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# Spatial Memory

A student walking to a classroom across campus must be able to stay oriented with respect to known locations within the campus environment. The consequences of becoming lost may only be a minor inconvenience to the student, but the consequences were surely much greater for our ancestors when navigating home from remote food sources. Current theories of navigation posit two types of spatial memories that work together to keep us oriented with respect to known locations. The first component is a long-term spatial memory of the environment through which the navigator is traveling. Long-term spatial memories contain distances and directions between objects, organized with respect to a spatial reference system centered on the environment. These long-term spatial memories play an especially important role in planning and executing navigational tasks.

The second component is a sensorimotor spatial memory, which contains distances and directions from the navigator to objects within the immediate environment. This memory is used to control actions such as walking around obstacles, passing through apertures (e.g., doorways), and moving toward intermediate landmarks. The sensorimotor spatial memory is limited in capacity, and therefore its contents are continually updated during self-movement; representations of objects are added and purged as a navigator moves from one locale to another.

Returning to the previous example, the student navigating across the campus must be able to identify salient features within the sensorimotor spatial memory (e.g., a recognizable building) and then match those features with the same features in the long-term spatial memory. If this matching process is successful, then the student can identify his or her location and orientation within the long-term spatial memory, thereby achieving an accurate sense of spatial orientation.

Perception plays an important role in both long-term and sensorimotor spatial memories. Whether learning from direct experience or indirectly through maps and other symbolic media, perception is the primary input used to generate long-term spatial memories of new spaces. Although most research on long-term spatial memory has focused on learning through vision, recent work indicates that many of the organizational characteristics of spatial memories are independent of learning modality. Additionally, perception of self-motion is critical to updating the body-to-object spatial relations contained within the sensorimotor spatial memory. Perception of body translations and rotations is based primarily on vision, proprioception, and vestibular stimulation. The rest of this entry covers some of the organizational principles of long-term and sensorimotor spatial memories, and address the roles of perception in both types of representations.

## Long-Term Spatial Memory

Location is inherently relative and must be defined with respect to a spatial reference system. For example, your current location could be described in terms of your position within a room, your position within a city, or even in terms of latitude and longitude (assuming that you are located within a room, within a city, on Earth as you read this paragraph). These alternative definitions of your current location are all based on different spatial reference systems.

Similar to how cities on Earth's surface are defined with respect to latitude and longitude, locations in long-term spatial memory seem to be defined with respect to a small number of reference directions selected on the basis of cues, such as the shape of the environment and one's experiences within the environment. This reference direction organization of long-term spatial memory holds true across a wide variety of remembered environments, ranging in size from table tops to cityscapes, and ranging in realism from carefully designed laboratory environments to cluttered natural environments.

Perspective-taking performance is commonly used as an index of the reference directions used to represent a learned space. In a perspective-taking task, participants are asked to point to objects from imagined perspectives within a remembered environment (e.g., imagine standing in your kitchen at home, in front of and facing the sink, now point to the oven). Pointing responses are often made with a joystick, and pointing speed and accuracy are measured to assess the reference direction structure. Comparison of pointing speed and accuracy across different imagined perspectives reveals the underlying reference directions used to organize long-term spatial memory, as perspectives aligned with a reference direction are typically easier to imagine than are misaligned perspectives. This facilitation occurs because interobject spatial relationships aligned with a reference direction are stored in long-term spatial memory, whereas misaligned interobject relationships must be inferred. This inference process is cognitively effortful, resulting in increased pointing error and latency when imagining perspectives misaligned with a reference direction. Figure 1 depicts a hypothetical object layout. In this example, the layout structure (objects A–G), the rectangular room walls (solid lines surrounding the layout), and the location of the learning perspective (arrow below the layout) have resulted in a spatial memory organized around a single reference direction parallel to the learning perspective (indicated by the thick gray arrow). As a result of this organization, subsequent perspective taking is facilitated for perspectives aligned with the reference direction (e.g., imagine standing at C, facing D, now point to B), compared to misaligned perspectives (e.g., imagine standing at D, facing A, now point to B).

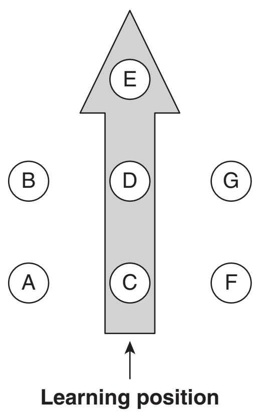


**Figure 1** Example of Array of Objects With Assumed Reference Direction Indicated by Gray Arrow

The selection of reference directions occurs during learning and depends on two broad categories of cues. First, one's early experience of an environment, such as the first view, can be a cue to establish a reference direction parallel to the initially experienced view. This type of organization, based on the initially experienced view, can persist even after learning occurs from many perspectives. Second, the structure of the environment is a cue used to establish reference directions parallel to salient axes within the environment. For example, the walls of a rectangular room impose their own set of salient orthogonal axes parallel to the walls of the room. The organization of objects within the room, such as rows and columns of chairs in a classroom, can also have a similar effect. These salient environmental cues can sometimes override egocentric cues, such as the first view. One surprising result of this principle is that people can have better access to imagined perspectives that were never experienced, but are aligned with the environmental structure, than to experienced perspectives that are misaligned with the environmental structure.

Although environments are typically learned through vision, they can also be learned through touch, audition, and even language. Research on long-term spatial memories acquired through these nonvisual modalities is relatively sparse, but the emerging consensus is that these spatial memories reflect the same organization based on reference directions, no matter how they are acquired. However, the relative saliencies of cues for selecting reference directions may be quite different for different sensory inputs. For example, egocentric experience may be a more salient cue to selecting reference directions when object locations are learned through touch or sound because environmental cues, such as room shape, are more difficult to convey through these nonvisual sensory modalities. As such, the same layout may be represented quite differently depending on whether it was learned through vision or touch, but in both cases, the long-term spatial memory will be organized with respect to reference directions. The difference is in the specific reference directions selected.

The organization of long-term spatial memories in terms of reference directions may explain another important property of these memories, namely, their hierarchical organization. Memories of the locations of objects are organized categorically and hierarchically, such that a region of space may be represented as a whole, containing other regions and locations, and as a part, contained in larger regions. This property may result from the use of spatial reference systems at multiple scales. For instance, the spatial layout of each of the rooms within a house may be specified in a spatial reference system unique to each room. These spatial reference systems may serve as elements in a higher-order reference system defining the spatial relations among the rooms within the house.

The fact that spatial memories of environments learned through different sensory modalities adhere to similar organizational principles does not mean that perception is unimportant in spatial memory. It may be that perception actually underlies the reference frame organization. For example, after learning objects within a classroom filled with chairs arranged in rows and columns, long-term spatial memories of that scene will probably be organized with respect to reference directions parallel to the rows and columns of the chairs. In addition, eye movements made when learning this scene would be expected to follow the rows and columns of the chairs. This correlation between eye movements and selection of reference directions highlights the role of perception in creating long-term spatial memories. Gestalt grouping principles might guide eye movements along a specific sequence of objects, thereby influencing the reference directions selected during learning.

## Sensorimotor Spatial Memory

Whereas long-term spatial memories are of great benefit when planning a route or reasoning about spatial relationships, they cannot be directly used to guide actions within the environment. Reaching for a coffee cup or walking toward a distant tree requires a representation of body-to-object spatial relations (referred to here as sensorimotor spatial memory), whereas the long-term memory only contains object-to-environment spatial relations. Because locations of objects with respect to the body in the sensorimotor memory change constantly as we walk and turn, this memory is not appropriate for long-term storage and is better understood as a working memory representation.

As with long-term spatial memory, the organizational properties of sensorimotor spatial memory can be revealed through perspective-taking performance. Whereas experiments on long-term spatial memory typically involve imagining perspectives within remote environments (such as imagining perspectives in one's home while seated in one's office), investigations of sensorimotor spatial memory involve imagining perspectives within the environment one currently occupies. Under these conditions, pointing responses made from imagined perspectives aligned with one's body are faster and more accurate than pointing responses made from perspectives misaligned with the body, indicating that object locations in the sensorimotor memory are represented egocentrically, in a body-defined framework. For example, it is easier to imagine facing the direction one is actually facing than to imagine facing the opposite direction. Recent accounts of this phenomenon suggest that the sensorimotor memory must be actively inhibited in order to imagine perspectives misaligned with the body. These misaligned perspectives are more difficult to imagine because this inhibition process is cognitively effortful.

Body-to-object spatial relations represented in the sensorimotor spatial memory must be updated continually during self-motion, a process known as *spatial updating*. Whereas reaching forward to pick up a coffee mug might be an appropriate action from one's current position, the same action would not be appropriate after turning 90° to the left or right. Instead, it is necessary to update the location of the mug with respect to the body as one turns to ensure the appropriate action from the new orientation. Research on the various perceptual cues to self-motion indicates that not all cues equally support spatial updating. These perceptual cues can be broadly categorized as idiothetic cues (internal cues, such as proprioception and vestibular stimulation) and allothetic cues (external cues, such as visual and auditory motion). Whereas idiothetic cues are often sufficient to perform spatial updating in the absence of allothetic cues, the reverse is not true. The importance of idiothetic cues is readily apparent when playing first-person video games, in which the user controls movement through the visual world by manipulating a joystick or a mouse. Such conditions provide allothetic but not idiothetic cues to self-motion and can rapidly cause the user to become lost in the video-game world. In contrast, adding idiothetic self-motion cues can make navigation much more natural. Virtual environments have proven to be an ideal tool for isolating idiothetic and allothetic cues to spatial updating, as participants can navigate through the exact same virtual environment by physically walking and turning or by manipulating a joystick. These experiments highlight the importance of idiothetic cues to spatial updating and the insufficiency of allothetic cues.

With sufficient self-motion cues, body-to-object spatial relations in sensorimotor spatial memory are updated continually when moving through the environment. Similar to findings on long-term spatial memory, where the reference direction organization is unaffected by learning modality, the body-based nature of sensorimotor spatial memory is also unaffected by learning modality. As such, imagined perspectives aligned with the body are facilitated for object layouts learned through vision, touch, audition, or even language.

### Spatial Orientation

In order to stay oriented with respect to a known environment, the navigator must match represented features from the sensorimotor spatial memory with those same features in the long-term spatial memory. In some cases, this can be accomplished by matching identifiable landmarks, like the student who uses an identifiable building to stay oriented to campus. In other cases, geometric properties of the surrounding environment, like the shape of a rectangular room, can be used to perform this match. This matching process is a critical step to staying oriented to a remembered environment and underscores the importance of coordinating long-term and sensorimotor spatial memories.

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*See also* Action and Vision; Navigation Through Spatial Layout; Self-Motion Perception

**Further Readings**

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## Speech Perception

*Speech perception* refers to the processes involved in identifying and understanding the meaningful patterns of spoken language. The speech signal originates from the concerted actions of the speaker's lungs, larynx, jaw, tongue, lips, and soft palate (soft tissue in the back of the roof of the mouth) to generate sounds that are shaped in particular ways. A fundamental problem in speech perception is understanding how a listener recognizes the complex acoustic pattern of sound waves as being composed of meaningful linguistic units (vowels, consonants, syllables, words, sentences, etc.). This problem becomes strikingly apparent when one realizes that there is no simple one-to-one mapping between the acoustic speech signal and our perception of what the talker said. This entry examines attributes of the human voice and speech signal, some of the major experimental findings, and several prominent theories that