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SPATIAL LOCALIZATION AND NEURAL MECHANISMS OF PATH INTEGRATION

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Abstract: In the past one hundred years, research on brain functions has continuously explored the principles of coding and decoding of the nervous system, including perception, recognition, positioning, The coding principles of motor control, decision-making, etc. are interpreted layer by layer. since 1971 Since the discovery of place cells, scholars have John O'Keefe Neuroscientists represented by the Department of Neurosurgery have conducted a large number of representative studies on spatial localization and path integration. Different types of nerve cells have been discovered one after another, and the neural network mechanisms encoded by them have become increasingly clear. At the same time, due to the vigorous development of unmanned systems in recent years, There is also a strong desire for good spatial algorithms in the engineering field. In this review, we review the current research progress in spatial localization in the field of neuroscience and discuss the latest relevant theoretical results achieved by applying artificial neural networks. In the foreseeable future, neuroscience experimental research and artificial neural network model research will promote each other and make iterative progress, and this cyclic development model will also make greater contributions to the fields of neuroscience and engineering.
Keywords: Path integration; Hippocampus; Entorhinal cortex; Grid cells

1. PLACE CELLS PLACE CELLS ARE CELL TYPES THAT ENCODE SPECIFIC LOCATIONS IN SPACE

Cell types involved in spatial localization in the mammalian brain
Evolution has given living organisms the ability to move. Different animals, and even Even some plants have their own unique ways of moving, but Better spatial positioning and path integration mechanisms are indeed the key to different mobile lives. the common needs of all things, and the booming development of wireless technology driven by modern technology. The human system also has accurate spatial positioning and path integration algorithms. A growing desire. Drawing on related neural network algorithms in the brain Designing better computing systems has become a consensus in related fields. and are increasingly valued. So how do animals, especially mammals? Completing these calculations is worth exploring.
the computational principles of spatial localization in the brain requires first Understand the cell types involved in spatial localization in the brain, in the field of neuroscience domain, from Since the discovery of place cells in 1971, the main cell types that have been discovered to be involved in real-time positioning and map construction in mammals include: Place cells, grid cells, head orientation cells, speed cells and boundaries cells etc. These cell types encode spatial locations and pathways in the brain Integrated computing provides the most basic building blocks for the release of these cells electrical characteristics, the basis of the neural network formed by its discharge, and the coding rules. The changes have attracted countless explorers.
The receptive fields of place cells are unique in space. If and only when the animal enters a specific location, the discharge activity of the place cells encoding that location will increase significantly (Figure 1). 1971, O'Keefe [1] scholars used multi-channel in vivo electrophysiological technology for the first time to record place cells from the hippocampus area of awake, freely moving rats.

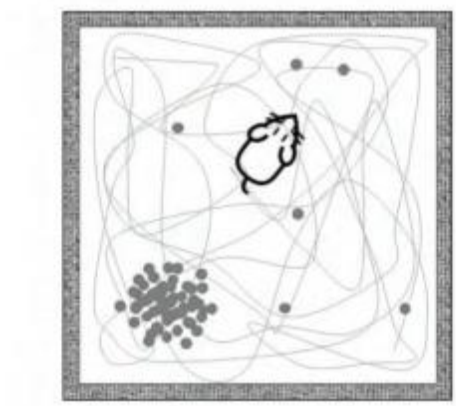

Fig. 1 Schematic diagram of the firing pattern of place cells [1]

Note: The light gray line is the trajectory of the rat in space, and the dots represent example place cells. discharge position. For this place cell, when the rat walks to the lower left corner of the confined space When, its electrical activity increases significantly

Recordings in the hippocampus indicate that there is a sense of position from dorsal to ventral The neuron with receptive field characteristics is given by 45% reduced to 18%, and the size of the corresponding positional receptive field has increased nearly three times [2]. But in extension In terms of flutter structure, place cells do not show consistency [3], that is, when solving Two anatomically adjacent place cells encode the spatial bits may not be relevant.
A large number of studies on the response properties of place cells have shown that place The discharge characteristics of cells have a high correlation with environmental information, and the location The response characteristics of a cell may not originate from a specific receptor or receptor Direct modeling of the environment, but from the upstream brain area neurons The signals are subjected to secondary calculation and integration [4, 5].

2. AFTER GRID CELLS DISCOVER PLACE CELLS IN THE HIPPOCAMPUS

A large amount of research work began to explore the upstream and downstream projections of place cells, and computational structures within the hippocampus. seahorse CA 1 Main area Accept information projections from three signaling pathways, namely EC 2 (Entorhinum Cortical layer 2) -CA3-CA1, EC2-D G (dentate gyrus) -CA3-CA1 as well as EC 3- CA 1. However, when the first two pathways are blocked [6, 7], The spatial location selectivity of CA 1 neurons was not significantly affected, So CA 3 The spatial information is most likely via EC 3 Direct investment Shoot. Based on the above inferences, follow-up studies in the entorhinal cortex The results are exciting. 2004 Year Moser et al. Research The team discovered that the medial entorhinal cortex has stable, discrete, and multiple locations. Set the cell type of the receptive field, which cell type is in Named grid cells in 2005 (Grid Cell) [8].
They are named grid cells because of their Discharge position (i.e. position receptive field) There are multiple, stable and weekly Periodic equilateral triangle mesh (picture 2A), multiple equilateral triangles form into a regular hexagon. The grid is spread throughout the environment, and when the experimental animals are exposed to Any vertex of the nearly triangular mesh corresponds to the electrical activity of the mesh cell will increase significantly. Intuitively, this development of grid cells The pattern resembles a measuring stick and was recognized early in its discovery. It is possible to encode a set of measurement systems in the process of spatial navigation [8].
Regular hexagonal space characteristics based on grid cell position receptive field properties, there are three indicators used to measure its characteristics (Figure 2B): (1) grid interval(Grid Scale or Grid Spacing), that is, two adjacent positions Feel the distance between fields; (2) direction, i.e. relative to the selected coordinates The declination angle of the system grid;(3) Phase, i.e. relative to a selected reference position The displacement vector of the grid, the phase is a vector rather than a scalar. fine with location The difference is that grid cells have a good spatial topology.: Adjacent grid cells usually have similar spatial spacing and orientation, but The phases are randomly distributed. From dorsomedial entorhinal cortex to ventrolateral entorhinal cortex layer, the spatial interval of grid cells gradually increases [9], which is related to the fine position The topological structure of the cell is corresponding. But for the orientation of grid cells This property, no consistent topology was observed in the medial entorhinal cortex Structure [8]. From the group level, the spatial intervals of multiple grid cells are Cluster distribution, and the ratio between different clusters is very stable, as 1.5 times [10], which can avoid large-scale errors in information encoding [11].
Mammals in which grid cells have been discovered include mice (Fyhn et al. 2008), rat (Fyhn wait. 2004),bat(Yart- sev etc. 2011) and humans (Doeller wait. 2010). Yartsev Waiting for the bat MEC Grid cells were discovered in, and they bear striking similarities to those of other mammals. Fine in the same position Like cells, Doeller et al. (2010) via functional MRI It has also been confirmed that grid cells also exist in the human brain. This shows that This discrete form of neuron firing that encodes spatial location is relatively conservative.

Fig. 2 Schematic diagram of the discharge pattern of grid cells [8]

Note: Grid cells have multiple positional receptive fields in space, covering the entire exploration space, and the three adjacent receptive fields are distributed in an equilateral triangle, and multiple equilateral triangles form an equilateral triangle hexagon.

3. HEAD-TO-CELL HEAD TOWARD THE CELL (HEAD DIRECTION CELL)

Which provides information about the direction of one's own head to the brain's navigation system. Ranck (1984) discovered head-orientation cells for the first time, whose most basic function is to sense the direction of one's own head and face at all times. Later, head orientation cells were found to be widely distributed in the brain, including the

thalamus [12], Retrosplenial cortex (retrosplenial c ortex) [13], entorhinal cortex [14], breast Lateral cephalic nucleus (lateral mammillary nucleus) [15] etc.

One of the important signal sources for head-direction cells is the vestibular system. Pass By integrating head rotation information, the network composed of head-direction cells is not Intermittent head orientation information is transmitted to cells such as grid cells, allowing grid cells to generate more stable and periodic signals when activated. Regular hexagon [16].

Sharp et al (2001) It is believed that the formation of the head-oriented cell network shape is due to the formation of a ring attractor network (ring attract or network) [17]: Neurons are arranged in a ring in sequence according to the direction they encode. Through appropriate excitatory and inhibitory connections, the attractor network It can output a stable " wave peak ", which is in the ring network. The position corresponds to the animal's own head direction (Figure 3). 2015 Year, An experiment conducted on fruit flies found that the flies' heads are oriented toward cells It is indeed circular in anatomical structure [18].

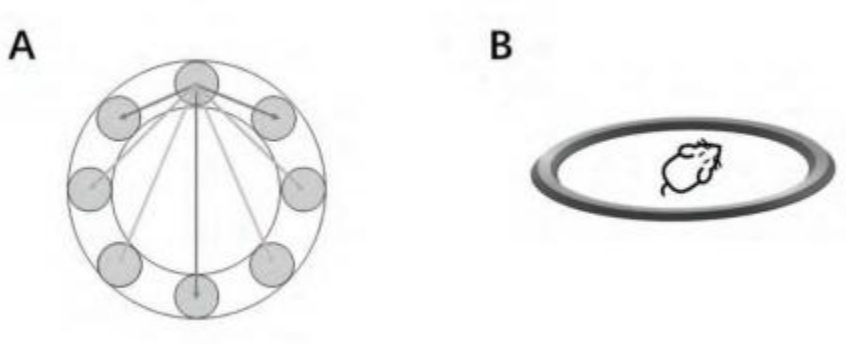

Fig.3 The formation mechanism of head-to - head cells - Circular attractor model [17]

Note: The ring attractor theory holds that head-facing cells are arranged in a ring according to their encoded head-facing direction. For any head-facing cell, it moves towards its neighboring cells. excitatory projections and inhibitory projections to distant cells. The shade of the arrow color represents the intensity of the corresponding projection. The illustration shows only the projection pattern of a head-directed cell, in All cells in the model project interactively. (B) In the ring attractor, the position with the highest activity represents the current head direction of the animal, which is about the right front in this diagram.

4. SPEED CELLS

2015 Year Moser The team started with the entorhinal cortex layer of cells with unknown function, a single species accounting for approximately 15% of the cell types, this cell is mainly related to speed, for head orientation There is a low correlation between directional and spatial information, so it is named speed cell [19]. The proportion of this type of cells in the hippocampus is slightly lower, ca. 10%.

Speed cells encode traveling speed linearly, and the firing frequency of most speed cells is positively correlated with speed.: The faster the speed, the higher the discharge frequency. And the discharge frequency of speed cells does not change with the surrounding environment. Changes due to changes in environment [19]. However, in the medial entorhinal cortex, there are still about 16% of speed cells have a negative firing frequency and speed. [20], this part of the speed cells may be related to the static state or deceleration. Movement related.

In the time dimension, the speed of the medial entorhinal cortex and hippocampus is small. The cellular codes are different: Speed cell coding in the medial entorhinal cortex is prospective, that is, encoding future travel speed, neuron firing, and behavior. The correlation of the advancement speed in the time window sliding is 54 ~82 reaches maximum in milliseconds; The coding of hippocampal speed cells is retrospective, that is, it codes the speed of travel in the past, and the correlation is -89 ~ - 59 Maximum is reached in milliseconds. This may be due to the respective connections between the medial entorhinal cortex and hippocampus. Receiving speed information from different sources, it may also be due to the time delay in the projection of the medial entorhinal cortex to the hippocampus [21].

(five) After boundary cells discovered place cells, O'Keefe Researchers believe that in order to maintain a stable encoding of the surrounding environment, location Cells should receive upward signals that encode environmental information, especially boundary information. You project, from this Hartley et al (2000) Boundary vector cells Computational model (boundary vector cell, BVC). The boundary cells predicted by this model encode a certain distance from itself and a specific angle. environmental boundary information, which is consistent with the findings in subsequent experiments. Follow Later experimental studies identified border cells in multiple brain regions, including the subiculum (subiculum) [22], inside Olfactory cortex [23], anterior subiculum (pre-subicu- lum) and para- subiculum [24] etc.

We summarize participation spatial positioning and routing decisions in the table below information about the five main types of neurons, which mainly Distributed in the medial entorhinal cortex and hippocampal formation. However, path integration and Not limited to these brain areas, the neurons involved are also found in a The series are widely distributed in brain areas, such as posterior parietal cortex [25], striae body [26], etc., as well as some neural circuits involving higher-level cortex as mentioned above Fronto - Thalamus - Sea Horseback road (prefrontal-thalam o-hippocampal circuit) etc. [27].

4.1 The Formation Mechanism of the Discharge Characteristics of Grid Cells and Place Cells

based on O'Keefe, Moser and other scholars have done a lot of research on the hippocampal structure and entorhinal cortex. In the past fifty years, scientists have The firing patterns of neurons involved in encoding spatial location in the brain have been revealed Into the understanding. At the same time, the field of computational neuroscience is also actively interpreting this the coding meaning behind these firing patterns, and the different types of neural How do elements communicate with each other through neural circuits to complete visual positioning, navigation A series of functions such as bit estimation and path planning. These model researchers It revolves around aspects such as grid cells, which have periodic firing patterns, and place cells, which encode spatial location.

(1) The formation of grid cell discharge characteristics— Oscillation interference The theory focuses on the special discharge patterns of grid cells. Currently, it mainly proposes Two types of theoretical models have been developed, namely oscillation interference theory (oscilla- story interference theory) and the attractor model (attr actor net- work model) [28~36]. On the one hand, these two types of models face grid cells When activated, the resulting stable, periodic regular hexagon Spatial discharge patterns provide an explanation and, on the other hand, neural networks Reasonable speculations were made on how to integrate and use speed information.

The oscillatory disturbance model was initially mainly O'Keefe etc [37] Proposed to explain the place cell discharge and EEG theta waves found in the hippocampus (7 ~12Hz) Phase-dependent experimental phenomena. When the experiment moves After an object enters the position receptive field of a certain position cell, the discharge of the place cell always occurs in the EEG The specific phase of the theta wave, and when the animal moves within the receptive field at this location, the phase corresponding to the discharge moves systematically, that is, the phase is progressive (phase p recession). Deactivation experiment table It is shown that the phase progression of the hippocampus is mainly inherited from the entorhinal cortex [38].

Oscillatory interference theory suggests that there is a speed-controlled oscillator (velocity-controlled oscillators, VCOs), this oscillator provides Got it Theta oscillation, and this oscillation is affected by the speed and direction of travel regulation, and then implement path integration [30].

Recordings in rats' medial septum, hippocampus, and anterior thalamus Records show that these brain regions do exist Theta cell, its issuance is in accordance with the rules lawful 4 ~12Hz. Theta cell The discharge frequency not only increases with the increase of the animal's traveling speed, but more importantly, it is related to the oscillation interference theory. As predicted by theory, Theta cell discharge and the direction of movement of the animal cosine value correlation, which provides a powerful basis for the oscillation interference theory Support (Welday et al. 2011). Furthermore, in order to verify that the grid scale is activated by hyperpolarization cation current (Ih), Giocomo et al. Decide, they specifically knocked out the hyperpolarization-activated cyclic nucleotide gate in the forebrain control channel HCN 1 and recorded grid cell electrical activity in mice, the study Research shows hcn 1 The expression is MEC important determinant of spatial scale white. exist In HCN 1 knockout mice, although the grid pattern The dorsal gradient is preserved, but the large grid cell discharge fields small and spacing, and the accompanying theta modulated period, at all It is expanded at the dorsal level. As the grid size increases, The interval time required to modulate the grid cells also increases, suggesting that the grid scale sum Theta frequency is mechanically related. This pair of " oscillation interference modes" "Type " calculation model also has potential impact [39].

(2) The formation of grid cell discharge characteristics - Since the discharge of grid cells has excellent stability and periodicity in the attractor model, a more intuitive conjecture is that this discharge form can be achieved through finely regulated inhibitory connections. Fuhs et al (2006) propose, Connections between grid cells are shaped like Mexican hats (Mexican - Hat), that is, each neuron is excited by nearby neurons, inhibited by neurons in the middle distance, and has no response to distant neurons.

To verify the attractor model, Couey et al. [40] performed ultrasonography on the entorhinal cortex. Pass Recordings from 600 pairs of neurons revealed that the second layer of the grid cell network The main cell - Astrocytes, primarily via inhibitory interneurons meta-connection, instead of gradually changing from excitement to inhibition as the connection distance increases. system. In the second half of this study, the attractor model was Improvement, the authors believe that stable grid distribution can be built through the backhaul suppression network.

Using optogenetic technology and multi-channel recording technology, we investigated the parvalbumin-expressing (PV +) interneurons (parval - bumin-expressing (PV) in the medial entorhinal cortex. +) interneuron) research shows that, PV + Interneurons inhibit all cell types in the medial entorhinal cortex and receive projections from grid cells with different phases (Buet - fering wait. 2014), Miao [41] used a pharmacogenetic method to directly inhibit PV or somatostatin (SOM), and record the mice ’s MEC layer II and III Neural electrical activity of grid cells in for direct comparison PV and SOM Interneuron activity influences MEC The influence of spatial formation and directional representation. suppressed PV interneurons can influence the spatial selectivity of grid cell hexagonal patterns, especially for MEC The influence of grid cells in the second layer is more obvious. PV Inactivation of interneurons greatly reduces the spatial periodicity of grid cells (spatial periodicity), the spatial information content is significantly reduced, and the spatial stability of the grid area is also greatly reduced. but PV Inactivation of interneurons did not completely eliminate the structure of the grid pattern and had no apparent effect on border cells or cells with other forms of nonperiodic spatial firing fields. opposite of this, SOM of neurons had a unique effect on the spatial selectivity of cells with aperiodic firing fields, whereas grid cells, speed cells, and boundary cells were unaffected. This double separation table Ming, PV and SOM Interneurons are composed of MEC part of a network and play different roles in the formation of space. The complementary role of the two shows that in MEC It is necessary to maintain constant

periodic spatial tuning in the second layer of grid cells. in the right PV Changes in grid patterns upon inhibition by interneurons are consistent with interneuronal functions proposed in computational attractor network models of grid cells.

5 BOUNDARY VECTOR CELL

Computational model (the boundary vector cell model) "boundary vector cells" are predicted to exist in Computational model of environmental input in spatial firing patterns of hippocampal place cells (O'Keefe and Burgess. 1996, Burgess et al., 2000 Hartley wait. 2000). Mainly from the hypohippocampal colliculus of rats (Entorhinal cortex and sea horse CA 1 between districts) The presence of such cells was recorded. these cells It can provide environmental information for place cell discharge and supplement path integration. information. Stretching a rectangular environment along an axis causes the position cells to The electric field stretches along the same axis. To explain this finding, O'Keefe and Burgess et al hypothesized " boundary vector cells " (BVCs) as a bit Set the cell's input. This model is also used to account for the geometric edges of the environment The influence of boundaries on place cell discharge [42, 43]. boundary vector unit (BVC) The model describes place cell firing as a continuous function, which is the relative distance between the surrounding barrier and the surrounding environment of the animal. Right location. Place cell activity is hypothesized to be driven by BVC before input Feed connection driver, which is emitted by an extended barrier (Such as walls, large objects, impassable water drops) Decide. BVC The launch of relative to the distance of the rat's position relative to the boundaries of the environment, independent of the rat Facing direction. Once environmental boundaries are specifically sensed by rat place cells When the receivers intersect, BVC It will discharge. If the place cell input Contains randomly selected BVC, the model captures statistics on the shape, number, and size of location fields as a function of the environment boundary configuration function. As the environment becomes familiar, the boundary vector cells and positions The plasticity of connections between cells causes place cell discharges to " reorganize " "Principle ", so that the area with lower discharge frequency is lost, and the area with higher discharge frequency is lost. High area discharge enhancement. Furthermore, by determining the best fit for a given A set of discharge data of cells BVCs A subset of, it is possible to predict the How cells will respond to new changes in their environment. BVC The model has conducted a satisfactory study on the impact of terrain changes on animal recognition environment. Meaningful explanation [44].

6. CALCULATION METHOD OF SPATIAL POSITION IN THE BRAIN AND HIPPOCAMPUS AREA FUNCTION

Whether in the complex mammalian brain, or In engineering applications, spatial positioning and path integration usually include two aspects:(1) A stable position signal source in the observation space, calculated from The relative position between the body and the signal source, positioning oneself; (2) When the signal source is lost, or interval observations are used due to limited calculations, based on the previous position information, and perform dead push by integrating motion sensor signals. Measure and estimate the optimal current position.

2018, Deep Mind The research team trained artificial neural networks to complete space exploration tasks [45]. Scholars collected the translational speed, angular speed and movement trajectory of rats during space exploration, and used the translational speed and angular speed as inputs to the artificial neural network to imitate the sensory information obtained by the brain. The purpose of network training is to predict its own position and head direction based on translational velocity and angular velocity. Speed information is first input into a long short-term memory network (long short-term memory, LSTM), the network applies backpropagation method optimization, and then LSTM The network is projected to the position unit and head orientation unit respectively through a linear connection layer. The linear connection layer is subject to regularization, and its dropout rate (dropout ratio) is 50%. During each iteration, the animal's actual position and head orientation are fed into the network for supervised learning. The trained neural network can complete path integration very well in space exploration tasks, and its performance can already exceed that of human experts. What is even more interesting is that in the linear connection layer, The researchers observed a network structure consistent with the entorhinal cortex, Including grid cells, head orientation cells, boundary cells, and a small number of place cells. The spatial intervals of grid cells in these artificial neural networks are also clustered, and the ratio between different clusters is approximately 1.5 times, which is very consistent with the results observed in animal experiments [10]. These related studies provide useful attempts to reveal the operational principles of the hippocampus and its related areas at a theoretical level.

In current neuroscience research, great progress has been made in the coding mode of dead reckoning in the brain that relies on the back-transmission of self-motion information. However, how visual, tactile and auditory information during movement encodes position signals is still Requires a lot of exploration. Although partial loss of visual, olfactory and auditory signals will not affect the discharge pattern of place cells, they are all important sources of signals that can participate in boundary recognition, and environmental boundaries exert a powerful control on the encoding of place cells. O'Keefe and Burgess [46] It is pointed out that when the place cell discharge frequency peaks, the distance between the location and the environmental boundary is constant. In addition, several areas are stretched on the axis of the environment, and some discharge frequencies change in a larger environment. It became Twin Peaks. Encoding of head orientation cells plays an important role in spatial map construction. The encoding of head-direction signals mainly depends on acquired visual signals, and the precursors that the brain selects as direction signs are stable. The

cyclic update of the spatial map depends on existing directional signs and emerging landmarks. In the past, it was believed that grid cell activation discharge was independent of the surrounding environment [31]. Because of its stability and periodicity, it was considered to be a universal and environment-invariant metric for navigation. Krupic et al. [47] found that grid cell discharge is affected by the geometry of the environmental boundary. Grid patterns can be positioned on polarized enclosure walls, such as squares instead of circles. Furthermore, in highly polarized environments such as trapezoids, the hexagonal symmetry is permanently broken, and the pattern is more elliptical and less uniform.

Of course, the hippocampus and its related areas are important conserved areas in mammals. Spatial positioning and path integration are only part of its functional performance. The main functions are memory and learning, including short-term memory, long-term memory, spatial memory and associative memory. At the same time, the hippocampus It also has archiving and retrieval functions. The function of the hippocampus as we generally know it is responsible for short-term memory in daily life. 1957 Scoville and Milner reported a very important case in neuropsychology, in which a patient with severe epilepsy underwent resection of part of the limbic system tissue under the temporal lobe cortex, including the hippocampus on both sides. Postoperative patients develop anterograde amnesia, that is, they lose the ability to form new declarative long-term memories anterogradely. A series of subsequent experiments also confirmed that the hippocampus is related to the storage conversion of long-term memory and the memory of environmental background. In 2000, University College London Macguire found that London taxi drivers had larger hippocampi, and that more experienced taxi drivers had larger hippocampi. In addition, MRI studies have confirmed that taxi drivers have larger hippocampi than ordinary individuals. In another NMR study, Kumaran and Maguire et al. found that when subjects imagined the best route between two friends' homes, hippocampal activity levels were significantly higher than baseline. These three experiments illustrate well that there is a map hidden in our hippocampus, that is, the hippocampus is also related to the storage and processing of spatial information. Scientists used epilepsy patients who had their hippocampus removed to The bubbles and cracks produced by individual human brain cells during their work were recorded, proving that the hippocampus has a certain relationship with associative memory. How to deeply explore the intrinsic connections between these functions will also be an important direction in neuroscience research.

7. CONCLUSION AND OUTLOOK

After nearly fifty years of unremitting research, regarding mammalian space The mystery of the neural mechanism of localization is gradually being lifted, computational neuroscience and research results in the field of artificial intelligence, and are gradually beginning to be able to simulate and generating neural networks with response properties similar to those in the brain. this These research results are being rapidly industrialized and are changing or about to Will change the world's production and life patterns.

Research on how spatial positioning is calculated in the brain has gradually From experimental research to deeper theoretical research, new questions also gradually emerged, as if only existence Dropout Neural network capabilities What is the mechanism hidden behind the generation of grid cells? The brain is like How to dynamically encode environmental information and how to integrate visual information paths in real time path to real-time planning? The in-depth development of these researches will surely lead to further development in computing science. It will bring wider application prospects in science and industry.

COMPETING INTERESTS

The authors have no relevant financial or non-financial interests to disclose.

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