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Reframing neuroergonomics in an evolutionary and active inference context

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Everyday situations, such as feeling nauseous in virtual-reality environments or getting dizzy when reading as a car passenger, reveal how easily our senses can become confused when modern technology disrupts the innate relationship between the physical environment and human sensory systems. Such disruptions expose the vulnerability of the human senses to conflicting input arising in technologically altered environments. Even in the absence of direct sensory conflict, in complex technological settings such as digital factories and modern operating rooms, the convergence of multiple competing stimuli within and across sensory modalities further amplifies sensory load and cognitive strain. The common denominator of all such problems is that our ancient sensory processing and perceptual systems do not fit well with the technological world we have created. This evolutionary mismatch is already significant, but it will become even more critical as mixed reality concepts and advanced digital technologies integrate more deeply into our daily lives. Focusing on sensory mismatch and sensory strain as two significant ramifications of the Anthropocene, we reframe neuroergonomics in an evolutionary and active inference context. Our reframing argues that neuroergonomics must prioritize technology design that respects evolutionarily tuned priors, and should additionally deploy measured epigenetic, gene–culture, and learning-driven interventions as complementary levers to support adaptive change. Thus, we highlight the importance of aligning and grounding neuroergonomic design with the human sensory system according to constraints and affordances defined by human evolutionary history.

KEYWORDS

active inference, evolution, multisensory processing, neuroergonomics, sensory conflict, sensory strain

1 Introduction

The Anthropocene, a term referring to our current era within the geological epoch of the Holocene, has reconfigured landscapes and their multisensory signatures: changes in land-use, infrastructure and material culture alter auditory, visual, somatosensory and chemosensory properties of environments across nested spatial and temporal scales (Pijanowski et al., 2011; Schafer, 1977). Contemporary landscapes carry layered acoustic

emissions from people, vehicles and industry; transformed visual texture from built structures and lighting; altered somatosensory affordances via engineered surfaces and vibration transmission; and reworked olfactory baselines from novel emissions and disrupted biogenic sources. These parallel changes increase multisensory background “noise”, elevate cross-modal masking and source ambiguity, and shift the ecological statistics to which human perceptual systems are adapted (Pijanowski et al., 2011; Stein, 2012).

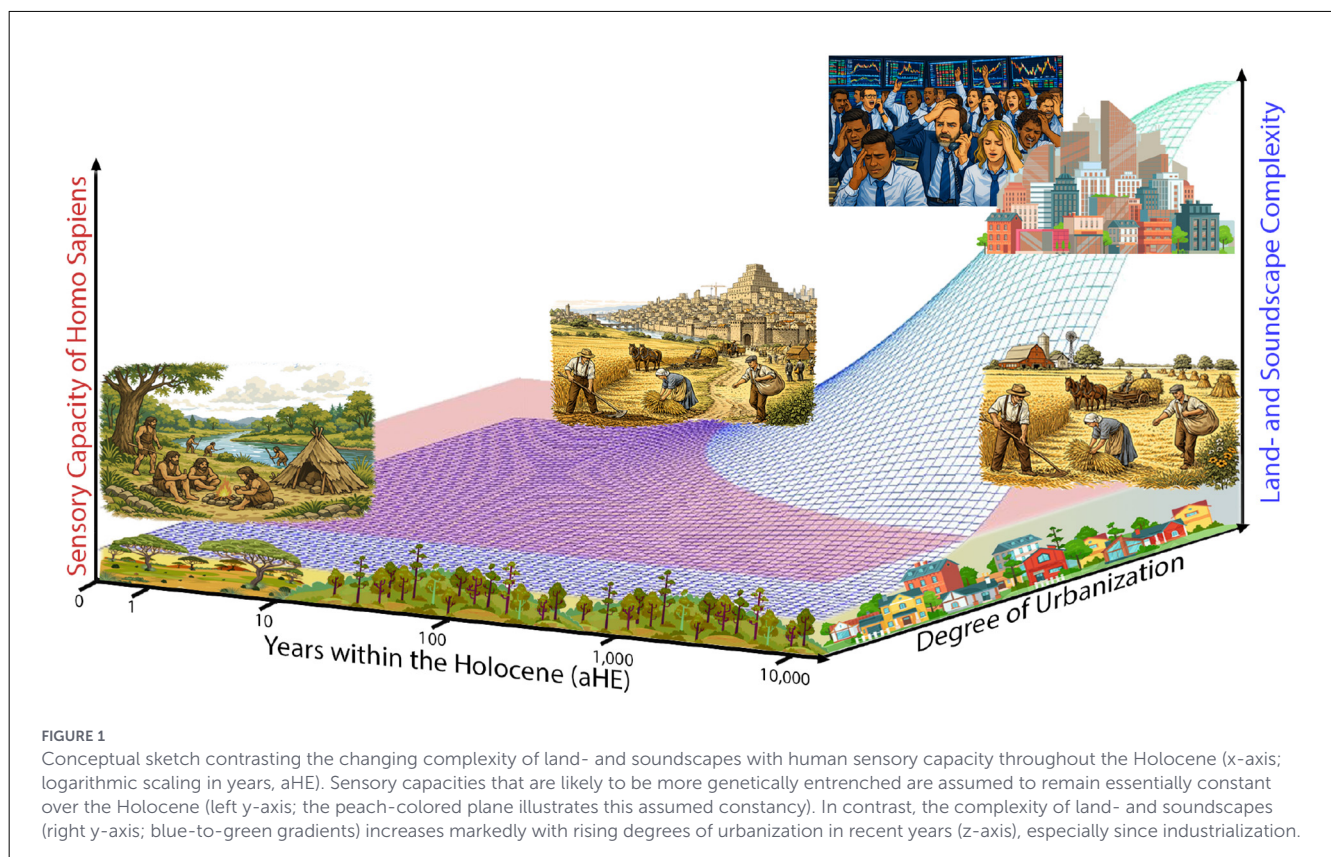
Each modality supplies complementary information for ecological active inference: audition for distant temporal events, vision for spatial layout and object identity, touch for substrate vibration and contact confirmation, and olfaction for slow, affect-rich chemical context (Ghazanfar and Schroeder, 2006; Herz, 2004). Landscape change is heterogeneous in scale and time: broad land-cover conversion alters ambient spectral and olfactory baselines over seasons to decades, while localized infrastructure (roads, industrial sites, ventilation, signage) creates point sources with steep spatial gradients and rapid temporal fluctuations that dominate local perception (Pijanowski et al., 2011; Kang and Schulte-Fortkamp, 2016).

Multisensory interactions are asymmetric and context dependent: congruent cues reduce uncertainty and improve detection and localization, whereas asynchronous or competing cues induce false binding, attentional capture and degraded inference (Calvert et al., 2004; Stein, 2012). Common landscape mismatches such as visually natural scenes paired with persistent industrial acoustic or vibratory signatures, or engineered lighting

regimes that conflict with olfactory and acoustic baselines, violate ecological priors and can alter navigation, habitat choice, stress responses and place attachment (Pijanowski et al., 2011; Herz, 2004).

Crucially, cultural and technological change has accelerated the transformation of multisensory environments far faster than biological evolution can accommodate. In Pleistocene environments, when many human perceptual priors were shaped, attending to non-human signals (predator calls, prey movement, wind, substrate vibration) was central to survival and coordinated action (Tooby et al., 1992). Rapid cultural niche construction has since altered multisensory statistics and affordances within mere generations, producing an evolutionary mismatch: integrative mechanisms tuned to ancestral statistics now operate in worlds with novel spectral content, temporal dynamics and engineered affordances (Boyd and Richerson, 1985; Pijanowski et al., 2011). As a result, modern multisensory urban landscapes may be both quantitatively richer and qualitatively different from those that shaped our perception. Cultural evolution has outpaced biological evolution by far, creating mismatches between evolved multisensory priors and present-day informational demands, see Figure 1.

By foregrounding sensory conflict and sensory strain in this perspective, we place neuroergonomics in an evolutionary perspective that recognizes how the multisensory landscapes of the Pleistocene differ from those of the Anthropocene and how this divergence affects perception, behavior and wellbeing.



2 Spatiotemporal symphony of the senses

We present a heuristic framing in which human perception is described as arising from the interaction between relatively stable, evolutionarily biased mechanisms (the “core”) and a set of modulatory, context-sensitive processes (the “mantle”). We adopt the “core” vs. “mantle” terminology as a pragmatic heuristic to capture differing degrees of stability and plasticity; these labels are intended to guide empirical inquiry rather than to assert a strict, immutable partition (see Figure 2, right), and they highlight different degrees of stability and plasticity as well as different functional emphases (species-typical biases vs. context-dependent modulation), rather than implying a strict anatomical or ontological partition. The “core” denotes *species-typical* biases that shape baseline priors for multisensory inference; the “mantle” denotes plastic, experience-dependent processes of *individual humans* (including learning, neuromodulatory gating, myelin and synaptic plasticity, and environmentally mediated epigenetic regulation) that tune those priors across development and context. Contemporary evidence emphasizes continuous, bidirectional interactions between predisposition

and experience (e.g., see Holtmaat and Svoboda, 2009; Ribic, 2020); accordingly, the boundary between “core” and “mantle” is porous and dynamic, and the terms should be read as pragmatic distinctions to aid exposition rather than as rigid scientific demarcations.

Many traits that we describe as part of the “core” reflect adaptations shaped in ancestral environments and continue to bias perception today. Given that evolution is extremely slow compared to the development of human culture and technology, it is reasonable to assume that a prehistoric *Homo sapiens* during the Upper Paleolithic (about 50,000 BCE) had a genetic makeup broadly similar to that of modern humans. From hunter-gatherers to ancient civilizations to contemporary societies, many species-typical tendencies persist. For example, humans are highly sensitive to unexpected sounds outside the visual field (Mobbs et al., 2015; Strauss et al., 2020; Olszanowski et al., 2023; Schroerer et al., 2023, 2024), to peripheral motion (Yantis and Jonides, 1984), and to social-affective cues in faces (Taubert et al., 2017); tendencies that plausibly reflect priors shaped by past ecological demands (Tooby et al., 1992; Dosen and Ostwald, 2016; Corbetta and Shulman, 2002). These predispositions are not immutable: they interact continuously with learning and other

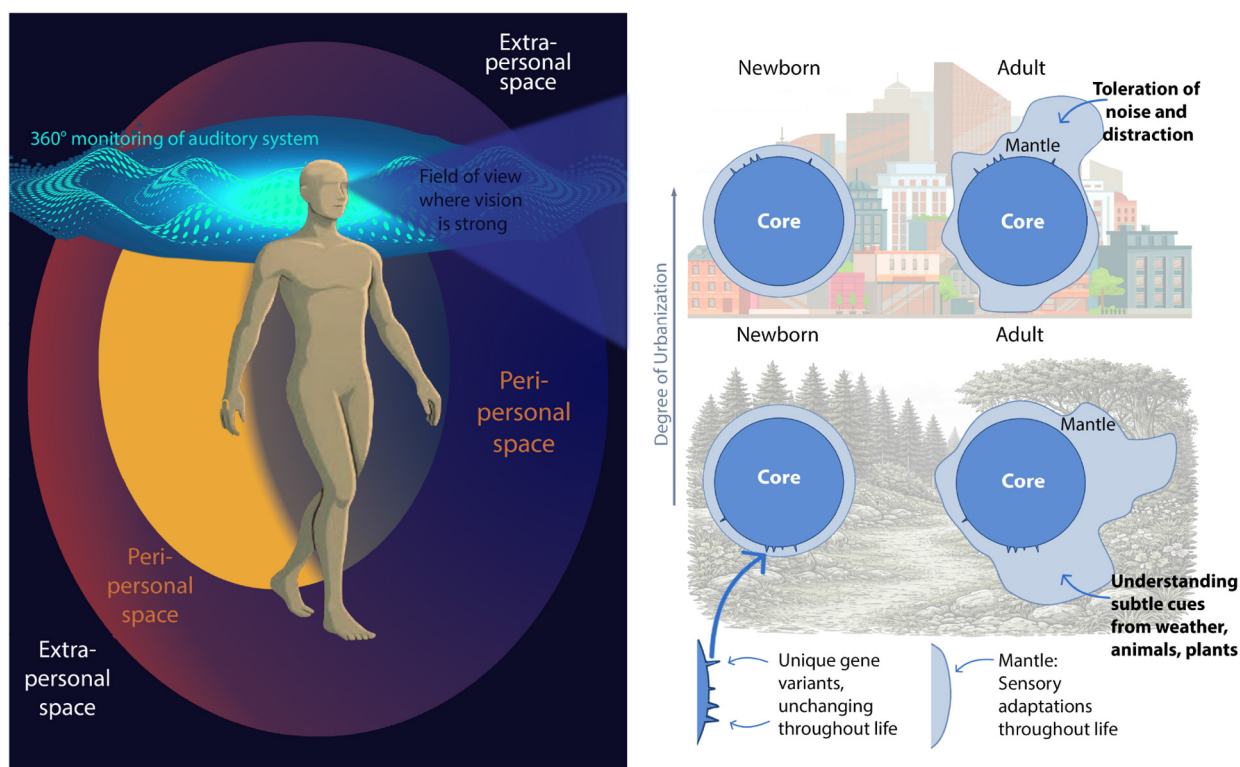


FIGURE 2

(Left) The spatial dynamics of genetically entrenched auditory, visual, and somatosensory systems: the 360° acoustic monitoring of the auditory system, sharp visual resolution within the field of view, and the peripersonal space with its strong visuo-tactile integration (see Rabellino et al., 2020) of humans. (Right) A speculative and heuristic illustration of the distinction between two conceptual layers that may affect human perception and cognition: The “core” shared by the whole species that features only small individual differences and that changes over evolutionary time scales, and the “mantle” of individual differences acquired over a life-time. Two humans in very different environments will begin life very similar and then their mantles diverge through modulatory influences.

modulatory mechanisms described below, so that evolutionary heritage and lifetime experience jointly shape perceptual inference and behavior.

2.1 The core: genetically entrenched concepts

Human multisensory architecture is anchored by a set of evolutionarily conserved, genetically biased mechanisms that provide the primary scaffold for perception and attention. These mechanisms represent the “species-level defaults,” the “core” of sensory integration in humans, shaping how information is weighted and combined across modalities. Several key features illustrate this foundational tier. First, 360° auditory monitoring provides continuous, omnidirectional surveillance of the environment, enabling detection of salient events outside the visual field and supporting rapid orienting toward potential threats or opportunities (Ignatiadis et al., 2025; Strauss et al., 2020; Olszanowski et al., 2023; Strauss et al., 2025). Second, early-developing vestibular–proprioceptive coupling stabilizes posture and establishes spatial reference frames, ensuring that movement and orientation are grounded in reliable bodily signals (Merfeld et al., 1999). Third, privileged foveal visual processing supplies high-resolution spatial detail in human vision, allowing fine-grained discrimination of objects and events within the central field (Spencer and Polich, 1999; Findlay and Gilchrist, 2003). Fourth, body-centered peri-personal multisensory mapping links touch, vision, and action to create an integrated representation of the space immediately surrounding the body (Noel et al., 2018). See Figure 2 (left) for a spatial mapping of these senses, which is pertinent to neuroergonomic design. Finally, the spatiotemporal symphony of the rapid cross-modal orienting responses in humans, involving these senses, is tuned to salient, behaviorally relevant events, enabling swift shifts of attention when survival or task demands require it (Calvert et al., 2000; Spence et al., 1998; Calvert et al., 2004; Strauss et al., 2024; Thinnies et al., 2025).

Of note, many features we describe as part of the “core” are plausibly shaped by evolutionary pressures and therefore may bias perception across contexts, but these tendencies should be treated as probabilistic predispositions that interact continuously with cultural and developmental influences. This means that there is a relationship between perception and cognition and our genes. Such bridges between psychology and genetics are notoriously difficult to reveal, but some clues can be found by harnessing neurodiversity. Outliers in cognitive tasks could also be outliers with respect to their gene variants, thus revealing the links (Parasuraman and Rizzo, 2007; Parasuraman, 2013). For example, people who show exceptional performance in reaction time, working memory, or visual attention were found to exhibit special genetic variants for certain proteins involved in brain activity (Greenwood et al., 2012, 2009; Parasuraman et al., 2012; Lancaster et al., 2017). These findings offer first glimpses into how our perception and thinking are influenced by our genes. But, of course, there is not only nature, but also nurture. The next section is concerned with influences other than genes, that shape us individually during our lifetimes.

2.2 The mantle: genetic, epigenetic, and experience-driven modulations

A distinct, superimposed set of influences, here grouped as modulatory processes, continuously tune, amplify, or attenuate the genetically entrenched scaffold across development, populations, and contexts, see Figure 2 (right). This category subsumes (1) epigenetic regulation, which gates gene expression and sensitive-period timing in response to early environment and activity; (2) gene–culture co-evolution, where persistent cultural practices and sensory ecologies create selection pressures that shift population-level priors over generations; and (3) individual learning and adaptation, spanning rapid synaptic reweighting, intermediate consolidation, and long-term cortical remapping (Ashe and Colot, 2021; Hawks et al., 2007; Gintis, 2011; Boduroglu and Shah, 2017; Jurkat et al., 2020; Laland et al., 2010). Epigenetic mechanisms (DNA methylation, histone modification, non-coding RNAs) mediate how environmental inputs and activity patterns alter the expression of genes relevant for synaptic plasticity and sensory system development, thereby modulating sensitive periods and lifelong responsiveness (Ashe and Colot, 2021; Kleim and Jones, 2008). This is why although identical twins begin life with the same genetic sequence, they diverge over time due to epigenetic modifications. Factors like diet, stress and lifestyle will influence how strongly genes are expressed, resulting in different health and disease susceptibility outcomes such as skin cancer or type 2 diabetes. Gene–culture feedback loops operate over generations by changing the sensory contexts in which selection acts (e.g., acoustic, visual, dietary, and tool-use environments), producing slow shifts in population priors that coexist with rapid, individual-level plasticity (Hawks et al., 2007; Gintis, 2011; Laland et al., 2010; Boyd et al., 2013). A classic example of gene culture co-evolution is (loss of) lactose intolerance: While most mammals lose the ability to digest milk after weaning, human populations that adopted dairy farming favored mutations allowing lifelong lactase production making milk consumption a genetic and cultural adaptation.

Learning and adaptation operate on multiple time scales—fast trial-by-trial reweighting, medium-term consolidation of perceptual skills, and slow representational restructuring—and should be parameterized explicitly as context- and history-dependent adjustments to the baseline priors, with quantifiable uncertainty (Kleim and Jones, 2008; Boduroglu and Shah, 2017). Learning to play a musical instrument encompasses all the stages. In the fast learning phase, the player corrects trial by trial mistakes by adjusting finger movements. With repeated practice, skills consolidate and playing becomes smoother. Finally, slow learning appears over years as musicians restructure mental representations, moving from memorizing notes to understanding harmony and improvising.

3 Sensory conflict and strain in our modern life

This section examines how the demands of contemporary environments challenge the coherence of our multisensory systems in neuroergonomics. Everyday technologies and immersive media

frequently generate sensory conflict, where incongruent inputs across modalities disrupt perception and induce discomfort. Beyond conflict, modern contexts also impose sensory strain, the cumulative burden of sustaining attention and recalibrating precision weights under noisy or demanding conditions, see also [Karwowski \(2006\)](#). To move beyond isolated accounts, this section culminates in Unifying Sensory Conflict and Strain Using Active Inference, offering a framework that integrates these phenomena into a single explanatory model of how the brain negotiates stability in complex, multisensory worlds.

3.1 Sensory conflict

Sensory conflict or sensory mismatch, defined as a violation of expected regularities in sensory input ([Treisman, 1977](#); [Bertolini and Straumann, 2016](#)), has been a recurrent phenomenon since *Homo sapiens* began developing technologies to facilitate daily life, particularly in the context of mobility—from ships (seasickness) to automobiles (motion sickness). A common example is the experience of nausea when reading as a passenger in a moving car: the visual system conveys a state of rest, while the vestibular system detects motion, resulting in a conflict that induces discomfort. Converging evidence suggests that the only “explanation” available to our ancient brain structures for such sensory mismatch is intoxication ([Nalivaiko et al., 2014](#); [Bertolini and Straumann, 2016](#); [Schneider et al., 2022](#)). Simulated interactive environments such as vehicle simulators and mixed reality worlds can push cybersickness to an extreme, either intentionally or unintentionally. Thus, they also provide excellent, highly controlled, multisensory contexts with which to study the origins, consequences, and individual differences in response to sensory conflict, allowing us to examine, for example, both general susceptibility and individual differences in habituation capacity to nausea ([Laessoe et al., 2023](#); [Buchheit et al., 2021](#); [Schneider et al., 2022](#); [Lehser et al., 2024](#)). These phenomena illustrate that sensory conflict is not only a perceptual anomaly but also a deeply embodied experience (see Section 2): cognition is inseparable from the body’s sensory systems and their interaction with the environment, e.g., see [Shapiro \(2011\)](#) and [Wöstmann and Obleser \(2026\)](#). Proprioception, the continuous sensing of body position and movement, is central here, as its alignment or misalignment with visual and vestibular cues can determine whether a situation feels stable or disorienting, see also [Limanowski and Friston \(2020\)](#). In this sense, embodied cognition offers a powerful lens for understanding why conflicts across modalities can so profoundly shape perception, action, and affective state. Although such mismatches are widespread, their generality across sensory domains and contexts, as well as the universal coping and compensation strategies humans employ, remain largely unexplored. This gap underscores the importance of neuroergonomic approaches that explicitly integrate embodied and proprioceptive dimensions into the study of human–technology interaction, which is particularly critical for virtual reality and emerging metaverse concepts ([Valori et al., 2020](#); [Bayramova et al., 2021](#)).

3.2 Sensory strain

The novel environments afforded by the Anthropocene, increasing exponentially in number and variety, exert profound effects on human attention and the allocation of perceptual and cognitive resources within our digital, information-driven society ([Stevens, 2013](#); [Gazzaley and Rosen, 2016](#); [Citton, 2017](#)). Contemporary life is characterized by AI-driven systems, digital media platforms, and global networks of individuals competing for attentional engagement. When designing these attention-demanding technologies, the evolutionary foundations of the human attentional system, shaped under the ecological constraints of hunter-gatherer environments, are frequently overlooked. In environments where humans collaborate with machines such as Internet-of-Things (IoT) factory infrastructures or highly digitized operating rooms ([Sendelbach, 2012](#)), attention-grabbing stimuli often attempt to organize communication with the machines. However, even when optimized for a single device or interaction modality, the simultaneous presence of multiple machines and overlapping stimuli can generate a cacophony of alerts that induce strain. Moreover, the abundance of stimuli signaling opportunities (real or illusory) presented by our digital companions negatively impacts our mental health (e.g., see [Gazzaley and Rosen, 2016](#); [Citton, 2017](#)). From an evolutionary perspective, attentional challenges remain insufficiently studied, and current approaches to neuroergonomic “attention assistance” technologies within regulatory frameworks are still underexplored. Future research should investigate how design and regulation can integrate evolutionary insights into attentional support technologies, ensuring that digital systems align more closely with human cognitive capacities, whether genetically entrenched (Section 2.1) or modulatory (Section 2.2).

4 Unifying sensory conflict and strain using active inference

Within a multimodal framework, sensory conflict and strain can be fruitfully modeled as natural expressions of active inference under the Free Energy Principle ([Friston, 2010](#)). Sensory conflict or mismatch arises whenever different modalities deliver incongruent information, producing prediction errors that signal that the brain’s generative model is insufficient to explain the current environment. For instance, when seeing but not feeling motion in virtual reality setups, the conflict with deeply entrenched physical regularities in the brain’s predictive model evokes the “full body response” of cybersickness, see Section 3.1. While for sensory conflict the connection to active inference and its generative brain-modeling approach is direct (see also [Limanowski and Friston, 2020](#)), it is more nuanced for sensory strain. Sensory strain reflects the adaptive, resource-intensive regulation required to stabilize inference under uncertainty: reallocating precision and attentional gain across modalities and spatiotemporal scales to sustain goal-directed perception and action in noisy, dynamic environments. This has recently been analyzed for the auditory modality in [Strauss et al. \(2025\)](#), using the unified exogenous- and endogenous-attention framework from [Parvizi-Wayne](#)

(2024). In particular, earlier models of attentional effort have been mapped to the free energy minimization framework that can be extended to multiple modalities (Strauss and Francis, 2017; Strauss et al., 2024). In a generative spatiotemporal scale space (Strauss et al., 2025), strain appears as coordinated control between the evolutionarily entrenched core (fast, local predictions and rapid exogenous adjustments) and higher, slower layers (abstract, forward-looking predictions and endogenous, reasoning-based loops). Precision-weight optimization determines which information streams are amplified or suppressed at each scale, depending on reliability, priors, and current goals (Feldman and Friston, 2010; Clark, 2013; Parvizi-Wayne, 2024; Strauss et al., 2025). Within the active-inference framework, minimizing uncertainty directly motivates the deployment of attentional effort (Sarter et al., 2006; Strauss and Francis, 2017) required to navigate sensory strain (see Feldman and Friston, 2010; Strauss et al., 2025). Operationally, this involves model updating, precision reweighting, and action/attention within an active inference framework, where attentional gain and noise suppression mechanisms enhance attended objects along the sensory pathways, and learned experiences modulate selection policies over time (Friston, 2010; Parr et al., 2022; Strauss et al., 2025). This perspective offers a concrete instantiation of this regulation: precision weights bias selection toward the target stream and away from distractors, integrating context and priors to maintain coherent tracking under load (Desimone and Duncan, 1995; Shinn-Cunningham, 2008; Trenado et al., 2009; Strauss et al., 2010). Strain, in this sense, is a graded expression of how much precision must be reallocated across the scale space to keep inference stable, increasing when distractor salience rises or when target predictability falls (Grossberg, 2005; Strauss and Francis, 2017; Parvizi-Wayne, 2024; Strauss et al., 2025). It also reflects the cost of maintaining long-horizon beliefs (e.g., conversational goals) against short-horizon exogenous overrides, with precision weights dynamically re-tuned as the (sensory) scene evolves (Clark, 2013; Parvizi-Wayne, 2024); see Strauss et al. (2025) for a specific example listening scenario. Because precision is context- and also experience-dependent (see Section 2.2), identical scenes can induce different strain profiles across individuals, as priors and learned contingencies shape the weighting of candidate streams and the thresholds for reallocation (Trenado et al., 2009; Strauss et al., 2010). Ultimately, sensory strain marks the ongoing effort of a unified, active inference system to minimize immediate and future surprise by continuously tuning precision across spatiotemporal scales by balancing rapid exogenous responses with sustained endogenous control to preserve perceptual stability in complex multisensory settings.

5 Implications for neuroergonomics

From this perspective, we argue that neuroergonomic design (Karwowski et al., 2003; Parasuraman, 2003; Karwowski, 2006; Parasuraman and Wilson, 2008; Salvendy and Karwowski, 2021) should adopt a first-principles approach to sensory processing, asking what environments human perceptual systems are originally

built for. Such an approach provides guidance on how best to support our senses in modern contexts and helps to clarify how all our senses can be used optimally to transfer information between humans, machines, and computers. Neuroergonomic approaches that unravel the responses of the central and autonomic nervous system to sensory conflict and strain, viewed from a unifying, evolutionary active inference perspective, enable us to study and understand underlying neuropsychological mechanisms such as crossmodal integration and attentional dynamics. For instance, sensory conflicts in virtual reality produce a cross-modal “semantic incongruity response” in the EEG signal (Lehser et al., 2024) that can be used to study the degree of fidelity and synchrony that must be achieved to maintain an immersive experience in mixed reality environments, see Strauss et al. (2024) or general evidence of sensory strain in mobile brain-body imaging studies (Gramann et al., 2011, 2010). In the car-sickness example (Section 3.1), such conflicts may be mitigated through sensory substitution, in which the missing visual information about the vehicle’s motion is conveyed via another sensory modality, e.g., see Schneider et al. (2026) for a virtual-haptics substitution approach. At the same time, the study of sensory conflicts can advance methods to decode human intentions, attentional focus, and affective states, thereby providing a principled foundation for designing human-centered technologies, e.g., in digital operating rooms (Thinnes et al., 2025) or industry 4.0 settings (Trapero et al., 2025). For example, neurotechnology-driven empathetic AI systems (McStay, 2024) are able to “read” human mental and emotional states by integrating signals related to cognition and affect acquired through neurotechnology, see Alarcao and Fonseca (2017) for EEG, Naseer and Hong (2015) for fNIRS, and Flotho and Strauss (2017), Flotho et al. (2023), and Bhamborae et al. (2025) for contactless, camera based methods. The availability of this information, and the ability to interpret it correctly, allows these systems to engage with human operators in a context-sensitive and state-adaptive manner, improving human-technology interaction, see also Gramann et al. (2021) and Bikson et al. (2024). Understanding the underlying cognitive and affective mechanisms and employing empathetic sensing can support a human-centered neuroergonomic design that might compensate for sensory mismatch and strain, thereby improving human-technology interaction despite increasing demands. For instance, such systems could pre-prioritize information in a context-sensitive manner and select the most appropriate sensory modality for its transfer. In a neuroergonomic digital operating room (see Thinnes et al., 2025), the system might recognize that a surgeon is visually engaged while following a pathway displayed through AR glasses and simultaneously auditorily engaged in conversation with the anesthetist. At the same time, it could detect context-sensitive risks, such as further cutting leading to nerve damage, and therefore choose the somatosensory modality to convey critical information via a haptic vest or smart textiles. Such examples extend to all environments in which digital systems generate large volumes of data, and this information can be harnessed to support humans with their limited attentional resources (see also Trapero et al., 2025). Moreover, Figure 2 (left) and our corresponding arguments also explain the haptic advantage for information transfer in Industry 4.0 and 5.0 settings

(Trapero et al., 2025), as haptic information transfer occurs within the most sensitive peri-personal space.

An implication of these findings, and the reason we introduce the distinction between core (species typical biases) and mantle (individual human), is that although we already understand certain regularities in human sensory and perceptual processing, current neuroergonomic knowledge is still far from sufficient to determine with confidence which mechanisms are evolutionarily entrenched and which can be reshaped through learning. We use this distinction as a pragmatic conceptual tool to highlight the empirical gaps that must be closed before design choices can be made with confidence. “Core” denotes perceptual and attentional constraints that appear resistant to short term change and that likely reflect genetically anchored operating ranges. “Mantle” denotes experience dependent, context sensitive modulatory processes underpinned by synaptic and neuromodulatory plasticity, attentional gain control, and reweighting of predictive priors; these are the components of perception and attention that can be altered by training, task demands, or changes in ecological statistics. At present the literature does not provide the systematic, causal and longitudinal evidence needed to map specific perceptual or attentional operations onto either category. This is precisely why the distinction is useful: it operationalizes the problem and motivates targeted experiments. A focused research program should therefore identify which features remain stable even after prolonged training, determine which features can be reweighted or habituated through immersive protocols, and map the timescales and transfer conditions for such plasticity. Learning and adaptation span rapid trial by trial tuning of sensorimotor loops, medium term consolidation of attentional routines, and slower representational restructuring, as illustrated in Figure 2 (right). Understanding which phases belong to core or mantle will guide whether systems should route critical information to evolutionarily robust modalities or invest in immersive VR training to teach users to manage sensory streams, habituate to specific conflicts, or reweight modalities for safer and more efficient interaction. And if future research is able to reveal more links between neurodiversity and specific gene variants (the individual genetic differences of the core), predictive power for outcomes of cognitive tasks might be gained. In short, the core-mantle distinction is a forward looking framework that makes visible what we do not yet know and directs research toward actionable knowledge for neuroergonomic design. Within the broader effort of unifying sensory conflict and strain through active inference, this distinction also highlights where future work must clarify how precision allocation, plasticity, and predictive control jointly shape the boundary between species typical constraints and individual level adaptation.

6 Conclusions

Future neuroergonomic research should adopt a first-principles, evolution-anchored approach to what environments humans are built for, especially given the growing sensory conflict and sensory strain that characterize the Anthropocene. This requires acknowledging that human perception operates

through both core, species-typical constraints and mantle-level, experience-dependent plasticity, which jointly determine how far sensory and attentional mechanisms can be adapted through training or technology in contexts that induce conflict or sustained strain. Design must therefore build on this dual structure, respecting genetically entrenched limits while leveraging modulatory learning processes to scaffold safe adaptation. Within a multimodal active inference framework, we show that sensory conflict and sensory strain can be fruitfully modeled, offering a unified theoretical framework while acknowledging that empirical validation across contexts is still needed. Advances in neurophysiological decoding and attention-aware modality selection may help mitigate these Anthropocene-specific pressures by dynamically prioritizing and routing information. This potentially yields more resilient and effective human-technology interactions that are better aligned with human perceptual and attentional capacities in increasingly complex environments.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

FC-S: Conceptualization, Formal analysis, Investigation, Methodology, Project administration, Supervision, Validation, Writing – original draft, Writing – review & editing, Visualization. JV: Conceptualization, Investigation, Methodology, Writing – original draft, Writing – review & editing. AF: Conceptualization, Investigation, Methodology, Writing – original draft, Writing – review & editing. ML: Investigation, Methodology, Writing – original draft, Writing – review & editing, Visualization. SM: Investigation, Methodology, Visualization, Writing – original draft, Writing – review & editing. DS: Investigation, Methodology, Writing – original draft, Writing – review & editing, Conceptualization, Formal analysis, Funding acquisition, Project administration, Resources, Supervision, Validation.

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Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The author(s) declared that generative AI was used in the creation of this manuscript. Some subpictures/icons in the larger Figures 1, 2 were generated or refined with AI. AI tools were also used to improve readability and clarity during drafting. All final content, analysis, interpretation, and conclusions remain the full responsibility of the author(s).

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References

- Alarcao, S., and Fonseca, M. J. (2017). Emotion recognition in eeg: a survey. *IEEE Trans. Affect. Comput.* 10, 374–393. doi: 10.1109/TAFFC.2017.2714671
- Ashe, A., and Colot, V., Oldroyd, B. P. (2021). How does epigenetics influence the course of evolution? *Philos. Trans. R. Soc. Lond. B Biol. Sci.* 376:20200111. doi: 10.1098/rstb.2020.0111
- Bayramova, R., Valori, I., McKenna-Plumley, P. E., Zandonella Callegher, C., and Farroni, T. (2021). The role of vision and proprioception in self-motion encoding: an immersive virtual reality study. *Attent. Percept. Psychophys.* 83, 2865–2878. doi: 10.3758/s13414-021-02344-8
- Bertolini, G., and Straumann, D. (2016). Moving in a moving world: a review on vestibular motion sickness. *Front. Neurol.* 7:14. doi: 10.3389/fneur.2016.00014
- Bhamborae, M., Schneider, E. N., Flotho, P., Francis, A., and Strauss, D. J. (2025). Lumed: image luminance based contactless correlates of electrodermal responses. *Physiol. Meas.* 13:025010. doi: 10.1088/1361-6579/adb369
- Bikson, M., Charvet, L., Pilloni, G., Dehais, F., and Ayaz, H. (2024). Neurotechnology for brain-body performance and health: insights from the 2022 neuroergonomics and nyc neuromodulation conference. *Front. Neuroergon.* 5:1454889. doi: 10.3389/fnrgo.2024.1454889
- Boduroglu, A., and Shah, P. (2017). Cultural differences in attentional breadth and resolution. *Cult. Brain* 5, 169–181. doi: 10.1007/s40167-017-0056-9
- Boyd, R., and Richerson, P. J. (1985). *Culture and the Evolutionary Process*. Chicago, IL: University of Chicago Press.
- Boyd, R., Richerson, P. J., and Henrich, J. (2013). "The cultural evolution of technology: facts and theories," in *Cultural Evolution: Society, Technology, Language, and Religion*, Vol. 12, eds. P. J. Richerson and M. H. Christiansen (Cambridge, MA: MIT Press). doi: 10.7551/mitpress/9780262019750.003.000
- Buchheit, B., Schneider, E. N., Alayan, M., Dauth, F., and Strauss, D. J. (2021). Motion sickness prediction in self-driving cars using the 6dof-svc model. *IEEE Trans. Intell. Transport. Syst.* 23, 13582–13591. doi: 10.1109/ITITS.2021.3125802
- Calvert, G. A., Campbell, R., and Brammer, M. J. (2000). Evidence from functional magnetic resonance imaging of crossmodal binding in the human heteromodal cortex. *Curr. Biol.* 10, 649–657. doi: 10.1016/S0960-9822(00)00513-3
- Calvert, G. A., Spence, C., and Stein, B. E. (Eds.). (2004). *The Handbook of Multisensory Processes*. MIT Press. doi: 10.7551/mitpress/3422.001.0001
- Citton, Y. (2017). *The Ecology of Attention*. Hoboken, NJ: John Wiley & Sons.
- Clark, A. (2013). Whatever next? Predictive brains, situated agents, and the future of cognitive science. *Behav. Brain Sci.* 36, 181–204. doi: 10.1017/S0140525X12000477
- Corbetta, M., and Shulman, G. L. (2002). Control of goal-directed and stimulus-driven attention in the brain. *Nat. Rev. Neurosci.* 3, 201–215. doi: 10.1038/nrn755
- Desimone, R., and Duncan, J. (1995). Neural mechanisms of selective visual attention. *Annu. Rev. Neurosci.* 18, 193–222. doi: 10.1146/annurev.ne.18.030195.001205
- Dosen, A., and Ostwald, M. (2016). Evidence for prospect-refuge theory: a meta-analysis of the findings of environmental preference research. *City, Territ. Architect.* 3:4. doi: 10.1186/s40410-016-0033-1
- Feldman, H., and Friston, K. J. (2010). Attention, uncertainty, and free-energy. *Front. Hum. Neurosci.* 4:215. doi: 10.3389/fnhum.2010.00215
- Findlay, J. M., and Gilchrist, I. D. (eds.). (2003). *Active Vision: The Psychology of Looking and Seeing*. Oxford: Oxford University Press.
- Flotho, P., Heiss, C., Steidl, G., and Strauss, D. J. (2023). Lagrangian motion magnification with double sparse optical flow decomposition. *Front. Appl. Math. Stat.* 9:1164491. doi: 10.3389/fams.2023.1164491
- Flotho, P., and Strauss, D. J. (2017). "Quantitative motion analysis for non-contact affective and neurocognitive assessment," in *Neural Engineering (NER), 8th International IEEE/EMBS Conference on* (Piscataway, NJ: IEEE), 106–109. doi: 10.1109/NER.2017.8008303
- Friston, K. J. (2010). The free-energy principle: a unified brain theory? *Nat. Rev. Neurosci.* 11, 127–138. doi: 10.1038/nrn2787
- Gazzaley, A., and Rosen, L. D. (2016). *The Distracted Mind: Ancient Brains in a High-Tech World*. Cambridge, MA: MIT Press.
- Ghazanfar, A. A., and Schroeder, C. E. (2006). Is the neocortex essentially multisensory? *Trends Cogn. Sci.* 10, 278–285. doi: 10.1016/j.tics.2006.04.008
- Gintis, H. (2011). Gene-culture coevolution and the nature of human sociality. *Philos. Trans. R. Soc. Lond., B, Biol. Sci.* 366, 878–888. doi: 10.1098/rstb.2010.0310
- Gramann, K., Gwin, J., Ferris, D., Oie, K., Jung, T.-P., Lin, C.-T., et al. (2011). Cognition in action: imaging brain/body dynamics in mobile humans. *Rev. Neurosci.* 22, 593–608. doi: 10.1515/RNS.2011.047
- Gramann, K., Gwin, J. T., Bigdely-Shamlo, N., Ferris, D. P., and Makeig, S. (2010). Visual evoked responses during standing and walking. *Front. Hum. Neurosci.* 4:202. doi: 10.3389/fnhum.2010.00202
- Gramann, K., McKendrick, R., Baldwin, C., Roy, R. N., Jeunet, C., Mehta, R. K., et al. (2021). Grand field challenges for cognitive neuroergonomics in the coming decade. *Front. Neuroergonomics* 2:643969. doi: 10.3389/fnrgo.2021.643969
- Greenwood, P., Lin, M., Sundararajan, R., Fryxell, K., and Parasuraman, R. (2009). Synergistic effects of genetic variation in nicotinic and muscarinic receptors on visual attention but not working memory. *Proc. Nat. Acad. Sci. U. S. A.* 106:3633–3638. doi: 10.1073/pnas.0807891106
- Greenwood, P. M., Parasuraman, R., and Espeseth, T. (2012). A cognitive phenotype for a polymorphism in the nicotinic receptor gene chrna4. *Neurosci. Biobeh. Rev.* 36, 1331–1341. doi: 10.1016/j.neubiorev.2012.02.010
- Grossberg, S. (2005). "Linking attention to learning, expectation, competition, and consciousness," in *Neurobiology of Attention*, eds. L. Itti and J. Tsotsos (Burlington, NJ: Academic Press), 652–662. doi: 10.1016/B978-012375731-9/50111-7
- Hawks, J., Wang, E. T., Cochran, G. M., Harpending, H. C., and Moyzis, R. K. (2007). Recent acceleration of human adaptive evolution. *Proc. Natl. Acad. Sci. U. S. A.* 104:20753–20758. doi: 10.1073/pnas.070650104
- Herz, R. S. (2004). A naturalistic analysis of autobiographical memories triggered by olfactory, visual and auditory stimuli. *Cogn. Emot.* 18, 695–703. doi: 10.1093/chemse/bjh025
- Holtmaat, A., and Svoboda, K. (2009). Experience-dependent structural synaptic plasticity in the mammalian brain. *Nat. Rev. Neurosci.* 10, 647–658. doi: 10.1038/nrn2699

- Ignatiadis, K., Barumerli, R., Deco, G., Tóth, B., and Baumgartner, R. (2025). Threat-related corticocortical connectivity elicited by rapid auditory looms. *Sci. Rep.* 16:834. doi: 10.1038/s41598-025-30552-x
- Jurkat, S., Koster, M., and Yovsi, R. (2020). The development of context-sensitive attention across cultures: the impact of stimulus familiarity. *Front. Psychology* 11:1526. doi: 10.3389/fpsyg.2020.01526
- Kang, J., and Schulte-Fortkamp, B. (Eds.). (2016). *Soundscape and the Built Environment*. Boca Raton, FL: CRC Press; Taylor & Francis.
- Karwowski, W. (Ed.). (2006). *International Encyclopedia of Ergonomics and Human Factors, 2nd Edn.* 3 volumes. Boca Raton, FL: CRC Press.
- Karwowski, W., Siemionow, W., and Gielo-Perczak, K. (2003). Physical neuroergonomics: the human brain in control of physical work activities. *Theoret. Issues Ergon. Sci.* 4, 175–199. doi: 10.1080/1463922021000032339
- Kleim, J. A., and Jones, T. A. (2008). Principles of experience-dependent neural plasticity: implications for rehabilitation. *J. Speech Lang. Hear. Res.* 51, S225–S239. doi: 10.1044/1092-4388(2008/018)
- Laessoe, U., Abrahamsen, S., Zepernick, S., Raunsbaek, A., and Stensen, C. (2023). Motion sickness and cybersickness – sensory mismatch. *Physiol. Behav.* 258:114015. doi: 10.1016/j.physbeh.2022.114015
- Laland, K. N., Odling-Smee, J., and Myles, S. (2010). How culture shaped the human genome: bringing genetics and the human sciences together. *Nat. Rev. Genet.* 11, 137–148. doi: 10.1038/nrg2734
- Lancaster, C., Forster, S., Tabet, N., and Rusted, J. (2017). Putting attention in the spotlight: the influence of apoe genotype on visual search in mid adulthood. *Behav. Brain Res.* 334, 97–104. doi: 10.1016/j.bbr.2017.07.015
- Lehser, C., Hillyard, S. A., and Strauss, D. J. (2024). Feeling senseless sensations: a crossmodal EEG study of mismatched tactile and visual experiences in virtual reality. *J. Neural Eng.* 21:ad83f5. doi: 10.1088/1741-2552/ad83f5
- Limanowski, J., and Friston, K. (2020). Active inference under visuo-proprioceptive conflict: simulation and empirical results. *Sci. Rep.* 10:4010. doi: 10.1038/s41598-020-61097-w
- McStay, A. (2024). *Automating Empathy: Decoding Technologies That Gauge Intimate Life*. Oxford: Oxford University Press. doi: 10.1093/oso/9780197615546.001.0001
- Merfeld, D. M., Zupan, L., and Peterka, R. J. (1999). Humans use internal models to estimate gravity and linear acceleration. *Nature* 398, 615–618. doi: 10.1038/19303
- Mobbs, D., Hagan, C., Dalgleish, T., Silston, B., and Präfvo, C. (2015). The ecology of human fear: survival optimization and the nervous system. *Front. Neurosci.* 9:121062. doi: 10.3389/fnins.2015.00055
- Nalivaiko, E., Rudd, J. A., and So, R. H. Y. (2014). Motion sickness, nausea and thermoregulation: the “toxic” hypothesis. *Temperature (Austin)* 1, 164–171. doi: 10.4161/23328940.2014.982047
- Naseer, N., and Hong, K.-S. (2015). fnirs-based brain-computer interfaces: a review. *Front. Hum. Neurosci.* 9:3. doi: 10.3389/fnhum.2015.00003
- Noel, J.-P., Samad, M., Doxon, A., Clark, J., Keller, S., and Di Luca, M. (2018). Peripersonal space as a prior in coupling visual and proprioceptive signals. *Sci. Rep.* 8:15819. doi: 10.1038/s41598-018-33961-3
- Olszanowski, M., Frankowska, N., and Tolopilo, A. (2023). “Rear bias” in spatial auditory perception: Attentional and affective vigilance to sounds occurring outside the visual field. *Psychophysiology* 60:e14377. doi: 10.1111/psyp.14377
- Parasuraman, R. (2003). Neuroergonomics: research and practice. *Theoret. Issues Ergon. Sci.* 4, 5–20. doi: 10.1080/14639220210199753
- Parasuraman, R. (2013). “Neuroergonomics of individual differences in cognition: molecular genetic studies,” in *Neuroergonomics: A Cognitive Neuroscience Approach to Human Factors and Ergonomics* (Springer), 144–162. doi: 10.1057/9781137316523_8
- Parasuraman, R., de Visser, E., Lin, M., and Greenwood, P. (2012). Dopamine beta hydroxylase genotype identifies individuals less susceptible to bias in computer-assisted decision making. *PLoS ONE* 7:e39675. doi: 10.1371/journal.pone.0039675
- Parasuraman, R., and Rizzo, M. (eds.). (2007). “Introduction to neuroergonomics,” in *Neuroergonomics: The Brain at Work* (Oxford: Oxford University Press), 3–12. doi: 10.1093/acprof:oso/9780195177619.003.0001
- Parasuraman, R., and Wilson, G. F. (2008). Putting the brain to work: neuroergonomics past, present, and future. *Hum. Factors* 50, 468–474. doi: 10.1518/001872008X288349
- Parr, T., Pezzulo, G., and Friston, K. J. (2022). *Active Inference: The Free Energy Principle in Mind, Brain, and Behavior*. Oxford: MIT Press. doi: 10.7551/mitpress/12441.001.0001
- Parvizi-Wayne, D. (2024). How preference enslaves attention: calling into question the endogenous/exogenous distinction from an active inference perspective. *Phenomenol. Cogn. Sci.* doi: 10.1007/s11097-024-10028-5
- Pijanowski, B. C., Farina, A., Gage, S. H., Dumyahn, S. L., and Krause, B. L. (2011). Soundscape ecology: the science of sound in the landscape. *Bioscience* 61, 203–216. doi: 10.1525/bio.2011.61.3.6
- Rabellino, D., Frewen, P. A., McKinnon, M. C., and Lanius, R. A. (2020). Peripersonal space and bodily self-consciousness: implications for psychological trauma-related disorders. *Front. Neurosci.* 14:586605. doi: 10.3389/fnins.2020.586605
- Ribic, A. (2020). Stability in the face of change: lifelong experience-dependent plasticity in the sensory cortex. *Front. Cell. Neurosci.* 14:76. doi: 10.3389/fncel.2020.00076
- Salvendy, G., and Karwowski, W. (Eds.). (2021). *Handbook of Human Factors and Ergonomics*. John Wiley & Sons, Hoboken, NJ, 5th edition. doi: 10.1002/9781119636113
- Sarter, M., Gehring, W., and Kozak, R. (2006). More attention must be paid: The neurobiology of attentional effort. *Brain Res. Rev.* 51, 145–160. doi: 10.1016/j.brainresrev.2005.11.002
- Schafer, R. M. (1977). *The Tuning of the World: Toward a Theory of Soundscape Design*. New York, NY: Knopf.
- Schneider, E. N., Buchheit, B., Flotho, P., Bhamborae, M. J., Corona-Strauss, F. I., Dauth, F., et al. (2022). Electrodermal responses to driving maneuvers in a motion sickness inducing real-world driving scenario. *IEEE Trans. Hum.-Mach. Syst.* 52, 994–1003. doi: 10.1109/THMS.2022.3188924
- Schneider, E. N., Lehser, C., Buchheit, B., Alayan, M., and Strauss, D. J. (2026). Impact of noncontact tactile stimulation on motion-induced electrodermal responses and subjective motion sickness. *IEEE Trans. Hum.-Mach. Syst.* doi: 10.1109/THMS.2025.3644434
- Schroeder, A., Andersen, M. R., Rank, M. L., Hannemann, R., Petersen, E. B., Rønne, F. M., et al. (2023). Assessment of vestigial auriculomotor activity to acoustic stimuli using electrodes in and around the ear. *Trends Hear.* 27:23312165231200158. doi: 10.1177/23312165231200158
- Schroeder, A., Corona-Strauss, F. I., Hannemann, R., Hackley, S. A., and Strauss, D. J. (2024). The vestigial pinna-orienting system in humans briefly suppresses superior auricular muscle activity during reflexive orienting towards auditory stimuli. *J. Neurophysiol.* 132, 514–526. doi: 10.1152/jn.00024.2024
- Sendelbach, S. (2012). Alarm fatigue. *Nurs. Clin. North Am.* 47, 375–382. doi: 10.1016/j.cnur.2012.05.009
- Shapiro, L. (2011). *Embodied Cognition*. New York, NY: Routledge. doi: 10.5840/philtopics201139117
- Shinn-Cunningham, B. G. (2008). Object-based auditory and visual attention. *Trends Cogn. Sci.* 12, 182–186. doi: 10.1016/j.tics.2008.02.003
- Spence, C., Nicholls, M. E. R., Gillespie, N., and Driver, J. (1998). Cross-modal links in exogenous covert spatial orienting between touch, audition, and vision. *Percept. Psychophys.* 60, 544–557. doi: 10.3758/BF03206045
- Spencer, K. M., and Polich, J. (1999). Poststimulus EEG spectral analysis and P300: attention, task, and probability. *Psychophysiology* 36, 220–232. doi: 10.1111/1469-8986.3620220
- Stein, B. E. (ed.). (2012). *The New Handbook of Multisensory Processing*. Oxford: MIT Press. doi: 10.7551/mitpress/8466.001.0001
- Stevens, M. (2013). *Sensory Ecology, Behavior, and Evolution*. Oxford: Oxford University Press. doi: 10.1093/acprof:oso/9780199601776.001.0001
- Strauss, D. J., Corona-Strauss, F. I., Schroeder, A., Flotho, P., Hannemann, R., and Hackley, S. A. (2020). Vestigial auriculomotor activity indicates the direction of auditory attention in humans. *Elife* 9:e54536. doi: 10.7554/eLife.54536
- Strauss, D. J., Corona-Strauss, F. I., Trenado, C., Bernarding, C., Reith, W., Latzel, M., et al. (2010). Electrophysiological correlates of listening effort: neurodynamical modeling and measurement. *Cogn. Neurodyn.* 4, 119–131. doi: 10.1007/s11571-010-9111-3
- Strauss, D. J., and Francis, A. J. (2017). Toward taxonomic model of attention in effortful listening. *Cogn. Affect. Behav. Neurosci.* 17, 809–825. doi: 10.3758/s13415-017-0513-0
- Strauss, D. J., Francis, A. L., Schädler, Z., Latzel, M., Corona-Strauss, F. I., and Launer, S. (2025). Understanding speech in “noise” or free energy minimization in the soundscapes of the anthropocene. *Front. Neurosci.* 19:1534425. doi: 10.3389/fnins.2025.1534425
- Strauss, D. J., Francis, A. L., Vibell, J., and Corona-Strauss, F. I. (2024). The role of attention in immersion: the two-competitor model. *Brain Res. Bull.* 210:110923. doi: 10.1016/j.brainresbull.2024.110923
- Taubert, J., Wardle, S. G., Flessert, M., Leopold, D. A., and Ungerleider, L. G. (2017). Face pareidolia in the rhesus monkey. *Curr. Biol.* 27, 2505–2509. doi: 10.1016/j.cub.2017.06.075
- Thinnes, D., Trapero, J., Wagner, E., and Strauss, D. J. (2025). Neuroergonomics in digital operating rooms: applying the two-competitor model of attention to the surgical context. *IEEE Trans. Hum.-Mach. Syst.* 55, 765–776. doi: 10.1109/THMS.2025.3601222
- Tooby, J., Cosmides, L., and Barkow, J. H. (1992). *The Psychological Foundations of Culture*. vol 19. New York, NY: Oxford University Press, 1–136. doi: 10.1093/oso/9780195060232.003.0002
- Trapero, J. A., Thinnes, D., Wagner, E., and Strauss, D. J. (2025). Haptic vest-attention assistance for outside field-of-view guidance and enhanced human–robot interaction. *IEEE Trans. Indus. Informat.* doi: 10.1109/TII.2025.3635535

- Treisman, M. (1977). Motion sickness: an evolutionary hypothesis. *Science* 197:493–495. doi: 10.1126/science.301659
- Trenado, C., Haab, L., and Strauss, D. J. (2009). Corticothalamic feedback dynamics for neural correlates of auditory selective attention. *IEEE Trans. Neural Syst. Rehabil. Eng.* 17, 46–52. doi: 10.1109/TNSRE.2008.2010469
- Valori, I., McKenna-Plumley, P. E., Bayramova, R., Zandonella Callegher, C., Altoé, G., and Farroni, T. (2020). Proprioceptive accuracy in immersive virtual reality: a developmental perspective. *PLoS ONE* 15:e0222253. doi: 10.1371/journal.pone.0222253
- Wöstmann, M., and Obleser, J. (2026). Spatial attention emerges from complementary modulation of the neural alpha rhythm and head movements. *bioRxiv*. doi: 10.1101/2025.11.10.687554
- Yantis, S., and Jonides, J. (1984). Abrupt visual onsets and selective attention: evidence from visual search. *J. Exp. Psychol.: Hum. Percept. Perform.* 10:601. doi: 10.1037/0096-1523.10.5.601