

## 8 Auditory Spatial Awareness as Evolutionary Artifact

Among scientific theories, the theory of evolution has a special status, not only because some of its aspects are difficult to test directly and remain open to several interpretations, but also because it provides an account of the history and present state of the living world.

—François Jacob, 1982

Evolution is a useful lens through which we can examine aural architecture, offering the potential of fusing contributions from diverse disciplines into a single picture. Theories about evolution have been successfully applied to broad questions such as the adaptive function of sex and the influence of geography on genetics, and to narrow questions such as the origins of lactose intolerance and sickle-cell anemia. In contrast, traditional disciplines, with their formal paradigms, cannot readily address some kinds of questions. Evolution is fascinating just because it has the potential to offer explanations about phenomena that would otherwise appear to have no explanation.

We begin with the simplified premise that the aural experience of space contributed, at least indirectly, to the reproductive success of our species. From a narrow perspective, our brain evolved specialized auditory substrates that could incorporate spatial attributes into awareness. But from a broader perspective, auditory spatial awareness also contributes to our ability to thrive in socially complex groups. Although we have already analyzed aural space from the perspective of art, science, cultures, and sub-cultures, we have only alluded to the dominant role that social cohesion plays in all aspects of aural architecture. All known cultures reinforce social cohesion by social, musical, or religious rituals, which take place in spaces, often spaces dedicated for particular ritual functions. Similarly, those who design or select spaces, as well as those who listen to those spaces, are also responding to their social context. We can therefore examine the evolution of auditory spatial awareness and the resulting aural architecture from the perspective of social cohesion.

Evolution is, however, a post hoc theory—using the same evidence twice—for both constructing and validating a hypothesis. According to Karl R. Popper (1959), that makes evolution a prescientific theory. Consider the discovery of a previously

unknown island with a unique terrain, inhabited by a tribe whose members have flat feet. An evolutionary argument reverses the observation so that it becomes “flat feet were a genetic adaptation that allowed the tribe to survive in their unique terrain.” It cannot be disproved. Stephen A. Gould and Richard C. Lewontin (1979) noted that it is relatively easy to create intellectual constructs when there is no independent means for testing their assertions. Evolution provides answers that are, at best, plausible and useful and, at worst, intellectual fictions. Scholars have in fact rather low confidence in the validity of specific evolutionary conclusions offered as the *most likely* explanations for what is observed.

Nevertheless, it is tempting to conclude our discussion on auditory spatial awareness by exploring the larger story of why we came to be what we are. Curiosity about our origins appears in virtually every culture, and evolution is the most recent explanation, often replacing myth and religion. In part, the motivation to understand our origins is driven by an apparent lack of rational and predictable behavior on the part of individuals, groups, and cultures. Behaviors that appear to be illogical or irrational become more comprehensible if we assume they are artifacts of adaptation to earlier ecological niches. Similarly, unusual auditory perceptual abilities, such as in-head aural localization when listening with headphones, may be nothing more than artifacts of older adaptations to ancient environments.

Every species of social animals, including human beings, developed its own sensory and social approach to surviving in its niche, which itself dynamically changed with shifts in weather, geography, and the adaptive choices of other competing species. Had the history of our adaptation been even slightly different, or had environmental stresses and opportunities appeared earlier or later during our evolution, auditory spatial awareness would have evolved other properties, which would have then influenced our aural architecture.

Evolution contributes five themes to our earlier discussions. First, as a subset of hearing, auditory spatial awareness allows us to perceive and locate physical obstacles in space (navigational spatiality), as well as to compensate for the influence of spatial acoustics on communications (social spatiality). Second, social cohesion is a core component of evolutionary theories; all aspects of aural architecture are based on assumptions about the function of social groups in a space. Third, our modern brains are an evolutionary solution to older problems; biological trade-offs over millions of years determined the properties of our auditory and cognitive cortices. Fourth, the wide variations among individuals in auditory spatial awareness and in the ability to enhance that skill with practice are explained by the diversity in the physical environments of our ancestors, on the one hand, and in our social environments as developing children, on the other. And fifth, the human brain did not necessarily evolve with the ability to understand itself or its properties; there is nothing in our understanding of evolution to suggest we should be conscious of how and why we use auditory spatial awareness in spaces.

Although we can actually observe how modern humans experience their acoustic spaces, we can also consider how our prehistoric ancestors might have experienced theirs. Evolution provided a neurological solution to their problem of surviving, and that solution is still with us in modern society. Researchers attempting to understand how early humans responded to stimuli and situations, extrapolate from modern humans and modern society. But humans were never designed for modern society, which is only a dot on the evolutionary timescale. Consider a mechanical analogy. An engine originally designed to run on alcohol is now fueled with gasoline because of its greater availability. If we are to understand how the engine is meant to perform, however, we need to explore its original design context, rather than focusing only on its current one. So it is with human beings. In some respects, our response in a modern environment is nothing other than an artifact of how our prehistoric ancestors responded in their environments. Our aural architecture has its roots in the prehistoric past.

Since Darwin first introduced the idea of evolution 150 years ago, it has come to permeate both popular and scholarly literature. Unfortunately, the popular literature often trivializes complex issues with specious conclusions, and the scholarly literature is riddled with arcane arguments of interest only to academic researchers. This chapter examines the basic principles of evolution as applied to auditory spatial awareness. When incorporating evolution into our interdisciplinary perspective, we find plausible explanations for some issues, and unexplainable mysteries for others.

### **Evolutionary By-Products Define Modern Humans**

Within the human animal, there are both special-purpose, hard-wired biological structures, such as the external ear and its low-level neurological processing of sounds, and general-purpose, soft-wired creative, cognitive, and perceptual structures such as learning to appreciate aural architecture. These solutions represent the two extremes of the continuum of possible responses to environmental stresses and opportunities. Hard-wired structures reflect how the gene pool of the species shifts toward a new phenotype (general properties of the species) over hundreds of generations. Soft-wired structures reflect how individuals learn new behaviors, perceptions, and cognitive strategies (unique properties of individuals) over hours, months, or years. All species display some degree of both.

Paradoxically, brain substrates designed to learn are actually a hard-wired solution that optimizes the trade-off between the efficiency of a hard-wired solution and the flexibility of a soft-wired solution. A substrate designed to learn from experience is like a general-purpose computer that does nothing until programmed, whereas a substrate designed for only one function is like the specialized computer in a cell phone that works immediately. Since both types of solutions exist within the same animal, and since all biological and neurological structures have an energy and space cost, over

thousands of generations, evolution carefully balanced their respective contributions of long- and short-term adaptation. For human beings, evolution favored the learning solution using self-modifying brain substrates, which is why culture plays a significant role in determining human nature.

Auditory spatial awareness is a perfect example of both types of adaptation. Unlike some species of bats, we do not have a hard-wired specialization to aurally visualize the world entirely by hearing sonic reflections from synchronized vocalization. But we have the hard-wired ability to fuse early sonic reflections with the direct sound, presumably because all acoustic spaces have a sound-reflecting floor. We have the soft-wired ability to learn to hear space as demonstrated by blind bicycle riders, and we adapt to spaces that vary from jungles to enclosed rooms.

The learning function has been optimized for acquiring abilities that contribute to survival—most notably, motor dexterity and pattern perception—all of which relate to the external world. From an evolutionary perspective, learning to recognize patterns was a fundamental survival skill. Interpreting animal tracks, forest sounds, weather patterns, star formations, soil texture, edible grains, and so on had immediate practical value; patterns are unique to each ecological niche. Traditionally, experienced elders taught their young by example. Learning was based on repetition. Eventually, the young males would become hunters, foragers, navigators, and ultimately, decision makers. Richard C. Lee (1979) describes a group of expert hunters who could identify an animal's sex, age, health, and eating patterns simply by examining its tracks. Because newly acquired abilities were often a matter of life and death, individuals who displayed unique learning intelligence would become leaders, inventors, innovators, and, most important, successful parents to the next generation.

Learning to interpret physical clues left by an animal is similar to learning to aurally visualize a space by listening to auditory cues. The method for learning both tasks, repeatedly studying numerous examples, is similar. Had you grown up in an aural “tribe,” you would have become an expert at recognizing acoustic cues, and interpreting their relationship to those spatial “animals” that created them. As an adolescent eager to learn new skills from aural “elders,” you would have been taken through thousands of spaces in the “forest” of soundscape niches. Many years of such training would have refined your auditory spatial awareness to a high art form. Because each ecological niche offers unique patterns, your ability to learn to recognize those important patterns would have contributed to your survival and to your tribe's survival.

### **Neurological Specialization Hides Self-Awareness**

What does “learning to hear space” actually mean? Among other things, it involves pursuing a lifestyle that provides multiple opportunities for attending to those aural cues provided by spatial acoustics. Attending to auditory spatial awareness over time changes individuals both internally (privately) and externally (publicly). Privately,

individuals may think, perceive, or feel differently because they sense spatial details aurally. Publicly, individuals may display an improved ability to navigate a space in the dark. Illustrating this distinction, language is both public and private; perception is mostly private; motor skills are public; emotions are an odd mixture of public (body language, voice tone, behavior), and private (mood, arousal, and attentiveness). From the perspective of evolutionary survival, only behavioral manifestations of learning would have been relevant because they alter individuals' relationship to the external environment. Private learning is irrelevant unless, however indirectly, it eventually produces some external consequences, which can then be observed.

Auditory spatial awareness is a perfect example of the problem of linking internal experience to observable ability. Behavior can be observed in carefully designed laboratory experiments or in everyday life, as when we watch a blind individual riding a bicycle. When spatial awareness produces an emotional reaction, however, such as a change in mood in a certain kind of acoustic space, we must find a way to make such private experiences observable. Failure to find a technique does not mean that there is no private awareness.

This leaves us with two intertwined issues. To what degree are we actually aware of acoustic spaces? And to what degree can that awareness be either observed or communicated? There are three possibilities: an absence of private awareness, unobservable awareness, and observable awareness. It is difficult, if not impossible, to distinguish the first two cases; even in the third case, external behavior may be only weakly or indirectly linked to internal awareness. Thus we need to explore the larger question of how internal states can be observed. In this respect, auditory spatial awareness cannot be studied without also assuming the existence of brain substrates that adequately translate internal states into behavior, consciousness, or observable manifestations. Recent research has begun to shed light on the intrinsic philosophic problems embedded in concepts such as awareness, perception, and consciousness, all of which are directly relevant to studying the human experience of aural architecture.

Let us now examine what is known about brain neurology to shed light on the problem of interpreting the experience of aural architecture. The eminent neurobiologist Michael S. Gazzaniga (2000) has stated: "the human brain is a bizarre device, set in place through natural selection for one main purpose—to make decisions that enhance reproductive success." One manifestation of neurological optimization is the evolution of specialized neurological substrates, each of which is optimized for specific functions. A brain that is organized into two distinct halves is an obvious example of an optimization because each half can contribute different functions, which increases efficiency of a limited quantity of neurological resources within a fixed head volume. The corpus callosum, which connects the two brain hemispheres, allows each half to share information from separate functions in the other half. Because each hemisphere acquired special abilities, only relatively important information is communicated

between them. The left hemisphere does not transmit information that is not needed by the right hemisphere, and vice versa. Neurological communication is biologically expensive, and unneeded communication reduces the efficiency of specialization. Communication and specialization, working in opposite directions, evolved a delicate balance.

Extensive study of patients with split brains over a period of 40 years has made the roles of the two hemispheres more apparent. Orrin Devinsky (2000) observed that lateral specialization, where each half of the brain takes on special functions, exists in many species. But in humans, that specialization has been further extended in order to support language in the left hemisphere, while leaving the right half available for traditional functions. As a generalization, the left hemisphere deals chiefly with language, reason, planning, and logical thought, whereas the right hemisphere deals chiefly with moods, emotions, visceral body states, and the affective meaning of external perceptions. The right hemisphere, which provides processing for attention, visuospatial, body schema, and emotional functions, supports self-awareness, body image, and their relationship to the social environment. In addition, Devinsky implicates the right hemisphere as the dominant locus for the perception and the expression of emotion, including comprehension, gestures, facial expression, intonation, as well as contextual inferences from nonverbal speech, music, pain, and the affective meaning of cartoons. Dahlia W. Zaidel (2000) argued that the asymmetry in processing between the two halves of the brain also appears in the concepts of meaning systems: the right hemisphere is home to novel and noncultural metaphors, whereas the left hemisphere is home to stereotypical and cultural metaphors.

Hemispherical specialization implies that various substrates are only partially aware of what other substrates are experiencing. In fact, what we think of as the unity of consciousness is not unified at all—it just appears that way. By implication, auditory spatial awareness is not a conscious and unified experience of an external environment. Awareness is actually the result of activities in many substrates in both hemispheres, and their ability to communicate with each other is, at best, imperfect. Gazzaniga (2000) commented that the left hemisphere is “driven to generate explanations and hypotheses regardless of circumstances. The left hemisphere of a split-brain person does not hesitate to offer explanations for behaviors that are generated by the right hemispheres. In neurologically intact individuals, the interpreter does not hesitate to generate spurious explanations for sympathetic nervous system arousal. In these ways, the left hemisphere interpreter may generate a feeling in all of us that we are integrated and unified.” If nothing else, this analysis explains the difficulty in verbalizing our affective states, and our reaction to affect laden stimuli, like music. Emotions, mood, and visceral sensations, which represent our body states, influence how an individual responds to the environment, but those states may not necessarily be describable.

“When the foregoing research is taken together,” Gazzaniga (2000) concludes, “rather simple suggestions are appropriate. First, focus on what is meant by ‘conscious experience.’ The concept refers to the awareness human beings have of their capacities as a species—awareness not of the capacities themselves but of our experience of exercising them and our feelings about them. The brain is not a general-purpose computing device, it is a collection of circuits devoted to these capacities.” The illusory unity of consciousness and the holistic nature of language mask the existence, limitations, relationships, and contributions of those separate neural circuits.

Patients who, for one reason or another, have had their corpus callosum cut, so that their two brain hemispheres operate independently (Baynes and Gazzaniga, 2000), exhibit truly bizarre behavior under controlled conditions, illustrating the segmentation of experience. For example, stimuli presented to the left visual field, which maps to the right hemisphere, can produce strong emotional responses but without the corresponding ability to describe the visual scene. The emotional experience is real, and often intense, but without the awareness of the stimulus that gave rise to the emotion, much like being unconscious of perception. To a far lesser extent, and also without realizing it, normal individuals also have segmented hemispheres, although their normal brains still provide better communications, however imperfect, between the hemispheres than do split brains.

The phenomenon called “blindsight”—seeing without seeing—also illustrates the partitioning of awareness. In her review of this topic, Petra Stoerig (1996) provided numerous examples of lesions in the primary visual cortex that prevented sight but where the individual could still experience the visual object. For example, when a monkey was made (totally) blind by having a bilateral occipital lobectomy, he still learned to navigate and discriminate visual objects (Humphrey, 1974). Removing the top picture level does not necessarily remove connections that allow other neural structures to remain aware of the external world. Awareness exists with and without consciousness. Think of our brain as a complex machine that happens to be equipped with indicators, which act much like windows of consciousness. Some states of the machine are accurately reported by these indicators, but others remain hidden.

Nicholas Humphrey (2000) goes further with the argument that evolution progressively shifted sensory awareness of external stimuli from publicly observable reactions to private experiences. Primitive organisms always respond publicly, whereas complex organisms most often respond privately. The degree to which such private experiences can be represented in words may reflect the degree of neurological connection between the language center and the particular perceptual substrate. When there is a modest degree of connection, some aspects of perception can be verbally communicated, often better communicated with practice, although only up to a point. In contrast, when there is no connection, no amount of effort will allow an experience to be communicated. On the other hand, if the perception changes your body state, such as making

your stomach muscles tighten, you can sense that change and report it, although there is a considerable difference between communicating a sensory experience itself and reporting its reactive consequence to your body state. However rich its vocabulary, English is still at a loss for words when communicating internal experiences, especially those which produce affect. Moreover, we may not be conscious of an internal state, even though it is being publicly broadcast, such as the involuntary blush that signals our feeling embarrassed.

In recognition of the importance of emotions in the aural architecture of musical spaces, Glenn Knickrehm (2004) searched for those performance spaces that had the reputation for producing “heart pounding, raised neck hairs, goose bumps and tears of joy.” Having visited some 600 musical spaces constructed between the eleventh and the nineteenth centuries, and having identified the ones with this reputation, acoustic scientists then only measured their acoustic properties (Bassuet, 2004). Other than simply asking listeners, there is no formal way to sort performance spaces into those of high and low affect. Many, perhaps most, emotional aspects of auditory spatial awareness are not readily observable. This view is entirely consistent with neurological research from an evolutionary perspective. Interpreting the impact, function, and meaning of aural architecture is therefore correspondingly difficult, limited, and anecdotal. Because evolution did not provide us with a reliable mechanism to observe and communicate affect, using scientific experiments to understand the aural experience of spatiality is fraught with risks and uncertainty.

### **Learning as an Adaptation to the Environment**

Some individuals are able to interpret spatial details by listening, and they are more likely to develop this ability if they grow up in an environment where such learning is stimulated and motivated. Rich aural environments encourage the acquisition and development of auditory spatial awareness, whereas aurally barren environments do not. Earlier, we observed significant differences in the aural architecture of cultures, and those differences are passed down from generation to generation through children. Even though explicit research on the connection between neurological development and cultural values is relatively sparse, many principles are now understood. Brain development and culture cannot be separated.

The archetype of learning is the baby. Jean-Pierre Bourgeois (1999) suggested that the dynamics of synaptic growth in the newborn, driven by genetic triggers and environmental stimulation, create an individual with unique abilities, propensities, intelligence, and perceptual sensitivities. Aspects of synaptic growth that are common to all individuals represent what we call “human nature”; aspects that differ substantially lead to the uniqueness of each individual, which includes, not just the obvious personality differences, but also subtle perceptual predispositions, sensory preferences, learning modes, cognitive strategies, and emotional temperament.



Several months before birth, the neuron inventory of the human fetus is fully developed but without stable connections; the wiring is still primitive (Bourgeois, Goldman-Rakic, and Rakic, 2000). Although the quantity and density of synaptic connections grow rapidly in a “biological exuberance” beginning shortly before birth and continuing during the next year, these newly formed connections are like an overgrown garden that needs to be shaped and pruned. Nature has chosen to grow massive connections and then to refine their properties by removing excess connections rather than adding new ones. This pruning process stabilizes after puberty, and continues into the third decade of life.

We can understand many of the principles of neurological change in the developing infant from studies of other species. Marcus Jacobson (1969) has identified how environmental exposure changes neural wiring. Individual neurons develop highly specific synaptic connections, but in the early developmental stages, these connections are modifiable. The window of flexibility depends on the type of neuron. Michael M. Merzenich and Christoph E. Schreiner (1990) found idiosyncratic differences in the auditory cortex among adults of the same species. Every individual shows some degree of auditory neurological adaptation, providing distinctive differences in aural spatial ability.

Especially for human beings, the division of labor among brain substrates for each sensory system is far less categorical than implied by the names that scientists give to specific substrates. For complex substrates, the names are only an indication of an embryonic understanding of both neurological functions and developmental dynamics. Anne G. De Volder and colleagues (2001) found that auditory and tactile imagination activated visual substrates. Similar cross-modal reorganization has been found in deaf individuals. Norihiro Sadato and colleagues (2002) observed a similar reorganization of the visual cortex for tactile discrimination tasks, but only for individuals who lost their sight before age 16. Disruptive magnetic stimulation of the visual cortex degraded Braille reading in early-onset, but not in late-onset, blindness (Weeks et al., 2000). These observations indicate that the susceptible period for this form of functional cross-modal plasticity<sup>1</sup> does not extend beyond age 14. Observations of early neurological plasticity in a wide variety of surgically blinded animals are fully consistent with such observations in humans (Kahn and Krubitzer, 2002). Brain substrates are highly flexible in terms of the functions they serve.

Neurological growth and environmental learning both involve changes to the brain. Jean-Pierre Bourgeois, Patricia S. Goldman-Rakic, and Pasko Rakic (2000) sort the pattern and timing of changes in the brain into three categories of learning that distinguish the contribution of environmental exposure to brain growth. *Experience-independent* (hard-wired) learning is innate, requiring limited environmental exposure; *experience-dependent* (soft-wired) learning is achieved only with significant environmental exposure; and *experience-expectant* (soft- and hard-wired) learning is mainly achieved during an innate window of opportunity, when the environment is the teacher.

In this third category, the hard-wired predisposition to extract information when exposed to the environment is largely restricted to a critical stage of brain development, after which learning is more difficult, if not impossible. Language acquisition is perhaps the best example of experience-expectant learning. From about age 2 to puberty, the brain acquires language by extracting semantic and syntactic rules from the exposure to *any* spoken language. When the brain is in this special learning mode, even a minimal exposure to speech will result in acquisition of language. Similarly, sensory integration, where the visual, auditory, and tactile senses of space are made to align, is also based on exposure during a critical window, which begins at birth (Stein, Wallace, and Stanford, 2000).

Among the likely many experience-expectant kinds of learning, auditory learning remains essentially a mystery except for the few cases that have been studied. A. H. Takeuchi and S. H. Hulse (1993) suggested that absolute pitch recognition cannot be learned after age 6, and D. A. Pearson (1991) describes a window between ages 9 and 11 for learning an auditory attention-switching task. A child's ability to suppress the influence of early reflections (the precedence effect) approaches the adult level only after age 5, when the child has been exposed to rich acoustic environments (Litovsky, 1997; Burnham et al., 1993). The ability of the blind to use echolocation to aurally visualize acoustic space or of music enthusiasts to become sensitive to the subtleties of a concert hall also has a learning window that starts to close at a young age.

Most studies of hearing assume, probably incorrectly, that perceptual abilities are predominantly experience independent (innate), such as the ability of newborn infants to crudely localize sounds without significant exposure to the sound world (Aslin and Hunt, 1999), or experience dependent, such as the ability to evaluate spatial simulators or to identify objects with sonar, which requires training.

Even when the experience-expectant learning window closes, some amounts of neurological plasticity must be preserved to accommodate changes in the environment, both internal and external. For example, the ability to aurally localize using binaural cues remains sufficiently plastic to keep visual and auditory space images aligned despite size changes produced by head growth or the use of eyeglasses (Shinn-Cunningham, Durlach, and Held, 1998). Equipped with visually shifting prisms for an extended duration, an owl modified its cognitive map of space to compensate for the perceived spatial change. But when the prisms were later removed, there was neurological evidence that the original map had been preserved, although temporarily deactivated (Zheng and Knudsen, 1999). The owl had created dual cognitive maps. Similarly, Paul M. Hofman and A. John van Opstal (1998) described how lateral location ability was dramatically disrupted in human subjects when the shape of their outer ear was modified, but after some practice, performance steadily improved. Richard Anderson and colleagues (1997) described the neural structures by which auditory location cues in a head-centered frame of reference are transformed into eye-

centered coordinates after compensation for eye fixation. Ultimately, subjects achieve a single external representation, with all sensory sources reconciled for consistency. The need for consistency implies some degree of plasticity.

Because the human brain is so adaptive, assertions about human nature or innate perceptual abilities are philosophically problematic. Such assertions fail to recognize the importance of culture: the microculture of the infant, the miniculture of the adolescent, and the macroculture of the adult. As a general conclusion, Dean V. Buonomano and Michael M. Merzenich (1998) explain: “the cortex can preferentially [re]allocate cortical areas to represent selected peripheral inputs. The increased cortical neuronal population and plasticity-induced changes is the coherent response... thought to be critical for certain forms of perceptual learning.” Learning is an adaptive response to the environment; our brain is a manifestation of culture.

With regard to the impact of culture on auditory perception, Georg von Békésy (1960) reported an experiment in which a male Rom subject showed normal pitch discrimination but extremely poor loudness discrimination. Because his musical tradition considered pitch rather than loudness as being dominant, he could hear loudness but discarded it as having no significance. Thus not attending to an auditory attribute is, in effect, equivalent to not experiencing it, like irrelevant background noise. Just as a bushman, having lived in the forest for his entire life, would find it difficult to recognize and interpret the acoustics of enclosed spaces, so would an academic researcher, having lived and worked almost entirely in enclosed spaces, find it difficult to navigate the acoustics of a forest.

The problem in studying auditory spatial awareness is that the dominant aspect of learning does not take place under controlled conditions of a school or laboratory. Most learning is woven into life, be it listening to a mother’s lullaby during the first nights of life in a nursery or attending weekly concerts and religious services in a church. In the school of life, it is usually not obvious what is being learned. By age 20, an individual has spent over 100,000 hours in a wide range of acoustic environments, which vary greatly across individuals and cultures. Olivier Deprès, Victor Candas, and André Dufour (2005) suggest that the improved auditory ability to localize found among those with myopia arises from the need to use auditory information during ordinary living. Rather than studying the biological properties of our species, scientists who explore auditory spatial awareness are actually observing culture. And depending on that culture, some individuals have more or less auditory spatial awareness than others.

### **Individuation by Learning and Genetic Predisposition**

When members of a culture learn new skills or new applications for old ones, culture takes a new direction. The evolution of aural architecture thus depends on the degree to which individuals learn to appreciate auditory spatial awareness. With enough

interest among enough people, a culture is likely to invest resources in aural architecture, which then provides an environment for the next generation to acquire similar spatial abilities. This process builds on itself, either encouraging or discouraging an appreciation for aural space.

What, then, does it mean to “learn to hear space”? Is such learning similar or dissimilar to acquiring other perceptual skills? Is learning simply a catchall concept that depends strongly on what is being learned? The answers to these questions are fragmentary and inconsistent. Although we know much about language acquisition, we know little about acquiring auditory spatial awareness. Nevertheless, some suggestive patterns emerge from a diverse body of research literature that is somewhat peripheral to our topic.

Consider the ability to identify or produce a pitch without a reference pitch. The consensus is that this ability represents, not special hearing, but rather the association of a currently heard pitch with a remembered one. This conclusion is consistent with the lack of correlation between the ability to discriminate pitches and the ability to identify them; indeed, those who can readily discriminate pitches may not be able to identify them. There are other examples. Training audio engineers to hear subtle differences in timbre also requires the acquisition of vocabulary, as well as a reliable auditory memory (Letowski, 1985). Auditory spatial awareness is very much like auditory awareness of timbre and pitch. Dramatic variations in a seemingly homogeneous population are explained by differences in auditory memory and labeling strategies, as well as by enhanced auditory acuity for spatial attributes. Listening is more than hearing; it is more than sensing, detecting, and discriminating sounds. Listening is the act of making sense out of an aural experience by incorporating all that has been remembered from previous experiences.

Even if auditory perceptual learning is not yet well understood, modern researchers can often detect changes in brain activity that result from the acquisition of a particular skill. For example, compared with nonmusicians, musicians show stronger neurological responses to timing errors as small as 20 milliseconds (Rüsseler et al., 2001), to slightly impure chords (Koelsch, Schroger, and Tervaniemi, 1999), and to perturbations in melodic patterns (Tervaniemi et al., 2001). Using magnetic resonance imaging as a measure of neurological activity in the auditory cortex, Christo Pantev and colleagues (1998) examined the difference between musicians and nonmusicians. When subjects were listening to piano notes, the region of neurological activity was 25 percent larger for musicians than for nonmusicians. Even though all the musicians in the study had been actively involved with music for the previous five years, practicing on average 25 hours per week, the size of the neurologically active region correlated with the age of initial musical training. Musicians who began practicing before age 12 had the largest active region. Similarly, using magnetic resonance imaging, Gottfried Schlaug and colleagues (1995) found that musicians with absolute pitch showed a marked increase in

brain asymmetry in those regions associated with the auditory cortex. Moreover, violin and trumpet players showed different neurological responses when listening to the same notes on their own and on others' instruments (Pantev et al., 2001b).

As an extreme example of learning an even narrower class of sounds, Laurent Demany and Catherine Semal (2002) trained subjects to distinguish a 3,000 Hz tone from those of slightly lower or higher frequencies. In the course of ten training sessions, the subjects' average performance improved by at least a factor of 2. More interesting, the newly acquired skill did *not* apply to discrimination at a markedly lower or higher frequency (1,200 Hz or 6,500 Hz). This result is consistent with a comparable study in monkeys that revealed an enlargement of the region of the auditory cortex responsible for the particular frequency used in training (Recanzone et al., 1993). Auditory perceptual training at specific frequencies had an observable manifestation in the auditory cortex. Neurons that matched the frequencies used in training showed greater tuning ability and increased latency. Demany and Semal also demonstrated that enhanced discrimination of pure tones did not transfer to complex signals with rich timbre, even at the same pitch. Pitch discrimination was timbre specific, namely, discriminating the pitch of sine tones only loosely correlates with discriminating the pitch of instrument tones. This result exposes the fallacy that sounds having the same pitch are neurologically equivalent. Substrates adapt to highly specific attributes of sound, and corresponding auditory learning is much more specific than initially expected.

Although the long-term neurological adaptation displayed by musicians arises from thousands of hours of practice, short-term neurological adaptations are found in the general population. Pantev and colleagues (2001a) tested the neurological response of subjects listening to music through a filter that suppressed the region between 700 Hz and 1,300 Hz. In three sessions lasting three hours each, they observed a short-term reduction in activity for neurons exposed to 1,000 Hz tones. When a specific neural region was no longer active, neurological changes were already taking place.

These are only a few examples that demonstrate neurological adaptation to the spatial aspect of sound. Consider an organ, whose pipes produce harmonically related notes at separate locations. Because pitch depends on location, organists do not fuse multiple pitches in the same way other musicians do (Brennan and Stevens, 2002). Similarly, conductors strongly experience the spatial components of music because the musicians they conduct are dispersed across the stage. Using neurologically evoked potentials, Thomas F. Münte and colleagues (2001) compared the spatial acuity of conductors, musicians, and nonmusicians at peripheral locations. Even though musicians and conductors have comparable exposure to and training in performed music, conductors are significantly better at peripheral localization. It is not only exposure to a situation that drives learning but also the motivation to benefit from that learning.

Like auditory training, repeated motor activities also change the brain. The somatosensory representation in the motor cortex for fingers was significantly changed in violinists compared with subjects in the control group (Elbert et al., 1995). When carried to an extreme, extensive practice can produce a hand disability called “focal dystonia” (Pujol et al., 2000). With this condition, musicians experience loss of control and degradation of skilled hand movement. Because intense exercise of a given finger expands its corresponding neurological region, and because the regions for the fingers are adjacent, they compete with each other for the same resources. There are no free neurological resources to be allocated. As they encroach on each other, adjacent regions produce the equivalent of a short circuit (Elbert et al., 1998). This pathology is generally irreversible, and musical careers have been ruined by focal dystonia.

Just as specific perceptual and motor skills may be unrelated so, too, emotional responses to sound may be unrelated to its perception. For example, Isabelle Peretz, Lise Gagnon, and Bernard Bouchard (1998) found evidence that recognizing the structural components of music was separate from evaluating the affective component along the continuum of happy–sad. In other words, perceiving music and experiencing music are neurologically separate, albeit related, processes. To the degree that this is true, sensitivity to musical attributes is unrelated to appreciation of the emotional and cultural meaning of music. There are anecdotal examples of listeners who have a heightened awareness of musical subtleties, but show little affect response, and conversely, there are listeners who experience an intense emotional response to music, but with little conscious awareness of its subtleties. We might also expect that listeners can respond emotionally to aural architecture without being consciously aware of acoustic attributes.

Unquestionably, extensive auditory training and exposure to sonic or acoustic environments alter the brain, with corresponding improvement in observable auditory abilities. But can every brain be trained on every auditory task? We all know that a child lacking either fine-motor coordination or sensitivity to sound will never become a brilliant musician. We also observe that some individuals who are blind from birth acquire the ability to navigate space by listening, whereas others do not. Even when we ignore the influence of motivation, we observe that some individuals are simply born with enhanced ability to both learn and perform certain tasks. By studying the degree of correlation in ability between genetically related individuals, Robert Plomin and L. A. Thompson (1993) attempted to form a probabilistic measure of abilities that have a strong or weak component of inheritance, but, unfortunately, these did not include auditory spatial awareness.

Howard E. Gardner (1999) has identified the following specific types of intelligence: linguistic, mathematical, musical, kinesthetic, spatial, interpersonal, intrapersonal, spiritual, moral, existential, and naturalist. Rosamund Shuter-Dyson and Clive Gabriel (1981) have shown that musical intelligence is further divided into melody,

harmony, pitch memory, and rhyme intelligence, among several other kinds. Correlations between these abilities are only modestly positive. Some individuals are good at recognizing a melody but only average at sensing time. We assume that skilled musicians are probably those who are good at all the required abilities that are part of performing music, a statistically unlikely outcome. I have no doubt that auditory intelligence is yet another specific kind of intelligence, distinct from visual, olfactory, and tactile. I also have no doubt that within auditory intelligence there are an equally large number of separable abilities, of which auditory spatial awareness is but one. And within that ability, there are still further separable abilities that include the ability to aurally localize, as well as the abilities to discriminate, respectively, sonic reflection densities, spectral colorations, spatial gradients, and so on. Auditory spatial awareness is actually only a label for a group of independent perceptual abilities involved in hearing space.

Few studies demonstrate auditory giftedness because most researchers ignore the large differences in auditory ability when studying specific tasks. Some evidence, however, is available concerning different levels of performance. Seymour Shlien and Gilbert A. Soulodre (1996), using only a few subjects, found a tenfold difference in frequency modulation sensitivity and a threefold difference in detecting the duration of a 2-decibel gap. Some listeners had exceptionally high sensitivity to small differences in loudness, whereas others had exceptional memory for tonal and rhythmic sequences. In a related study, Kristin Precoda and Teresa A. Meng (1997) found that listeners repeating tasks, though consistent with themselves, were not consistent with each other. In his study of gifted listeners, Shlien (2000) confirmed that the ability to detect specific audio degradations varies significantly across the population.

Unlike psychologists, who study learning paradigms in controlled laboratory situations, educators must work in the real world with real people. Describing a school environment, David A. Sousa (2000) asserts that learning depends on sense and meaning, which is to say, it depends on the ability both to detect an attribute (sense) and to assign it personal relevance (meaning). It is difficult to learn a skill when the experience is felt to be emotionally irrelevant. In addition, educators recognize that some people are mainly auditory learners; others, mainly visual or kinesthetic learners. Sousa warns of a mismatch between the preferred sensory modality and the nature of the experience; visual and kinesthetic learners do not readily attend to the subtlety of auditory information, be it emotional or verbal.

If we assume that the previous research applies equally to auditory spatial awareness, and if we also assume that the lack of evidence of such awareness essentially reflects our culture's indifference to it, we come to at least three important conclusions. First, scientists will never detect the subtle and varied differences in auditory spatial awareness abilities among individuals unless they design suitable protocols that will uncover those differences. Second, for as long as there is little encouragement or opportunity to acquire, let alone develop, auditory spatial awareness, our society will surely have an

impoverished aural architecture. And third, to produce a subculture of aural architects with a high level of such awareness requires exposing children to a rich aural environment, which encourages those with any genetic disposition to become experts and leaders.

Children who spend most of their time watching television and adults who sit at a desk for thousands of hours each year have far less exposure to acoustic variety than those in many earlier cultures who grew up hunting in forests and on mountains, tending farm animals after dark, navigating noisy towns with low illumination, or, in more recent centuries, attending dozens of opera and concert performances. Our children are acquiring their aural attitudes from the spatial and sensory legacy of now several generations of aurally impoverished listeners. It is up to us to enrich that legacy.

### Awareness as a Composite of Emotions and Perceptions

A sound that is meaningful, by definition, produces an emotional or affective response. For aural architecture to be meaningful, it, too, must produce an affective response in the listeners who avail themselves of it—an emotional response to space. How should we explore such an elusive topic? The *Oxford English Dictionary* defines emotions as “mental feelings,” which sheds little light on the matter. Drawing on findings from the fields of evolution, perception, and neurobiology, cognitive scientists have begun to explain why such a ubiquitous concept as emotion remains so elusive. Emotions are everywhere, like water for fish. Whenever we care about what we are perceiving, an affective component must be present. Thus emotions become an amorphous concept for everything that gives meaning and texture to our perceptual experiences. If, however, we want to understand how aural architecture produces spatial experiences that have impact and relevance, we need to examine the affective attributes of acoustic spaces.

When Zoltan Kövecses (1990) examined the semantic content of emotional concepts in common language, he concluded that there was, in effect, a relatively consistent underlying model. Emotions, like a fluid filling the body, are expressed in a body language. Rather than being just a literary tool, metaphors provide clues about the internal representation of emotions. Consider, for example, metaphors for anger: “You made my blood boil” (heated fluid); “Her face was scarlet” (hot container surface); “I blew my stack” (excessive internal pressure); “He bottled up his emotions” (strong container). But where we have a closed container model for anger, we have an open container model for sadness, melancholy, affection, love, and similar emotions. Visceral changes to the body, which can be sensed, are the only window into this subterranean process. Emotions relate to physiological changes: “He felt it in his gut”; “She had a heavy heart”; “It took my breath away.” Thus, as Kövecses sees the folk language of emotion, the body is the container holding emotions, and the body surface displays them.



Why would evolution have produced a brain that responds to stimuli without being consciously aware of doing so? Conscious awareness is not always advantageous. The limited computational capacity of an animal's brain is best used if the animal attends only to the most important tasks of the moment, devoting all its biological resources to the most essential aspects of the environment. Selective attention solves the problem of being overloaded with irrelevant data that would confuse or otherwise delay choosing the appropriate response. Because an animal needs to react to danger, not simply to think about the meaning of lurking predators, the auditory thalamus feeds in parallel the amygdala (automatic feelings) and the neocortex (conscious thought) to give both systems an opportunity to evaluate sound on its own terms. Being a contemplative and flexible process, rational thought is too slow to produce a rapid response to high-impact stimuli. In his simplified model of fear, Joseph E. LeDoux (2000) represents awareness of sound as resulting from multiple inputs: from the amygdala, which extracts the emotional affect of the stimulus; from the hippocampus, which remembers the associations of previous experiences; and from the auditory cortex, which processes features of the signal.

The emotional brain, which is sometimes labeled the "limbic system," has no direct representation in brain consciousness, though it is a major, or perhaps *the* major, contributor to perception. As with many brain substrates, we observe only how it influences aspects of our experience, like seeing a shadow but not the object that cast it. The emotional brain controls the degree of arousal, which largely determines how much effort to invest in attending to the outside world, selecting aspects of the stimuli that are worth focusing on. The emotional brain also provides associations to those stored memories of historical experiences that are relevant to the current situation. In summary, the emotional brain determines which aspects of an experience are worth remembering, what meanings to ascribe to the components of the experience, and when to draw upon those experiences in the future.

Even without knowing the neurological details, we have enough insight to place emotions in a social context. We can view self-awareness of emotions as the result of the brain broadcasting to itself information that is directly relevant. For example, as long as we are consciously aware of needing food, there is no utility in our being similarly aware of low blood sugar, which is the hidden neurological response to a visceral state. We observe our stomach making noises, we observe ourselves staring at a steak, and we observe ourselves experiencing an irritable response to a neutral situation. Low blood sugar is reported indirectly without the need for a sensor. Kent C. Berridge and Piotr Winkielman (2002) argued that "liking" is also an unconscious emotion whose only observable manifestation is in the way that it influences immediate or planned behavior. Do we choose something because we like it, or do we like something because we observe ourselves wanting to choose it? "I like concert hall 'A' better than 'B' because I prefer to hear music there." The feeling of liking something is also indirect.

This suggests that *feelings* are conscious awareness of the body's relationship to the environment, whereas *perceptions* are conscious awareness of the environment itself. I see the book (perception); I contemplate taking it (conscious awareness of an action); I interpret the sequence as coveting (feeling the pleasure of possession). Timo Järvillehto (2000, 2001) goes further by treating consciousness as the awareness of the unitary organism-environment. Positive emotions result from increased harmony between the individual and the environment, and negative emotions result from increased disharmony. In this view, emotional activities in the brain are distributing information about the organism-environment relationship to parts of the brain and body that need to know how to plan a response to the harmony, or lack thereof. From this perspective, only certain information is relevant to providing a conscious interpretation of the environment, perhaps to planning a strategy for improving harmony. Only some information is communicated to the language center for articulating the motivation for a planned action, and that information may not fit into natural language; language did not evolve to support introspection. Like the iceberg, 90 percent of our emotional life is hidden from view. Moreover, our emotions evolved to handle the important organism-environment relationship in prehistoric environments, not in modern society.

Broadcasting your emotional state to other individuals in your group has survival value because that knowledge can be used to influence the behavioral choices of others. To you as an individual, other members of your group are part of the environment. For instance, when you are not feeling aggressive, your smile communicates that state to others, who then form their response based on that knowledge. Emotional broadcasting is a language that supports group cohesion. Many aspects of emotional displays are, in fact, involuntary forms of body language without awareness. Self-awareness is irrelevant if a broadcast is automatic, not requiring consciousness or voluntary action. Karen L. Schmidt and Jeffrey F. Cohn (2001) view the face as a biological adaptation that provides a low-cost and spontaneous means of emotional signaling—for publicly and reliably showing a state of fear, joy, disgust, sadness, anger, excitement, deference, grief, or comfort.

An external stimulus connects you as an individual to your environment, and produces a combination of public, private, and hidden reactions. Some aspects of your current relationship to the environment are communicated to consciousness, some aspects are communicated to your group, some aspects are communicated to your emotional brain and to other brain substrates, and some are communicated to specific biological organs. In each case, you are “aware” of the stimulus but your awareness depends on your personal and biological agenda. Your emotional state is the *adaptation process* for interpreting the stimulus in relation to that agenda. Your emotions bias the choice of action, reaction, coping strategy, perception, and attention. In short, your emotions are the meanings assigned to your relationship to the environment that pro-

duced the stimulus. Under this broad definition, virtually all aspects of experience are emotional, and every experience has an emotional component, albeit often weak and unconscious.

There is very little agreement on how terms such as *affect*, *feelings*, *emotions*, and *moods* should be defined. Joseph P. Forgas (2000) proposed the following: as a broad concept, *affect* refers to both moods and emotions; *moods* refers to the relatively low-intensity, diffuse, and enduring affect states that have no obvious cause and little cognitive content; in contrast, *emotions* refers to short-lived, intense affect states that usually have an obvious and direct cause. An auditory stimulus that contains an affective component can change the affective state of listeners, whether this refers to short-lived and intense emotions, to longer-term and diffuse moods, or to both.

We are finally in a position to integrate the concept of affect into our discussion of auditory spatial awareness. Like all forms of art, aural architecture can change the affective state of listeners, perhaps with only a subliminal shifting of mood, or perhaps with an overwhelming emotion. When aural architects function as artists, they are intending to influence the affective state of the listeners within the spaces they design. Many spaces, even those without a designer, still qualify as aural architecture if their acoustics influence the affective state of listeners. We now understand why musical and religious spaces are the most prominent forms of aural architecture. Such spaces emphasize the affective experience, and listeners may feel that the space has personal significance. Finally, our inability to explain how, why, or even whether listeners experience a change in affective state does not mean that such changes have not occurred. Although there are countless anecdotes of paintings and music bringing viewers or listeners to tears (Elkins, 2001), there are few such anecdotes for visual or aural architecture. Some art forms simply have less affective content than others, and weak affect is difficult to observe or communicate. Moreover, even when the affective components of aural architecture are strong, few recognize the origins of their mood changes and emotional shifts.

### Hearing as a Means for Navigating and Communicating

It is impossible to know how or why our species evolved an auditory system sensitized to certain aspects of spatial acoustics. Instead, we can explore how our and various other extant species are still adapting to their current environments. Two themes emerge. Hearing is the sensory means for receiving vocalized communications among conspecifics, and hearing is also the means for sensing the soundscape, which is composed of the physical environment and the sonic events contained therein. These two themes relate to each other in different ways for each species.

Why did mammals evolve an auditory system that detects sound vibration? There are other ways for sensing the environment. Some bony fish are aware of weak electric

fields in water (Nelson and Maciver, 1999); some birds are aware of the earth's weak magnetic field (Diebel et al., 2000); some amphibians are aware of humidity gradients; and some animals can create a map of their environment using infrared heat (Bullock and Cowles, 1952) or ultrasonic sound (Mann et al., 1998). With sensory acuities beyond those of human biology or advanced technology, many animals can sense an imminent earthquake (Tributsch, 1982). Hearing is only one of the many ways animals sense and navigate an environment.

In addition to sensing the environment, individuals of a species must communicate with one another, and vocalization combined with hearing is an excellent means of doing so. Regardless of the social structure, every social animal must advertise sexual availability, demonstrate healthy genes, and find a mate. In order to maintain social connection with the genetic pool of appropriate partners, an individual animal must broadcast the appropriate signals. One common signaling choice is vocalization, which has a more controllable and often wider geographic range than visual displays or chemical pheromones. It is not dependent on illumination and visibility. It is relatively immune to being blocked by physical obstacles. And it is biologically efficient to maintain. From this perspective, the auditory system would have adapted to receiving vocal broadcasts. Yet the human voice rarely extends above 6,000 Hz, whereas an undamaged ear can hear frequencies above even 20,000 Hz. Clearly, the extra bandwidth can be used to detect, recognize, and localize other kinds of sounds. Hearing has been optimized for something beyond communications among conspecifics.

W. C. Stebbins (1980) argued that the auditory system evolved in early mammals in order to exploit nocturnal niches that were free of large diurnal predators. In a dark environment, smell and hearing would have been the chief means for detecting other animals. And hearing would have been the only means for detecting distant objects and surfaces. The extinction of the predator population then allowed mammals to radiate into a much larger diurnal environment, where sensory evolution progressed. Only then did vision become a major contributor to survival.

Although the details differ, all mammalian species developed a similar auditory system, composed of the external pinna and ear canal, and the internal tympanum, three-bone ossicular chain, coiled cochlea, and auditory cortex. Because of this similarity among mammals, Richard R. Fay and Arthur N. Popper (2000) asserted that all auditory variations are the evolutionary modifications inherited from a common ancestor. Modern human beings, however unique our adaptations, are just one of many branches from that ancestor. Douglas B. Webster, Richard R. Fay, and Arthur N. Popper (1992) argued that differences among those branches reflect the unique environmental stresses and biological constraints in each ecological niche. The modern human auditory system is therefore a result of the evolutionary path taken by mammals, primates, and early *Homo sapiens*.

Over time, hearing evolved to become useful in a wide variety of situations: receiving vocal signals from conspecifics, monitoring those from prey and predator species, detecting dynamic sonic events in the environment, and aurally visualizing physical objects and geometries from their acoustic perturbations. Each of these uses played an important role in determining how a species competed for a stable ecological niche. Because air is a common resource, which can become overtaxed, cluttered, or degraded by nature and other users, auditory strategies adapted to particular environments. In addition, strategies evolved to balance the advantages of successful communication with conspecifics against the disadvantages of both warning prey and attracting predators. In general, the biological machinery for hearing and vocalization evolved as part of a composite system. How we hear aural architecture is the result of this process. Human beings also evolved while being embedded in a social environment, which itself was embedded in a physical environment.

### **Adapting to Acoustic Environments**

Although our knowledge about how early humans adapted to their acoustic niches is speculative, we do have a large body of information about how extant birds, primates, and other species are still adapting to acoustic environments. Acoustic evidence about early habitats, which were mostly forests, jungles, and savannas, is available in a few regions where civilization has yet to intrude. By combining these fragments of information, we observe some general principles. We know that any given acoustic environment hosted competing species with competing solutions to the task of survival. Each species evolved its specific solution in response to the solutions adapted by other species.

A summary of the basic acoustics of early environments illustrates the evolutionary complexity of adapting the auditory system and vocalization strategies to a local ecology. Evolution provided both genetic and learning adaptation so that small groups could respond to the specifics of local environments. Both solutions are evident in a variety of species.

We begin by examining acoustics of natural spaces. In an open plain with no obstacles, sound intensity decreases in proportion to the distance between the sender and receiver. Upon encountering an object, such as a tree branch, a sound wave is absorbed, reflected, transmitted, or any combination of the three. Each of these processes is itself complex. For example, flat planar surfaces produce coherent echoes, whereas highly irregular surfaces disperse sound waves in many directions. Dense vegetation absorbs high frequencies but the ground surface reflects low frequencies. Wind, which moves branches and leaves, both creates turbulent noise and modulates the intensity and frequency of sound. Ambient noise, which then interacts with objects, is nonuniformly distributed in the environment. Some regions are quieter than others,

some have less high-frequency sound, and some have diffused sound fields. Finally, air is far from an ideal transmission medium. Its turbulence disperses high frequencies; its humidity absorbs them. Its thermal layers create both dead zones, with no sound, and hot spots, with focused sound. All of these forms of acoustic degradation increase with distance.

Each species in these early environments evolved a vocalization strategy that was consistent with these specific acoustic degradations. And each choice, whether long steady tone, short burst, or chirp with modulated variations in amplitude or frequency, had its trade-offs in terms of the amount of information carried and the distance over which it radiated. Information in the sound was often more fragile than the sound itself. In modern terms, more often than not, you might understand that someone was talking but not what was being said.

In a forest, the signal path from sender to listener includes a multiplicity of small sonic reflections from every surface of every tree, which reflects sound back into the forest, arriving at the listener well after the direct sound. At greater distances, the direct sound weakens, but the sonic reflections remain as forest reverberation. In their study of the acoustics in deciduous forests, Douglas G. Richards and R. Haven Wiley (1980) illustrated how a 25-millisecond tone burst at 1,000 Hz becomes a 150-millisecond diffuse pulse at a distance of 25 meters (80 feet), but an 8,000 Hz pulse does not spread as much because its sonic reflections are absorbed by foliage. Similarly, a steady 2,000 Hz sine wave was received with large random amplitude fluctuation (acoustic degradation) at a distance of 60 meters (200 feet) from the source, and fluctuation intensity was strongly dependent on the wind velocity near the ground.

Weather alters the acoustic geography, enhancing or degrading the transmission of sound. In the middle of the day, when the heat of the sun produces stratification layers, atmospheric turbulence increases, acoustically degrading transmitted sound. As the distance between sound source and listener increases, phase fluctuations gradually become more random, making the received signal sound less and less like the original. On the other hand, a thermal inversion, hot air layer above cold, enhances sound transmission because sound waves are channeled through a sonic conduit, with upward radiating waves redirected by the boundary between the two layers of air back toward the ground (Humphreys, 1940). Indeed, Peter M. Waser and Charles H. Brown (1984) observed thermal inversions in the Kenyan rain forest with a 4-decibel gain at 100 Hz.

Each acoustic environment has a different capacity to transmit sonic information, and this varies according to the time of day, the season, and the weather. More important, animals in the forest compete for the most desirable auditory channels. Like food and land, air is a limited common resource that is contested as well as shared. Animals with strong voices may dominate those with weak ones, but loud broadcasts also invite predators. Forest reverberation may prevent predators from aurally local-

izing a prey animal, but it also prevents the animal's conspecifics from doing so, a decided disadvantage for a distressed monkey calling for help. Thus selecting an appropriate auditory strategy and acoustic environment involves both evolution and social learning.

In their comprehensive compendium of the ecology and evolution of acoustic communication in birds, Donald E. Kroodsma and Edward H. Miller (1996) illustrated the adaptive process by which numerous species balance information capacity, predatory risk, sonic competition, and the acoustic constraints of the environment. Evolutionary flexibility becomes readily apparent when examining the wide range of adaptive responses among birds. Some species sing special songs at dawn, when atmospheric conditions favor the long-distance transmission of sound. Given that acoustic degradation increases with distance, Marc Naguib (1995) suggested that Carolina wrens listen for reverberation and high-frequency attenuation independently to determine the distance of a singing fellow wren. Those same birds adapt their song to the acoustics of the native environment in order to create a recognizable group identity, much like a social dialect (Gish and Morton, 1981). Birdsongs show greater acoustic degradation in alien than in native habitats. Birds in forest habitats sing at lower frequencies (in the neighborhood of 2,000 Hz) than birds in grasslands because forests have less noise at these frequencies, thereby increasing the transmission distance of their songs (Ryan and Brenowitz, 1985). All aspects of the acoustic environment put evolutionary pressure on a given species to take advantage of local acoustic properties. To optimize vocalization to the nuances of a habitat, individual birds learn the details of their song rather than being born with a predefined song.

Nor are birds unique in adopting auditory strategies. A comparative analysis shows that the blue monkey is 18 decibels more sensitive to low-frequency tones than the semiterrestrial rhesus monkey of about the same size in the vocalization region of 125–200 Hz (Brown and Waser, 1984). By adapting their vocalization and auditory thresholds to this relatively noise-free frequency region, blue monkeys are able to increase their calling range by a factor of 16. The macaque monkey has evolved a vocalization and auditory sensitivity to a class of sounds that serves to identify members of the group, thus producing social cohesion in an acoustic environment where nonmembers are otherwise similar. Specialized use of a particular auditory channel, however, depends on a particular group, not on the generic properties of the species (Dittus, 1988).

Similarly, bats in the Amazon valley shifted their vocalization from the more typical 100,000 Hz region to 8,000 Hz because the high humidity of the tropical rain forests rapidly attenuates ultrasonic signals (Griffin, 1971). Male short-tailed crickets can increase the area of their calling song by a factor of 14 by perching in treetops instead of on the ground (Paul and Walker, 1979). Fish take can take advantage of the high-frequency cutoff of shallow water to avoid detection by predators but still maintain

communication with their conspecifics (Forrest, Miller, and Zagar, 1993). As these examples clearly illustrate, animals are more than merely aware of their particular acoustic environment. They use that awareness to evolve more useful communication strategies within a shared competitive auditory channel.

Interpreting the meaning of vocalization reveals several philosophical problems, which also apply to studies of human hearing. Meredith J. West and Andrew P. King (1996) summarized one problem: “labeling a communications system by its predominant sensory modality may be misleading, and bias us towards too narrow a view.” In an alternative construction, William M. Mace (1977) suggested that the role of hearing is found by “asking not what’s inside your head but what your head is inside of.” Local habitat ultimately defines the nature of the animal. James J. Gibson (1966) shifted the focus to an instrumental view: “Animals [including human beings] do not perceive or communicate for the sake of perceiving or producing a display but for the sake of managing the social environment.” A goal-directed view of hearing and vocalization is more informative and predictive than a mechanical one. Perception and vocalizing are a means to an end: surviving in social groups.

The range over which conspecifics can hear each other’s vocalizations, which in chapter 2 was called the “acoustic horizon,” determines the geographic area of a cohesive social unit. Like the French village of the nineteenth century, where the acoustic horizon of the church bell determined membership in the village, the size of the social group is determined by the choice of listening and vocalization strategies, in combination with acoustic geography and population density. In the evolution of many species, these four factors aligned: group size, vocalization strategy, population density, and acoustic geography. For our species, there was more flexibility in that alignment, but the same four factors still play a role. Acoustic geography influences social geography (culture).

When the nature of acoustic degradation is consistent, predictable, or familiar, the auditory cortex can extract sufficient information from it to enhance survival. For example, because acoustic degradation is proportional to distance, modeling the type and amount is a means of determining the distance to the source. Marc Naguib and R. Haven Wiley (2001) concluded that perceiving distance implies both a neurological model of the acoustic degradation and a neurological model of the sound source before being degraded, which can then be compared to each other. Similarly, binaural processing using two ears, when combined with a model of acoustic degradation, is another means of reducing its influence. Such neurological solutions probably evolved to overcome the limitations of early soundscapes.

Assuming that our auditory cortex evolved the means to model the acoustics of forests, jungles, and savannas, we are now using old evolutionary solutions to hear new spaces. There is no better example of this than how we aurally experience reverberation. What does it mean to hear a concert hall with ears designed for a forest?



Characterized by a high density of low-level sonic reflections from surfaces typically found in the environment, tree trunks, branches, and leaves, forest reverberation is generally limited in duration to about 200 milliseconds, compared with many seconds for large enclosed spaces. When we earlier analyzed the perception of concert hall reverberation, we observed that early sonic reflections fuse with the direct sound, whereas later ones form sustained, enveloping reverberation. The boundary between these two aspects of reverberation is the same order of magnitude as the duration of forest reverberation, about 100 milliseconds. We hear the early reverberation of an enclosed space with brain substrates that evolved for forest reverberation. The adaptation of fusing early sonic reflections into a perceived single source would have been useful to our early ancestors. Moreover, what we now call “apparent source width,” which is a property of early reverberation, appears to be nothing more than an auditory awareness of the degradation of sound by forest acoustics.

Except for the occasional cavern, there was never any historical counterpart of an enclosed space that was capable of spreading sound energy over a long duration, what we call “sustained reverberation.” Moreover, early humans did not make caverns their natural habitat. Similarly, except for an occasional cliff or steep embankment, there was no mechanism for creating a sonic reflection with sufficient delay that could be heard as a discrete echo, a discrete event. Forests, jungles, and savannas do not produce echoes. From a survival perspective, it would have been critical for an early human to distinguish between a single event with multiple sonic reflections and multiple sonic events from different sources. It is therefore not surprising that sound arriving well beyond the fusing interval is heard as distinct from the direct sound, either as a coherent echo or as diffuse reverberation. Both are perceived as if originating from different sources, even though we, as modern humans, know that the spatial acoustics create the second event from the first. The linking of reverberation with the direct sound is cognitive rather than perceptual.

Another difference between indoor and outdoor acoustics is the degree to which sound transmission is static, without time-varying changes to the auditory channel. Even in large enclosed spaces, such as a cathedral, air is relatively stable and homogeneous, at least compared with natural environments. The auditory cortex expects to hear spectral and temporal variations produced by turbulent air, shifting thermal layers, and the surfaces of moving objects. Animal vocalizations also contain similar variations. Even without acoustics, sound sources were never spectrally pure, perfectly periodic, or reliably repeatable. The need for such variation, in order to sound natural and pleasant, is exemplified by the musical tradition of vibrato and tremolo, explicit changes to pitch and amplitude. But the same is true of spatial acoustics. Our auditory cortex is designed with the expectation of variability when perceiving space. Reverberators using a static algorithm sound more mechanical, whereas those which include the appropriate random modulations sound more natural.

In addition to segmenting sound into discrete sonic events, the ability to aurally localize the source of a single sound exists in almost every mammal. It is easy to understand why localization is useful. Where are the prey or predators, and which path leads to food or safety? Many parts of the auditory cortex and the resulting auditory perceptions they produce are entirely consistent with the need to aurally localize. The affective component of aural localization, which contributes knowledge about the sender's location, is separate from and independent of the affective component of the direct sound, which contributes knowledge about the sender's message and emotional state. If aural localization of important sounds is that critical to survival, we can assume that inability to aurally localize would make an animal attentive, uncomfortable, and perhaps anxious. Such would then be the case for diffused reverberation, where sonic reflections lacking a strong direct component arrive from all directions.

To localize a sound source, the auditory cortex suppresses the irrelevant information in early sonic reflections while extracting the difference in time and amplitude for the direct sound, which arrives before the reflections. Perceptual and neurological scientists, who have been studying this ability for years, call it the "precedence effect," whereas audio engineers, who use this in the design of public address amplification systems, know it as the "Haas effect." In its simplest form, localization of the direct sound remains stable even when followed by a single discrete sonic reflection in the time window from 2 to 20 milliseconds after the direct sound. Because this effect is robust, stable, and consistent across the population, it invites an evolutionary explanation. Fusing the numerous early sonic reflections in a 100-millisecond time window is consistent with forest reverberation. What is the analogy for a single strong sonic reflection in a 20-millisecond time window? The only flat hard surface that could consistently produce a large specular sonic reflection is the ground, and the delay between the direct sound and a sonic reflection from the ground would be on the order of 5 milliseconds for a primate standing at a modest distance; for primates living in trees, the delay would be significantly longer. A single sonic reflection from the ground is a universal property of all spaces that existed for ancient and modern animals.

We in modern society still experience acoustic spaces in a way consistent with our inherited legacy from our early ancestors in their prehistoric spaces. Scientists can observe aspects of this aural inheritance in their laboratories; composers incorporate aspects in their musical creations; aural architects embed aspects in their spatial creations; and listeners hear aspects when attending a concert or conversing in their living rooms.

There are unexpected modern auditory experiences that have no evolutionary antecedents, for example, static acoustics. The acoustic world of early humans was never static. Perhaps the most dramatic example, however, is in-head aural localization, which occurs when listening to sound with headphones: the spatial contradictions between the sounds heard by the right ear and those heard by the left have no

natural spatial counterparts. Unable to determine a location in the external world using its inherited rules, the auditory cortex simply places the source inside the head, thus seeming to preserve the reliability of detecting real sound from real events in real spaces. That placement is itself an evolutionary optimization. Faced with spatial contradictions, the auditory cortex, rather than making a best guess about location, simply removes the sound source from the external world. This is consistent with the difficulty that engineers have in creating signal-processing algorithms that consistently produce externalized sounds.

### **Spatial Imaging Using Echolocation**

With the realization by Donald R. Griffin (1944, 1958) and others in the mid-twentieth century that several species could navigate with their ears, scientists began to realize that this ability was a more than an odd curiosity. For many species, nature had indeed evolved an aural means for sensing objects and geometries by the way that they influence sonic attributes.

Sound illuminates a space in the same way that light does; ears as well as eyes can sense illuminated objects. Like a built-in biological flashlight, vocalization is a means to illuminate the environment, and the clicking tongue or tapping cane of a blind person walking down the street is an acoustic flashlight. By attending to how the environment changes the sound, an aural image of an acoustic space can be created, a process called “echolocation.” But when an animal uses background sounds from other sources, the process is auditory spatial awareness. The distinction, which is often ignored, depends only on the origin of the sound source.

In some species, evolution elevated the importance of auditory spatial awareness, and in a small percentage of these, additional evolutionary pressure matched their vocalization to their auditory cortex. This linkage between hearing and vocalization for echolocation, such as in bats, dolphins, and a few other kinds of animals, is relatively rare; originally, the auditory system developed for communications between conspecifics, and for decoding sonic events in the soundscape. Michael J. Novacek (1985) and M. Brock Fenton (1985) suggested that ultrasonic echolocation in bats evolved from its initial use for communications, only later becoming a specialized means for sensing the physical environment and replacing vision. But George D. Pollack (1992) makes the additional point that the auditory foundation for echolocation is nothing more than an enhancement of the generic capacity for auditory spatial awareness, but optimized jointly with the evolution of specialized vocalizations. The neurological foundation for auditory spatial awareness, perhaps in vestigial form, is not unusual among a wide variety of species. The auditory spatial awareness of bats and dolphins is only a specialized extension of a common ability. A less specialized version of auditory spatial awareness exists in rats, hamsters, and shrews, as well as in humans.

Golden hamsters have the ability to locate a shallow platform by the way it changes the acoustic ambience, a skill consistent with their nocturnal activities and their underground habitat (Etienne et al., 1982). The shrew, also with an underground habitat, has a weakly developed visual system that is limited mostly to sensing light intensity. Although it relies mostly on touch to gain information about its surroundings, echolocation is its only means to acquire remote information before approaching an object. E. R. Buchler (1976) found that the wandering shrew (*Sorex vagrans*) uses echolocation chiefly as means of exploring unfamiliar environments: it increases its rate of ultrasonic transmissions to as high as 20 per minute when placed into a new maze, but then decreases them to about 1 per minute after exploring the maze for six minutes.

Other species of shrews, namely, the masked shrew (*Sorex cinereus*), the American shrew (*Sorex palustris*), and the short-tailed shrew (*Blarina brevicauda*) also show some evidence of echolocation ability when exposed to strange surroundings. They emit short pulses in the frequency range of 30,000–60,000 Hz (Churchfield, 1990). These shrews can discriminate between an open and closed tube at a distance of 20 centimeters (8 inches) using ultrasonic vocalization (Forsman and Malmquist, 1988). Thomas E. Tomasi (1979) observed that individual shrews showed differential echolocation ability on the different tests. Some were good at distance detection, others at discriminating small openings, and still others were able to detect objects around corners.

Griffin (1986), who studied the larger topic of acoustic orientation of animals, describes a class of nocturnal birds that use echolocation in much the same way as bats. The oilbirds fly quite confidently deep within the fully darkened caverns of Guácharos in Venezuela by emitting 1-millisecond sound pulses at about 7,000 Hz. When they leave the caverns for an illuminated environment, these pulses cease. With blocked ears, the birds flew directly into the cavern walls. In Griffin's view, any nocturnal bird, indeed, any bird inhabiting a dark environment, is an evolutionary candidate for echolocation.

James Gould and Clifford Morgan (1941) showed that the rat could easily detect high-frequency auditory signals; John W. Anderson (1954) demonstrated that rats could vocalize at high frequencies. Donald A. Riley and Mark Rosenzweig (1957) showed that rats could detect, entirely from acoustic cues, an alley blocked by a vertical barrier. Although a rat is capable of consistently producing and hearing high-frequency vocalization, and although it can hear a barrier, such skills are rarely observed in the laboratory. Rather, rats are far more often observed to use numerous other mechanical noises to illuminate the space: sniffing, sneezing, loud clicking of teeth, scratching the floor. When traditional experiments involving rats in a maze were reexamined, earlier results were questioned and challenged because experimenters had not considered the rat's ability to detect spatial properties using the auditory channel.

Although difficult to study, the dolphin is one of the best examples of how evolution fused auditory and visual imaging as a means for navigating the complexity of an

underwater environment. Adam A. Pack and colleagues (2002) observed that dolphins could match objects perceived visually with those perceived by echolocation. Moreover, rather than just detecting specific attributes of an object with sight or hearing, the dolphin experiences the external world holistically; vision and echolocation make equivalent contributions to the representation of objects. Barry E. Stein and M. Alex Meredith (1993) described multisensory neurons that responded to both visual and auditory stimuli as a possible explanation for a fused image. As a large mammal with highly developed cognitive skills, the dolphin is an example of a species that uses sight and hearing interchangeably. In contrast, most mammals favor one of these senses over the other for navigating the environment. From this perspective, the dolphin is unique.

Studying echolocation and auditory spatial awareness is fraught with methodological difficulties, uncertainties, and ambiguities. Without carefully controlled experiments that mimic the appropriate social and physical niche, an animal may simply choose not to use echolocation. Individual animals have the ability to selectively choose a strategy based on their immediate needs. There is no reason to believe that an animal would display behavior that reveals it unless there was a need to. Because of the increased risk of predatory attack when vocalizing, animals would have evolved selective uses of sound generation when needed, and only when the risk-reward ratio was favorable. Generated sounds may serve either to signal conspecifics or to echolocate. We cannot read an animal's mind, and we cannot determine if, or when, auditory spatial imaging is taking place. We can only interpret observed behaviors that are sometimes consistent with a navigational strategy using hearing.

We now know that the ability of a species to hear space ranges from nonexistent to highly refined, depending on the evolutionary path taken by its ancestors as they adapted to the stresses and opportunities in a unique sequence of environmental niches. A species acquired its ability only when certain brain substrates were allocated for decoding acoustic cues from objects and spatial geometries. Because these substrates may be artifacts or vestiges of other evolutionary optimizations that only partially served the function of hearing space, auditory spatial awareness may be a primitive supplement to refine visual awareness. Only in rare cases have auditory substrates been optimized for echolocation.

Even without understanding the details of evolutionary optimization in brain substrates, we know that there are several adaptation mechanisms. Although multiple abilities compete with one another for sparse neurological resources in a fixed brain volume, different abilities may share a resource, performing double duty without a corresponding extra cost. In fact, the ability to isolate a single voice in an environment containing spatially distributed sound sources is a close cousin of auditory spatial awareness. In both cases, the auditory cortex builds an auditory model of the environment. That model is simply used in different ways. In the first case, the model suppresses the influence of acoustics on the perception of the target voice; in the second,

the model provides information about the space itself. The neurological ability to suppress acoustic degradation can just as easily be used to decode spatial acoustics. With humans, decoding speech and aurally visualizing acoustic spaces share brain substrates because both depend on similar types of acoustic cues.

Along with shared substrates, there are also vestigial ones that were used in the remote past, but have less relevance now. At some time, a group of individuals may have evolved an ability to use auditory spatial awareness during extended periods of darkness in protective caves, or for tracking unseen game through complex forests. Dense forests are acoustically different from open grasslands, which are yet different from complex mountain ranges, tundra, and coastal fishing regions. When a group of individuals remained in a particular environment for dozens of generations, some adaptation is likely to have taken place.

Our ability to hear spatial attributes or to learn to hear them may thus depend on the degree to which that ability helped our ancestors survive and propagate themselves. This may in part explain why only some of us demonstrate an ability to learn echolocation. Auditory spatial awareness may depend on the lifestyle of our particular ancestors. The same evolutionary pressure that led individual species to optimize their auditory cortex for different functions also operates on small groups of individuals living in their particular soundscape niche.

Evidence, unfortunately unrelated to spatial hearing, shows that isolated human populations acquire a degree of biological specialization within a few dozen generations. Consider some examples. Because the ability to digest lactose foods as an adult is based on a genetically controlled enzyme, this adaptation has been traced to populations that had a history of living with domesticated farm animals (Johnson, Cole, and Ahern, 1981). Light-skinned individuals can trace their ancestors to the northern climates where light skin pigmentation favors the ability to absorb vitamin D from limited sunshine (Loomis, 1967). In contrast, near the equator, there is greater need for melanized skin protection against ultraviolet rays, which destroy folic acid (a critical B complex vitamin) and injure sweat glands, disrupting thermoregulation (Jablonski and Chaplin, 2000). A human gene has been identified that correlates with improved athletic endurance in high-altitude mountaineers (Montgomery et al., 1998). Because of the differences in increased heat loss with increase in body surface area, most populations from the tropics have longer and slimmer body shapes than do populations from the Arctic (Jones, 1992). The ability to function at high altitudes at low oxygen levels has been described in terms of both individual and genetic adaptation (Hochachka, Gunga, and Kirsch, 1998). We may speculate that those with an enhanced auditory spatial awareness had ancestors living in an environment where that ability had survival value.

Aural architects, musical composers, and scientific researchers are therefore taking advantage of vestigial abilities as they discover how to apply prehistoric solutions

to modern life. As a species, we were not designed for our current environment of enclosed spaces and complex soundscapes. Robin Fox (1997) summarized the inconsistency between humans and our institutions: “In some sense [spaces] are human because they are human inventions. But it is one of the paradoxes of an animal endowed with intelligence, foresight, and language, that it can become its own animal trainer: it can invent conditions for itself that it cannot handle because it was not evolved to handle them.” The aural architecture of our modern spaces trains those of us who occupy or inhabit them.

### Interdependence of Biology, Nature, and Culture

When we trace the common themes in aural architecture back to their origins, we find them inevitably intertwined with social, cultural, and biological evolution. How then can evolution explain aural architecture? Like many creative and intellectual endeavors, aural architecture is an extension of earlier evolutionary solutions, which allowed our species to survive through thousands of generations. Although the specific spatial designs and our experience of them are unique to each social situation, common themes transcend specifics. Individuals formed social groups because they improved their chances of propagating. These groups then constructed their aural architecture as a manifestation of the social properties. Using social cohesion as a framework, let us then connect auditory spatial awareness of architecture to the survival value of our evolutionary trajectory. Despite being speculative (and appearing to be a digression), the following arguments and explanations provide answers that are, at the very least, consistent with early discussions. We are applying the concepts advanced by Peter J. Richerson and Robert Boyd (2005) to aural architecture: genes and culture shared an interdependent evolutionary trajectory.

The subspecies *Homo sapiens sapiens*, which first appeared in Europe and Asia around 50,000 years ago as the modern human, descended from the archaic human *Homo sapiens*, which first appeared in the fossil record 250,000 years ago. There is fossil evidence that this evolutionary antecedent descended from *Homo erectus*, who appeared at least a million years ago. There are some 50,000 generations between early and modern humans. Although the evolutionary path has been long, complicated, and mostly unknown, several milestones can still be seen to influence the aural architecture of our species in the twenty-first century.

Each of the thousands of biological properties that define a species is subject to evolutionary pressure, but once a property changes, the context changes. The auditory system exists within the context of an external physical environment as well as an internal biological one. A small change in one internal biological system then changes the context for all other such systems. Carl Gans (1992) explains: “The structures involved in vertebrate audition reflect parallel shifts in various biological roles, such as

ventilation, ingestion, and the perception and production of sounds. Understanding of the shifts requires a parallel consideration of the physical principles and functional morphology of the systems, as well as the ecology and behavior of the organism.”

Consider an illustration. When the visual system of a species evolved a small high-acuity region, its auditory system came under adaptive pressure to evolve a wide-field localization ability to provide steering information to the visual system—ears telling eyes where to look. In contrast, if its visual system had evolved uniform acuity over a large field of view, its eyes could have detected important objects without requiring steering information; there would have been less environmental pressure for its auditory system to develop accurate localization ability. But now consider what would have happened if predators entered its environment. The species might have taken refuge in dark caves, thereby avoiding the predators, but that change would also have shifted the balance from vision to hearing. Vision would have been useless in a dark cave. The visual system might then have atrophied, putting yet more pressure on the auditory system to provide a comprehensive aural image of the environment using auditory spatial awareness. If, a thousand generations later, the predators disappeared, the species might have moved back to open spaces and continued to evolve, but from a very different evolutionary starting point. The auditory and visual systems of the species leaving the caves would be very different from those of the species that first entered them. If the species had developed echolocation while in the caves, it might become a nocturnal predator, or its echolocation ability might atrophy, leaving only a vestigial residue. Thus the temporal sequence of adaptive responses heavily influences the evolutionary trajectory taken. Optimization is local, not global; a species evolves as a sequence of minor design responses to a continuously changing environment.

When geography limits the mobility of individuals, thereby preventing breeding among distinct groups, the genetic pool of each group evolves along its particular trajectory. Individuals within an isolated group become more homogeneous, even as each group diverges from other isolated groups. With respect to auditory spatial awareness, one group might be the progeny of thousands of generations of adaptation to forest acoustics, whereas another group might have had ancestors that adapted to the acoustics of an open expanse of tundra, or to the strong echoes of craggy mountains. When individuals respond to stimuli in a spatial awareness experiment or to the aural architecture of a space, their experience is necessarily influenced by the social and environmental history of their ancestors.

### **Social Intelligence of Enlarged Brain Creates Culture**

Most manifestations of aural architecture provide communal spaces. Audiences who listen to music in concert halls are participating in the shared experience of a group. Large spaces are expensive to build, thus requiring groups of investors. Scientists who study auditory spatial awareness are members of professional groups. Throughout the



earlier discussions, we repeatedly referred to culture, which is the largest group that shares values. To expand our understanding of aural architecture, we must explore not only how and why our species creates social groups and cultures, but also how our social and biological evolution relate to one another, and how all of this influences our aural architecture. Answering these questions will give us some insight into the function of aural architecture in our modern context.

We begin with bipedalism, the ability to move on two feet, which is considered one of the major biological shifts that initiated the evolutionary transition to human beings. Bipedalism, combined with other adaptations, played a crucial role in determining the requirements of social groups, especially with regard to energy balance: nutritional intake and energy expended. Kevin D. Hunt (1994) suggested that chimpanzee bipedalism and australopithecine anatomy both originate from the same adaptive pressure, to collect low-hanging fruit. David R. Carrier (1984) argued that the morphology and physiology of human bipedal locomotion became specialized for long-distance running to hunt animal prey by relentless pursuit. The shift to better-quality food sustained larger social groups, the antecedent for culture.

Nina G. Jablonski and George Chaplin (1993) postulated that bipedal displays and mock fights would have served as a noninjurious and socially ritualized method of resolving intragroup conflicts, thereby reducing the mortality rate. One of the critical issues in groups of mammals is the mechanism by which conflicts over limited resources, territory, and sexual partners are resolved. The survival value of individuals that could efficiently hunt as a collective unit, and the survival value of individuals that could ritualistically fight without injuring each other, were important precursors to primate and eventually human societies. Individuals that evolved a predisposition toward the social intelligence necessary for working within a group had a better chance of reproducing.

Following bipedalism, the human brain became larger and more complex, elevating the importance of mental abilities. As an alternative to speed, agility, and strength, thinking shifted the balance from physical to mental processes. Smarter individuals had a better chance of outthinking and outwitting prey, predators, and sexual rivals. Moreover, when combined with the coordinated activities of groups, elevated intelligence became somewhat like a large distributed brain in a dispersed organism. Bipedalism expanded range and mobility, and enlarged brains made those activities more efficient. With multiple brains, ears, eyes, arms, and legs joined by social cohesion, hunting parties became a potent force. The elevated intelligence of individuals contributed to the elevated intelligence of the collective group.

When nonhuman primates first learned that participating in small groups provided better survival value than working alone, they also elevated the value of group cohesion. Without cohesion, internal conflicts over allocating tasks, resources, and sexual partners would destroy the group, forcing individual members to focus on their own

survival. Yet even within a group, individuals are still competitors. Social intelligence balances individual needs against the benefits of deferring to the group. Understanding that balance, as well as enforcing group cohesion, required social intelligence. Nonhuman primates evolved along an evolutionary branch that elevated the importance of social intelligence in forming complex social groups, and human beings went still further in forming complex societies.

Once having followed the evolutionary branch of functioning within large complex groups, each individual human could contribute particular skills, abilities, and intelligences, such as hunting, cooking, navigation, farming, tool building, and so on. Intellectual diversity had more value to a cohesive group than to an individual. Today, we still observe diverse forms of mental ability: some of us are better at auditory pattern recognition, others at mathematical logic, still others at conflict resolution, and so on. From an evolutionary perspective, uniformity in intelligence would have been a weaker choice than diversity, and that is still true.

From an evolutionary perspective, advanced intelligence is not straightforward. Large brains have a biological cost that must be balanced against their contribution to survival. Although it accounts for only 2 percent of total body weight, an adult human brain consumes 20 percent of total energy intake (Aiello and Wheeler, 1995). Relative to body weight, which is the relevant metric, the human brain is three times larger than any other species (Passingham, 1982). Leslie C. Aiello and Peter Wheeler (1995) argued that, compared with other primates of comparable weight, human beings increased the energy available to their brains by decreasing the energy available for digestion, rather than by increasing their total energy needs. Over the past 4 million years, the hominid brain has increased in volume from 400 to 1,400 cubic centimeters, with a corresponding decrease in energy budget of the digestive system.

The evolutionary consequence of a large brain is even more apparent in the large head of a human infant. A newborn consumes upward of 70 percent of its caloric intake to maintain its brain metabolism. By age 10, a human child will have consumed more than a million calories provided by others. Whether measured in calories or money, human children have always been expensive. Not only are the adults in a social group supporting the nutritional cost of their large brains, but they are also supporting the costs of their children's developing brains. Social cohesion supports these costs.

Statistically analyzing a primate database, Tracey H. Joffe (1997) showed that larger brains correlate with an extension of the time period spent as a juvenile, during which the intricacies of complex social life must be learned. Unlike the infants of other mammals, the human infant is subjected to strong social forces and environmental interactions while its brain is completing its growth. Edward F. Adolph (1970) showed that the developmental order of growth stages in a fetus is the same for the twelve species of mammals that he considered, except that a significant part of human growth takes

place after birth, whereas for other mammals, growth is essentially complete at birth. Using the ratio of brain to body weight as a measure of growth, A. Barry Holt and colleagues (1975) came to the same conclusion: among mammals, the growth and development of human infants are unmatched for their slowness. At birth, our brains are still growing at fetal rates; some neurological and cognitive abilities are not fully developed until well into the third decade of life. The basic development of a human child is being completed at the same time that the child is acquiring extensive experience in a particular environment, and that experience influences how development will transform the child into an adult. Because the brains of developing children are still plastic while being molded by culture, culture evolves synchronously with biological evolution.

Stephen A. Gould (1977) summarized the essence of our species:

Human evolution has emphasized one feature of this common primate heritage—delayed development, particularly as expressed in late maturation and extended childhood. This retardation has reacted synergistically with other hallmarks of hominization—with intelligence (by enlarging the brain through prolongation of fetal growth tendencies and by providing a longer period of childhood) and with socialization (by cementing family units through increased parental care of slowly developing offspring). It is hard to imagine how the distinctive suite of human characteristics could have emerged outside the context of delayed development. This is what Morris Cohen (1947), the distinguished philosopher and historian, had in mind when he wrote that prolonged infancy was “more important, perhaps, than any of the other anatomical facts which distinguish *Homo sapiens* from the rest of the animal kingdom.”

For Louis Bolk (1929), genetically determined extended childhood is the driving force of society. Even as culture molds the child, the needs of the child mold the culture.

Raising children is natural selection operating at the level of genetically based psychology. Humans with personality attributes that were antisocial or ultraindividualistic, hence not child centered, did not produce as many descendants as those who put their energies into families. Culture is simply an efficient mechanism by which individuals can find sexual mates to produce viable children, to supply families with an adequate supply of nutrition, and to protect them from predators such as wolves, hyenas, and wild cats and from other dangers. Humans and their primate cousins use culture in the same way—because it provides reproductive advantage.

Individuals of all social species evolved groups of particular sizes and properties, and such groups then became the environment within which individual members lived and propagated their genes. Our species is no different. The previous discussion characterized the original properties of our particular type of social unit, which was dominated by the delayed development and extreme dependency of our infants. As a species, our gene pool evolved within this social environment, creating generations of social animals that could live and thrive in these social units. Although modern society includes a few individuals who prize isolation and individuality, and although most of

us prize participation in multiple groups of varying sizes and properties, we all carry a genetic proclivity to form social units similar to those of our early ancestors.

Aural architects and those who experience aural architecture are part of this evolutionary trajectory. Regardless of our artistic, scientific, or intellectual talents, we carry with us the survival value of delayed brain development and the social intelligence to function within a cohesive group. Even today, we can see the evolutionary importance of group harmony in why we design spaces, and how we use them. Some aural architects and research scientists may claim to be independent of their cultural biases, but, as a species, we evolved as social animals. Our aural architecture is by and for such social groups.

### **Culture as an Evolutionary Invention**

Appreciating the nature of human culture is easier if we explore some of the universal patterns of animal cultures. Nearly all known animals exist in groups of conspecifics for a multiplicity of benefits: defense against predators, cooperative food acquisition, division of labor, and nurturing and educating the next generation. For all our uniqueness as a species, nearly every attribute of modern human society can be found, albeit in a less complex form, within some animal culture. Animal cultures, like their human counterparts, serve to train their young to survive in specific ecological niches, including adapting to local soundscapes. Because sounds and acoustics vary from region to region, learning is still a better evolutionary strategy than a fixed biological solution.

For example, avian species, even with their bird-sized brains, are genetically endowed with the ability to create a primitive culture that is passed from generation to generation. That culture includes an oral-aural tradition of songs that are adapted to the acoustics of the environment. Species of birds living in one region produce songs that are different from those in neighboring regions, and those differences increase with distance. European blackbirds teach naive conspecifics to use mobbing calls to indicate when a dangerous predator is nearby (Curio et al., 1978). Like birds, colonies of Weddell seals living in fiords only 20 kilometers (12 miles) apart each have unique vocalizations (Morrice, Burton, and Green, 1994), whose differences are learned. Similarly, isolated groups of male elephant seals each use different threat vocalization dialects, which persist from generation to generation (Le Boeuf and Peterson, 1969). With their more complex cultures, velvet monkeys teach their infants to differentiate types of birds by using eagle alarm calls for six predatory raptors (Seyfarth and Cheney, 1986). At least in controlled laboratory conditions, a male chimpanzee who had learned sign language was observed actively teaching it to his son (Fouts, Fouts, and van Cantford, 1989).

The major difference between human beings and other primates is that we followed an evolution branch that led to a rich vocalized language, whereas other primates did not. Except for that difference, Duane D. Quiatt and Vernon Reynolds (1993) con-

firmed what every visitor to a zoo observes: primates are very similar, both physically and behaviorally, to humans. However, the primates do not have an efficient way of passing on their experiences to the next generation. Some communication methods allow a limited amount of information to be transmitted, but that information is insignificant compared with what a human child learns in only a few years. Because of this inefficiency, chimpanzee cultures do not display any “ratcheting” by which each generation can cumulatively build on what they inherited from previous generations. There is simply too much information lost to reach the critical stage where information accumulates.

The development of language, and its role in communication between generations, is therefore central to discussions about human culture, for it dramatically expands the complexity and depth of information. Public language is the mechanism by which the human mind extends beyond the scope of what an individual brain can muster. “Once people communicate with language,” Steven Mithen (2000) observed, “it makes little sense to conceive of mind as being constituted within the body of a single person, as each person draws upon, exploits, and adds to, the ideas and knowledge within other people’s minds.” Language, especially written language, binds generations. Our evolutionary branch of primates, endowed with genetics to support a collective mind, is the only species that supports cultural evolution. Although the inclusion of cultural evolution as a manifestation of individual genetics is relatively recent, it supports the observation that human culture originates from human evolution, not independently of it (Barkow, Cosmedes, and Tooby, 1992). Certainly language is the major link between biological and cultural evolution.

For all its power to propagate cultural knowledge, because of its weak ability to represent auditory spatial awareness, language is not particularly useful for communicating aural architectural traditions. In this respect, the cultures of humans are actually similar to those of birds and monkeys; each kind of animal adapts its particular culture to local acoustics and social needs. In itself, aural architecture is more a secondary than a primary component of human culture, where space serves the derivative function of supporting social cohesion.

For accumulated knowledge to be passed on to other members of a community and, more important, to the next generation, there needs to be a stable social structure that preserves the community. Members need a sense of communal obligation, assigned tasks, and an appreciation for the mutual gain of staying together. Myths, religion, rituals, song, dance, music, traditions, rites of passage, and other such activities, serve to bind individuals together in larger units. In communities lacking such stability, communal knowledge decays and future generations are more vulnerable to environmental challenges. Thus artistic religious expression has high value rather than just being art for its own sake. The word *religion* derives from the Latin *ligere*, which means “to bind”; religious institutions bind individuals together. Bernard Grant Campbell (1998)

summarized the implications: “In fact, all rituals may be described as religious, for not only do they bind individuals to the core of social knowledge, but, by performing them, individuals are bound to each other in a common activity often requiring much skill and effort.” Such rituals require special spaces with properties matched to them; hence, aural architecture has its roots in binding rituals.

Like those of other species, each human culture evolved along its own social path, with specific values, rituals, and organization. Cultures that grew and thrived expanded their scope, successfully competing for resources. Cultural niches expanded and contracted as they encountered one another, and those better adapted to the sociophysical environment absorbed, overpowered, invaded, or destroyed weaker cultures. Consequently, over the millennia, we evolved from a multitude of isolated and small groups of hunter-gatherers into a single, massive global community linked by efficient trade and communications.

In parallel with this social expansion, the size of our aural architecture expanded to accommodate larger audiences, which progressed from a few dozen (ritual caves), to hundreds (early Greek temples), to thousands (open-air amphitheaters, cathedrals, and concert halls), to millions (recorded and broadcast virtual spaces). The size of spaces supporting performed music and religion as forms of social cohesion evolved with the size of cultures. And because the cohesive power of music and religion arises in part from its emotional content, the influence of spatial acoustics on emotions becomes a critical component in aural architecture.

### **Properties of Social Cohesion in Small Groups**

Besides examining our larger culture as a means of understanding aural architecture, we also need to explore culture on a small scale. Like other primates, human beings were not designed to function in social units comprising millions of people. As societies and their cultures grew in size, following the genetic imperative to form traditional cultures, people created smaller social units, which we call “subcultures,” comprising perhaps no more than a few hundred individuals and resembling primate and early hominid societies. When we examine the details of aural architecture, we clearly observe that acoustic spaces are the creation, not of the larger culture, but of subcultures, sometimes on behalf of the larger culture, and sometimes independently of it. Although the larger culture may support science, those actually studying auditory spatial awareness are a small group of researchers who work together in an auditory subculture as an extended family or tribe. Those who share an appreciation for acoustic nuances, such as audio mixing engineers creating virtual spaces or the blind navigating a space using echolocation, also form auditory subcultures.

Having considered the evolutionary process in terms of brain substrates, individuals, and the larger culture, let us now consider subcultures, the original form of human society, and the layer intermediate between the larger culture and the individual. A

subculture exists in an environment containing other subcultures, like multiple tribes sharing a forest. Subcultures also adapt to their environmental stresses and opportunities. We can learn much about the origins of aural architecture by examining the behavior and properties of modern subcultures. We can observe how subcultures operate within the larger culture, and how individuals behave within their particular subculture, which is more homogeneous than the larger culture. Subcultures are small enough to explain individual behavior, yet large enough to respond to the larger culture. Moreover, as the natural social unit, the subculture provides consistency over our history as human beings: the general properties and behavior of any given subculture, originating from genetics, provide a stable framework that does not depend on details.

The analogy between traditional older societies and modern subcultures is not perfect because a modern individual usually belongs to many subcultures, or occasionally to none at all. Nevertheless, there is much to be learned by exploring those aspects of the analogy that have explicative value. The following discussion amplifies the description of auditory and professional subcultures in chapter 7. Such subcultures have a secondary set of properties that often overpowers their primary goal of building and analyzing acoustic spaces. To survive, a subculture also needs its version of social cohesion. For individual members of a subculture, the necessary social skills to survive within the subculture are as important as the architectural skills to build spaces.

The first human social groups, which existed thousands of years ago, are not available to study, but our close cousins on neighboring branches of the primate tree still exist. Humans, bonobos, and chimpanzees share a close common ape ancestor dating back 7 million years, unlike the Old World monkeys composed of gorillas, baboons, and macaques, which split off from our evolutionary line of descent much more than 30 million years ago (Sibley and Ahlquist, 1984). The human species shares 20 million more years of common history with the chimpanzees than either species does with the Old World monkeys. For this reason, chimpanzees provide a reference for understanding our common ancestors.

The world's largest captive chimpanzee colony, at the Arnhem Zoo in the Netherlands, has been studied for over a decade by a team of primatologists led by Frans de Waal (1998). The depth and longevity of this study allowed researchers to assign each individual chimpanzee a unique name, personality, history, family, and relationship to every other chimpanzee in the colony. This integrated study illustrated the complex working society that displayed elements of cooperation, alliance, confrontation, deception, and reconciliation not unlike those found in other primate societies, including our modern human subcultures. The variety and complexity of these social dynamics required a particular kind of animal intelligence to achieve group cohesion and social stability. More important, understanding the social tools used to maintain the intimate bonds between individuals having to resolve physical aggression, dominance conflicts,

and competition over sexual partners provided a model of how the benefits of group membership balanced the costs of group living.

Because primate societies are a major research focus, numerous examples illustrate how social skills are critical, especially during periods of instability or stress. For example, when an alpha male attacked a female, others came to her defense, and shortly thereafter, the conflict was resolved with a reconciliation kiss. Bonobos use sexual release for pacification, especially at feeding time, when the potential for conflict increases (de Waal, 1989). There are numerous instances in the 1989 de Waal study where a third chimpanzee intervened to bring peace between two fighting opponents, and then withdrew when peace was achieved. Because chimpanzees are working within relationships that have a past, present, and a future, conflict resolution repairs the damage already done and avoids more serious future damage that could result if harmony were not restored. An unresolved conflict can cost a friend and companion, with the resulting loss in mutual support benefits, which are substantial.

In a later study, de Waal (2000) described primates as having a natural heritage of conflict resolution. Filippo Aureli (1997) proposed that postconflict anxiety reduction, rather than the alternative pragmatic choices of tolerance and avoidance, motivated reconciliation, which is more reliable than just a temporary truce. Only harmony reduces the uncertainty about what will happen when opponents meet again; fear of future confrontation also has a cost. Even though we cannot penetrate the primate mind by observing behavior, professional primatologists are convinced that other primates also have an internal emotional life (Dittrich, 1992). Our knowledge of primate societies suggests an evolutionary pressure to acquire both the mental processing skills for reading subtle behavioral cues and the emotional communications skills to influence the outcome of a conflict.

In chimpanzees, the most common form of conflict reconciliation involves physical contact, such as kissing, grooming, touching, sexual release. Mutual grooming, cleaning fur of plant debris picked up during normal travel, serves more a social function, based on age, sex, rank, and kinship, than a hygienic one, often consuming 20 percent of the animals' time. Grooming is most intense when solidifying an unstable relationship. Friends show greater behavioral tolerance, support one another in encounters with others, protect one another's status against assertive threats, and ensure better access to reproductive partners. At the biological level, grooming as a form of soothing correlates with the release of endorphins, natural opiates (Dunbar, 1996). Monkeys who have been groomed show higher levels of these hormones than those who have not actively engaged in grooming behavior, which induces relaxation and a mild form of euphoria, reducing social tensions. In contrast, social deprivation during the critical learning period destroys the ability of the individual to function in a group (Russon, 1997); high levels of harassment in marmosets prevent young females from under-



going puberty. Social harmony has survival value in all primates, including human beings.

We can clearly observe not only overt sharing and conflict, but also the subtler forms of dishonest signaling by withholding or actively falsifying information among other primates (Hauser, 1997b). Depending on its hunger level, which of its fellows is watching, and the quality of its food, a rhesus monkey may choose not to vocalize a food call to the group in order to have more for itself. Moreover, even though those with positive social skills are likely to profit from the expertise of others by teaching and sharing knowledge, they could just as easily behave like beggars and scroungers to acquire the fruits of another's expertise without any effort (Russon, 1997). Since deception is a choice, individuals try to protect themselves from being victimized by looking for signs of duplicity, seeking to confirm reliability, and identifying the status of the caller, and by the trust implicit in the relationship to the caller. In general, primate deviousness parallels behavior found in children at the earliest stages of socialization (Whiten, 1997).

Within this complex world of multiple social interchanges, genetically based social intelligence determines the number of interactions. Each relationship requires a detailed model of interactive history, individual preferences, and an understanding of individual psychologies. Those with the keenest social skills develop a wider network of potential collaborators. Modern political leaders, like their primate counterparts, are often those with a highly developed ability to communicate emotionally, convincingly, and manipulatively with a large number of individuals, without necessarily having an enhanced standard of morality or honesty. On the other hand, in smaller egalitarian groups, peer pressure is extremely effective at limiting the power of any leader; leaders are followed by choice, not by enforceable power. Christopher Boehm (1993) argues strongly that counterdomination behavior allows subordinates to neutralize the nominal power of the alpha individuals. In fact, Mark Bekoff (2001) believes that morality was the direct result of experiencing the advantages of trust, fairness, and cooperation in small groups.

Intelligence to exploit the physical world of inanimate objects, as we know from experience with some antisocial experts in specialized professions, is altogether different from the social skills required to make friends, to be accepted and supported by the group, or to attract a sexual partner. Although modern society often focuses on scholastic intelligence and displays an ambivalent attitude toward social skills, the value of emotional intelligence is now being recognized as the best predictor of life success (Goleman, 1997). The old adage "It is not what you know but who you know" still rings true in modern subcultures.

A large number of researchers now agree that social intelligence was the major component in human evolution that enabled ever larger groups to form, even if there are

conflicting theories to explain the details (Whiten and Byrne, 1997). Language skills and emotional intelligence are two obvious tools that allow individuals to exercise their influence in a social situation. Richard Dawkins and John R. Krebs (1978) view vocal signaling as being a highly efficient application of a low-energy force to manipulate the behavior of the listener. By explicitly rejecting the informational interpretation of vocalization, with its assumption of a sender speaking to a listener, they substitute the concept of the actor's impact on the reactor, not unlike electronic amplification, where a small energy input can produce a disproportionately large response. An observable behavioral interaction may as often serve to manipulate as to share information.

Primate groups typically comprise some 30 individuals, with limitation on group size arising from the exponential growth in the number of one-to-one relationships that need to be maintained with a given set of tools. Robin Dunbar (1998) extended the earlier Machiavellian hypothesis of Richard W. Byrne and Andrew Whiten (1988), which viewed mental ability as social intelligence, by showing a strong relationship between the size of the neocortex and the size of the social group. Simply stated, smart individuals can interact with many friends and enemies. Using the data from a multiplicity of primate species, Dunbar showed that larger-brained species function in larger groups. That relationship is strong for both the larger definition of the social group, based on the number of potential coalition partners, and the smaller definition of clique, based on the number of intimate grooming partners. A further analysis (Kudo and Dunbar, 2001) asserted that the size of the neocortex determines the individual's ability not only to store knowledge or learn mechanical skills, but also to manipulate complex social information.

For modern humans, the predicted maximum size for a collaborative group is about 150, using the average size of the human neocortex as the variable from Dunbar's research. Numerous examples, whether prehistoric, historical, or modern, support that number. Neolithic villages from 6500 B.C. in Mesopotamia contained 25 dwellings with an average of 6 people per dwelling. Hutterites in communal farms in South Dakota consist of some 110 individuals, East Tennessee rural mountain communities have roughly 200 residents, and professional armies, modern as well as ancient Roman, employ fighting units of 150 soldiers. Beyond a size of 150 individuals, a formal and stratified hierarchy with authoritarian figures is needed to preserve social stability. Dunbar interpreted the working maximum size of 150 as reflecting the cognitive limit on the number of relationships that could be maintained at a sufficient depth to provide mutual support.

The implications of Dunbar's basic thesis are profound. Defined as a social skill, not as intellectual knowledge, social intelligence comprises elements of alliances, friendships, feuds, seduction, physical fighting, deception, and manipulation. With insufficient social intelligence, relationships become unstable, and participation in the

group produces emotional stress and mortal dangers. In many primate societies, death by group members accounts for the highest mortality rate—essentially murder when peaceful solutions have failed to solve a problem.

Dunbar (1993) observed that the need for efficient bonding among humans would be served by language because it provides a way to keep emotional connections. Individuals share gossip to stay informed about the activities of others. Listening to the conversation in university common rooms, he observed that no more than 25 percent of the conversation was devoted to matters of intellectual, political, scientific, or cultural issues. The remainder was devoted to social subjects. Gossip still survives in modern society as a marker of group inclusion. If you are not in the gossip network, you are not part of the group (Barkow, 1992). Moreover, when used responsibly, gossip serves as a social control mechanism to regulate individual behavior (Wilson et al., 2000). It is increasingly apparent that much of human social intelligence involves sensitivity to subtle relationships, and the ability to manipulate those relationships.

The importance of social intelligence and social cohesion aligns with the observation throughout this book that aural architecture and the subcultures of aural architects depend on social cohesion. Small groups of individuals are responsible for creating spaces used by other small groups. Neither an individual nor a larger culture designs and builds a cathedral, concert hall, or spatial simulator. Rather, subcultures, often with power disproportionate to their size, create spaces for the larger culture. The design of such spaces is driven by the social dynamics within subcultures of architects with knowledge about aural architecture. But that knowledge coexists along with other (unspoken) goals. Aural architects are also social animals.

Creating an acoustic space is only a means to an unrelated end; we manipulate spaces for social reasons. Spatial design never exists outside of its social context, which is composed mostly of specific subcultures. Plastic is the more scientific concept for properties that can be molded by environmental pressures.

