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Sensory disruption and sensory inequities in the Anthropocene

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Abstract

Anthropogenic disruptions to animal sensory ecology are as old as our species. But what about the effect on human sensory ecology? Human sensory dysfunction is increasing globally at great economic and health costs (mental, physical, and social). Contemporary sensory problems are directly tied to human behavioral changes and activity as well as anthropogenic pollution. The evolutionary sensory ecology and anthropogenic disruptions to three human senses (vision, audition, olfaction) are examined along with the economic and health costs of functionally reduced senses and demographic risk factors contributing to impairment. The primary goals of the paper are (a) to sew an evolutionary and ecological thread through clinical narratives on sensory dysfunction that highlights the impact of the built environment on the senses, and (b) to highlight structural, demographic, and environmental injustices that create sensory inequities in risk and that promote health disparities.

KEYWORDS
Anthropocene, audition, evolutionary ecology, olfaction, sensory dysfunction, sensory ecology, sensory inequity, vision

1 | INTRODUCTION

Once viewed as a simple linear progression out of nature into the built environment, the human ecological niche (responses to and alteration of the distribution of resources and competitors) is much more complex. Ecological niche construction is driven by behavioral plasticity, which depends on the successful integration of numerous sensory stimuli—the perceptual landscape. Our perceptual landscape provides the parameters of what might be behaviorally achievable in an adaptive situation and, ultimately, shapes the ecological niche.[1] Our perceptual landscape has enabled the global distribution of the human species to a variety of environments and subsistence activities—a diversity of human ecological niches.[2] The field of sensory ecology focuses on the mechanistic role of the senses in obtaining information about the environment (perceptual processing of data streams), behavioral responses to information (decision-making), and the functional adaptation of sensory systems to aid survival and reproduction within diverse ecological niches.[3] The behavioral and evolutionary ecology of a species is perhaps best understood through sensory rather than geographic boundaries.

The senses are the primary source of information about the local environment. An organism's interpretation of sensory information takes a leading role in adaptation and is fundamental to evolution. As a result, sensory adaptation to an ecological niche involves finding the sweet spot between minimizing signal degradation (signaler) and maximizing signal reception (sensory modalities of the receiver) against the properties of an ecological niche.[4] Each sense is tuned to a different information channel and filters noise from signals and cues to aid survival (e.g., avoiding danger, finding food) and reproduction (e.g., mate quality, adequate nutrition to maintain pregnancy). Adaptation is a tricky concept because the current function of a trait may not represent that trait's function in evolutionary time.[5] Sensory signals, sensory receptors, and sensory-guided (or driven) behavior are functionally related—a coupled system—and constrained by environmental factors such as the physics of transmission (temporal and spatial variation in temperature, wind speed, humidity), biophysics of signaling (biological capacity to produce a specific physical signal), physiology of receiving, and neurobiology (signal detection and perception integrated into behavioral suites).[4]

[Correction added on 26 February 2021, after first online publication: Figure 5 was added.]

BOX 1 GLOSSARY

Anosmia, acquired: Complete loss of sense of smell due to idiosyncratic life event (e.g., head trauma, infection).

Anosmia, congenital: Complete or absence of smell, functional or severe loss of smell, partial or reduced sensitivity to an odor or group of related substances.

Anosmia, partial or odor specific: Inability to smell a particular odor, odors, or class of odors.

Audiogram: Pure tone hearing test that measures the audible threshold of standardized frequencies.

Audiometry: Like an audiogram but measures pitch and intensity (considered a behavioral audiogram).

Cone photopigments: Light-sensitive molecules made up of proteins called opsin and functional cofactors located in photoreceptor cells.

Dysosmia: Qualitative alteration or distortion of sense of smell.

Hearing Impairment: Having mild (loss of 20-40 dB), moderate (loss of 40-69 dB), severe (loss of 70-94 dB), or profound (>95 dB) hearing loss.

Hyperosmia: Over sensitivity to odors.

Hyposmia: Reduced sensitivity to odors smell (can vary in intensity from mild to severe).

International Dollar (I$): International dollar would buy in the cited country a comparable amount of goods and services a U.S. dollar would buy in the United States.

Myopia: Near-sightedness or reduced ability to focus on distant objects (distance vision loss) due to axial elongation of the eyeball, which causes light to focus in front of the retina; most common cause of impaired vision in people under age 40.

Normosmia: Normal sense of smell measured by some clinical tool; most common tools are Sniffin' Sticks' and UPSIT (University of Pennsylvania Smell Identification Test).

Olfactory bulb: Essential structure of the olfactory system supported by the cribriform plate of the ethmoid bone above the nasal sinuses process, transmits information from olfactory receptors in the nasal epithelium to the brain.

Olfactory dysfunction: Impaired sense of smell that includes hyposmia, dyosmia, phantosmia, parosmia, and types of anosmia.

Parosmia: Altered or distorted odor perception, may be specific to one or a limited number of sources but can also be general, often unpleasant.

Particulate matter: Solid and liquid particles suspended in air, usually refers to hazardous particles and includes organic and inorganic particles (e.g., dust, pollen, soot, smoke).

Phantosmia: Odor perception in absence of odor; smelling an odor (or odors) that is (are) not there.

Presbyopia: Difficulty focusing on near objects due to hardening of the eye lens.

Refractive errors: An error in refraction or the bending of light as it enters the eye and passes through the cornea and lens. Refractive errors occur when the light is not focused on the retina, often due to abnormal eye morphology (e.g., elongated eyeball and/or an overly curved cornea, old lens). Includes myopia (nearsightedness), hyperopia (farsightedness), presbyopia (loss of near vision with age), and astigmatism.

Trichromatic color vision: Primates have both two (red-green) and three (red-green-blue) color vision.

Visual acuity: The ability to focus on objects and discern shapes and details, sharpness of vision.

Visual Impairment: For distance (near-sightedness), a visual acuity worse than 6/18 in the better eye (World Health Organization).

A key feature of sensory ecology is understanding sensory tuning relative to environment—what is the best ecological fit with the coupled system that results in maximal signal-to-noise detection? Changes in one aspect of the coupled system will result in changes to the others and, if they are related to some aspect of ecological change, can shed light both on contemporary functions as well as evolutionary processes.[4]

Minimal attention has been paid to the sensory—or evolutionary—ecology of the human primate.[6,7] The evolutionary ecology of the human sensorium diverges sharply from our closest primate relatives due to ecological, genetic, cultural, and behavioral adaptive changes. Both human ecology and environment have changed significantly across time.[6] Despite our shared evolutionary origins with other apes, the genus *Homo* eventually stood alone in the grasslands having widened its horizons beyond the forest canopy and having escaped the arboreal die-off occurring in Africa at about 2.5 million years ago.[8] *Homo* has a larger geographic range than any other primate—an adaptive radiation that took us to almost every part of the planet. We also have broader adaptive niche—one that has impacted local ecosystems.

Human activity has been affecting the behavior of other animals through hunting, sedentism, plant and animal domestication, dense urban settlements, and most recently, industrialization and the large scale harvesting of natural resources.[9] Increasingly dramatic anthropogenic changes to the environment continue to alter the sensory landscape and cause detrimental disruptions to animal behavior, such as the interference from traffic noise on attention to conspecific surveillance calls[10] or the effect of air pollution on chemical communication between plants and animals.[11] Human behaviors are also affected by anthropogenic environmental changes.[12] The built environment is harming the ecology of other species and placing the human sensorium in jeopardy.

During the latter half of the 20th century, the frequency of myopia (near-sightedness) increased in educated western society and, quite rapidly, spread demographically and globally.[13] Hearing damage increased in the 17th century during the industrial era and occupational hearing loss continues to be an issue today[14]—the frequency of non-senescence-based hearing loss is increasing despite the invention of protective equipment.[15] A limited number of studies have indicated that olfactory dysfunction may also be increasing.[16] Other sensory modalities are either functionally stable—taste, for instance, is not easily deceived by the artificial flavor compounds (e.g., sucralose) that come with evolutionarily recent lifestyles[17]—or are underexplored (e.g., touch and proprioception).

The aim of this paper is to elucidate the mismatch between current and evolutionary environments, how the senses are affected by the current environment, and the costs of the mismatch. Each of the three jeopardized senses (vision, audition, olfaction) is explored from the perspective of sensory ecology and how contemporary environments and lifestyles impair the senses. Each section concludes with a discussion of the financial and health costs of impairment to highlight the impact of mismatch in contemporary living. The conclusion summarizes change to our sensory ecology due to anthropogenic disruptions that are harmful to human sensory health.

2 | VISION

2.1 | Sensory and evolutionary ecology

Like most mammals, primates are able to see colors which is achieved by the stimulation of retinal cones cells by different spectral frequencies.[18] The spectral frequency ranges from 400 to 700 nm with peak spectral frequencies and ranges varying relative to each primate species.[19] Unlike most mammals who have two-color vision (dichromacy), some primates have three-color vision (trichromacy) (Figure 1). The mechanistic explanation for trichromacy in trichromat catarrhines and South American howler monkeys is gene duplication.[20] These animals carry two genes for two separate cones on the X chromosome that detect different spectral frequencies.[21] The mechanistic explanation in platyrrhines (excepting howler monkeys) is X-chromosome polymorphisms.[22,23] In these animals, there is one polymorphic X-chromosome gene and males and homozygous females have one of two types of dichromacy (either short wave/medium wave or short wave/long wave) while female heterozygotes carry two different copies of the gene and are trichromats.

An evolutionary explanation for selective pressures acting on trichromacy is not yet established. Two general macro level explanations include feeding ecology (e.g., finding ripe fruit and/or young

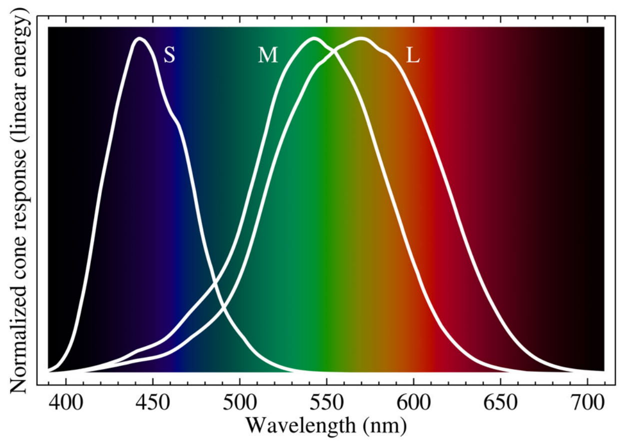

FIGURE 1 Normalized response spectra of human cones, to monochromatic spectral stimuli, with wavelength given in nanometers. Public domain image

leaves)[24] and the discrimination of objects in leafy environments.[25] A less accepted explanation is a trade-off between olfaction and vision due to the loss of active olfactory receptors in primates[26] but errors in the original study reporting this trade-off undermined the strength of the conclusion.[27] Further, other studies have found no correlation between olfactory receptor loss and the evolution of primate trichromatic vision.[28] Indeed, different processes are acting on olfactory receptor evolution.[29]

The primate specialization in red and green hue discrimination has an adaptive explanation related to foraging,[30] social signaling,[31] and possibly predator detection and finding insects.[32] While social and sexual advantages (e.g., sexual swellings in females, brightly colored mandrill faces, differentially-colored infant coats) have been used to explain pressures acting on trichromatic color vision, these functions are more likely to have recruited trichromatic color vision rather than exerted evolutionary pressure on it.[19] Advantage during foraging (whether fruit, leaves, or insects) has been a dominant hypothesized explanation for the evolution of trichromacy in primates[19] but dichromatic vision is not without advantages—it is better in detecting cryptic (hidden or camouflaged) insect prey.[33] Further, there is growing evidence that balancing selection may be operating to maintain both trichromatic and dichromatic vision, even in humans.[34]

Elements of our evolutionary visual tuning for food quality assessment are still apparent. We have a positive bias toward red hues as an indication of food quality and a negative bias against green hues as an indication of lower food quality (e.g., lower caloric content).[35] In addition, color is the single most important sensory cue when it comes to flavor expectations of food and drink.[36] But, the evolutionary function of vision for food assessment has been replaced in the built environment by other tools (e.g., food labels, alteration of foods to increase their nutritive content). There are some elements of evolutionarily tuned visual function still operating, such as the ability to transmit and detect social signals via variation in facial coloration.[37] Further, some research has suggested that past evolutionary tuning resulted in specialized visual acuity that has a sex-based component. Women, in particular, retain visual skills useful in traditional lifestyles such as situating food sources in spatial memory.[38]

2.2 | Visual impairment in non-traditional environments

Visual impairment broadly includes refractive errors (near sightedness, far sightedness, presbyopia or age-related visual decline, and astigmatism), cataracts, glaucoma, color blindness, and macular degeneration.[39] Only a small percentage of people suffer from color vision impairment globally—with the highest frequencies (~8%) of red-green color blindness in white males.[19] Despite its evolutionary importance, impairment to color vision in contemporary cultures is not critical but loss of vision is. The most common visual impairment is refractive errors, particularly myopia or near-sightedness,[40] which negatively impacts visual acuity to see distant objects. In vision, refraction refers to the bending of light as it enters the eye and passes through the cornea and lens.

Visual acuity is the ability to focus on objects and discern shapes and details—sharpness of vision—and is achieved by the action of ciliary muscles on the flexible lens of the eye (Figure 2). When muscles are relaxed, the focal length is at its maximum which causes distant objects to be in focus. When the muscles are contracted, the shape of the lens changes to bring near objects into focus.[41] Visual acuity is measured via standard eye charts that test the sharpness and clarity of letters, numbers, and/or other symbols. The clinical definition of normal distance vision is the ability to see clearly objects that are 20 ft away, 20/20 vision (in countries using the metric system, 6/6).[39] The denominator reports the standard distance required to read a specific line on an eye chart and the numerator reports the individual distance required to read the same line on the chart. Impairment is defined as mild (worse than 20/40 or 6/12), moderate (worse than 20/60 or 6/18), severe (worse than 20/200 or 6/60), and blind (worse than 20/400, or 3/60).[42] A score of 20/200 best corrected distance vision is considered legally blind and disabling. Refractive errors occur when the light is not focused on the retina, often due to abnormal eye morphology—an elongated eyeball and/or an overly curved cornea will both bend the light in front of the retina and cause distant objects to look blurry. To correct a refractive error, a new lens (e.g., glasses or contacts) is used to correct the optical power of the eye, which in a person with normal visual acuity would be about 60 diopters.[39] Diopters measure the focal power of a lens, which is scaled relative to focal length.[39]

A common refractive error associated with aging (40+) is presbyopia which is caused by a hardening of the eye lens and results in difficulty focusing on near objects.[41] The leading cause of non-age-related distance vision loss (poor ability to focus on distant objects) across the globe is myopia, which is axial elongation of the eyeball thought to be caused by a biomechanical signal from excessive downward gazing to focus on near objects (e.g., reading).[43] There is another potential cause of myopia—amount of exposure to sunlight during childhood. Despite overwhelming evidence linking myopia and reduced sunlight, there is not yet an explanation on how sunlight might alter the underlying morphology of the eye.[13] Education, long posited as the primary explanation for increases in myopia prevalence, involves both excessive downward gazing and reduced amount of time spent in sunlight during childhood. Increased use of computers and portable devises exacerbates the problem.[43] While interventions exist (e.g., glasses, contacts, surgery), many cases of refractive error remain uncorrected, often due to a lack of financial resources and health care but sometimes due to individuals not realizing they require corrective lenses.[42] In 2016, ~23% of the global population had myopia (≤−0.50 D) and ~3% have high myopia (≤−5.00 D). By 2050, the prevalence of myopia is projected to increase to 50%, 10% for high myopia.[44] While Asia is the most affected region,[13] there is a global demographic inequity in the cost burden for uncorrected refractive error, with females and individuals in lower socio-economic brackets experiencing greater economic loss.[40,45] Gender and socio-economic disparities may explain the lack of action taken on national and international levels—the primary stakeholders have little to no power.

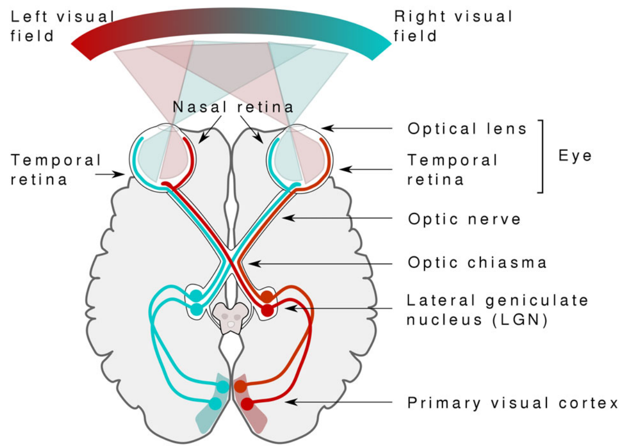

FIGURE 2 A simplified schema of the human visual pathway. Image by Miquel Perello Nieto. Licensed under the Creative Commons Attribution-Share Alike 4.0 International license

What has changed? Genetic factors explain an increasingly smaller proportion of vision problems in non-traditional populations while factors related to evolutionarily recent lifestyle changes explain an increasingly larger proportion.[46] The daily activity patterns of extant hunter-gatherers involve exposure to abundant sunlight and engagement in tasks requiring variation in the focal length of the eye lens. As discussed above, this is not true for most people (especially children) today. There are three pieces of evidence for a negative impact on vision from evolutionarily recent changes in human activity. First, visual acuity is maintained throughout the life span in extant hunter-gatherers.[47,48] Second, the prevalence of myopia in hunter-gatherers increases when they transition from traditional lifestyles to more western lifestyles.[49] Third and last, loss in visual acuity in non-traditional lifestyles has been linked to an increased use of ciliary muscles to bring near objects into focus (e.g., reading, sewing/embroidery) and daily activity patterns that reduce exposure to natural light.

2.3 | The cost to health

The upper limits of the estimated economic cost of uncorrected refractive error is US$202,000 million per year.[50] Compare this to the estimated cost of building the necessary infrastructure to treat uncorrected refractive error across the entire globe (educating practitioners and established refractive care facilities)—a maximum of ~US $28,000 million over a five-year period.[50] Despite the financial gains achieved by correcting refractive error globally, the solutions presented above have not been implemented. The health costs of impaired vision to the individual are reduced quality of life, reduced ability to earn an income, and reduced participation in education.[45] Myopic eyes are also at increased risk for ocular abnormalities including detached retina and glaucoma.[13]

3 | AUDITION

3.1 | Sensory and evolutionary ecology

Primate hearing is characterized by a shift from higher frequencies in early nocturnal mammals to lower frequencies in Miocene Epoch catarrhine crown species.[51] Hearing sensitivity depends on sound waves entering the pinnae (ears), where they are conducted to the ear drum (Figure 3). The ear drum sends vibrations to the middle ear and the ear bones. Ear bones transmit the vibrations to the inner ear where the cochlea, filled with fluid, moves the stereocilia. Audiograms describe the perception of noise—a graphic representation of the softest pure tone (no background noise) an animal can hear (the lowest decibel, dB) at different frequencies 50% of the time.[52] Variation in extant primate species' audiograms[52] reflects differences in habitat acoustics, body size, and activity patterns (Figure 4).[51] The majority of vocalizations made by primates are to signal social separation and predator detection.[53] There is a strong positive correlation between larger group sizes (as an index of social complexity) and greater auditory sensitivity.[53] Small-bodied primates today have small heads with narrow interaural distances, which aid sound localization[52,51]—a useful trait when isolating potential threats in response to a high frequency alarm call. Haplorrhines (the group that includes all monkeys, apes, and tarsiers) are generally less sensitive to high-frequency sounds, produce few high frequency localization cues, and have limited ability to produce high-frequency alarm calls. As such, they may have relied less on high frequency alarm calls and more on other anti-predator strategies, which resulted in the low-frequency sensitivity of humans.[54] The social drive hypothesis combines the complexities of sociability and habitat changes because it posits that larger groups travel greater distances and traverse a wide range of habitats, requiring better ability to detect discrete vocal signals in a variety of acoustic environments.[53] This also would account for tuning to lower frequencies because they attenuate at a slower rate, which allows tracking conspecifics, and reduces signal-to-noise ratios. In hominins, the shift to lower frequencies may also reflect an adaptive advantage in new habitats that were characterized by open spaces.[54] Human audition is considered to the derived from the ancestral state due to loss of higher frequency detection and an expanded midrange frequency detection. Humans have a W-shaped curve with one peak sensitivity (at ~3 kHz).[55] Morphological changes in ear anatomy across hominin fossil species suggest this change occurred early in the lineage.[55] The hypothesis that human auditory specialization is due to human speech perception is not supported because most animals are able to detect and interpret the vocalizations of other species—practically, this allows multiple auditory channels of information about the environment. Most likely human speech is tuned to the audible hearing range.[55]

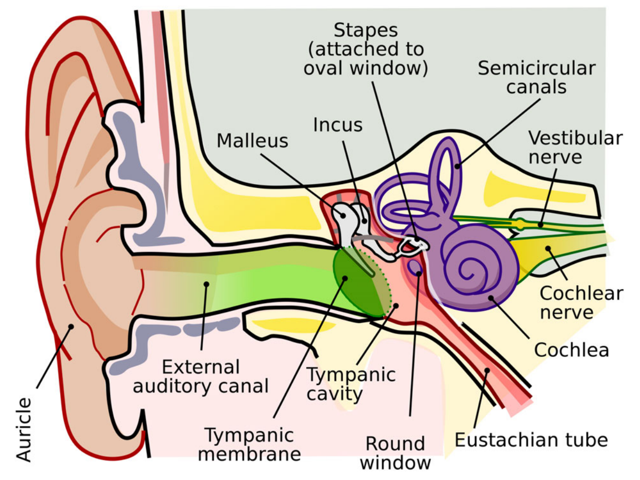

FIGURE 3 Anatomy of the human ear (the length of the auditory canal is exaggerated). Image by Lars Chittka and Axel Brockmann. Licensed under the Creative Commons Attribution 2.5 Generic license

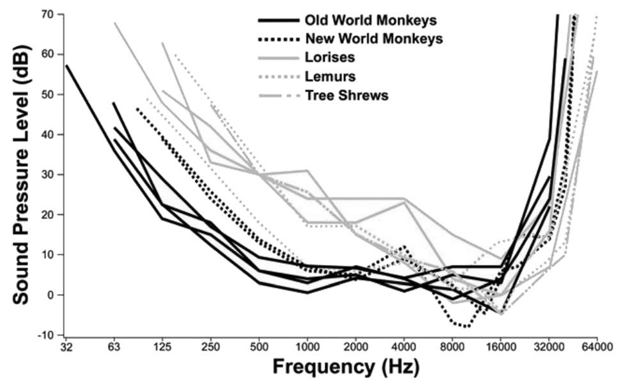

FIGURE 4 Species mean primate audiograms presented in Coleman and Colbert, Journal of Morphology 271: 511-532. Copyright WILEY-LISS, INC

Animal hearing is generally tuned to the detection of other animals (e.g., vocalizations, movements) in order to locate the source of the sound and assess the properties of the noise in order to determine if the information is useful and how to use it.[52] Sound localization may be evolutionarily related to vision—the best sound localizers also have the narrowest field of vision.[52] Audition is a natural complement to vision because it allows perception of animals (for example) that are out of sight and directs the eyes to the location of the sound.[51] Elements of our ancestral tuning to the activity of other animals (including humans) that are out of sight is still apparent today. For example, extant Papua New Guinean hunter-gatherers (Umeda,[56] Kaluli[57]), use noises to navigate their environment. Even factory workers in industrialized societies place greater value on verbal warnings from co-workers than wearing protective headphones (which creates risk for occupational hearing loss).[58] The built environment and technology have altered the global soundscape and perhaps our auditory functioning has changed as a result—we pay less attention to the auditory cues of the natural environment (e.g., active blocking from noise canceling headphones, passive blocking from anthropogenic noise pollution) and pay more attention to the noises of the artificial soundscape of the built environment (e.g., car horns, fire alarms).

3.2 | Auditory impairment in non-traditional environments

Hearing impairment includes reduced sensitivity (pitch and intensity), trouble with speech perception (clarity of speech), and feature discrimination (speech-in-noise).[59] Reduced sensitivity (hearing loss) is the most common hearing impairment across the lifespan around the globe.[60] Hearing loss is a partial or complete inability to hear in one or both ears[60] and can be accompanied by tinnitus or (hissing noise or high-pitched ringing in the ears when sound is not present), tympanophonia (or autophonia, abnormal hearing of one's own voice), hyperacusis (sensitivity, pain), and vertigo (problems with equilibrium).[61] Tests for hearing loss measure hearing sensitivity via an audiogram, which is a graph of individual audible thresholds (intensity and frequency of a given tone) plotted against a standard curve.[62] The clinical definition of normal hearing sensitivity is 25 dB or better in both ears, with impaired hearing sensitivity defined as mild (26–40 dB higher than normal), moderate (41–60 dB higher than normal), severe (61–80 dB higher than normal), and profound (81 dB or greater).[60] Hearing loss is considered disabling if greater than 40 dB in the better of both ears.[60]

Noise-related hearing loss is caused by damage to the stereocilia—hair cells that do not regenerate in mammals.[63] Stereocilia damage is made worse by occupation and risky behaviors (e.g., personal listening devices, failure to use personal protective equipment).[64] Damage accumulates across the lifespan and partly explains increased prevalence with age (and increasing prevalence in youth). Other factors that promote hearing loss include drugs, environmental chemicals, and trauma. Hearing impairments such as tinnitus are not yet correctable but new findings may allow molecular intervention for treatment.[65] Feature discrimination is treatable with training[66] but hearing loss and perception require electronic hearing aids and, potentially, cochlear implants. Global hearing aid production meets just 10% of the need, leaving the majority of cases untreated[60]—in developing countries, the production meets less than 3% of the need.[60] Age-related hearing loss has a sex-based pattern with males having an average lower high frequency threshold[67] (above 1 kHz) and females having the reverse pattern (below 1 kHz).[68] Males experience more occupation-related hearing loss[14] but age (individuals aged 65+) and income (low- to middle-income countries,[60] individuals with lower socio-economic status[69]) are the primary demographic risks.

Five percent of the world's population has disabling hearing loss but projections suggest this will increase to ~10% by 2050, with a further ~10% of people aged 12–35 at risk.[60] Global rates of disabling hearing loss (over 40 dB in the better of both ears) doubled between 1985 and 1995 from 0.9% to 2.1%. Projections suggest an increase from 5% in 2018 to almost 10% in 2050. Hearing loss trends are stronger in urban areas where daily noises are frequent and louder.[70,71] Age is the leading non-genetic cause of hearing loss in non-traditional populations and occupational hearing loss is the second largest cause of hearing loss in non-traditional populations in the world—linked primarily to industrial settings starting in the 17th century.[72] Roughly 19% of American workers (mainly mining and construction) are exposed to loud noises that cause occupational hearing loss[73,74] but 20% of American cases of hearing loss are due to the loud noises of everyday living (e.g., sirens, washing machines, leaf blowers).[74] Regular exposure to gun use is another occupational hazard[58] but even non-occupational exposure to firearm discharges is risky if occurring regularly (e.g., hunting, shooting sports).[15] Hearing loss from exposure to loud noises is preventable, whether occupational or secular.

What has changed? While genetics, medicine, and chemicals explain many cases of hearing loss, an increasingly larger proportion is explained by exposure to loud noise—evolutionarily recent alterations to the human soundscape, starting with the Industrial Era and continuing with technological advancements that increase risk, such as listening to music at unsafe decibels or prolonged exposure (>8 hr) to sound levels above 85 dB (e.g., road traffic, guns, and domestic and industrial machinery).[64] Non-industrialized populations tend to live in soundscapes with lower levels of ambient background noise. For example, a series of studies on the Mabaan in the Sudan indicated that average daily noise was ≤40 dB and as low as 34 dB with the only exceptions during celebrations involving song and music (highest recorded 110 dB).[75] These populations maintain hearing sensitivity comparable to healthy aging adults in industrialized societies but have superior detection of high-pitched sounds as they age.[76,75] Another example is found in the native populations of Easter Island, also called "the island of the great silence."[77] When comparing individuals that remained on the island and individuals that left the island to live in industrialized cities, remainers maintained sensitivity (and had better hearing than healthy counterparts from industrialized societies) and leavers experienced loss proportional to the time they were exposed to the loud noises of everyday living in cities.[77] A final example is the absence of hearing loss associated with age in Hadza hunter-gatherers—only a few individuals over age 50 experienced very gradual, mild hearing loss.[48] The natural and evolutionary auditory environment is in marked contrast to the post-industrial one where we are exposed to unnatural and loud noises on a daily basis with increasing regularity.[64]

3.3 | The cost to health

The estimated costs of uncorrected hearing loss are US$750 billion.[60] The costs of intervention are much less expensive than the economic and social costs of hearing loss. Regular screening starting in childhood is a no-cost preventative tool (the WHO offers a free screening app) which makes early intervention easy—an estimated 60% of cases of childhood hearing loss is preventable. Passive screening as a preventative measure, however, is not always implemented in schools and fails in adults—CDC data suggest that 24% of people with non-occupational hearing loss believe they have excellent hearing and do not seek testing.[74] The health impacts caused by hearing loss can be painful in extreme cases (e.g., tinnitus) but mostly impact social health, such as decreased verbal communication and reduced social connectively.[15] The knock-on effects of poor communication abilities are reduced economic, educational, and social opportunities. Associated health problems with age-related hearing loss include cognitive decline[78] and injury from falls.[79]

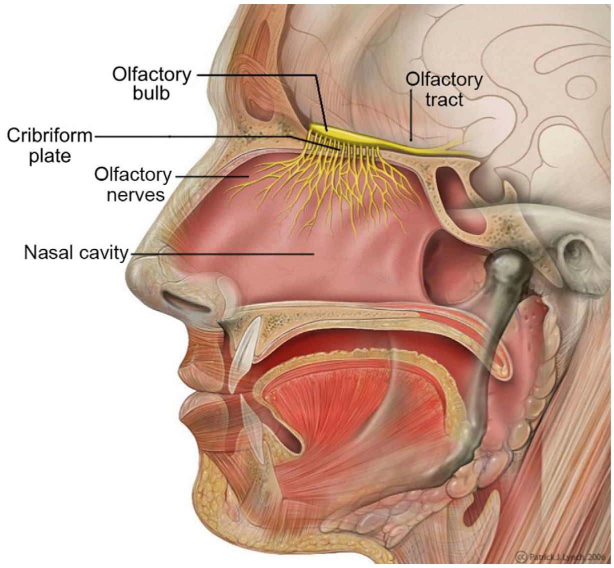

FIGURE 5 Anatomy of the human ear (the length of the auditory canal is exaggerated). Image by Lars Chittka and Axel Brockmann. Licensed under the Creative Commons Attribution 2.5 Generic license

4 | OLFACTION

4.1 | Sensory and evolutionary ecology

Olfaction is a highly conserved vertebrate trait (even sharing similarities with invertebrates), genetically[80] and morphologically[81]— the anatomical system and the genes that control receptors follow the same basic structure (Figure 5). Primates tend to have a smaller number of putatively functional olfactory receptors compared to other mammals.[82] Receptor number is not a singular maker of ability to detect and perceive odors or act on information received from olfactory cues in the environment. For instance, high individual heterozygosity in olfactory receptor variation expands the effective size of the olfactory repertoire tremendously. Olfactory repertoire is effectively larger than the number of functional olfactory receptor genes due to high allelic heterozygosity.[83] Genetic, physiological, and behavioral data demonstrate that primate olfaction performs well, is not derelict, and is highly functional in daily life.[8485,86]Ability to detect odors depends on odorous volatile molecules entering the nose where they are shepherded through the mucus to the olfactory epithelium. Within the olfactory epithelium lie olfactory receptors expressed on the tips of olfactory sensory neurons. After a critical mass of receptors are activated through the binding of odorants, the neurons fire a signal to the olfactory bulb and the information is bundled and sent to different parts of the brain.[87]

There is nothing particularly notable about the human primate relative to other primates in terms of olfaction (our tempo of genetic change in terms of genes lost and gained is the same[82,88]) but we do have our own olfactory repertoire that is distinct from our closest relatives.[89] Olfactory repertoires are specialized to evolutionary ecological niches.[89] How differences are ecologically salient is not yet known but there is a growing body of evidence pointing to the role of ecology in shaping our repertoire. For instance, a mammal-wide transcriptome study identified a higher abundance of olfactory sensory neurons devoted to food-specific odors compared other types of odors.[90] Further, the presence of selective pressures operating on the primate olfactory system suggests that ecological factors drive variation.[91] Olfactory repertoires are also specialized to behavior (e.g., mate and kin identification, social cue response, danger avoidance, food foraging).[7,92] Behavioral uses of olfactory cues and signals vary across primate species but all primates use olfaction for odor quality perception and share a general dietary bias for calorically dense food,[93] which may be mediated partly by odor cues.[94] Like other big-brained primates, humans require calorically dense food for adequate energy.[95] We use odor cues from foods to identify fats, which have more than twice the amount of energy as other macronutrients and require minimal energy to digest.[96,94] We also cook our food (as did other members of our genus),[97] which increases food digestion and stimulates the olfactory system. Most captive apes prefer cooked food when given a choice, which suggests a shared preference for foods with higher nutritional quality that are easy to chew.[98]

The human sense of smell functions much as it always has—detecting food, social cues, and avoiding danger.[92,7] Humans have the ability to follow a scent trail without additional sensory input beyond the olfactory modality.[99] Humans can detect fear[100] and other emotions[101] in other humans. They are able to make social judgments (e.g., pleasantness and intensity of odor, likeability and friendliness based on odor, similarity odor to self and friends) about individuals based on whole body odor (including perfumes and deodorants) as well as when based on pure body odor.[102] Reflective of primate sociality, individuals with larger social networks tend to exhibit greater olfactory sensitivity and functional connectivity of the amygdala with the orbitofrontal cortex.[103]

4.2 | Olfactory dysfunction in non-traditional environments

Quantitative olfactory dysfunction includes hyperosmia (over sensitivity), hyposmia (reduced sensitivity), and anosmia (complete or absence of smell, functional or severe loss of smell, partial or reduced sensitivity to an odor or group of related substances). Qualitative olfactory dysfunction includes parosmia (altered odor perception) and phantosmia (odor perception in absence of odor).[104] The most common forms of olfactory dysfunction are hyposmia and anosmia.[105] There are no standard tests for olfaction, let alone diagnosis for olfactory dysfunction, but composite assessments that include odor sensitivity or threshold, odor discrimination, and odor identification tend to be the most accurate.[106] Given the lack of common test materials, there are no standards and norms but the most widely used test is Sniffin' Sticks (SST), which has a total score range from 0–48 points.[107–109] Based only on normative data for western populations only, the clinical definition of normal olfaction falls within the 10th percentile of test subjects (24.9 for ages younger than 15, 30.3 for ages 16–35, 27.3 for ages 36–55, and 19.6 for ages 55+). Hyposmia is defined as an SST score < 30.3 for individuals aged 18–35. Functional anosmia is defined as an SST score ≤ 16 (assuming a sensitivity score of one), and anosmia as 0.[106] Clinical definitions of olfactory dysfunction are complex, however, as they tend to be age and sex dependent (females consistently outperform males aged 16–55)[109] and children require special tests because their performance on olfactory assessments is different from adults.[106] Despite an understanding of the problems associated with olfactory dysfunction, there is minimal clinical, medical, or public health discussion about the disability it causes. As of 2019, the WHO does not have a fact sheet on olfactory disorders of any kind (https://www.who.int/news-room/fact-sheets#l).

Olfactory dysfunction is commonly caused by damage to soft tissues—often irritation of the epithelium (e.g., allergy, infection) which causes the neurons to die. Olfactory dysfunction related to COVID-19 infection is slightly different in its targeting of olfactory supporting cells.[110] Frontal bone trauma can cause anosmia if the trauma severs the nerve connecting the receptors to the bulb. Exposure to chemicals and the use of specific medications (often with aging) can cause dysfunction but the most common cause of dysfunction in industrialized populations is age.[111] In the early 21st century, air pollution was implicated as a cause of mild-to-moderate hyposmia in the general population, often in urban areas[16]—and pollution loads are linked to respiratory, including COVID-19, infection rates.[112] Long-term pollution exposure—mainly traffic-related particulate matter—causes not only olfactory dysfunction but brain damage, increased risk of neurodegeneration, and cognitive impairment.[113] There is no intervention for severed nerves or congenital anosmia. For hyposmia linked to sinonasal disease, use of corticosteroids has shown promise.[106] COVID-19 related olfactory dysfunction is variable in intensity (usually coupled with taste dysfunction) and persistence after the virus clears the body.[114] For other causes of hyposmia, the only treatment is smell training, which improves cognitive processing of odors and appears to improve odor identification but does not restore the sense of smell.[115]

One estimate for the number of people experiencing some form of olfactory dysfunction is 5%[106] but these data are primarily from western countries. The data gap in Africa, South America, and Asia (excepting Korea) prevents calculation of actual global prevalence of olfactory dysfunction. Only one study has been conducted in Africa in the Democratic Republic of the Congo and this was to adapt the Sniffin' Sticks test for use in the sub-Saharan South Kivu population. In a sample of 150, the average score in young adults was about 30, which is on par with Sniffin' Sticks test normative values.[116] Putting aside the data gap, there are other reasons we have little information, even at the national level, for olfactory dysfunction. First, olfactory testing is rarely included in national health assessments, except recent inclusions in the early 21st century to those in the United States[117] and Korea.[118] This may change because there is a growing awareness of the importance of smell testing in aging populations due to the connections between neurodegenerative disorders, primarily Parkinson's and Alzheimer's,[104] and also due to the fact that loss of smell and taste are sometimes the only symptoms of COVID-19.[119] Second, incidences are not clinically tracked (perhaps due to the limited number of treatment options).[120] This may change if interventions are found. Third, even if incidences were clinically tracked, people do not often realize they have lost their sense of smell—this includes those born without it.[106] With these caveats in mind, survey data from clinical studies in Europe (Germany, Spain, Sweden) suggest that ~16% of the population experiences olfactory dysfunction.[106] In the US, 24% of the population have reported olfactory problems but these data are limited to individuals over the age of 40.[121] The Korean National Health Survey estimates 4.5% of the population experiences olfactory dysfunction.[118]

Risk for olfactory dysfunction is increased differentially by socio-economic and political circumstances, such as poverty, minority status, education.[122] To further complicate the unequal burden of risk and negative health outcomes (see next), exposure to pollution—an underlying cause of olfactory dysfunction—is not equal across social demographics.[123] Demographically, females report a greater impact on social and domestic life and experience more mental health problems from dysfunction.[124]

What has changed? While age and trauma explain many cases of olfactory dysfunction, sinus problems,[111,106] pollution,[16] and COVID-19[119] are increasingly common sources of damage to olfactory tissues—all of which can be linked to changes in air quality. Humans have radically and recently altered the odorscape via activities related to agriculture and industry. We further alter the odorscape with the smells of activity, such as cooking, scent-branding (e.g., Lush, Subway), our own perfumes and deodorants, and cleaning. Indirect evidence from olfactory language terms[125] and genetics[126] suggest greater hunter-gatherer acuity in olfactory ability but neither have included psychophysical data as confirmation. There are no comparative data from populations living traditional lifestyles, but age-related decline in olfactory ability, prebyosmia, may be inevitable in non-traditional populations.[127]

4.3 | The cost to health

The costs of not treating olfactory dysfunction are unknown given under-reporting and lack of systematic data collection on dysfunction rates. The costs of treating olfactory dysfunction are difficult to estimate because of the extremely limited treatment options—smell training (which does not restore a lost sense of smell) and corticosteroids for some sinonasal problems. The costs to health are great and cross-cut physical, mental, and social domains.[6] Often used as a measure of olfactory functioning, olfactory bulb size (measured via MRI or CT scans) is reduced in patients diagnosed with depression compared to control patients.[128] Individuals with depressed olfactory functioning report reduced quality of life,[111] and lack of engagement with formerly pleasurable activities such as sex[129] and eating and drinking.[130] Anxiety from body odor and potential danger in the home (e.g., gas leaks, rotten food) are also concerns.[131] While most individuals with a reduced sense of smell gain weight because they feel less sated and seek fats and salts (leading to both adult and child obesity),[132] some suffer malnourishment and weight loss from lack of interest in eating or due to eating an unbalanced diet.[111] Olfactory dysfunction is negatively correlated in older women (50+) to sociability.[133] Individuals without a sense of smell (particularly congenital anosmia) report missing social cues that cannot be read from facial expression alone[131] and this impacts social network size and connectivity. Oxytocin mediates behavioral responses to social odor cues, such as recognizing conspecifics[134] and detecting sickness[135] and emotions.[136] Further, individuals with autism spectrum disorder perceive social odor cues the same as typically developed adults but evoked behavioral responses differ, which causes social impairment.[137] Indeed, olfactory impairment is also linked to affective personality characteristics that have a negative impact on well-being.[138] Potentially, our ability to detect emotional status[139] in other humans is compromised in non-traditional settings, not just in the virtual world but also in real-world settings that contain odor noise and pollution. Some research has suggested that ambient odors in urban environments provoke emotions.[140]

5 | CONCLUSION

The primate sensory ecology of vision is characterized by two separate evolutionary changes from dichromacy to routine trichomacy.[18,20–23] Feeding ecology has been implicated in explanations for evolutionary pressure acting on trichromacy[19,30] but there also may be balancing selection acting to maintain both forms of color vision in primates.[34] The human use of vision for near work in non-traditional societies has been implicated in global increases in myopia frequency, a visual impairment caused by a refractive error. Behavioral changes from our evolutionary past to present that act on myopia tend to alter eye morphology pathologically, namely an increased focus on near objects and lifestyles that limit exposure to daylight.[43,13]

The sensory ecology of primate audition has been shaped by body size and habitat.[51] Lower frequencies attenuate at a slower rate which reduces signal-to-noise ratios and also allows larger groups traveling through a variety of acoustic environments to better track conspecifics.[53,54] The human habitat, characterized by comparatively open spaces, has furthered the trend to lower frequency hearing.[54] Humans have a highly derived audiogram with one peak sensitivity rather than two, which expands detection in the mid-range of freqencies.[51] The primary auditory impairment in non-traditional populations is loss of hearing sensitivity, which is caused by damage to hair cells in the ear (often from occupational noise hazards and the loud noises of daily living).[63,64]

The primate sensory ecology of olfaction is characterized by a reduced number of olfactory receptors (relative to other mammals)[82] but increased allelic heterozygosity that expands the effective size the human olfactory repertoire.[83] along with other factors that contribute to olfactory ability (e.g., copy number variation, epigenetics, and accessory proteins such as olfactory binding proteins). Humans exhibit a specific olfactory repertoire that is distinct from chimpanzees (our nearest cousins)[89] and subject to selective pressure.[91] The primary olfactory impairment in non-traditional populations is reduced ability to detect and perceive odors,[105] which is caused by damage to soft tissues from infection[111,106] and anthropogenic air pollution, especially particulate matter.[16]

Our evolutionarily tuned senses and their primary functions have not changed significantly in recent human evolution, but our environments have due to behavioral adaptations. The post-industrial built environment has brought about age-related declines in audition and vision as well as impairments to hearing, seeing, and smelling across the lifespan. Alongside the direct damages, caused by contemporary adaptations, sensory pollution is a major social problem and constant nuisance that often disrupts sleep, particularly—but not exclusively—in urban areas.[64,141,142] The health impacts of sensory dysfunction in each modality occur at great personal, social, and global health costs. Despite the cost to correct impaired senses being much lower than the cost to correct them, many cases go uncorrected. And, in the case of olfaction, the lack of interventions and poor tracking of cases result in limited clinical knowledge on prevalence. Given that hunter-gatherers do not typically experience the same age-related senescence in vision and hearing, there may be relaxed selection taking place in later stages of life history on sensory maintenance in post-agricultural societies, but there is not enough data yet to understand what the mechanism for retention of acuity is—or conversely, the mechanism for age-related impairment.

Sensory disruption is a contemporary social problem of global proportions but one that is not equally experienced. Urban populations tend to be at greater risk for sensory dysfunction[6] and the UN predicts most of the world will be urbanized by 2050—54% of the world's population resided in urban areas in 2014 (Africa, 40%; Americas, 81%; Asia 48%; Europe, 73)[73] and that percentage will increase to 66% in 2050. The urbanization trend increases the urgency of understanding how daily life and health are impacted by sensory disruption. Further, the populations most at risk for each sensory impairment tend to be in marginalized demographic categories (e.g., socio-economic status, social race, educational level, gender) who represent a disproportionately larger share of the global population than those with power to make a change.

Several research avenues to understanding human sensory evolution and ecology are open. An excellent starting place might be to measure the sensory landscape and then evaluate contemporary sensory traits comparative and relative to ecology. This approach, however, is not as easy it may seem. Measuring tools such as spectrophotometers (electromagnetic radiation), sound level meters (intensity in dB), oscilloscopes (pitch in Hertz), gas chromatography and mass spectrometry (of air samples to identify and quantify volatile organic compounds), and olfactometers (odor dilutions) exist but appropriate sampling strategies for a robust research design and affordable, portable field tools are needed. Both vision[19] and olfaction[91] appear to be more strongly driven by feeding ecology and a likely place to start might be sampling ecological variation in light and smell relative to a species' dietary preferences. Much work has been done on ecologically salient color variation relative to foraging and eating behaviors[143] but very little on ecologically salient odors. Given the temporally and spatially dynamic nature of odors, assessing signal-to-noise in an odorscape would be highly challenging. Audition is more strongly guided by sociability[53] and assessing signal-to-noise ratios across time and during periods of specific activity might help determine ecologically salient noises. The sensory ecology of primates is a rich field of study, but temporal constraints are tightening for studies focused on the human primate—traditional economies are increasingly becoming integrated into market economies and their associated sensory toll.

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