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NEUROSCIENCE FOR ARCHITECTURE

Thomas D. Albright

Buildings serve many purposes. One might argue that their primary function is to provide shelter for the inhabitants and their possessions—a place to stay warm and dry, and to sleep without fear of predators or pathogens. Buildings also provide spaces to safely contain and facilitate social groups focused on learning, work, or play. And they provide for privacy, a space for solace and retreat from the social demands of human existence.

These primary physical requirements, and their many subsidiaries, simply reflect the fact that we are biological creatures. In addition to building constraints dictated by site, materials, and budget, an architect must respond to the nonnegotiable facts of human biology. Indeed, architecture has always bowed to biology: the countertop heights in kitchens, the rise:run ratio of stairs, lighting, water sources, heat and airflow through a building, are all patent solutions to salient biological needs and constraints. There are creative technology-based extensions of these solutions afoot in the form of smart homes. But there are subtler instances in which a deeper understanding of human biology affords a qualitatively superior solution. Consider, for example, the ascendance of the door lever as a design imperative imposed by biology. Seen from a strictly biomechanical perspective, a door lever is a far better tool than a traditional round doorknob for opening the latch. Pressure to adopt this superior solution came largely from recognition that it could benefit people with certain biological limitations ("physical disabilities"). Not surprisingly, the U.S. Americans with Disabilities Act (1990) has mandated the use of door levers because their design is easy to grasp with one hand and does not require "tight grasping or pinching or twisting of the wrist to operate."[1] Here is a case in which design centered explicitly on the details of a biological problem allows for greater accessibility and enhanced use.

At the same time that our buildings provide physical solutions to problems dictated by human biology, we also expect them to satisfy our psychological needs. We expect them to inspire and excite us, to promote mental states that lead us to discover, understand and create, to heal and find our way, to summon the better angels of our nature. We expect them to be beautiful. Not surprisingly, psychological considerations have been a part of the design process since humans began constructing lasting communal environments. The ancient tradition of Vaastu Veda, which dictated the design of temples and dwellings in early Hindu society, focused on ways in which a building directs "spiritual energies" that influence the souls of the inhabitants[2]—or, in today's parlance, the ways in which design influences the many facets of mental well-being. Feng shui, the ancient Chinese philosophy of building design, emerged for similar reasons.[3]

VAASTU VEDA IN THE AGE OF NEUROSCIENCE

While the basic psychological needs of a building's inhabitants today remain largely the same as they were in ancient times, we have one notable tool that promises a new perspective on how buildings influence our mental states: the modern field of neuroscience. Considered broadly, neuroscience is the umbrella for a collection of empirical disciplines—among them biology, experimental psychology, cognitive science, chemistry, anatomy, physiology, computer science—that investigate the relationship between the brain and behavior.[4] There are multiple internal processes that underlie that relationship, including sensation, perception, cognition, memory, and emotion.

There are also multiple levels at which we can investigate and characterize the relationship between brain and behavior. We can, for example, describe behavior in terms of the interactions between large brain systems for sensory processing and memory. Or we can drill down and explore how cellular interactions within circuits of brain cells (neurons) give rise to larger system properties, such as visual perception. Deeper still, we can explore the molecular components and events that underlie the behaviors of individual neurons, or the genetic codes and patterns of gene expression that produce the cellular substrates and organized circuits for brain function.

Most importantly, modern neuroscience affords the tools and concepts that enable us to identify the causal biological chains extending from genes to human behavior. This powerful approach, and the rich understanding of brain function that it affords, naturally has broad implications for and applications to many problems in human society, particularly in the field of medicine. But one might reasonably ask—and many do—whether there is any practical value for architecture and design that comes from knowing, for example, how neurons are wired up in the brain. I argue that there is value: knowing how the machine works can offer insights into its performance and limitations, insights into what it does best and how we might be able to tune it up for the task at hand. In the same way that understanding of an amplifier circuit in your car radio can lead to principled hypotheses regarding the types of sound it plays best, knowledge of how the human visual system is wired up may, for example, lead to unexpected predictions about the visual aesthetics or navigability of a building. At the same time, of course, the level of analysis of brain function should be appropriate for the question. In the same sense that knowledge of electron flow in a transistor offers few practical insights into what your radio is capable of, it seems unlikely that today's knowledge of patterns of gene expression that underlie brain circuits will yield much grist for the mill of design. That said, our understanding of brain development, function, and plasticity is still evolving, and we may find that the larger multilevel picture eventually leads to new ways of thinking.

THE BRAIN AS AN INFORMATION-PROCESSOR

In trying to understand more concretely how neuroscience might be relevant to design, it is useful to think of the brain as an information-processing device, which of course it is. Indeed, it is the most powerful information-processing device known to man. The brain acquires information about the world through the senses and then organizes, interprets, and integrates that information. The brain assigns value, affect, and potential utility to the acquired information, and stores that information by means of memory in order to access it at a later time. These memories of information received form the basis for future actions.

Thinking further along these lines, we can make the argument that architecture is a multifaceted source of information. The sensory appearance tells us how space is organized, and thus its utility and navigability. Similarly, the appearance and its relationship to intended function may be profoundly symbolic, conjuring up a broader view of the responsibility to the users of the space and their relationship to society. Prior experiences with the world will of course come into play in understanding the meaning of the space and how it might most effectively serve its intended purpose, or inspire other unintended uses. And, of course, information conveyed by our senses, considered in a symbolic and functional context, may be the source of strong aesthetic and emotional responses, including our perception of beauty.

Building on this information-processing perspective, we can begin to articulate a few basic principles about how knowledge of the brain may bear upon architectural design. These principles conveniently fall into categories of information *acquisition*, *organization*, and *use*. In terms of acquisition, the built environment should be optimized to neuronal constraints on sensory performance and information-seeking behavior, and optimized with respect to the adaptability of those constraints. At the simplest level, for example, knowing something about human visual sensitivity—what we see best and what we have difficulty seeing—may define rules for efficient design of environments for labor, learning, healing, and recreation. I will elaborate on some examples of optimizing sensory performance later in this chapter.

In terms of organization, the built environment should facilitate perceptual organization and engender the formation of cognitive schema/neuronal maps for the task at hand. An example of the relevance of neuronal maps can be found in research on wayfinding behavior.[5] A rich vein of neuroscience research has revealed much about how space, and the location of an observer in space, is represented by populations of neurons—neuronal maps of space—in a brain structure known as the hippocampus.[6] This knowledge, in conjunction with an understanding of how landmarks and other sensory cues in the built environment facilitate wayfinding, may lead to new ideas about how to facilitate navigability by design. These ideas, in turn, may help those who suffer from memory disorders associated with dementia, and help to improve design of transportation hubs and public areas in general.[7]

In terms of use, the built environment should elicit internal states that benefit sensory, perceptual, and cognitive performance and behavioral outcomes. "Internal states" here refers to those associated with focal attention, motivation, emotion, and stress. A number of recent studies support the plausible conjecture that certain environments elicit attentional states,[8] or states of anxiety and stress,[9] which can either facilitate or interfere with the ability of observers to respond to information embedded in the environment or to carry out actions for which the environment was intended. In work with Alzheimer's patients, for example, John Zeisel[10] has shown that architectural design elicits certain outcomes that have clinical value: anxiety and aggression are reduced in settings with greater privacy and personalization; social withdrawal is reduced in settings with limited numbers of common spaces that each have a distinctive identity; agitation is reduced in settings that are more residential than institutional in character. This type of knowledge could similarly inform the design of classrooms, lecture halls, health care facilities, workspaces, and more.

VISUAL FUNCTION, PERCEPTION, AND ARCHITECTURE

One area of neuroscience research that is particularly amenable to this kind of information-processing approach—and its relevance to architecture—is that associated with study of the visual system. This is true in part because vision plays a primary role in architectural experience, but also because we now have a wealth of information about how the visual system works.[11] In the following sections, I will highlight some examples drawn from our current understanding of vision, in order to illustrate the merits of this way of thinking. To set the stage, I will first briefly summarize the basic organization of the human visual system, as well as the neuroscience research methods used to study it.

Visual experience depends, of course, on information conveyed by patterns of light. Most of the patterned light that you see originates by reflectance from surfaces in your environment—sunlight returned from the façade of a building, for example. This reflected light is optically refracted by the crystalline lens in the front of your eye, yielding a focused image that is projected onto the back surface of the eye. This back surface is lined with a crucial neuronal tissue known as the retina, which is where phototransduction takes place: energy in the form of light is transduced into energy in the form of electrical signals, which are communicated by neurons. Retinal neurons carrying information in the form of such signals exit the eye via the optic nerve and terminate in a region near the center of the brain, known as the thalamus. Information reaching this stage is conveyed across chemical synapses and relayed on by thalamic fibers to reach the visual cortex. The visual cortex comprises the most posterior regions of the cerebral cortex, which is the large wrinkled sheet of neuronal tissue that forms the exterior surface of the human brain. The visual cortex is where high-level processing of visual images takes place, and it is the substrate that underlies our conscious visual experiences of the world. Our objective here is to understand how the organization of the visual cortex might have implications for the design of human environments.

EMPIRICAL APPROACHES TO UNDERSTANDING VISION

There is a variety of powerful experimental tools for studying the organization and function of the brain, which are summarized here as they apply to an understanding of the visual system.[12] Perhaps the simplest approach involves analysis of behavioral responses to sensory stimuli. This method, known as psychophysics, dates to the nineteenth century and involves asking people under very rigorous conditions to tell us what they observe when presented with visual stimuli that vary along simple dimensions, such as wavelength of light or direction of motion. From this we are able to precisely quantify what stimulus information observers are able to perceive, remember, and use to guide their actions. This approach is particularly valuable when used in conjunction with other experimental techniques, such as those that follow.

One important complement to psychophysics is neuroanatomy, which reveals the cellular units of brain function and their patterns of interconnections. With this approach we can, for example, trace the neuronal connections from the retina up through multiple stages of visual processing in the cerebral cortex, thereby yielding a wiring diagram of neuronal circuits.[13] Such wiring patterns reveal, in turn, computational principles by which visual information is combined and abstracted to yield perceptual experience.

Another powerful experimental technique is electrophysiology, the main goal of which is to understand how information flows through the system. To measure this flow, we use microelectrodes—fine wires that are insulated along their lengths and exposed at the very tips—that are inserted into the brain to monitor electrical signals (known as action potentials) from individual neurons. From such experiments we know that the frequency of electrical signals carried by a visual neuron is often correlated with a specific property of a visual stimulus. A neuron might thus “respond” selectively to a particular color of light, or to a specific shape.[14] These patterns of selective signaling reflect the visual information encoded by neuronal circuits. Moreover, by monitoring the ways in which signals are transformed from one processing stage to the next, we can infer the “goals” of each stage and gain insights into the underlying computation.

Fine-scale electrophysiology of the sort described above is largely restricted to use in experimental animals, but there are larger-scale approaches that involve assessment of patterns of brain activity recorded from the surface of the scalp. Despite the relative coarseness of the latter approach, electroencephalographic (EEG) methods are advantageous for our interest in architecture because they can be used to assess broad patterns of neuronal activity noninvasively in humans who are actively exploring an environment.[15]

Electrophysiological approaches are often complemented by a newer experimental technique known as functional magnetic resonance imaging (fMRI). This noninvasive method exploits the fact that: (1) oxygenated blood has a distinct signature in a magnetic resonance image, (2) oxygenated blood is dynamically redirected to regions of the brain that are metabolically active, and (3) neurons that are electrically active have a higher metabolic load. Thus the fMRI blood flow signal serves as a proxy for measurements of neuronal activity and can be used to identify brain regions that are active under different sensory, perceptual, cognitive and/or behavioral conditions.[16]

The various experimental techniques of modern neuroscience, summarized above, are most powerfully used in concert with one another, where they can collectively yield a rich and coherent picture of the ways in which information is acquired and organized by the brain, and used to make decisions and guide actions.

ON THE STATISTICAL PROPERTIES OF VISUAL INFORMATION

With this brief introduction to the organization of the visual system and the methods by which it can be studied, we can consider how current knowledge of information processing by the brain might suggest principles for design of human environments. I will begin with the premise that the brain has evolved to maximize acquisition of behaviorally relevant information about the environment, but must do so in the face of biological constraints. These constraints include various sources of noise and bottlenecks inherent to the neuronal machinery of the brain itself, the consequence of which is that our sensory systems are less than perfect transducers. Or, to put it more concretely, there are some things that we see better than others.

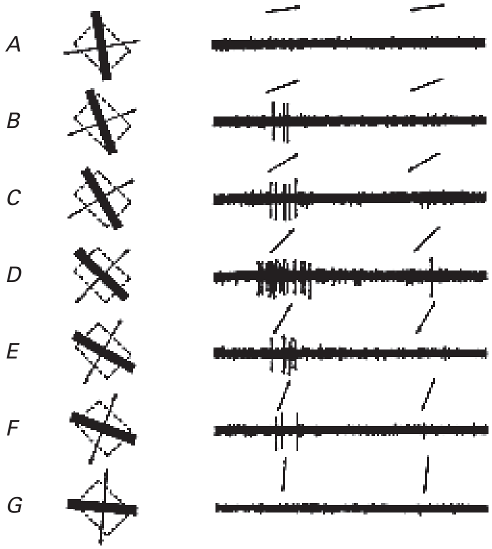
To illustrate how this limitation applies to architecture and design, we can start by measuring the physical properties of visual scenes from which the brain extracts information. There are many ways to do this—both natural and built environments have measurable statistics and we can quantify simple things like the frequency distributions of primary features, such as the different colors in a scene, or the orientations of contours (for example, those forming the frame of a window, or the branches of a tree). These simple statistics can be compared with the empirically determined sensitivity of the visual system for the same features, which provides a measure of the extent to which people can actually acquire (and thus use) certain classes of information present in the environment.

Employing the same approach, we can also quantify the statistics of higher-order image features—which are arguably more directly relevant to human behavior in natural and built environments—such as particular shapes and the joint probabilities of certain features (e.g., how often a specific color coincides in space with a certain shape). One specific example that has been looked at in some detail is the relationship between different line orientations as a function of their proximity in visual space.[17] As intuition suggests, there is a strong tendency for image contours that are nearby to have similar orientations, but as distance between them increases there is a progressive increase in the variance between pairs of contour orientations. One need only look at the contours of common man-made or natural objects—a teapot, for example, or a rose—to see that this distance-dependent contour orientation relationship simply reflects the physical properties of things in our visual world. The functional importance of this relationship can be seen by contrasting it with man-made objects that violate the principle: the image statistics of a Jackson Pollock painting,[18] for example, reflect a riot of angles and colors whose relationships yield no real perceptual synthesis.

FUNCTIONAL ORGANIZATION OF THE VISUAL BRAIN

Some unexpected insights and predictions come from consideration of image statistics in conjunction with knowledge of the organizational features of the visual cortex. Over the past few decades we have learned that there are a number different regions of the visual cortex that are specialized for the processing of unique types of visual information; one region processes contour orientation, another motion, another area processes color, and so on.[19] This knowledge has come, in part, from electrophysiological studies of the sort described above, in which the response (measured as frequency of action potentials) of a given visual neuron varies with the value of a simple stimulus along a specific feature dimension: for example, the particular angle of an oriented contour, or the particular direction of a moving pattern.

Figure 10.1 illustrates this type of cellular "tuning" as originally discovered for neurons in primary visual cortex.[20] The data represent action potentials recorded as a function of the orientation and direction of motion of a simple visual stimulus (an oriented contour). In this case, the recorded neuron responded best to a slightly off-vertical orientation moving up to the right, and the neuronal response waned as a function of the angular deviation of the contour relative to this preferred orientation. The vast majority of neurons in the primary visual cortex exhibit this property of “orientation selectivity.” Their discovery in the 1960s by David Hubel and Torsten Wiesel transformed the way we understand the visual system, and fostered the development of a whole new set of techniques to study it. The existence of this specialized population of neurons in the cerebral cortex, and other populations that represent stimulus direction[21] and color,[22] accounts for the primacy of such simple features in our visual experience of the world.



10.1 Orientation selectivity in the primary visual cortex. D. H. Hubel and T. N. Weisel, 1968.

Each of these functionally specific areas is further arranged according to certain organizational principles. One of these is columnar organization, which means that similar values of a given feature dimension (such as contour orientation or direction of motion) are represented in adjacent cortical tissues.[23] These functional columns extend through the thickness of the cerebral cortex and are mediated by neuronal microcircuits that correspond anatomically to the functional columns.[24] The neuronal architecture is such that the preferred value of the relevant feature (e.g., the preferred contour orientation) remains constant as one moves from the surface through the depth of the cortex, but changes gradually as one moves in the orthogonal plane, i.e., parallel to the cortical surface.[25] The scale of this system is fine, with a complete cycle of preferred orientations contained within less than a millimeter of cortex. A highly similar columnar system exists in a region of visual cortex specialized for encoding direction of motion.[26] In this case, the individual neurons represent specific directions, rather than contour orientations, and a complete cycle of direction columns similarly spans a region of cortex less than a millimeter across.

Another organizational principle of the visual system is built around the concept of association fields.[27] Association fields reflect patterns of local anatomical connections that link neurons representing specific values of a visual feature dimension. In the primary visual cortex, the specificity of these connections is made possible by the existence of an organized columnar system for representing contour orientations (see above). The connections are manifested as anatomical links between columns representing specific contour orientations. In particular, within cortical regions representing close-by locations in visual space, there exist strong connections between columns that represent similar orientations and only weak connections between columns that represent widely different orientations (perpendicular being the extreme).[28] As the spatial distance grows, the pattern of anatomical connections becomes more isotropic.

ASPECTS OF PERCEPTION FACILITATED BY NEURONAL ARCHITECTURE

These highly specific organizational properties for representing information about the visual environment raise interesting questions and conjectures about their relationship to visual perception. For one, we note that there is an apparent symmetry between the association fields for contour orientation and the statistics (summarized above) of contour orientations in the visual world. As we have seen, contours that are nearby in visual space are more commonly similar in orientation, relative to those that are distant in visual space. Analogously, in the visual cortex, cells representing similar orientations are preferentially interconnected provided that they also represent nearby locations in visual space. There are evolutionary arguments one can make: it seems highly likely that this cortical system for organizing visual information conferred a selective advantage for detecting statistical regularities in the world in which we evolved. At any rate, we hypothesize that the existence of the system helps to facilitate the processing of commonly occurring relationships between visual features.

A key part of this conjecture, which has implications for architecture and design, is the word *facilitate*. Human psychophysical experiments have shown, for example, that when people view random patterns of line segments, any colinear, or nearly colinear, relationships within those patterns tend to stand out perceptually from a background of

10.2 Field of wheat.

10.3 Green bodhi leaves.

10.4 Alaskan tundra.

10.5 Feathers of an ostrich.

noise[29]—according to our hypothesis, perceptual sensitivity to these arrangements is *facilitated* by the organizational properties of the visual cortex.

As implied by the foregoing arguments, visual patterns in which there is a statistical regularity between adjacent contour orientations—repeating lines in colinear, curvilinear, parallel and radial patterns, for example—are ubiquitous in the natural world. Fields of grass, waves in the ocean, the veins of a leaf, the branches of a tree, the leaflets of a palm frond, or the barbs of a feather are all commonly encountered examples that embody this principle.

We hypothesize that man-made designs that adopt this same principle "benefit" in some way—detection of them is "facilitated"—by tapping into the highly organized neuronal

10.6 Fay Jones, Thorncrown Chapel, Fayetteville, Arkansas.

system for representing contour orientations. One need not look hard to find prized exemplars in the built environment that feature colinear, curvilinear, parallel and radial patterns: Fay Jones's Thorncrown Chapel in Fayetteville, Arkansas, the colonnades in Romanesque churches and monasteries such as the abbey at Assisi, or the rose window in the cathedral of Notre Dame. The cable-stayed bridge, which is commonly constructed using radial fans of cables to cantilever the road bed, is a particularly notable example. This is the most commonly built highway bridge today. There are many reasons for this that stem from advances in materials science and engineering, as well as economy of construction. But I speculate that the popularity of the cable-stayed bridge is also due, in part, to the fact that the gradually changing contours tap into something fundamental in the native organization of our visual system. There is, I will argue, an attractiveness to

10.7 Cloisters, Monreale, Sicily.

these designs that originates from the ease with which they are processed and perceived by our visual systems.

THE SENSE OF ORDER

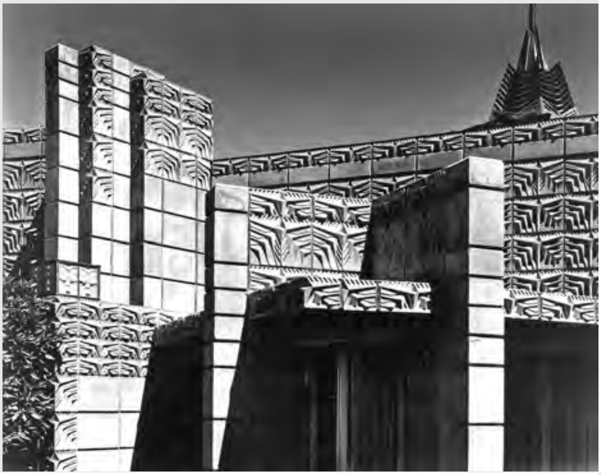
Neuroscientists were not the first to make this connection. Ernst Gombrich, one of the great geniuses of twentieth-century arts and humanities, wrote and reflected deeply on the relationship between art and visual perception.[30] His text *The Sense of Order: A Study in the Psychology of Decorative Art* addresses the use of certain timeless design features in art and architecture. Summarizing his thesis elsewhere, Gombrich wrote: “I claim that the formal characteristics of most human products, from tools to buildings and from clothing to ornament, can be seen as manifestations of that sense of order which is deeply rooted in man's biological heritage. These ordered events in our environment which exhibit rhythmical or other regular features (the waves of the sea or the uniform texture of a cornfield) easily 'lock in' with our tentative projections of order and thereby sink below the threshold of our attention while any change in these regularities leads to an arousal of attention. Hence the artificial environment man has created for himself satisfies the dual demand for easy adjustment and easy arousal."[31]

Gombrich was not a neuroscientist, of course, but his concept of "manifestations of that sense of order which is deeply rooted in man's biological heritage" and his suggestion that "these ordered events in our environment … easily 'lock in' with our tentative projections of order" resonate deeply with the view that our perception of the world depends heavily upon highly ordered neurobiological characteristics of the human visual system. Again without knowledge of the neuroscience of vision, Gombrich expanded along similar lines: "There is an observable bias in our perception for simple configurations, straight lines, circles and other simple orders and we will tend to see such regularities rather than random shapes and our encounter with the chaotic world outside. Just as scattered iron filings in a magnetic field order themselves into a pattern, so the nervous impulses reaching the visual cortex are subject to the forces of attraction and repulsion."[32] Gombrich's iron filings metaphor is striking in the present context, as it poetically captures the notion that the organizational properties of the visual system serve to efficiently encode statistical regularities in the visual world.

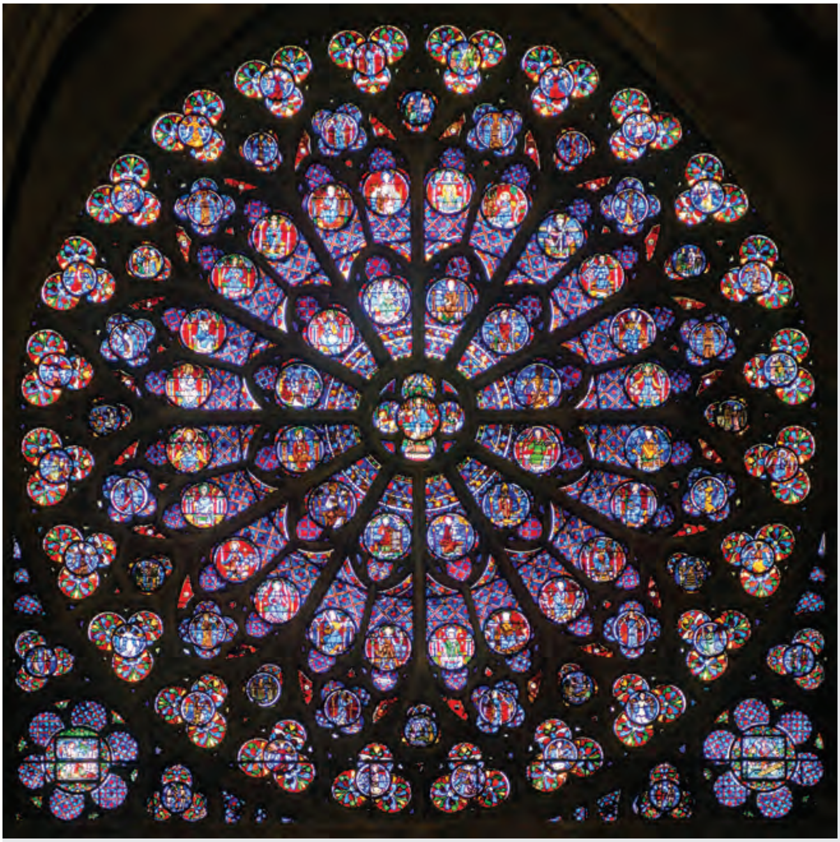
Gombrich spoke at length about designs that impart this sense of order. Some examples include the mosaics at the Alhambra, and the paper and textile patterns of William Morris. To these I would add the decorative designs of Frank Lloyd Wright from a similar period to those of Morris. For each of these examples, it is not necessary to sit and examine how it is put together; you see one part and a perceptual understanding of the whole follows without visual scrutiny—they are repetitive designs that capitalize on the ordered nature of the visual cortex.

Similar arguments apply to mandalas, which have been used as meditation aids for centuries in the spiritual practices of Hinduism and Tibetan Buddhism. As for the decorative patterns cited above, mandalas have image statistics that are complementary to the organization of the visual cortex. Our conjecture is that they have an ordering effect owing to the ease of visual processing—they are calming, regular structures.

10.8 Frank Lloyd Wright, textile block pattern.



10.9 Frank Lloyd Wright, textile block house, Los Angeles.



10.10 Rose window at Notre Dame, Paris.

By the same logic, of course, we should expect that images possessing irregular statistics, or properties that do not tap into to the organizational features of the visual cortex, should require greater effort to process and may lead to confusion, disturbance, and distraction.

FAMILIARITY VERSUS NOVELTY

I interpret Gombrich's statement that the built environment "satisfies the dual demand for easy adjustment and easy arousal" to mean that the optimal environment has varying degrees of familiarity and novelty. That is, we create features in our environment with a sense of order; of things that are familiar. Without visual scrutiny, such features are

10.11 Tibetan sand mandala. Minneapolis Institute of Arts.

easily processed because they tap into the inherent organization of our brain systems for visual perception. This order provides a suitable background—and liberates neuronal resources—for detection of novelty (a predator or an intruder, perhaps, or a new piece of furniture), which is nearly always of behavioral significance and demanding of attention. To put it simply, the built environment tends to reflect the way visual perception works.

Gombrich was not the only person who noticed this phenomenon. Oscar Wilde also observed: "The art that is frankly decorative is the art to live with. The harmony that resides in the delicate proportions of lines and masses becomes mirrored in the mind. The repetitions of pattern give us rest. Decorative art prepares the soul for the reception of imaginative work."[33] Again, Wilde is using literary language to describe how the visual system functions between the poles of familiarity and novelty. Repetition gives us rest, because we are not required to scrutinize every part of it. Comfort derives from ease of visual processing. Wilde suggests that the regularity of background sets the stage for truly imaginative work, for something new to emerge.

BRAIN AND BEAUTY

It should not go unnoticed that these ideas have implications for the neurobiology and evolution of aesthetics. There are surely many different reasons for the aesthetic judgments that we make about features of the natural and built environment, many reasons why we find beauty in one form and ugliness in another. Much of this is cultural and learned. Doubtless many people will tell you that Leonardo's *Mona Lisa* is beautiful, simply because that is what we have taught them. Oftentimes judgments of beauty will reflect frequent exposure to certain stimuli in the presence of reward (money, information, social power, or sex), or a cultural "consensus" defined by commercial interests and displayed through magazines, billboards, and television. But the foregoing discussion suggests a definition of beauty based on ease of visual processing—beauty defined by the extent to which features of the visual environment engage organized processing structures in the visual brain, and are thus readily acquired, organized, and "understood." Evolution is invoked in this definition of beauty, since we hypothesize that the relevant brain structures exist because they conferred a selective advantage for survival and reproduction in an environment replete with the image statistics described herein.

GENERALITY OF PRINCIPLES

The latter part of this chapter has focused on a specific set of organizational features in the visual cortex—those involved in the detection and representation of oriented contours—primarily because this is the visual submodality that we know the most about. The principles exemplified by this submodality are likely to be very general, however. Indeed, there are good reasons to believe that a detailed understanding of the architecture and function of brain systems for other visual submodalities (e.g., color or visual motion processing), or for other sensory modalities (e.g., audition and touch), will have similar implications for understanding the built environment.

PLASTICITY AND VISUAL ATTUNEMENT

Finally, it is important to note that the information-processing features of our brains are not rigid over time. On the contrary, they are plastic and tunable by experience. Recent evidence indicates that the sensitivities of our sensory systems are adapted to the statistics of our environment, but those sensitivities may change—they may be recalibrated—when the properties of the world change.[34] This adaptability has profound implications for design. Suppose, for example, that I adapt you to the baroque opulence of Marie Antoinette's bedroom in Versailles, and then move you to a minimalist home designed by Mies van der Rohe. The transition will elicit recalibration and will, we hypothesize, necessarily involve windows of time in which sensitivity is nonoptimal for the new environment. These considerations have particularly important implications for the design of spaces for work and learning, as frequent changes of environmental statistics may interfere with the ability of observers to acquire, organize, and use information from the environment.

CONCLUSIONS: TOWARD A NEUROSCIENCE FOR ARCHITECTURE

Neuroscience is a new research discipline in the armament of longstanding efforts to understand the influence of built environments over human mental function and behavior. Using a variety of powerful experimental approaches, and focusing efforts on the information-processing capacities of the brain, we have begun to develop an empirical understanding of how design features influence the acquisition, organization, and use of information present in the built environment. On the basis of this understanding, we argue that selective pressures over the course of human evolution have yielded a visual brain that has highly specific and tunable organizational properties for representing key statistics of the environment, such as commonly occurring features and conjunctions of features. Simple visual pattern types, which are commonly used in architectural and decorative design, mirror these environmental statistics. These patterns are readily "seen" without scrutiny, yielding a "sense of order" because they tap into existing neuronal substrates. A fuller understanding of these relationships between organizational properties of the brain and visual environmental statistics may lead to novel design principles.

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