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EVOLUTIONARY NOVELTIES

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Abstract

Evolutionary biological novelties are discussed in the broad context of cosmic and complexity evolution, the history of life and the Darwinian evolutionary theory by natural selection. The origin and evolution of structural, physiological and behavioural novelties, at both the organismal and molecular levels, is interrelated with ecological, functional, and developmental changes. The major demonstrations are from the evolution of blind subterranean mole rats of the *Spalax ehrenbergi* superspecies in Israel. *Spalax* adaptive mosaic eye evolution involved regression of the image-forming eye and brain structures, and the progression of photoperiodic perception through retinal elements and the corresponding brain structures. Blindness also led to the evolution of compensatory expanded communication systems. Seismic communication evolved as a major modality in *Spalax* substantiated neuroanatomically by the expansion of the somatosensory cortex into the visual cortex. At the molecular level of the immune system of the Major Histocompatibility Complex (MHC), duplication of the class I genes to about 65, and reorganization of class II genes are discussed. Both eye and MHC evolutions derive from the shift of mole rats to the subterranean ecotype which is characterized, *inter alia*, by darkness and parasites. Thus, the mole rat evolutionary model dramatically demonstrates how evolutionary novelties at both the organismal and molecular levels arose gradually, through reorganization of previously existing structures due to the new functional changes, triggered by the Darwinian adaptive shift to cope with the unique challenges and stresses of underground life.

Introduction

THE HISTORY OF THE UNIVERSE

The evolutionary process from radiation to matter – then to life and mind is unquestionably the most dramatic and fascinating chain of events envisioned by man. The universe unfolds a large-scale evolution of order emerging from chaos and primordial uniformity (Davies, 1988; Hawking, 1988). The expanding universe, following the Big Bang, 15 Ba (billion years ago), evolved hierarchical cosmic order of galaxies, stars, planets, life and man. The emergence and evolution of life, and later consciousness (Darwin, 1859, 1872; Haldane, 1932) from inanimate matter are wonders equal in significance to the cosmic birth.

Organisms evolved from star stuff and the atoms comprising their bodies were born in primordial nuclear fires at the birth of time or were derived from dying suns. The solar system was born about 4.6 Ba. Life's origin is still a deep scientific mystery, though its evolution from inanimate matter is highly plausible and decipherable. Overwhelming geochemical, biochemical, biological and fossil evidence reveals that life originated about 3.8, but possibly 4 Ba (Margulis, 1982). Based on replication, metabolism and transmission of information over generations, life evolved relentlessly over time with variable tempos (Simpson, 1953; Grant, 1991). The emergence of matter from radiation, life from inanimate matter, and mind from living matter, are the three major dramatic innovations of universal history.

THE HISTORY OF LIFE ON EARTH

Overall, life's evolution displays an increase in biodiversity and complexity of organisms, ecosystems and biota, as well as structural and physiological complexity. While biodiversity proceeds to increase, background regional and global mass extinctions recurred in Earth-history, always followed by innovation and diversification (Raup and Jablonski, 1986; Levinton, 1988; Chaloner and Hallam, 1989; Donovan, 1989; Hoffman, 1989; Grant, 1991; Wilson, 1992). Originations and extinctions, *i.e.*, life's evolution, are associated primarily with terrestrial factors both abiotic (geological, climatic, environmental) and biotic (parasites, predators, competitors). Extraterrestrial impacts (asteroids, comets, bolides) might have affected the evolution of life, but their relative importance may be secondary, and, at any rate, are currently hotly debated. While several massive extinctions clearly occurred in the Phanerozoic, the predominant background and mass extinction of species, ecosystems and biotas, analogous to individual mortality, has operated through life's evolution, opening ever-new ecological niches for life's evolutionary experimentation, innovation and emergence.

The unceasing continuous evolution of life, from simple lifeless to complex living structures, culminating in complexity in the human brain, comprises chemical, organizational and phylogenetic increasing complexities driven by a combination of stochastic and deterministic factors. However, from molecular to organismal evolution, and from the original few life forms that evolved from inanimate matter to current all-time high biodiversity (Wilson, 1992) and complexity (Kauffman, 1993), evolution has been primarily dominated by natural selection (Darwin, 1859, 1872; Williams, 1992) despite its strong interaction with stochastic processes and conflicting constraints.

Cosmic evolution – physical, biological and cultural (human) appears to display a trajectory from simplicity to complexity at all levels (Davies, 1988; John and Miklos, 1988; Wake and Roth, 1989). This trajectory towards increasing complexity depends on self-organizing, materialistic, physical, chemical and biological laws. Cosmic evolution seems to be continuous since the Big Bang, about 15 Ba, and may either proceed relentlessly, or crush and recycle, depending on cosmic conditions. So long as the sun provides planet Earth free energy, and unless extraterrestrial astronomical or terrestrial and human forces destroy the biosphere, life's evolution and increasing order will keep going on without any obvious target excepting that of better survivorship against all odds, and expansion by adaptive radiations into all open ecological niches.

Life's evolution is based on a unified chemical language transmitted by the genetic code (DNA transcribed into RNA and translated into proteins) and genome evolution (John and Miklos, 1988), generating increasing order and infinite biodiversity of individuals, populations and species (Wilson, 1992). Thus, unity and diversity are the cornerstones of the ever-increasing biological evolution. Only humans can instil meaning in this ongoing game of survival beyond sheer survival. Only man can understand the past, present, and, only very partly, plan and control the foreseeable future.

DARWINIAN BIOLOGICAL EVOLUTIONARY THEORY

Darwinian biological evolutionary theory assumes that all living organisms evolved gradually and continuously from a common descent, a single origin of life (Darwin, 1859, 1872). The mechanism driving the evolutionary process was and is natural selection, the key factor of evolutionary change. Natural selection operates according to Darwinian theory on the enormous heritable variation among individuals that abounds in natural populations, through survivorship and reproductive success primarily of individuals, but also of groups (Williams, 1992). Parents usually produce a large number of offspring, but very few survive and reproduce, leaving survivors. Those who survive are the best adapted to the physical (*e.g.*, geological and climatic) and biotic (*e.g.*, parasites, diseases, competitors, predators and enemies) environment.

This mechanism of Darwinian evolution through genetic individuality, replication, mutation (*i.e.*, variation) and natural selection resulting in environmental adaptation, might have been operating since the origin of life. At the primitive level of molecular evolution it has been shown experimentally in artificial RNA by Manfred Eigen. Later, complex adaptive systems presumably adapt to and exist on the edge of chaos, according to the emerging science of complexity (Kauffman, 1993).

The origin of life, from the standpoint of genetics, was the appearance of the first replicating molecule (which could metabolize and transmit information) on earth presumably about 4 Ba. Future progressive evolution involved improving homeostasis and complexity by optimizing structural and functional diversity. Likewise, biodiversity generally increased slowly and gradually, set back occasionally by mass extinctions (Raup and Jablonski, 1986; Chaloner and Hallam, 1989; Donovan, 1989).

Darwinian postulates faced since their origin extensive challenges. While the concept of an evolving world, rather than a static one, was almost universally accepted, the concepts of common descent, but particularly gradualism and natural selection, were and are bitterly contested by some critics till the present day (reviewed in Grant, 1991). Saltationism, rather than gradualism was advocated since the origin of the Darwinian theory by T. H. Huxley, otherwise a vigorous supporter of Darwinism. Saltationism was also advocated by Mendelian geneticists at the turn of the century. Hugo de Vries, proposed the mutation theory of species origin. In 1940, the geneticist Richard B. G. Goldschmidt proposed "systemic mutations" or "hopeful monsters" as the source of higher types. At present, the speciation theory of punctuated equilibrium (Eldredge and Gould, 1972) proposes bursts as the basis of speciation.

The Emergence of Evolutionary Novelties

A major repeated objection to Darwin's gradualism was that it could not explain the origin of evolutionary novelties, that is, of entirely new morphological structures, physiological functions, or behavioural patterns. For example, how can a forelimb be transformed into a wing ? A leg into a paddle ? Oesophagus into a lung, enabling terrestrial breathing ? Sexual attraction of gametes into mate choice ? Light perception into image perception of shape, colour and movement ? Prokaryotes into eukaryotes ? Asexual into sexual organisms ? In general, how can an embryonic structure, function, or pattern be favoured by natural selection until it is fully functional ? To take an extreme and dramatic example, how can a fish – or for that matter – *Amphioxus* brain evolve into the human brain ? How can the old brain (rhinocephalon) of lower mammals which controls emotional activities, evolve into the human neocortex which controls intellectual and cognitive activity ? Can Darwinian natural selection lead from scratch to the evolution of complex structures, large genomes, and high biodiversity as well as complex functions and behavioural patterns ?

The Darwinian (1859, 1872) response to explain structural complexity involved a gradual and accumulative evolutionary change due to a change in function. This positive cybernetic relation between function and structure was generally ignored until elaborated by Dohrn (1875), Severtsov (1931) and Mayr (1960). The problems has recently gained momentum (Nitecki, 1990), a restructuring of the concept has been attempted (Muller and Wagner, 1991) and new challenges arise both at the organismal (*e.g.*, Wake and Roth, 1989) molecular and genomic levels (*e.g.*, John and Miklos, 1988).

The eye was always the challenge to Darwinian gradualistic evolutionary theory. Critics argued that such a complex organ could not have been formed just by numerous successive slight modifications. In extensive anti-Darwinian literature; the eye became the test object of natural selection. Darwin's rebuttals have been extended by Hesse between 1896 and 1908 (*e.g.*, Hesse, 1908) and Plate (1924). Recently, the evolution of photoreceptors and eyes have been extensively analyzed and reviewed by Salvini-Plawen and Mayr (1977). They have concluded that (i) photoreceptors have originated independently in at least 40, but possibly up to 65 or more different phyletic lines including protozoans, porifera, worms, brachiopods, coelenterates, gastropods, bivalves, sea-stars, sea cucumbers, arthropods, crustaceans and insects, cephalopods and vertebrates; (ii) photoreceptors in metazoans originated in either of two entirely different tissue elements : from ciliated epidermal cells or from parenchyrnous cells of ganglionic nature; (iii) four basic types of photoreceptoral cells can be recognized through ultrastructure studies : diverticular, ciliary, rhabdomeric, and unpleated; (iv) convergent evolution led to similar ultrastructural types; (v) photoreceptors can evolutionarily change structurally and organizationally in a phyletic line due to new requirements; (vi) ciliary photoreceptors appear to be phylogenetically young and their function is not connected with the directional movement of its bearer; (vii) photoreceptors of invertebrates function in either light detection or in orientation; (viii) in more than 20 independent phyletic lines, a trend of eye perfection can be observed among extant relatives. This includes at least 15 lines which evolved convergently eye lens; (ix) no correlation was found (but see later for mole rat eye evolution) between eye differentiation and adaptive zones, food niche or locomotion type; (x) eye's diversities emerged near the radiation into major phyla and classes of recent organisms. Furthermore, there is no correlation between photoreceptoral type and major phylogenetic lines. These conclusions highlight the extensive independent evolution of eyes across phylogeny.

EVOLUTIONARY NOVELTIES IN SUBTERRANEAN MAMMALS

The enigmatic problems of evolutionary novelties can be resolved by analyzing the global experiments of convergent evolution originating due to shared ecological stresses on unrelated taxa. One of the most dramatic experiments of convergent evolution in nature is the evolution of subterranean mammals across the planet. This global experiment originated mainly in Oligocene times 40-30 Ma following drastic climatic changes of aridization (Prothero and Berggern, 1992). These have driven representatives of several mammalian orders, and families to partial or total life underground. Currently, subterranean mammals involve three orders (marsupials, insectivores and rodents), ten families and at least 250 species (Nevo, 1979). The stressful life underground resulted in diverse adaptive strategies to cope with the unique physical and biotic environmental conditions of the subterranean ecotype (Nevo, 1979, 1991; Nevo and Reig, 1990).

Convergent evolution in subterranean mammals was intimately connected with regressive evolution of morphological, physiological and behavioural characters, associated with distinct parallel progressive evolutionary phenomena in all the above organizational levels. The Eurasian family of subterranean rodents, the Spalacidae (Savič and Nevo, 1990), and particularly the intensively analyzed superspecies *Spalax ehrenbergi* (Nevo, 1991), ranging from southeast Turkey through the Near East to North Africa, represent an extreme adaptive case of mammalian herbivores (rodents) to life underground. I will exemplify here two of the numerous emergent evolutionary novelties in subterranean mole rats of the *Spalax ehrenbergi* superspecies, eye evolution, and seismic (vibratory) communication.

EYE EVOLUTION OF *SPALAX* : NOVELTIES AMIDST ATROPHY

When vision is no longer required, the eyes of vertebrates may become rudimentary or even disappear in the course of evolution (Walls, 1963). Lightless habitats that allow such a regressive evolution include the abyssal depths of the sea, dark caves, muddy rivers and burrows under the ground. In subterranean vertebrates, a sense of light and darkness is often still retained, so that they may be aware when their burrows have been broken into by the weather or by predators. The loss of visual function does not necessarily imply that all rudimentary eyes are completely functionless. It is possible that in certain cases, morphologically very aberrant eye rudiments are being retained for as yet unresolved functions (Remane, 1956).

Complete disappearance of the eyes has not occurred in the evolution of any mammalian species (Duke-Elder, 1958). Some strains of mice can, however, be completely eyeless (Silver and Hughes, 1974), indicating that mutations in one or a few genes can readily prevent any eye development. Maintenance of eye rudiments after millions of years of adaptation to a lightless environment might therefore suggest that such rudiments still have some role in the development and functioning of the animal. The most degenerate eyes of any subterranean mammal are probably found in the mole rats of the rodent family Spalacidae (Nevo, 1979; Savič and Nevo, 1990).

The *Spalax ehrenbergi* superspecies occurs in Israel in four morphologically indistinguishable chromosomal species which are under dynamic process of ecological speciation (Nevo, 1991). The normal visual function of the eye has been completely lost in the course of adaptation to a subterranean way of life of probably more than 25 million years (Hofmeijer and de Bruijn, 1985). The atrophied microphthalmic eyes of this animal are situated under the skin, and show many unusual morphological features, although a differentiated retinal layer can still be recognized (Cei, 1946; Sanyal *et al.*, 1990). Mole rats do not respond to light stimuli, but in spite of their effective blindness they can detect photoperiodic changes (Haim *et al.*, 1983). Mole rats have, moreover, a circadian rhythm (Nevo *et al.*, 1982), which is entrainable by light (Rado *et al.*, 1991). It, thus, appears that the mole rat eye is still involved in photoperiod perception, even though image perception was lost. The mole rat eye thus offers an attractive opportunity to study the various effects of the evolutionary loss of function, or of function changing of an organ. Studies have comprised all levels : neuroanatomy, neurophysiology, as well as at the molecular level of proteins and DNA.

We have studied in-depth the mole rat rudimentary eye at several levels of organization : embryology (Sanyal *et al.*, 1990); neuroanatomy, retinal projections to the brain (Cooper *et al.*, 1993a, b; Herbin *et al.*, 1993), and molecular biology of proteins and DNA (de Jong *et al.*, 1990; de Grip *et al.*, 1992). In the early embryos, the presumptive eye regions – the epithelium, lens vesicle, and optic cup – appear initially normal (Sanyal *et al.*, 1990). As development progresses, the iris-ciliary body complex originates prematurely from the margin of the optic cup and shows a very rapid and massive growth. This pigment-laden tissue mass remains attached to the corneal stroma, obliterates the anterior chamber, and prevents the formation of the corneal endothelium and Descemet's membrane. In the developing lens the elongation of the lens fibers leads to the formation of a rudimentary lens nucleus that becomes disorganized and vacuolated and eventually also becomes vascularized. The optic tissue fails to close, the eyes remain colobomatous, and the optic disc appears atrophic. In contrast, retinal histogenesis progresses relatively normally, resulting in structurally reduced but well-differentiated photoreceptor, neuronal and ganglion cell layers in the adult eye. Immunohistochemically, the presence of opsin could be demonstrated in the photoreceptor cells (*cf.* Figs. 1 and 2 in Sanyal *et al.*, 1990).

The relatively normal development of the retina in contrast to the lens degeneration, raised immediately the question whether retinal and visual thalamo-cortical connections were still retained despite the general atrophy of the eye. Indeed, our subsequent studies of retinal projections to the brain (Cooper *et al.*, 1993a, b; Herbin *et al.*, 1993) unravelled a complete visual system in contrast to earlier claims of incomplete visual system (Bronchti *et al.*, 1991). We demonstrated that severe regression of thalamic and tectal structures involved in form and motion perception is coupled to a selective progression of structures subserving photoperiodic functions. As an alternative to the prevalent view that ocular regression results from negative or nonselective evolutionary progress (*e.g.*, Wright, 1964), the differential reduction and expansion of visual structures in *Spalax* can be explained as an adaptive response to the underground environment.

We suggested (Cooper *et al.*, 1993a, b) that the photoperiodic system, sustaining appropriate reproductive and thermoregulatory responses, has been selectively expanded, whereas the acute metabolic burden of maintaining a large eye and non-functional "image forming" visual system provides the underlying evolutionary impetus for their morphological regression. Thus, ocular regression, linked to selective progression of photoperiodic pathways, represents one aspect of the unique and widespread range of adaptations (Nevo, 1991) that subterranean mammals have evolved to cope with environmental challenges imposed by the stressful underground niche (Nevo, 1979).

The mosaic evolution of the eye of *Spalax* is also dramatically revealed at the molecular level of proteins and DNA (Quax-Jeuken *et al.*, 1985; de Jong *et al.*, 1990; de Grip *et al.*, 1992). Our studies of the gene for the lens protein α-A-crystalline in the mole rat demonstrated a considerable acceleration of its rate of evolutionary changes as compared to that in rodents with normal vision (Hendriks *et al.*, 1987). This suggests a relaxation of selective constraints on this protein after the loss of visual function of the mole rat's eye. However, the rate of evolution is not as high as might be expected if the gene were now without any function. We, therefore, suggested that expression of the α-A-crystalline gene is still required as a necessary component in the developmental program of the mole rat eye (Hendriks *et al.*, 1987). It has recently been demonstrated that genetic ablation of the lens in transgenic mice greatly disturbs the development of other eye components (Kaur *et al.*, 1989).

Knowledge of structure and molecular mechanisms of visual pigments and of receptor-effector coupling mechanisms has advanced tremendously over the last two decades (de Grip *et al.*, 1992). Emerging studies on non-visual photoreceptor proteins and the first molecular analyses suggest that the visual and circadian photoreceptors utilize a very similar set of photoreceptor proteins, but may have adapted their signal processing. We used the mole rat as a model to study the circadian photoreceptor in a blind mammal, in which there is no interference in the retina from the abundant photoreceptors prevalent in the normal mammalian eye. We have earlier shown that removal of the eyes abolishes the circadian response (Pevet *et al.*, 1984), indicating that also in this subterranean mammal, the circadian photoreceptor is located in the eye.

Molecular studies (de Grip *et al.*, 1992) showed opsin immunoreactivity in the pineal, but the retinal photoreceptor layer exhibited strong positive immunostaining for rod opsin and arrestin, suggesting a high degree of homology to the rod photoreceptor proteins of sighted animals. However, the mole rat opsin is exceptional in its high migration (43 kD) as compared to other vertebrate rod opsin analyzed so far (all close to 40 kD). These results, which would be extended in the future, could suggest that the mole rat retina still harbours a functional circadian photoreceptor system. In order that this system will be functional, the entire retina has to develop normally, as indeed was found (Sanyal *et al.*, 1990). We expect in the future to unravel how the "visual pigment" program of *Spalax* is coded into the opsin-sequence, thus participating in the circadian rhythm system.

Circadian rhythms were examined in free-run experiments for 36 hours (Ben-Shlomo *et al.*, 1992). Sixty four animals, from four different species, were tested. There were no species-specific or sex-specific differences in circadian patterns. However, animals exhibited three activity patterns : 1. Regular circadian rhythm (17 animals); 2. Altered-circadian rhythms (shorter or longer than normal, 34 animals); and 3. Arhythmic (13 animals). Nineteen animals were retested, and 84% showed the same pattern in the second test as in the first. We then explored the period (*Per*) gene complex associated in *Drosophila* with rhythmicity.

Hybridization of the period-homologous sequence of the mouse (Shin *et al.*, 1985) to mole rat DNA digested with EcoRI, demonstrated multiple DNA homologies. One region from 5.4 to 6.2 Kb showed four polymorphic bands in all species, probably corresponding to 2 genes (2-3 bands per individual). Four correlation tests were performed between the activity pattern and the existence of a specific band on the same data set. Because we made multiple statistical comparisons we used the conservative α-level of 0.0127. Activity pattern was correlated with the presence of one of the bands (band 3) ($r_s = -0.2606$, $p < 0.05$). Although the correlation was not statistically significant using the conservative level, the existence of this association is certainly suggestive and warrants further investigation. Another correlation of *Per*-polymorphism in *Spalax* may suggest that *Per* is also involved in the mating call rhythmicity (Ben-Shlomo *et al.*, 1993), as has been earlier shown in *Drosophila*. We currently explore *Per* activity in the suprachiasmatic nucleus (SCN), presumably the central organ of the circadian clock.

The mosaic eye evolution of *Spalax*, represents a unique novelty clearly associated with the ecological shift to the underground ecotype where the animals are sealed in closed burrows most of their lives, but still rely on the circadian clock. The architectural reorganization of the *Spalax* eye appears to be microphthalmically adaptive to the unique subterranean environment, but retaining the perception of light which is needed for realizing a circadian rhythm. The vertebrate eye combines both vision and photoperiodic perception. In the case of *Spalax*, vision is lost but photoperiodic perception is expanded and reinforced. Thus, the eye novelty of *Spalax* results from the combined interaction of negative and positive selection pressures. Factors favouring regression include mechanical aspects metabolic constraints and competition between sensory systems (Cooper *et al.*, 1993b).

The primary advantage of sensory atrophy is the metabolic economy gained by reducing visual structures which do not contribute significantly to the animal's fitness. Atrophy of the eye in *Spalax* results in a sharp reduction of the total number of retinal ganglion cells to 850, a low mean density, and a homogeneous topographic distribution in the retina (Cooper *et al.*, 1993a, b; Herbin *et al.*, 1993). Cell soma sizes show a unimodal distribution and large sized ganglion cells are absent (Cooper *et al.*, 1993a). Effects of reduced retinal input on central structures include hypoplasy, a lack of intrinsic cytoarchitectural differentiation and a degradation of precise topographic connections. Comparison with observations in anophthalmic and microphthalmic mutants, bilaterally enucleated animals, as well as to cases of human microphthalmous suggests a homologous or analogous genetic mechanisms operating during a critical period of optical vesicle formation. However, in natural populations, additional mechanisms acting within a framework of atrophy and degeneration have resulted in a positive anatomical and physiological shift of emphasis from visual to photoperiodic perception, which is critical for thermoregulation and reproduction.

The mammalian eye is normally an essential intermediate in conveying photoperiodic information to the pineal gland. The mole rat eye, has lost vision but is still involved in photoperiod perception. This unique eye may thus offer an interesting model in which two functions, vision and photoperiod perception, that are normally intimately and inextricably associated in vertebrates, have become uncoupled during probably more than 30 million years of subterranean life. The evolutionary novelty involved the suppression of one function of the eye, vision, and the reinforcement of the second function, photoperiodic perception.

SEISMIC COMMUNICATION IN A BLIND SUBTERRANEAN MAMMAL : A MAJOR SOMATOSENSORY MECHANISM IN ADAPTIVE EVOLUTION UNDERGROUND

What happens evolutionarily when a major sense organ is atrophied and therefore a major communication mode, such as vision, is eliminated ? Will other sense organs and communication channels compensate (Nevo, 1979; Burda *et al.*, 1990a) ? We have extensively studied this problem in blind (Haim *et al.*, 1983) subterranean mole rats of the *Spalax ehrenbergi* superspecies in Israel. The superspecies consists of four, parapatrically distributed, young sibling chromosomal species ($2n = 52, 54, 58$ and 60). Each species is adapted at multiple molecular and organismal levels to underground life and to four increasingly arid climates (Nevo, 1991).

COMPENSATORY COMMUNICATION MODALITIES IN *SPALAX*

Regressive evolution of the atrophied eye in *S. ehrenbergi* was coupled with progressive evolution in photoperiod perception (described earlier) and biorhythmicity (Nevo *et al.*, 1982). Olfaction communication (Nevo, 1986, 1990; Nevo *et al.*, 1976, 1987a; Menzies *et al.*, 1992) is also an important ethological reproductive isolation mechanism underlying assortative mating and enhancing speciation, as well in adaptive evolution of feeding (Heth *et al.*, 1992). Progressive evolution of short-range acoustic communication in *S. ehrenbergi* was described behaviorally (Nevo *et al.*, 1987b), physically (Heth *et al.*, 1988), transmissionally (Heth *et al.*, 1986) and morphophysiologically (Bruns *et al.*, 1988; Burda *et al.*, 1989, 1990b). Species of *S. ehrenbergi* have a rich vocal repertoire with a main vocal energy below 1 kHz (Heth *et al.*, 1988). This low frequency is optimal for underground transmission (Heth *et al.*, 1986), matching with their cochlear and brain audiograms (Bruns *et al.*, 1988). Recently, Heffner and Heffner (1992) concluded that *Spalax* has severely limited and probably degenerate auditory abilities. This appears to be at odd with the above evidence. However, the effectiveness of *Spalax* vocal communication is primarily at short distances when animals meet, as during the mating season.

SEISMIC COMMUNICATION

Seismic communication, through low-frequency and patterned substrate-borne vibrations are generated by head thumping, and travel long distances underground. It is important as a major nonvisual communication modality of subterranean mole rats of the *Spalax ehrenbergi* superspecies (2n = 52, 54, 58 and 60) in Israel (Heth *et al.*, 1987; 1991; Rado *et al.*, 1987; Nevo *et al.*, 1991). The seismic signals are produced by the thumping of the flat head (which originally served to bulldoze soil and compact the tunnel) onto the tunnel ceiling. The seismic signals are temporally patterned and display a species-specific rhythm of thumping frequency with low (around 100 Hz) spectral energy that may travel long-distances underground. These vibrations provide an effective long-distance communication modality between the solitary and territorial individual mole rats (Nevo, 1961).

The mole rats communicated vibrationally during agonistic encounters in the laboratory in alternate pattern and responded to played-back stimuli. Field observations of thumping exchanged between mole rats indicated communication between individuals in neighbouring territorial domains. Recent field experiments (Zohar and Nevo, unpublished) showed how resident mole rats communicate vigorously through seismic communication with another mole rat that had been introduced in a tube into their burrows. Seismic communication assists in spreading out individuals in space, reducing aggression and contributing to effective resource partitioning. It appears to also act as premating isolating mechanism in speciation (Heth *et al.*, 1992). Underground seismic communication is therefore important in adaptation within populations, and in speciation between diverging populations.

Although the inter-individual and species-specific behavioral pattern of seismic signalling are known, the perceptive mechanism and neuronal processing of this communication modality remained obscure in subterranean mammals (Burda *et al.*, 1990b) and generally so in all animals (Markl, 1983). Fay and Popper (1985) speculated that substrate-borne vibrations are mediated by bone-conduction through massive auditory ossicles, analogous in function to the otoliths of fishes, by providing inertial mechanism of detection of relative skull movement. Rado *et al.* (1989) suggested that the transmission of vibrational signals is mediated by the contact of the mandible with the tympanic bulla through the ear to the brain, compensating for the limitation in receiving air-borne signals. However, Nevo *et al.* (1991) demonstrated that in mole rats of the *S. ehrenbergi* superspecies, the mechanism of seismic signalling through substrate-borne vibrations is basically somatosensory, and functions independently of the auditory mechanism. In mole rats, and apparently in some other subterranean mammals, seismic somatosensory communication evolved as a major evolutionary behavioural novelty as a long-distance communication channel underground, in the twin evolutionary processes of adaptation and speciation.

We have recently explored the neuroanatomy (Rehkamper *et al.*, 1993) and neurophysiology (Necker *et al.*, 1992) of the *Spalax* cortex. We demonstrated electrophysiologically that there is no cortical representation of the visual system following visual stimulation (Necker *et al.*, 1992). The occipital cortex, which serves vision in sighted animals, is occupied by a somatosensory cortex that is somatotopically organized as in the laboratory rat, but seems to be enlarged. The thalamic organization in *Spalax* differs drastically from that of the laboratory rat, *Rattus norvegicus*, especially in the dorsolateral parts. The somatosensory system, rather than the auditory one as concluded earlier (Bronchti *et al.*, 1989; Heil *et al.*, 1991) provides the anatomical and physiological basis for the seismic communication described above. The somatosensory system expands far into the occipital cortex and there is no identifiable visual cortex (Necker *et al.*, 1992). Likewise, the architecture of the dorsolateral thalamus is in part quite different from that of the rat (Rehkamper *et al.*, 1993).

Thus, the expansions of the somatosensory cortex into the visual cortex which lost its function, apparently subserves the new function of seismic communications described above. Furthermore, the mechanism of thumping itself is done onto the burrow ceiling by the flat head which is otherwise used to bulldoze the soil out of the burrow system forming the familiar mounds so characteristic of a *Spalax* territory. Thus, while the visual cortex was replaced by a new function through the invasion of the somatosensory cortex, the flat head retains its old burrowing function but also assumed the new thumping function, thus performing two totally different functions.

Multiple adaptive structures and strategies evolved by natural selection in mole rats at both the organismal and molecular levels (reviewed in Nevo, 1991). We added to the previously reviewed adaptations also the middle ear ossicles (Burda *et al.*, 1990a), adapted for the unique low-frequency underground call transmission (Heth *et al.*, 1986). Likewise, presumably adaptive structures evolved by sexual selection in penile differentiation as morphophysiological premating isolating mechanisms during speciation (Simson *et al.*, 1993).

THE EVOLUTION OF NOVELTIES AND TINKERING

How does evolution operate ? Like a planing engineer or like an improvising tinkerer ? Jacob (1977) has provided evidence suggesting that evolution does not produce novelties from scratch. Natural selection, Jacob suggests, operates as a tinkerer rather than as an engineer. The engineer, in contrast to the improvising tinkerer, works according to a pre-conceived plan, foresees his end product, uses specially prepared materials and utilizes machines designed for accomplishing the work. By contrast, evolution, like the tinkerer, is endlessly improvising and is far from perfection, as already argued by Darwin in his fight against the argument of perfect creation.

Nature abounds with biological imperfections and improvisations as abundantly exemplified at both the organismal (Darwin, 1859, 1872) and molecular levels (Jacob, 1977). Background and massive extinctions (Raup and Jablonski, 1986; Chaloner and Hallam, 1989; Donovan, 1989) characterize life's history testifying to the widespread imperfection of species, when facing drastic ecological challenges. While millions of species now exist, and biodiversity indeed increased over the history of life (Wilson, 1992), nevertheless, all billions of species that lived in the geological far past went extinct.

Natural selection has no foresight, is highly opportunistic and "works like a tinkerer, uses anything at his disposal to produce some kind of workable object' (Jacob, 1977). Thus, the lung of terrestrial vertebrates developed as an extension of the esophagus in freshwater fish living in stagnant water (Mayr, 1960). Likewise, the forelimb of vertebrates can serve several functions : terrestrial locomotion, digging, swimming, gliding and flying. In general, heterochrony played an important role in evolution (McKinney, 1988). Evolution, as we have seen in the *Spalax* case works on what already exists. Natural selection indeed eliminates detrimental mutations, but also establishes coadapted blocks of genes as a response to environmental challenges. Natural selection orients chance, producing progressively ever more complex adaptive structures, functions, and biodiversity in the form of new species. Novelties, as suggested by Jacob (1977) arise from previously unseen associations and reorganization of old material. In his words "to create is to recombine". Kauffman (1993) suggested that evolution is not just tinkering, but it is emergent order due to the interaction of selection and self-organization.

Molecular tinkering also abounds in nature (Jacob, 1977). For example, in *Spalax* molecular evolution a drastic gene reorganization occurred in the Major Histocompatibility Complex (MHC) due to a transfer of function between class II genes (Nizetic *et al.*, 1987). The DR (and probably also the DO) loci have been deleted and their function(s) has been taken over by the highly polymorphic DP loci, which have expanded to a great extent. Thus, functional interchange ability of the individual subclasses of class II loci may occur in evolution. Furthermore, evolutionary expansion of MHC class I loci to about 65 probably arose from the duplication of either the entire class I set or the different class I families (Vincek *et al.*, 1987).

These reorganizations in MHC may relate to the unique subterranean environment which is constantly humid and warm, hence, abounds with ecto- and endoparasites (Nevo and Klein, 1990). Indeed, MHC heterozygosity is highest in the area most infected by ecto- and endoparasites (Nevo and Beiles, 1992; Couch *et al.*, 1993).

The homeobox genes, important regulators of embryonic development, provide the molecular basis across animal phylogeny for unraveling the mysteries of evolution and development. The conservation of the homeobox sequences in metazoan evolution and their gene duplication during the last billion years of evolution is extraordinary, and underlies embryological and developmental evolutionary process (Marx, 1992). Our recent finding of homeobox DNA polymorphism in *Spalax* (Nevo *et al.*, 1992) may suggest the earliest indication for the morphological reorganization that subterranean mammals underwent by colonizing the underground ecotype.

Molecular tinkering by natural selection is widespread. Once life had started as a self reproducing molecule, further evolution proceeded mainly through alterations of pre-existing compounds. This is testified by the extensive molecular homology and conservation across phylogeny. Gene duplication as suggested earlier for the doubled number of the class I loci of *Spalax* MHC and for the homeobox genes apparently predominated throughout molecular evolution (*e.g.*, Ingram, 1963; Ohno, 1970). Gene duplication permits retention of the old function while releasing genetic material for new experimentation and functions. This is the basis for polyploidy in plants and gene duplication across life in general. Natural selection can progressively change, reorganize, modify and improve the genetic material. Even a single amino-acid difference confers major pharmacological variation between human and rodent 5-HT$_{1B}$ receptors (Oksenberg *et al.*, 1992), let alone large scale genomic evolution.

The increase in genome size and complexity from several thousands to several billions of nucleotides (*i.e.* from a few genes to many thousands of genes) might have arisen from a few ancestral genes. While basic metabolic biochemistry must have evolved early in the history of life, life's biodiversity involves increase in genome size, organization and regulation. Much of the molecular changes resulting in new adaptations and species may derive from changes in copy number heterozygosity of tandem or dispersed genomic repeated DNA (Trifonov, 1989, 1990). These sequences appear to be crucial for tuning of the gene expression patterns, adding the important element of graduality to the evolutionary processes. Moreover, the genetic codes carry several overlapping codes increasing their complexity as compared to human texts.

Conclusion

Evolutionary novelties arise when structures change their functions due to ecological shifts, stresses or changes, as already proposed by Darwin. Usually, structures may initially perform two functions as in the case of the vertebrate eye, which lost vision in *Spalax* but reinforced photoperiodic perception. Likewise, the expansion of the somatosensory cortex into the visual cortex occurred when vision was lost and seismic communication developed into a major communication modality. At the molecular level gene duplication is frequent, as in the doubling of *Spalax* MHC class I genes to 65, thus simultaneously retaining the old immune function and generating novel material for experimentation; or, as in the reorganization of MHC class II genes in *Spalax* which was expanded and reorganized apparently to cope with the overload of parasites and pathogens in the microclimatically relatively constant subterranean environment (Nevo, 1979). One of the most dramatic aspects of molecular evolution underlying embryology, development, and reorganization of the bauplane in evolution, is determined by homeobox gene evolution across phylogeny.

The evolution of novelties by natural selection is an ongoing saga of duplicating, reorganizing, transforming and recombining earlier material, either at the molecular or organismal levels, to face environmental challenges and stresses (Hofman and Parsons, 1991) with newly created functions. The emergence of evolutionary novelties is usually gradual, and slow, progressively increasing complexity and diversity of new functions and of new species. Tinkering rather than engineering is the name of the game. The major evolutionary innovations are all demonstrations of tinkering. These involve the origin of life, prokaryotes, eukaryotes, meiosis, sex, multicellularity, genome complexity and organogenesis such as eye evolution. Likewise, neurogenesis, *i.e.*, the evolution of consciousness and awareness by the emergence of the new brain, neocortex, surrounding the old brain, paleocortex, demonstrates tinkering. The evolution of eukaryote, sex and cortex are all gradual steps in increasing complexity and augmenting the potentialities for ever-more efficient adaptations and homeostasis to changing and unpredictable environments. The role of self-organization in evolution should be further explored (Kauffman, 1993).

Clearly, evolutionary tinkering is far from perfect, and while optimization of a system is the final target, suboptimization and much patchwork prevails due to compromises, conflicts, availabilities and opportunities. Cosmic physical and biological evolutions of radiation, matter, life and consciousness represent a grand cosmic evolutionary and historical saga, of ever increasing complexity in the physical, chemical and biological worlds. In the living world, ecological opportunities and stresses throughout the history of life result in genotypic, phenotypic and biodiversity adaptive novelties. The emergence of ever increasing order from chaos characterizes both the physical (Davies, 1988; Hawking, 1988) and biological (Simpson, 1953; Kauffman, 1993) worlds. However, while the rules of increasing complexity may involve thermodynamic constraints in both, adaptation to ever changing environments is superimposed on sheer physics in the world of biology.

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