Brief Communication

How Evolutionary History and Physical Constraints Shaped Human Sensory Perception of Mechanical Waves and Electromagnetic Radiation

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ABSTRACT

Human sensory perception operates within narrow and well-defined ranges of mechanical waves (approximately 20 Hz–20 kHz for sound) and electromagnetic radiation (roughly 400–700 nm for visible light). These limits are not arbitrary; rather, they reflect evolutionary trade-offs shaped by ecological relevance, anatomical feasibility, metabolic cost, and the physical properties of the environment. This review examines how such constraints have influenced the evolution of human sensory systems in comparison with those of other species. Human hearing is tuned to frequencies relevant for communication and environmental awareness, supported by anatomical specializations such as the ossicular chain and coiled cochlea. Human vision is similarly restricted to a spectral window that coincides with peak solar irradiance and efficient atmospheric transmission, allowing effective photon detection without the energetic burden of broader spectral sensitivity. Comparative examples from echolocation in bats to infrared sensing in pit vipers demonstrate how sensory systems can diverge dramatically under different ecological pressures. Importantly, the absence of direct sensory perception does not imply the absence of biological interaction with environmental stimuli. In some contexts, organisms exhibit physiological or cellular adaptations rather than sensory awareness. Using populations exposed to elevated natural background radiation as a case study, we evaluate the hypothesis that the lack of evolved sensory organs for ionizing radiation may reflect limited evolutionary advantage for conscious detection rather than biological irrelevance. Overall, sensory systems emerge as energy-efficient solutions for detecting ecologically meaningful signals within strict physical and biological limits.

Keywords

Sensory Perception; Evolution; Biological Adaptation; Selection; Auditory Perception; Electromagnetic Radiation; Echolocation

Introduction

Human sensory experience is confined to relatively narrow bands of mechanical and electromagnetic stimuli. Auditory perception typically spans frequencies between approximately 20 Hz and 20 kHz, while vision is limited to electromagnetic wavelengths between roughly 400 and 700 nm [1, 2]. These bounds are often perceived as natural or inevitable, yet they represent the outcome of evolutionary processes shaped by environmental structure, physical laws, and

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biological constraints. Rather than reflecting the full range of stimuli present in nature, sensory systems sample only a small fraction of available information specifically, information that has proven useful for survival and reproduction [3, 4].

This paper synthesizes evidence from evolutionary biology, sensory physiology, and comparative ecology to examine how such limitations arise. We emphasize that sensory systems are not optimized for completeness, but for **ecological relevance and energetic efficiency**. While organisms can respond biologically to stimuli outside their perceptual range, conscious sensory detection is most likely to evolves when it confers an adaptive advantage. Comparative examples across taxa illustrate how different ecological pressures lead to distinct sensory solutions, while also highlighting common constraints imposed by physics and metabolism.

Material and Methods

This study was conducted as a narrative, non-systematic review of the literature. Relevant publications in the fields of evolutionary biology, sensory physiology, biophysics, and comparative ecology were identified through searches in PubMed, Web of Science, and Google Scholar. The analysis focused on theoretical, experimental, and comparative studies addressing physical and evolutionary constraints on sensory systems. No experimental procedures or human/animal subjects were involved. The selected studies were qualitatively analyzed and synthesized to support a conceptual discussion on the evolutionary limitation of human sensory perception, including the absence of sensory detection mechanisms for ionizing radiation.

Results

Section 1. Human Auditory Perception (20 Hz–20 kHz)

Human hearing is sensitive to a frequency range that overlaps strongly with human speech and many biologically relevant environmental sounds [5, 6]. This range reflects both ecological utility and mechanical constraints of the auditory apparatus. The middle ear ossicles efficiently transmit airborne sound vibrations to the inner ear, while the tonotopically organized cochlea enables frequency discrimination within this limited band [7].

Although other species detect much higher or lower frequencies, expanding auditory sensitivity would require significant changes in receptor mechanics and neural processing. Frequencies outside the human range may have offered limited additional survival benefit relative to their energetic and anatomical cost. Thus, the stability of the auditory range across human populations suggests long-standing selective balance rather than arbitrary limitation [8].

Section 2. Human Visual Perception (400–700 nm)

Human vision is restricted to a narrow region of the electromagnetic spectrum that coincides with high solar irradiance and efficient atmospheric transmission [9]. This spectral window is particularly informative in terrestrial environments, where reflected visible light conveys critical information about object boundaries, motion, and biological signals such as fruit ripeness or vegetation health [3].

Extending vision into ultraviolet or infrared wavelengths would require different photoreceptor chemistries and optical media, potentially increasing metabolic cost while offering uncertain ecological benefit for ancestral humans [10, 11]. Although some species have evolved sensitivity beyond the visible range, these adaptations reflect niche-specific advantages rather than a general evolutionary trajectory.

Section 3. Comparative Sensory Adaptations Across Species

Species occupying specialized ecological niches often evolve sensory systems that differ markedly from those of humans. Bats and dolphins employ ultrasonic echolocation to navigate and hunt in environments where vision is limited [12]. Pit vipers detect infrared radiation via specialized pit organs, enabling the localization of warm-blooded prey in darkness [13]. Elephants communicate over long distances using low-frequency infrasound that propagates efficiently through air and ground. Aquatic predators such as sharks and platypuses rely on electroreception to detect weak bioelectric fields produced by prey [14].

These examples demonstrate that sensory evolution is **context-dependent**. When specific environmental challenges make certain signals reliable and valuable, selection can favor highly specialized sensory organs. Conversely, in the absence of such pressures, such systems are less likely to evolve even if the physical stimulus is present.

Section 4. Absence of Sensory Detection Versus Biological Interaction: The Case of Ionizing Radiation

Humans lack sensory organs for detecting ionizing radiation such as X-rays or gamma rays. One possible explanation is that natural background levels of such radiation have historically been too low or too sporadic to require immediate behavioral responses. Unlike sound or light, ionizing radiation does not typically convey spatially or temporally structured information that could guide adaptive behavior [15].

As illustrated in Figure 1, populations exposed over many generations to elevated natural background radiation have not evolved dedicated sensory mechanisms for radiation detection. This observation is conceptually analogous but not mechanistically equivalent to sensory regression in cave-dwelling fish, where the absence of light renders vision non-informative and leads to the relative enhancement of other sensory modalities. By contrast, ionizing radiation does not convey actionable navigational or behavioral information, even when present at very high natural levels (for example, annual doses reported to reach ~260 mSv in certain Ramsar high-background radiation areas). Consequently, the evolution of conscious radiation perception offers little adaptive advantage, potentially favoring cellular and molecular responses such as DNA repair and stress-response mechanisms [15].

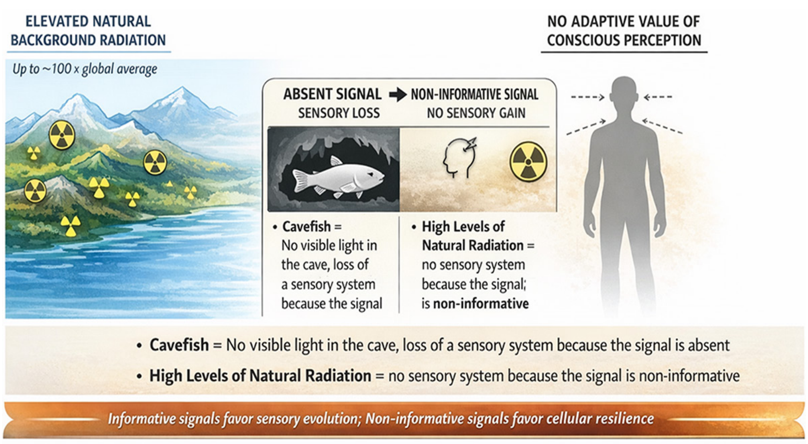

Figure 1: Populations chronically exposed to high natural radiation have not evolved radiation-sensing mechanisms, as ionizing radiation provides no actionable behavioral information. This is conceptually analogous to vision loss in cavefish, where absent light renders vision non-informative. Consequently, adaptation may favors cellular and molecular resilience such as enhanced DNA repair rather than sensory perception.

Discussion

Section 1. Evolutionary and Physical Constraints on Sensory Systems

Sensory systems are constrained by multiple interacting factors. First, **physical laws** govern how mechanical waves propagate and how electromagnetic radiation interacts with matter [2]. Second, **anatomical feasibility** limits the size, structure, and sensitivity of receptors that can be built by biological tissues. Third, **energetic cost** plays a central role: sensory organs and neural processing are metabolically expensive, and selection tends to favor systems that provide sufficient information at minimal cost [16].

As a result, evolution does not favor maximal sensory bandwidth, but rather **selective sensitivity** to signals that are reliably present in the environment and informative for behavior. Signals that are rare, weak, heavily filtered by the environment, or difficult to transduce biologically are less likely to drive the evolution of dedicated sensory organs.

Section 2. Why Sensory Range Expansion Is Limited

Several factors constrain the expansion of sensory ranges. Detecting long-wavelength radio waves would require antenna-like structures far larger than the human body, while sensing ionizing radiation would necessitate molecular-scale detectors capable of registering sparse, stochastic events [2]. Moreover, increasing sensory input imposes downstream costs in neural processing, storage, and interpretation [16].

Environmental filtering further reduces selective pressure. Many wavelengths are absorbed or scattered by the atmosphere or biological tissues, limiting their availability as reliable signals [9]. Together, these constraints explain why most organisms, including humans, operate within narrow sensory bandwidths despite the vast range of physical stimuli in the environment.

Section 3. Hypothesis: Lack of Sensory Organs Reflects Limited Adaptive Value

Populations living for generations in regions with elevated natural background radiation sometimes up to two orders of magnitude above global averages have not evolved dedicated sensory organs for radiation detection. One hypothesis is that this absence suggests that such radiation levels, while biologically interactive, did not impose selective pressure favoring conscious perception. Instead, any adaptive responses would be expected to occur at the cellular or molecular level, such as enhanced DNA repair or stress-response pathways [15].

This hypothesis draws a **conceptual analogy** not a mechanistic equivalence to cave-dwelling fish such as *Astyanax mexicanus*, which have lost functional vision while enhancing non-visual sensory systems. In cavefish, the absence of light made vision useless, while mechanosensory and olfactory cues became more informative. By contrast, ionizing radiation does not provide navigational or behavioral cues, even when present at elevated levels, limiting the potential benefit of sensory awareness.

Section 4. Evaluation of Hypothesis Strength

The strength of this hypothesis is **moderate but limited**. Its plausibility lies in established evolutionary principles: sensory systems evolve only when perception enables adaptive behavior. However, evidence supporting evolutionary adaptation to high background radiation in humans remains inconclusive and controversial. Existing studies are limited in size and scope, and alternative explanations such as phenotypic plasticity or non-adaptive tolerance cannot be excluded.

Importantly, the absence of sensory detection should not be interpreted as evidence that radiation is harmless. Rather, it suggests that **selection did not favor perceptual mecha-**

nisms, likely because perception would not improve survival outcomes. This distinction is critical: biological interaction can occur without sensory awareness, and adaptation need not involve perception.

Section 5. Technological Extension of Human Perception

Although biological evolution constrains natural sensory systems, humans have developed technologies that extend perception far beyond innate limits. Instruments such as radio telescopes, infrared cameras, and radiation detectors translate otherwise imperceptible stimuli into forms accessible to human senses [17-19]. These tools effectively decouple perception from biology, allowing humans to explore physical domains that played no role in shaping our sensory evolution [20-22].

Conclusion

Human sensory perception reflects an evolutionary compromise shaped by ecological relevance, physical constraints, and metabolic cost. The narrow ranges of hearing and vision are not deficiencies but effective solutions to ancestral environmental challenges. Comparative biology reveals that radically different sensory systems can evolve under different ecological pressures, while the absence of perception such as for ionizing radiation does not preclude biological interaction or adaptation.

Understanding these constraints clarifies that human perception is not a universal measure of reality, but a species-specific interface with the environment. As technology continues to expand this interface, it offers new ways to probe aspects of the physical world that were never part of our evolutionary past.

Authors' Contribution

F. Zaker conceptualized the study, made a substantial contribution to data collection, drafted the major sections of the manuscript, and critically revised the content. SMJ. Mortazavi contributed to the study design, participated substantially in data collection, drafted and organized significant parts of the manuscript, performed scientific editing, critically reviewed the manuscript, conducted the final proofreading and corrections, and assumed responsibility for the integrity and accuracy of the content. M. Hashemizadeh and M. Arshadi contributed to the writing and critical review of the manuscript. All the authors read, modified, and approved the final version of the manuscript.

Conflict of Interest

SMJ. Mortazavi, as the Editorial Board Member, was not involved in the peer-review and decision-making processes for this manuscript.

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