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Neuroscience and Architecture: Seeking Common Ground

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As these paired Commentaries discuss, neuroscientists and architects are just beginning to collaborate, each bringing what they know about their respective fields to the task of improving the environment of research buildings and laboratories.

At first glance the disciplines of neuroscience and architecture might appear to have little in common. Architecture traditionally has relied on observation and intuition rather than the experimental method and proof that constitutes neuroscience research. Yet advances in neuroscience are now able to explain the ways in which we perceive the world around us and navigate in space and the way our physical environment can affect our cognition, problem-solving ability, and mood. Thus, an understanding of the principles of neuroscience, particularly in the area of perception and spatial orientation, can inform the design of built spaces to include environmental features that minimize negative physiological, cognitive, and emotional effects (see the Commentary by Goldstein, page 243). For example, poor lighting renders edges difficult to discern, and lack of landmarks or presence of multiple choice points in the absence of visual cues triggers anxiety and a stress response.

Jonas Salk was convinced of the importance of this crossdisciplinary understanding. In his legacy, Salk requested that neuroscientists continue to work with architects, just as he had done with the great 20th century architect Louis Kahn to design the Salk Institute, such that built work space would enhance creative ability (see Figure 1). No doubt Salk would be pleased to know that this year's Society for Neuroscience annual meeting opened with a lecture by the renowned architect Frank Gehry as part of the "Dialogues between Neuroscience and Society" series (see Figure 2).

What Defines an Environment?

When one considers the factors that contribute to an environment we tend to think of the spatial features that define it, such as the configuration of prominent stimuli or landmarks and the paths that can be taken when moving through it. These characteristics influence both the form and function of an environment and each contribute to different aspects of spatial perception and memory.

An intriguing finding in the neurobiology of spatial memory is the involvement of the hippocampus in navigation as well as in the formation and retrieval of memory of autobiographical events (Jeffery and Hayman, 2004). This intimate relationship between memory and sense of place is reflected in the observation that the hippocampus appears to be critical for both functions. Our memory of events may depend upon a strong sense of place, and by extension, our

Figure 1. Can Architecture Enhance Creativity?
Jonas Salk worked with the master architect Louis Kahn to design the Salk Institute as a research center where the built space would enhance creative ability. (Photo courtesy of the Salk Institute for Biological Studies.)

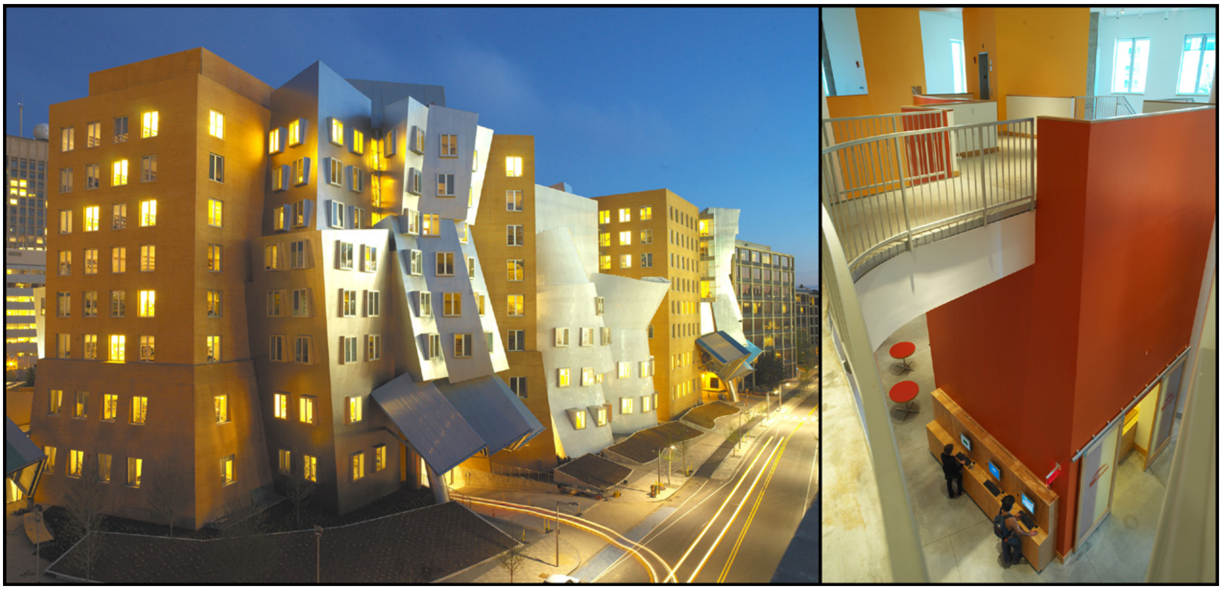

Figure 2. Reflecting the Research Within
MIT's Stata Center for Computer, Information, and Intelligence Sciences was designed by Frank Gehry with the goal of fostering interdisciplinary collaborations. Photo by Andy Ryan/courtesy of MIT's Stata Center.

sense of place may be influenced by the integrity of the memories formed there. Thus, consideration of factors that influence memory may help to enhance architectural designs of research buildings, hospitals, and any space occupied by a community of individuals trying to navigate their way to a particular location.

Our understanding of the neural basis of spatial perception and memory has been advanced by recordings of neural activity within the hippocampus as rats explore an environment. Such studies reveal that individual neurons respond when the animals move to certain locations in that environment, with different patterns of neural activity corresponding to different locations. Unlike neurons in sensory areas of the brain, these "place" neurons are not activated by any one type of stimulus, such as a visual feature, or a sound, or a smell, but rather by the combination of features that serve to define the animal's internal sense of place (Nakazawa et al., 2004). (Perhaps this is the neuroscience equivalent of what is known in architecture as the "haptic sense," that is, an awareness of one's surroundings.) Place neurons are also dependent upon a strong sense of orientation within the environment, and different environments are associated with different patterns of neural activity. Because our sense of "place" may be defined by the activity of these neurons, understanding the factors that influence them may help to elucidate how we are impacted by architectural design elements.

Space versus Place

Although places are typically associated with spatial environments, the notion of a place differs from that of space with a critical difference being the requirement for interaction by the individual. The internal representation of a place is strongly influenced by the way in which an individual moves within it, with different places connected based upon the ability to move between them. For example, two locations separated by a glass wall may be physically adjacent in space (separated by a small distance), but the hippocampus will treat them as separate places because the individual cannot move directly from a location on one side of the wall to a location on the other. In this way, a glass partition, while allowing plenty of light, still provides a separation between one room and another.

These barriers do not have to be physical. Factors that reinforce consistent paths of movement through an environment will also serve to separate the representations of place within the hippocampus. Hallways are an example of spaces that are typically navigated in two directions. Indeed, in animal experiments, each of those directions is represented by different patterns of neural activity—travel in each direction is effectively treated as a different environment with unique places within it. This can be extended to open spaces in which the design has individuals consistently traveling from one location to another, such as from a stairwell to a room or hallway. Environments that encourage free exploration will create representations of "place" that are not as strongly influenced by the paths taken through them. This phenomenon may be applied in the design of spaces that are intended to enhance a sense of being within the environment rather than a sense of just passing through.

A central idea is that within an environment, a sense of place is defined by the way in which locations are connected through exploration or movement (the topology of the environment), and not simply by the configuration of the space itself (the topography of the environment). This emphasizes the benefit of architectural designs that address both the functionality of a space (topological characteristics), such as movement and usage patterns, and aesthetic elements (topographic characteristics), such as physical layout and form. A strong sense of place may result from the effective integration of these factors.

Orientation and Place

The way in which visual landmarks reinforce a strong sense of place may depend upon the way in which they contribute to determining the location and orientation of individuals within an environment. Much like a compass keeps track of our heading relative to a global reference frame (absolute north), there are neurons in the brain that keep track of the direction that an animal is facing within an environment. These "head direction" neurons provide an internal sense of direction that, unlike a global compass, can change when an animal moves between environments (Taube, 1998).

This internal compass can be updated by keeping track of self-motion information (such as visual flow), by tracking motor movements (such as footsteps), and by monitoring acceleration and deceleration through activity of the vestibular system of the inner ear. However, the advantage of visual landmarks is that they can serve to keep people "oriented" as they move within and between different environments, such as rooms or hallways. A sense of disorientation may stem from a difficulty in keeping track of heading within an environment and relating the orientation of one environment (such as a room) to another. Windows that provide access to external distant landmarks, such as identifiable buildings or other prominent features, are particularly effective in supporting this orienting system and in so doing provide stability to the spatial representations within the hippocampus, reinforcing a strong sense of place. Although prominent individual landmarks enable animals and ourselves to become oriented within an environment, it is the configuration of multiple cues, both distant and nearby (such as unique architectural design features or stationary decorations), that contribute to the evaluation of location within an environment. This can be used to define important spaces within an environment through the combined use of local cues and features.

In learning paradigms in which rats are placed in milky water and swim to a hidden platform underwater, the presence of clearly discernable shapes on the wall around the pool facilitates their ability to learn the position of the platform (Schimanski and Nguyen, 2004). Lack of such landmarks not only delays learning of the location of the platform but also activates the stress response. This stress reaction is recognizable to any who have found themselves in unfamiliar buildings, including hospitals and laboratory buildings, in which long hallways with no landmarks present multiple choice points, just the type of dilemma faced by a rodent in a maze. The role of prominent stimuli in an environment contributing to a strong sense of place is further supported by the observation that features that draw the attention of an animal contribute to the stability of representations of place within the hippocampus.

What Makes Places Memorable?

Experiments that measure the way in which memories of places are formed during exploration of an environment and then later retrieved show that memory of place is not composed of isolated locations but rather sequences of connected locations (Lee and Wilson, 2002). By carefully considering the paths that will be taken by people moving within an environment, architects can incorporate design elements that allow these paths to be more readily navigated and remembered.

Journeys through an environment can be described as routes involving travel between a series of locations. Those locations may be associated with particular cues that may serve as landmarks for segments of a route and can be used to direct paths when a choice must be made, such as turning left or right at an intersection. Landmarks or cues that are associated with this type of following of a route-based path are treated differently from distant landmarks that serve to orient both the individual and the representation of the environment. These landmarks can be closely associated with particular locations and can take the form of local decorations such as pictures, objects, distinct colors of a wall, or textures of a floor. Although such features do not contribute significantly to the sense of orientation within an environment, they do contribute to a sense of place as indicated by the consistency of neural activity in the hippocampus in the presence of such stimuli. By providing prominent local cues that serve to establish uniquely memorable routes, along with distant cues that strengthen a sense of orientation, the "memorability" of an environment can be enhanced, and hence a strong sense of place can be reinforced.

Physical Environment and the Stress Response

In the field of rodent behavior, it is well established that crowding, sudden loud noise, bright lights, multiple choices, lack of landmarks, and new environments are all potent triggers of the physiological stress response (Bailey et al., 2006). All of these features of the physical environment can activate both the hypothalamic pituitary adrenal axis and the adrenergic component of the autonomic nervous system (Mormede et al., 2002; Glaser and Kiecolt-Glaser, 2005). Studies using these environmental variables reveal activation of the stress response, including increased hypothalamic production of the stress hormone corticotrophin-releasing hormone (CRH), increased pituitary gland secretion of adrenocorticotropin hormone, and release of glucocorticoids from the adrenal cortex. Similarly, there is also activation of adrenergic brainstem regions involved in focused attention and vigilance and adrenergic outflow sympathetic responses that govern heart rate. At a cognitive level, both acute and chronic stress are known to be associated with impaired problem-solving ability and increased error rates in decision making. Chronic activation of the stress response is also associated with suppressed immune responses resulting in health effects such as prolonged wound healing, a decreased antibody response to vaccination, and increased severity and frequency of viral infection (Sternberg, 2006).

A rich neuroscience literature exists that can be mined by architects who wish to optimize the design of built space. Although these studies have not been performed with the goal of studying built spaces, environmental variables are routinely altered in such studies to identify neurobiological mechanisms and nervous system responses. Such studies provide information about features of the environment that trigger various neural and physiological responses that may induce a sense of comfort or anxiety. Architectural designs that take into account these principles of neuroscience are likely to enhance the creativity, cognition, and comfort of those occupying or working in such spaces.

REFERENCES

Bailey, K.R., Rustay, N.R., and Crawley, J.N. (2006). ILAR J. *47*, 124–131.

Glaser, R., and Kiecolt-Glaser, J. (2005). Nat. Rev. Immunol. *5*, 243–251.

Jeffery, K.J., and Hayman, R. (2004). Rev. Neurosci. *15*, 309–331.

Lee, A.K., and Wilson, M.A. (2002). Neuron *36*, 1183–1194.

Mormede, P., Courvoisier, H., Ramos, A., Marissal-Arvy, N., Ousova, O., Desautes, C., Duclos, M., Chaouloff, F., and Moisan, M.P. (2002). Psychoneuroendocrinology *27*, 563–583.

Nakazawa, K., McHugh, T.J., Wilson, M.A., and Tonegawa, S. (2004). Nat. Rev. Neurosci. *5*, 361–372.

Schimanski, L.A., and Nguyen, P.V. (2004). Neurosci. Biobehav. Rev. *28*, 463–483.

Sternberg, E.M. (2006). Nat. Rev. Immunol. *6*, 318–328.

Taube, J.S. (1998). Prog. Neurobiol. *55*, 225–256.