hex-cell grid needs to be identifiable and visually clean to be recognized as an interactable component. Thus, we developed a non-textured grid and a dynamic strategy whereby the hex-cell grid revealed itself by changing colour when the player collides with it. In practice, this strategy was used not only as a visual indicator for the hexagonal grid, but also played a functional triggering role for neuronal Interaction (Figure 7).

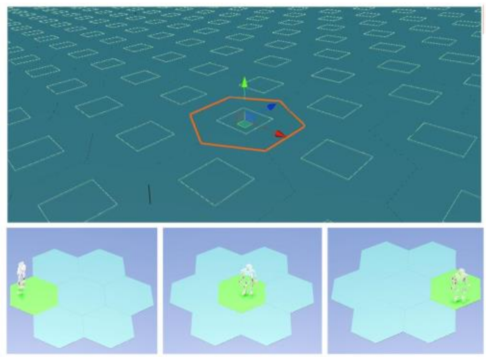

Figure 7: Development of a grid collider for triggered player interaction (Above). The effect of collider application (Below).

3.2.2 Player Interaction

We utilized a grey box character as our first controllable object to examine the core movement functionalities. As we tested interactive behaviours such as wandering, zooming, and ducking, we realized that objects and interactions needed to serve the target experience using different recognizable states, otherwise the identification with the movements would be weak (Figure 8).

Applying ideas from the architectural inspiration previously described, we attempted to enact the synecdochical characteristic of human navigation, which recapitulates its micro form in its macro form. For instance, human macro behaviours such as calculating distance from subject to subject is related to the micro behaviour of coordinate measurement by grid cells. Meanwhile, the micro process of replaying is analogous to macro processes such as learning by vicarious trial and error. The covert activity that happened in our brain can be regarded as a mirror for the overt activity in reality.

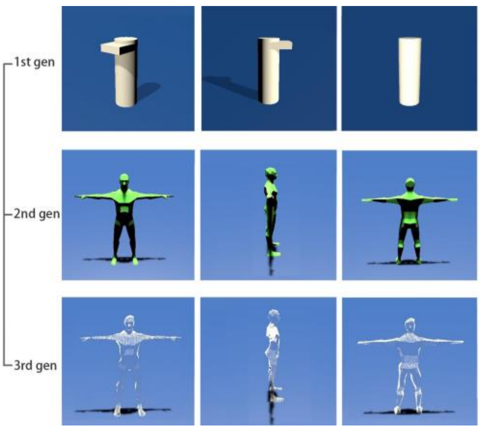

Figure 8: Iteration of the controllable player from the 1st generation to the 3rd generation.

This consideration provided a new viewpoint for our design of interactive components. In order to connect the world of neuron structure and the virtual environment, we introduced the humanoid as the player in our second iteration. This application allowed us to include a range of animated behaviours that served to bring the players into the role. In order to aid identification with the controllable character, we used a semi-transparent shader for the third iteration. This shows the generic player as a placeholder for the audience itself in transparent form.

Another issue that came along with the implementation of player control is the camera perspective. We experimented with first person and third person perspectives. First person perspectives allowed players to gain a more immersive experience, but the point of view is more limited, and it's hard to observe what tile you're on and get a global view of the entire space. As players interacted with objects, they needed to constantly switch sight from hex-cell grid to the 3D models that were above them. In third person perspectives, players were able to observe objects in the scene in a global view. However, as the controllable object moved far away, the details diminished due to the confines of the screen size and resolution.

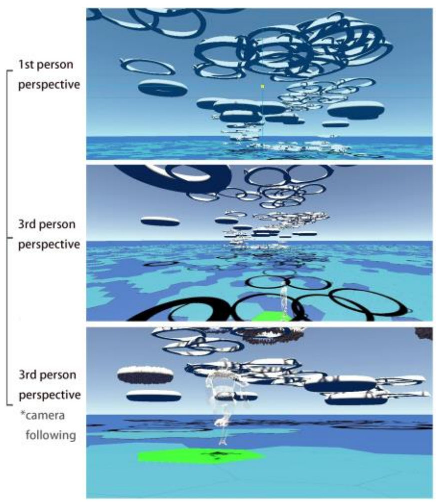

Figure 9: Player point-of-view in different camera perspectives.

For our last iteration, we wanted to combine the global view of a third person view with the immersiveness of a first person view by using Cinemachine in Unity to have the camera automatically follow the player when it's moving. We believed utilization of this technique combined the merits of the first person and third person perspective, for it not only illustrated place cell activities in a global view when not moving, but also the player's interactive behaviour of triggering that caused the cells firing in the local view when moving (Figure 9). Finally we used AI Navmesh in Unity to allow click-based navigation, so that players can use arrow keys to control the camera while not moving to customize the global view.

3.2.3 Neuronal Interaction

With the 3D model, hexagonal spatial map, and controllable player configured, we moved on to incorporate all three elements into the core interaction design. In this we are inspired by the neuroscience insights from cognitive maps, namely the properties of rescaling, remapping, and replay in place cells.

Based on what we know about human spatial navigation, grid cell metrics can be regarded as an internal spatial-coding system, and place cells utilize that coordinate reference along with other cues to generate location awareness [5]. In other words, place cells fire in sequence based on path and grid metric processing. To adapt this cell mechanic to an interaction mechanic, we used hex-cell grids as the trigger that lead to place cell model firing. Thus, a player walking through the hexagonal space would create a path that causes a series of place cells to fire in sequence.

On the other hand, replay is believed to both consolidate spatial memories and predict navigation planning during periods of rest [29]. Thus we introduced an idle stage as part of interaction to mimic the spatial replay in place cells. That is, when the player is idle, the path and cells sequence replay past behaviours or test out future possibilities. Idle stage replay can be helpful for contextual understanding, as one pauses and reflects on mental model assumptions of causes and effects in the world, much as in the field of walking simulators in video games [18]. The interactive loop proposed is shown in Figure 10, while the algorithm for the interaction is Figure 11.

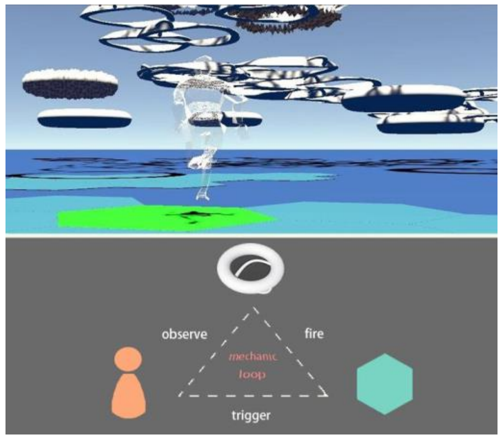

Figure 10: Interactive main loop. The grid is triggered by the player that leads to cell firing. Activation of cell firing serves as visual feedback to the player.

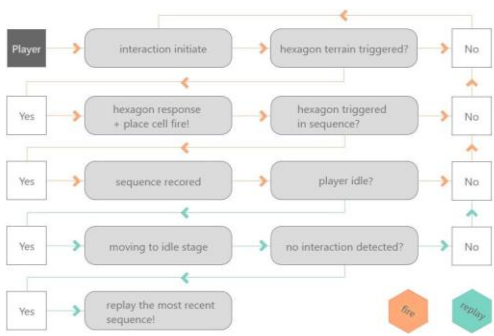

Figure 11: Step by step interactive procedure. The loop consists of place cells firing (orange) and chronological sequence replay while idle (cyan).

3.3 Generative Processes

There are two generative processes underlying our work: generating cells in space that respond to particular receptive fields by activating, and generating the receptive field boundaries themselves.

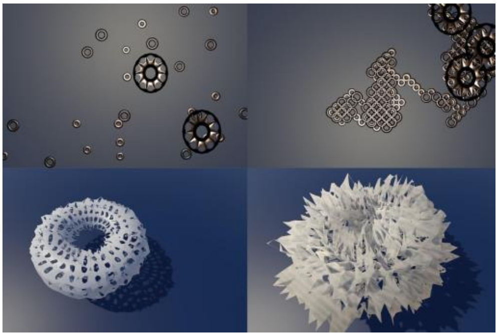

Figure 12: (Above) Generating neuronal cell population using uniform randomality (Left) and Brownian Motion induced randomness starting from centre of the space (Right). (Below) Representing activation of a cell using displacement vertex shader. Beginning of firing sequence (Left); peak of firing (Right).

We wanted to generate the cells above the players in order to allow the player to see them easily as part of the landscape of the space they are navigating. Beginning with two cell types that could be matched to, say globally or partially remapped place cell for instance, we populated them in our space first using uniform distributions (Figure 12). Upon examination of the outcome, we realized that people have a better sense of which cells correspond to which hexagonal receptive field if they are arranged in a probabilistic manner. Thus we followed a Brownian Motion generation procedure to create cells that are successively one step away from each other:

1. Create cell at current location.
2. Move step-length randomly in either positive or negative x and y directions (50% probability each).
3. Move in z direction following smooth 1D Perlin noise.
4. Create a new cell there with different probabilities for different cell types and return to 2.

The resulting hex-cell grid has a probabilistic but consistent relationship with the neurons in that cells that are close to each other are likely to have receptive fields that are closer to each other during the co-generation process.

To represent the activation of cells, i.e. how they fire in response to the player being at a certain location, we used a vertex displacement shader to perturb the displacement amount every time the player triggers the collider of the hexagonal cell corresponding to the particular cell. Speed of firing depends on a tuneable parameter that determines the rate of relaxation back to zero displacement.

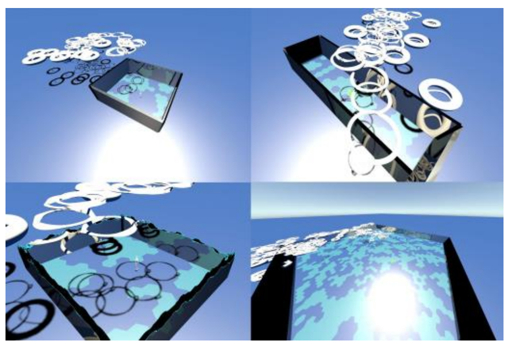

Figure 13: Generative boundary creation conditions. Small and large spaces for interaction are procedurally generated using an algorithm that respects the hexagonal tile locations. (Lower left) process of removing the walls using a dissolve shader during remapping to a different space.

The other generative process involves making the boundaries of interaction that allows a transition from confined space to open space (Figure 13). When the player triggers a specific tile in the scene, the walls come down and we remap to a new space depending on the locations of the randomly generated tiles. The spaces get progressively larger as the player continues to find trigger tiles at each stage. These generative spaces illustrate the evolution from confined to open spaces through exploration.

4 Outcomes

Our web-based environment allows the player to explore a generative world that shows the properties of the player's own cognitive map in the form of stylized shapes that become active in different ways when environments are regenerated.

4.1 Rescaling

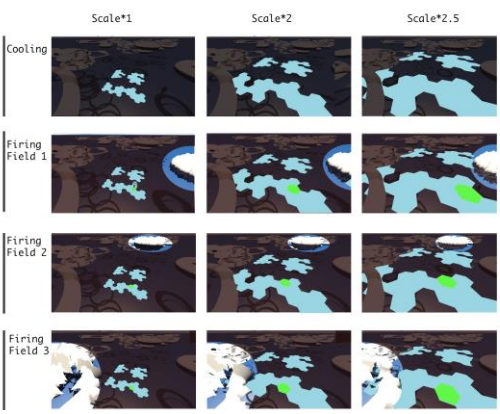

Figure 14: Grid maps generated in different scale (Scale increasing from left to right). Note that no matter how the scaling condition changes, the binding relationship between the place cell and grid remains the same.

A robust finding from the neuroscience of spatial navigation is that when the scale of the room changes, the area that causes a particular place cell to file scales with the environment [21]. In our application, when the space is regenerated with different grid sizes, the relationship between location and particular cell activity is preserved (Figure 14), showing place field scale independence.

4.2 Remapping

Particular place cells remap their activity when encountering new spaces, both by changing the location that activates it, and by the rate of spiking the activation triggers [16] (Figure 15). In our application, the new spaces are generated by the player as it explores the environment. A small, confining space becomes a bigger, explorative space when the right tile is triggered, leading to further exploration.

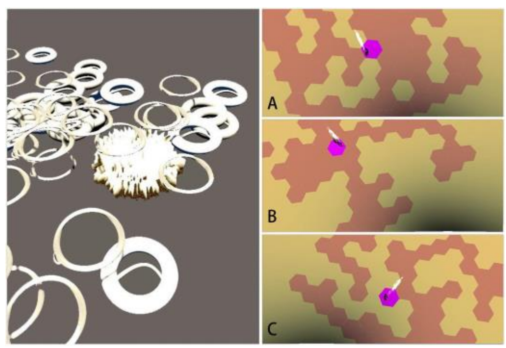

Figure 15: Receptive fields for a single place cell when spaces are regenerated. The cell in question (Left) responds to different areas of a remapped grid rearranged in the form of different cognitive maps (Right) caused by changes in the space occupied.

In the new space, certain cells retain their receptive fields while others take on new fields as the space is changed, both when the space is fully innervated, and when it's partially innervated by the grids.

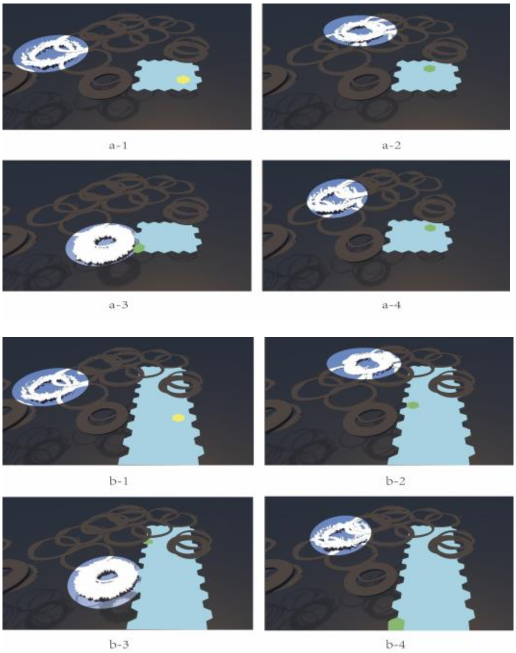

Figure 16: Characteristics of remapping. When a new space is encountered, place cells adapted to a particular space can remap to fire to different locations. Here, a small boxed-in space (a) is changed to a corridor (b). (a-1) and (b-1) portray the phenomenon when one cell fires to a location that remains the same upon regeneration of space.

In the fully innervated situation, every location in the space leads to a place cell activation (Figure 16). When the space changes, the cells may fire to a new location or to the same location if that location still exists in the new space.

In the partially innervated situation, a set of locations that lead to place cell activity is changed when the player encounters a new environment or is in a different mind set (Figure 17). Here, the place cells have remapped to different locations that partially cover the location, and some of the locations have lost their place cells.

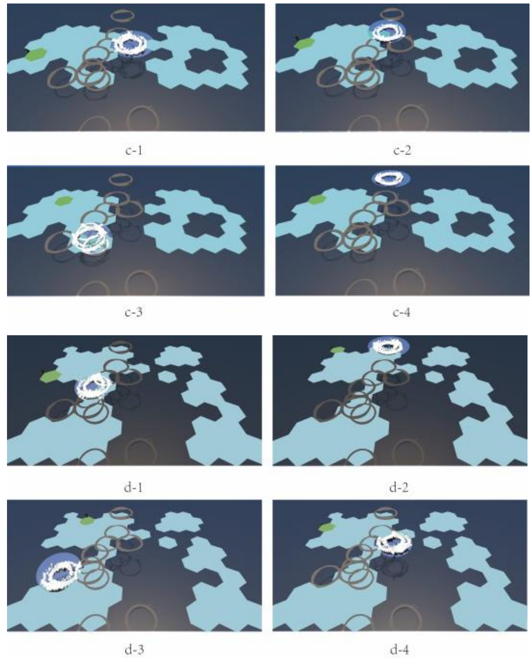

Figure 17: Characteristics of remapping in the case where spaces are partially covered by the present set of place cells. Place cells that fire to particular locations before remapping (c) change their location of activation when in new contexts (d). Some locations lost their place cell, while other locations gained a new place cell upon regeneration.

4.3 Replay

Even when spaces don't change, place cells can engage in replay of its recent activity [2] or predict future decisions [32]. The replay can show a reverse sequence of past visited paths that helps to consolidate the exploratory behaviour the player has seen in her actions to trigger the regeneration of space (Figure 18). Replay can also be activations that help determine imagined future possible choices as a vicarious trial and error decision making strategy (Figure 19).

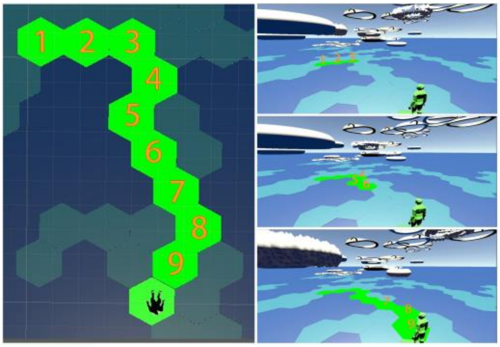

Figure 18: Replay while idle. The grid tiles change colour while cells fire one by one in reverse chronological order (Left). What the player sees while looking at a path she had visited before (Right).

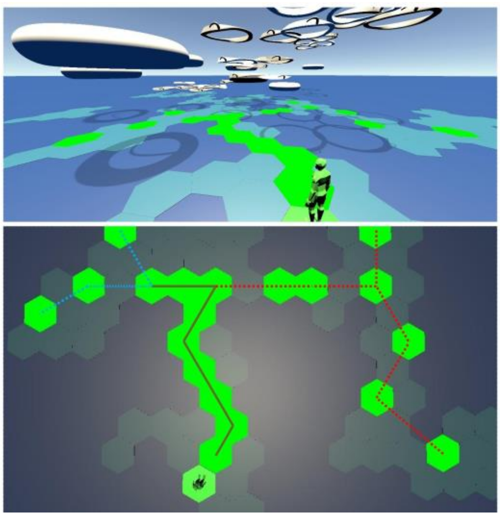

Figure 19: Replay on future decisions. When a fork path is presented to the player, replay tests the potentially routes at a branch point (Above). Left turn (Blue) and right turn (Red) routes (Below).

The former occurs in our framework as a random traversal of cell firing sequences for previously travelled paths without player movement. The latter occurs when the player encounters a decision point at a previously unknown location.

5 Summary

Our work shows how mental aspects of spatial navigation can be shown in an interactive, generative environment. As audiences explore their way out of confined spaces by finding the locations of interest, they can begin to understand how their own cognitive map of space is altered by rescaling, remapping, and replay of place cell activity specifically tuned to their spatial experiences.

We are now conducting work to build a physical analogue of the immersive space using projection mapping to configure the generative spaces and display corresponding cell activations. Physical interactions using human movement and gestures will provide greater identification with spatial confinement and naviation.

6 Supplemental Material

A preliminary playable prototype is found at: https://recfro.github.io/navigating-in-place/

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