THE HEAD'S NAVIGATION SYSTEM

TEXT: CATARINA PIETSCHMANN

Finding yourself in a foreign city, you quickly feel lost in the maze of unfamiliar buildings and streets. But after a short time, you can find your way even without a city map or navigation system. Christian Doeller from the Max Planck Institute for Human Cognitive and Brain Sciences in Leipzig and his team are researching how this is possible for us. The researchers also want to understand how the navigation system is used for other brain functions, such as memory, knowledge acquisition or abstraction.

Anja Hanisch travels in virtual reality: the scientist navigates her way through the rooms, which are fed into her VR goggles. Measuring devices record their “directional changes” in the process.


PHOTO: MPI CBS

You see them everywhere, especially in cities: people holding their smartphone in front of themselves like a compass and turning in circles when they lose their bearings. How to get from the train station to the hotel? “Turn left here, then the third right – it should be right there.”

“We call this kind of navigation ‘egocentric.’ Children orient themselves in the same way,” says Christian Doeller, head of the Psychology Department at the Max Planck Institute. As we get older, the way we navigate changes. Egocentric orientation continues to function, but our navigation system increasingly relates the location of places to their relative positions to each other rather than to ourselves. This allocentric navigation system works like a personal city map in your head. Animal studies have shown that different types of neurons in the rodent brain are involved in orientation: place cells in the hippocampus and grid cells in the adjacent entorhinal cortex, for example. Both brain regions play a role in the memory storage process and are intricately linked.

“Each place cell is responsible for a specific location in space. For example, if a rat explores a room, a different cell is active at each location. In the next room, other nerve cells become active,” Doeller explains. When the animal comes back into the same room a few days later, the same neurons fire again in the same places. While place cells are responsible for a specific position in space, grid cells are active at various locations. Connecting these places together creates a grid of triangles. Depending on the anatomical location of a grid cell in the entorhinal cortex, these triangles have sides of different lengths: in one part of the entorhinal cortex, for example, a cell fires regularly every 30 centimeters when the animal walks a straight line; in another part, the animal must walk several meters for a cell to fire. This, in principle, is how the brain can measure distances. Therefore, the grid cells create a coordinate

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system of the environment, and the cells register the position of the animal. This creates a map of the environment in the mind, kind of like a geographical map. In addition, there are other cell types that are important for navigation, such as head direction or compass cells. “They don’t care about position in space. They only become active when the animal runs in a certain direction. Together, these three cell types enable animals to orient themselves in space,” the researcher explains.

MRI and virtual reality

Because the electrical impulses of the nerve cells can be measured using incredibly fine electrodes, it is possible to directly observe the “navigation system” in the brains of mice and rats. These experiments also give Christian Doeller important clues for his research on the human navigation system. But instead of electrodes, in this case he and his team are employing magnetic resonance imaging and virtual reality: equipped with VR goggles, test subjects “move” through virtual rooms, while the MRI simultaneously records their brain activity. “The participants have to solve orientation tasks in the virtual world, and we then watch the brain do its work,” Doeller says. Even the most modern MRI devices are not yet as accurate as measurements performed with electrodes. “The advantage over experiments with animals, on the other hand, is that we can study far more complex cognitive functions and interview participants as they complete their tasks.”

Doeller’s results show that it is not only rodents who have a firmly differentiated navigation system in the brain, humans do too. This is probably true for most other mammals as well, because, from an evolutionary point of view, the hippocampus is an old part of the brain. The researchers also discovered that grid cells aid both orientation and perception in humans, just like they do in monkeys. “Grid cells are like pedometers or indicators of structure: we use them to determine the size of a room or the composition of images. Presumably, they are also there to abstract knowledge,” explains Doeller. “For example, someone who normally goes shopping in a supermarket in Berlin will also be able to find their way around one in Leipzig. Fruits and vegetables come first, and then at the checkout there’s candy and gum.” With the aid of the place and grid cell system in the hippocampus, knowledge that has been stored in the brain can be repeatedly retrieved and adaptably applied to new contexts.

Today, we know that the navigation system is the template for other brain circuits. The example of memory can show how the navigation system might act as the model for other brain functions. Thus, our sense of place is part of episodic memory. To create this “map memory,” the hippocampus and entorhinal cortex link locations in space. They can do the same with events by combining visual, auditory, and olfactory sensations into a multilayered memory in addition to spatial impressions. To recall them, all it takes is a certain smell, an incidence of light, or a sound: the smell of almond cookies, for example, can evoke memories of a café in Siena, on a street leading down to Piazza del Campo. The air is filled with the scent of these cookies, the Ricciarelli. This aroma blends with that of espresso. The afternoon sun casts a warm glow over everything, passers-by hurry past, Vespas clatter by…

The memory could belong to a trip to Italy. The sense of place would then be a part of it: where exactly the café is located and how to get from there, for example, to the cathedral with its magnificent dome, would also be saved. “After the hippocampus links the individual elements of an episode, they are stored in different regions distributed throughout the brain. One key stimulus is then often enough to trigger recall. The hippocampus uses this stimulus to reassemble the entire episode,” Doeller explains.

If you tell people about experiences or write them down, these are reinforced and stored again. This is how memory solidifies. However, it can be changed again under special circumstances. Highly emotional events really

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SUMMARY

Different types of neurons are involved in the human brain’s sense of direction. Place cells in the hippocampus register specific locations within a space, grid cells in the entorhinal cortex estimate distances, and compass cells measure direction.

The circuits of the orientation system are used by other brain functions: our memory and our ability to abstract use the same processing methods.

As we age, our map-like memory diminishes. In the case of dementia, the ability to orientate also deteriorates at a very early stage. This is probably due to the failure of place and grid cells.

"burn" themselves in. "Strangely enough, I remember very clearly that I was sitting at the hairdresser's when I heard the news of Franz Josef Strauss' death on the radio. Why I remember this of all things is a mystery to me. The news must have moved me at the time," recalls Christian Doeller. That was in 1988, when Doeller was just 14 years old. Our memories, however, are not immutable all time. For instance, if subsequent Italian vacations are added over the course of a lifetime, the brain combines these distinct memories into a generalized memory of Italy that includes pasta, lemon ice cream, heat, olive groves, and cypress trees. All this is semantic knowledge: that is, knowledge based on facts stored during several stays in Italy. These facts are remembered even when the individual vacation is forgotten. However, it would be possible to reconstruct the holiday on the basis of the "archived" details.

"Even though we use navigation systems now, I don't think we'll ever be able to completely do without our sense of place."

CHRISTIAN DOELLER

Christian Doeller is convinced that our navigation system not only serves episodic and spatial memory, but also sorts memories, for example, according to temporal sequence or spatial proximity. "It's basically perfect for this because it can put information in a fixed coordinate system. In addition, the navigation system can map individual locations thanks to its location cells. It can also generalize from individual experiences to generate factual knowledge. These skills almost certainly play a role in other areas as well." The memory of a place can be linked to other memories in this way. And there is more: if one remembers an experience, sometimes others emerge that are spatially or temporally linked to it. So, in a sense, we can travel in the past from place to place or in time.

Order in cognitive spaces

Furthermore, recent research indicates that our brain employs the same network of place and grid cells to organize objects or sensory impressions into what we refer to as "cognitive spaces." Each property represents a dimension in the mental map. In it, contents with similar characteristics are close to each other, while those with different characteristics are further apart. Doeller's team found that the hippocampus represents distances in these kinds of abstract spaces. Animals can be sorted by size and speed, for example. In this cognitive space, a small, slow snail is far apart from a large, fast horse. Each animal, for example, defined by its typical combination of size and speed, occupies a "place" in cognitive space and thus can be represented by the place and grid cell system. This system is highly dynamic at the same time and can span very different mental spaces.

Christian Doeller's department seeks to understand how we orient, how we remember, and how we learn. Their research shows that all three abilities rely on the same network in the brain.

"The mental maps produced by the place and grid cells represent a basic principle of human thought. Our brain organizes not only places and memories, but also general knowledge in this way. This allows us to generalize what we've learned and apply it to new situations," Doeller says.

But let's get back to orientation skills. Like many other brain functions, this changes throughout life: when it comes to infants and toddlers, it still has a largely egocentric, or bodily-based, function. Gradually, however, the allocentric system, which is based on external reference points, takes over. But with increasing age, this then diminishes again. The egocentric system, on the other hand, remains stable for much longer. Spatial memory deficits are also among the first signs of deterioration in dementia. The reason for this in both cases is damage to the entorhinal cortex, which is responsible for episodic memory and orientation. Several years ago, Doeller's team carried out a study in which they examined this connection. The researchers compared the brain activity of individuals with a gene variant that increases the risk of developing Alzheimer's disease later in life to that of genetically unaffected individuals of the same age. "In the individuals with the Alzheimer's risk gene, the navigation system in the entorhinal cortex was already less active, and this was long before their ability to orientate deteriorated," Doeller explains. Interestingly, however, the activity of the hippocampus was higher in those affected. "As a result, their brain was probably already attempting to make up for the progressive loss of function of the grid cells in the entorhinal cortex." It is not yet known how this happens.

Alzheimer's disease: fading sense of place

PHOTO: NIKOLAUS BRADE, BERLIN

Alzheimer's disease usually begins in the entorhinal cortex. This is where the first clumps of amyloid protein are deposited, the so-called plaques. "We know from studies of animals with Alzheimer's-like diseases that the place and grid cells are less precisely active. Their activity patterns look absolutely washed out, and spatial precision diminishes." The sense of place and the sense of distance disappear: places that have been familiar for decades suddenly seem foreign. Doeller likes to compare it to nearsightedness: a person is also more likely to get lost when cellular resolution diminishes.

Navigation systems in smartphones or cars today take most of the navigational work out of the brain. Is there a possibility that this could impair our ability to orient ourselves? "In the long run, it's possible. But we'll probably never be able to do without the sense of place so completely. After all, we need it to find our way around at home, at work, or in unfamiliar buildings. But even if it were to become completely redundant, the orientation system circuitry would still be used for tasks such as memory or abstraction. Perhaps, some other tasks would also come along." Should it one be possible to navigate through life exclusively with external navigation systems, therefore, the freed brain capacities could be used elsewhere. Then perhaps you could talk to other people again in peace, without having to struggle to find your way.

www.mpg.de/podcasts/orientierung (in German)