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Sensory Signal Processing and Brain Imaging: From the 3D to 2D Neural Representation

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Abstract: The sensory system is extremely important to humans, allowing them to interact with their surroundings. The sensory system functions by converting external stimuli into neural signals, which subsequently undergo processing to generate coherent perceptions. Three-dimensional spatial and temporal information needs to be transformed into two-dimensional neural representations, and this transformation is the basis for understanding perception, as well as cognition and action. This review covers a number of discussions, including mechanisms of sensory coding in visual modalities, neural transmission in auditory modalities, and cortical representation in tactile modalities. Interactions between sensory systems, between multisensory integration, and between neuroplasticity will also be examined. In addition, challenges and future directions will be discussed to stimulate further research on sensory processing and its applications in neural engineering.

Keywords: Sensory Signal Processing, Multisensory Integration, Neuroplasticity

1. Introduction

The sensory system is extremely critical to humans. It helps humans to perceive and interpret their surroundings and also helps them to interact with their environment. These systems detect external stimuli, like light, sound as well as touch. They then convert these external stimuli into neural signals for the brain to process. Each sensory modality has specialized receptors and neural pathways. These receptors and neural pathways collaborate with each other to encode the spatial and temporal features of the external world [1-3].

How to precisely explore the conversion of complex 3D environmental stimuli into structured neural representations is a fundamental and critical question within sensory neuroscience. This conversion process is of great importance for subsequent perceptual activities and interactions with the environment. In the visual system, the conversion of external stimuli begins with retinal encoding of 2D projections. The two dimensional projections encoded by the retina are further organized and integrated into the retinal view in cortical areas such as V1 [4,5]. Although this mapping principle is not unique to vision, it extends to all sensory systems. In the case of tactile perception, it is mainly through the mechanosensory afferents to achieve the task of encoding the spatial and temporal characteristics of external stimuli, based on which a representation of the body position is constructed. These representations are important for the precision of object manipulation and movement, and are essential for the precise execution of physiological activities [6,7]. The ability of these afferents to

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adapt to vibratory inputs and detect sliding demonstrates the dynamic and responsive nature of sensory coding [8]. Overall, these cross-modal findings emphasize the efficiency of neural architectures to abstract the essential features of 3D stimuli into actionable 2D representations that support interaction and navigation in complex environments. Multisensory integration further enhances perception by combining information from different modalities. This process is critical for tasks such as object recognition, navigation, and communication [9,10]. Furthermore, the brain's remarkable plasticity enables adaptation to sensory loss, as seen in cross-modal reorganization [11,12]. Understanding these processes is not only a theoretical challenge but also a practical one, with implications for developing prosthetics, BCIs, and sensory substitution devices [13-15].

This paper reviews the mechanisms of sensory signal processing, from detection and encoding to cortical representation and integration. It highlights recent advances in sensory neuroengineering and discusses challenges and opportunities for future research.

2. Sensory Signal Detection and Encoding

2.1. Mechanisms of sensory detection

In the research perspective of sensory neuroscience, sensory receptors constitute the initial interactive interface between the external environment and the nervous system. These specialized cells carry out the key translational function of converting received physical or chemical stimuli into electrical signals, thereby triggering the initiation mechanism of the entire perceptual process. For example, photoreceptors in the retina are able to acutely detect the intensity and wavelength of light, a property that is fundamental for visual processing [5,16]. Similarly, mechanoreceptors in the skin respond to pressure, vibration, and stretch, while cochlear hair cells convert sound vibrations into neural signals [8,17,18].

The sensitivity and specialization of these receptors are adapted to their respective modalities. For example, the optic cones adapt to specific wavelengths of light, resulting in color vision, while the optic rod cells specialize in low-light environments [16]. Auditory hair cells are arranged along the cochlea in a tonal pattern, with different regions responding to specific sound frequencies [6,19,20]. In the tactile system, receptors such as Merkel cells and Ruffini endings provide detailed spatial and temporal information about surface texture and skin deformation [17,21].

2.2. Neural Coding Strategies

In the processing of sensory information, once sensory information is detected, it is converted into neural signals using various coding strategies, including rate coding, temporal coding, and group coding. The core principle of rate coding is to characterize the stimulus intensity based on the frequency of action potentials, i.e., the higher the frequency of an action potential, the higher the stimulus intensity; whereas temporal coding focuses on capturing and recording the precise timing of neural spikes to encode the specific content of sensory information [22]. Population coding integrates the activity of multiple neurons to encode complex stimulus features such as motion or texture [23].

For example, in the visual system, ganglion cells in the retina preprocess spatial and temporal information to transmit signals about contrast, edges, and motion to the brain [4]. Similarly, the auditory system uses phase-locking mechanisms to encode low frequency sounds and interaural time differences for sound localization [20,24,25]. In the haptic system, neural assemblies encode pressure and vibration patterns for texture and shape perception [21].

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3. From 3D input to 2D neural representation

3.1. Visual Conversion

In neuroscience, the visual system can be characterized as a prime example of converting three-dimensional inputs into two-dimensional cortical maps. The retina undertakes the task of capturing 2D projections of the visual scene and subsequently constructs retinograms in the V1 region. An important property of these retinograms is the ability to preserve spatial relationships between objects, which provides a key basis for depth perception as well as motion analysis [5,23,26]. The formation of depth perception requires the synergy of multiple factors, including binocular disparity, motion parallax, and monocular cues such as shadows and texture gradients. The former provides binocular disparity and visual changes for the brain to judge distance and depth, while the latter provides depth position information alone, and together they construct depth perception [23-25].

Advanced sensory systems imaging studies have emphasized the importance of integrating information from multiple modalities for consistent perception and action. For example, as explored by Calvert et al., multisensory integration focuses on elucidating how visual, tactile, and other modal signals are dynamically processed to enhance environmental awareness and object recognition. This perspective has led to a shift in emphasis from isolated sensory pathways to synergistic qualities of perception. The central role of interconnections within the architecture of complex neural systems has been emphasized [16]. In the complementary process of research, the exploratory work of Park et al. on hyperelastic pressure sensing is of crucial significance and value. Park et al. succeeded in constructing a bio-inspired model that provides insights into how refined sensory inputs, particularly those typified by tactile feedback, can facilitate dynamic interactions with the external world [23].

3.2. Auditory Transformation

ITDs and interaural level differences (ILDs), processed in the superior olivary complex and auditory cortex, achieve auditory spatial mapping. Tone maps in the auditory cortex organize sound frequencies in a spatially coherent manner, facilitating the integration of spatial and temporal auditory features [20,24,25]. Studies have shown that auditory cortex regions dynamically adjust their sensitivity to improve sound localization and speech understanding in noisy environments [19].

3.3. Tactile Transformations

Within the mechanism of operation of the tactile system, tactile information contained in three-dimensional space is encoded and converted into a two-dimensional form of somatosensory mapping. These maps accurately reflect the differences in the distribution density of tactile receptors in different body regions of the human body. Specific regions, such as fingertips and lips, have a higher density of tactile receptors and therefore show a more significant neural representation in the cortical somatosensory mapping, i.e., a stronger cortical representation [17,21]. The plasticity of the somatosensory cortex allows it to dynamically reorganize itself to adapt to sensory deficits or impairments [26].

3.4. Multi-sensory integration

Integrating sensory input from multiple modalities enhances perception and decision-making. Neural centers such as the superior colliculus and posterior parietal cortex combine visual, auditory, and tactile information to form coherent perceptions [10]. For example, visual-auditory integration improves speech comprehension. And visual-haptic integration provides rich sources for the brain to construct object representations, enhancing recognition accuracy and efficiency [19,24].

Cross-modal plasticity is further evidence of the brain's ability to adapt. In blind people, visual deficits result in functional remodeling of the visual cortex. Based on the principle of neuroplasticity, non-visual sensory acuity and information processing are enhanced by adjusting neural circuits and connections involved in auditory or tactile information processing [11,21,26]. This phenomenon underlies sensory substitution devices such as the tactile visual substitution system, which convert visual input into tactile signals [23].

4. Neuroengineering Applications

4.1. Sensory Prosthetics and Substitution

In the field of sensory impairment treatment, the emergence of sensory prosthetic technologies such as cochlear implants and retinal prostheses has triggered a revolutionary change. The mechanism of action of cochlear implants, for example, is to provide effective auditory input directly to the auditory system by skillfully bypassing the already damaged hair cells. This has enabled many hearing-impaired patients to regain the ability to hear the world. In the case of retinal prostheses, the Argus II is a typical example of an implant that activates neural signaling in the visual pathway through precise stimulation of retinal ganglion cells, thus successfully restoring partial vision [14,16]. Artificial skin with embedded pressure sensors can achieve haptic feedback. It captures and translates pressure information to enable more precise and coordinated prosthetic function, increasing user control confidence and satisfaction [17].

4.2. Brain-Computer Interface

Brain-computer interfaces (BCIs) build direct and efficient communication bridges between the brain and external devices, offering hope to patient populations who suffer from severe motor or sensory impairments. Recent studies have developed a system that precisely stimulates the somatosensory cortex to effectively restore tactile perception. Based on an in-depth understanding of neurophysiological mechanisms and the application of advanced engineering techniques, this system opens up new pathways for re-establishing the patient's tactile experience. In addition, there is a new device that precisely decodes neural signals to enable flexible control of prosthetic limbs. By monitoring, analyzing and interpreting the nerve signals from the brain in real time, the device accurately translates the brain's motor intentions into movement commands for the prosthetic limb. These greatly enhance the manipulation performance and practicality of the prosthesis, and provide a strong technical guarantee for the reintegration of patients with physical disabilities into social life [13,14,25].

5. Conclusion

This review highlights the complex process by which sensory systems translate complex three-dimensional environmental stimuli into two-dimensional neural representations. In turn, 2D neural representations are the basis for perception, cognition, and action. Sensory modalities such as vision, hearing, and touch operate through neural mechanisms that specifically encode spatiotemporal information to ensure effective representation and integration throughout the cerebral cortex. Multisensory integration and neuroplasticity further enhance these representations, allowing the brain to dynamically adapt to sensory deficits and environmental changes. Advances in the field of neuroengineering, such as sensory prosthetics, brain-computer interfaces, and sensory substitution devices, highlight the critical importance of understanding sensory signal processing for practical applications.

However, this field also faces many challenges and limitations. Despite advances in imaging and computational modeling, there is still a lack of understanding of the multiple neural mechanisms involved in the 3D-to-2D conversion process, especially for complex stimuli in real-world environments. In addition, sensory processing varies across individuals and populations, which complicates the dissemination of research results and the development of generalized technologies. Ethical issues such as accessibility, privacy, and long-term safety of neuroengineering applications also require careful consideration.

In the future, interdisciplinary collaboration will be crucial to overcome these challenges. Computational modeling, high-resolution imaging, and advanced neural decoding techniques will enable researchers to further unravel the complexity of sensory systems. Applying these findings to therapeutic innovations has enormous life-changing potential, both in terms of deepening the understanding of perception and opening the way for new technologies for sensory restoration and enhancement.

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