Sensory Inputs Guiding Cognitive Behaviors and Decision Making

Jiarui Lin

Department of Psychology, Skidmore College, United States

jiaruilin@skidmore.edu

Abstract. Understanding human behaviors and higher cognitive functioning has long been an ultimate goal for psychologists and neuroscientists. Sensory inputs are pivotal in shaping the intricate landscape of complex behaviors and decision-making processes in both humans and animals. The distinct pathways through which the sensory information is perceived from the environment are referred as sensory modalities. Each sensory modality corresponds to a specific type of sensory input or sense, such as vision, hearing, or tactile, enabling us to gather information about the world around us. Sensory inputs integrate information of various sensory modalities at different levels of nervous system and networks, are filtered by attention, forming the perception of the external environment. Through the interaction with various neural circuits and networks, the sensory inputs activate memories and emotions, leading to further information processing. The conversion of sensory information into behavior and decision making is a complex neuronal process involving context evaluation, emotional arousal, memory activation and reward system prediction, with sensory inputs impacting immediate reactions and shaping long-term memory and future responses. This paper is a systematic review of recent literature studies that explain cognition and behaviors, providing an overview of the multifaceted interplay between sensory perception and the execution of complex behaviors, while highlighting the significance of sensory processing in cognitive neuroscience and behavioral science.

Keywords: Cognition; Decision-making; Attention; Perception.

1. Introduction

In the realm of neuroscience and behavioral psychology, one of the most intriguing and enduring puzzles has been the intricate interplay between sensory inputs and the complex behaviors and decision-making processes. This dynamic relationship between perception and action is at the heart of our understanding of how we interact with our environment, adapt to changing circumstances, and make choices that shape our lives. From the simplest reflexes to the most elaborate cognitive processes, the role of sensory inputs in guiding behavior and decision making is paramount. Sensory modality refers to a specific way by which sensory information is detected, received, and processed by our sensory systems. Each sensory modality corresponds to a distinct type of sensory perception. Sensory inputs are gathered through sensory receptors and organs that detect and transduce various types of stimuli into neural signals through action potentials, and travel to the cerebral cortex. The sensory information we receive from the world around us serves as the raw material upon which our brains construct a multifaceted and coherent perceptual representation of the external world. This mental construct drives our actions, directs our choices, and ultimately influences the trajectory of our lives. Through incorporating findings from neuroscience and psychology of recent years, this paper aims to discuss the underlying mechanisms of sensory processing and cognition, in which the sensory inputs are filtered, integrated, and transformed within the neural circuits of the brain, forming behaviors and decisions.

2. Sensory Information

Sensory inputs are information received about the external world by sensory organs and transmitted between neurons along the neuropathway to the cerebral cortex. Many studies have shown that usually multiple sensory modalities are integrated in the brain to create a coherent representation of the external environment that leads to higher cognition and decision-making.

Schaeffner et al. investigate the concept of sensory-motor modality compatibility, which relates to how well sensory inputs align with the modality of motor responses. Previous studies have shown that coordinating incompatible mappings combining sensory and motor modalities leads to higher performance costs compared to compatible mappings [1]. In specific, Schaeffner et al. study the influence of compatibility of verbal and nonverbal input motor modality on language production as one of the higher cognitive behaviors. In this research, the authors manipulated processing codes as incompatible and compatible sensory-motor mappings for the participants to switch between. The result shows that switching between incompatible mappings incurred higher switch costs relative to switching between compatible mappings This indicates that sensory modalities are compatibly integrated for information processing in more complex human behaviors.

Cruz et al. discusses the conventional understanding of how cortical and subcortical brain regions interact to enable flexible responses to complex external environments. The authors challenge the traditional notion that neuronal functions are confined to specific unitary brain regions. Cortical and subcortical brain regions were thought to operate in a strict hierarchy with specialized subcortical circuits handling rapid responses to salient stimuli, while the neocortex was responsible for adaptability and context specificity. However, recent advances in technology suggest that behavior is represented by brain-wide activity, including early signals of choice in subcortical structures, challenging this hierarchy. Cortical and subcortical regions engage in cooperative interactions encompassing both top-down and bottom-up signaling pathways, with a specific emphasis on the involvement of the thalamus. The authors describe how the brain circuits are formed interconnecting with each other and the thalamus, creating a unified information-flowing system of parallel loops and complex networks [2].

In details, Basso et al. discusses the superior colliculus, a sensorimotor structure that primarily coordinates reflexive behaviors integrating sensory information, involves in cognitive functions such as attention and decision-making working with the cerebral cortex as recent experiments suggest. The authors suggest that sensory information project to the superior colliculus terminates in several different layers in an organized topographical manner [3]. Specifically, visual regions exhibit a tendency to primarily connect with the upper layers, whereas auditory, somatosensory, multimodal, and association regions show a preference for connecting with the deeper layers of the superior colliculus [3]. The ascending outputs of the superior colliculus are more numerous than the descending ones, suggesting that it plays a more substantial role in cognitive functions typically associated with the forebrain. In all vertebrate species studied, the largest output systems of the superior colliculus are the ascending projections, highlighting a closer integration between the superior colliculus and forebrain circuits [3].

3. Cognition

3.1. Attention

Sensory inputs are often filtered and processed by the sensory systems. The brain selectively concentrates on specific aspects of sensory information or stimuli while ignoring others, which is referred to attention. It is a complex and crucial mechanism that allows the brain to allocate limited cognitive resources to the most relevant information and enhance the efficiency of sensory inputs processing in higher cognitive behaviors. Sometimes attention is driven by a top-down process, in which we voluntarily decide on which external stimuli to focus on; while in other case, the focus is primarily driven by external stimuli or sensory input automatically without the individual’s conscious intention, which is the bottom-up process.

As Katsuki & Constantinidis suggest, the process of paying attention happens in the visual cortical regions within both the dorsal and ventral pathways. There is significant interaction between top-down and bottom-up attention mechanisms, particularly involving brain areas in the posterior parietal cortex (PPC) and prefrontal cortex (PFC) as research in recent years suggest [4]. The authors highlight the idea that attention is directed toward objects or specific locations that currently triggers the highest neural activity in the brain [4].

Rueda et al. emphasized the important concepts of attentive state, executive attention, and developing attention network in their research. The authors explain that attention requires a certain level of nervous system activation and alertness linking to cortical arousal [5], as it can rapidly change the brain's state for information processing and prioritizing sensory inputs that are salient. Attention is also associated with the executive control of thoughts and actions. Executive control involves specific circuits in frontal and parietal structures, supporting goal representation, maintenance, and adjustment of responses, which is highly important in decision-making tasks. These executive circuits exhibit enhanced functional integration when tasks require attentive control [5].

3.2. Perception and Contextual Understanding

The sensory inputs that are filtered by the attention are interpreted by the brain, which is called perception. Perception helps to understand the context in which we are making decisions or engaging in cognitive tasks. This contextual information is critical for assessing the significance and implications of various options.

Mirza et al. present a mental state attribution task that examines how the perception of a facial expression with either unclear or clear emotions is affected by the social context conveyed by the surrounding scene. Active inference models are used to show that individual's interpretation of sensory inputs can be modified by the social context, and they find that when the context aligns with the facial expression and emotion, it enhances the decision-making performance [6]. The authors also discuss the failure of patients with schizophrenia in contextual understanding through sensory perception. This study highlights that manipulating sensory inputs can alter perception and contextual understanding in cognitive behaviors.

Consciousness refers to the state in which we are perceiving the sensory information received from the external environment. Garcia-Larrea & Bastuji discusses the neural processes involved in the conscious perception of pain. The authors explain that consciousness awareness of pain is arises from the coordinated activity of a set of continuous complex neural network, referred to as the "pain matrix" [7]. One network, called the 'nociceptive matrix,' receives input from nociceptive systems and is responsible for the physical aspects of pain [7]. Another set of structures handles the 'salience' of painful stimuli, cognitive control, and the formation of conscious pain from pre-conscious nociception [7]. Electroencephalogram (EEG) responses observed in humans reveal that nociceptive processing initiates in sensory, motor, and limbic regions before progressing to engage various networks, ultimately resulting in the conscious awareness of pain [7]. The authors also present a model of pain processing that commences with unconscious processing and culminates in full consciousness through the integration of memories and self-awareness. This sequence occurs during wakefulness but suggests that even in unconscious individuals, repeated activation of limbic and vegetative pathways by painful stimuli can lead to the formation of implicit memories and atypical responses [7].

3.3. Memory Activation and Emotional Arousal

Sensory areas interact with other pathways and networks in the brain. As a result, sensory inputs can trigger memories and evoke emotions. When encountering sensory cues that are associated with past experiences, it can activate relevant memories and emotions associated with those experiences. These memories may inform decision-making by providing insight into similar situations that have been faced in the past.

The perception-action cycle is a concept that describes the continuous and dynamic interaction between sensory input and action in behavior and decision-making. Posterior structures are primarily responsible for sensory functions whereas the anterior parts of the brain are involved in motor functions. However, in the cortex, this distinction becomes less clear due to the interconnection and overlapping between perception and action in the perception-action cycle [8]. This cycle incorporates inputs from sensory-evoked perceptual memory, originating in the neocortex, and biological memory, which emanates from limbic structures through the orbito-medial cortex [8]. The outputs from this cycle are directed towards pyramidal and diencephalic structures, while feedback inputs monitor at various stages of the cycle [8]. Prefrontal functions such as working memory and executive attention are prospective, they are oriented toward achieving the goals of the perception-action cycle in the future [8]. Different prefrontal cortex subregions involve in handling specific types of inputs including memories and emotions [9]. Damage to the lateral prefrontal cortex impairs these functions, while damage to the orbitofrontal cortex can lead to issues with impulse control, risk-taking behavior, mood instability, and antisocial behavior [8].

Prior research has shown that physical features of sensory information, such as the characteristics of shapes, speech, colors, and movements, play a role in determining our emotional arousal [10]. Imaging studies in humans have demonstrated that stimuli associated with rewards lead to activation in the pregenual cingulate cortex, a brain region linked to emotional responses [11]. Furthermore, the hypothalamus receives signals from the orbito-frontal cortex and the amygdala, while these regions engage in the processing of emotions as well [11].

Evidence suggests that all sensory experiences are evaluated based on whether they are beneficial or detrimental to us [12]. Emotions have representation across various tiers of our sensory systems, and these emotional representations influence various cognitive functions, including perception, attention, learning, and memory [12]. Todd et al. (2020) highlights that the emotional representations create a cohesive emotional, perceptual, and cognitive experience, rather than treating them as isolated events. In other words, our brain integrates emotional experiences with other cognitive processes, leading to unified perceptions.

3.4. Decision-making

Decision-making is to choose one course of action among several alternatives, and it is a complicated cognitive process that involves the interaction of varies of brain regions and networks. The prefrontal cortex, basal ganglia, and parietal cortex are among the brain regions implicated in decision-making. These areas collaborate to evaluate options, assess potential outcomes, and ultimately make a choice. Ibos and Freedman (2017) examine the process through which the specificity of neurons for visual attributes is converted into signals associated with decision-making in the posterior parietal cortex, specifically in the region known as the Lateral Intraparietal Area (LIP), while conducting neuronal recordings within the context of a visual matching task. LIP consists of a range of neurons involved in processing sensory inputs, combining these signals, and translating them into signals related to macaque' decisions about the importance of visual stimuli [13]. It plays a role in encoding the significance of stimuli, converting sensory data into decisions regarding eye movements, and encodes cognitive information like rules or abstract categories [13]. LIP neurons integrate inputs from attention-modulated activity in higher-level visual cortical areas, suggesting that LIP performs a linear integration of bottom-up sensory information [13].

The brain's reward system plays a pivotal role in decision-making. The opioid system is crucial in regulating reward, pleasure, pain, and affection [14]. The opioid receptors are widely existed in the cognition related brain regions such as the parietal and frontal lobes [14]. Evidence suggests that opioids can affect cognitive processing and decision-making in varies brain regions [14]. The activation of opioids triggers the mesolimbic reward system in the brain [15]. This system initiates activity in the ventral tegmental area (VTA), leading to the release of the neurotransmitter dopamine (DA) in the nucleus accumbens (NAc) [15]. Dopamine neurotransmitter is closely linked to the anticipation and receipt of rewards and the reinforcement of rewarded behavior. The basal ganglia circuit is heavily influenced by the neurotransmitter dopamine, which is produced by neurons in the substantia nigra. The basal ganglia circuit receives the input from the cerebral cortex and interacts with the dopamine system, affecting cognition, behaviors, and decision-making.

Sensory inputs are crucial for planning, decision-making and executing actions. They provide feedback on the outcomes of the actions and help to adjust behavior based on the sensory feedback received. The dopamine neurons can learn to predict reward by firing to the stimulus that predicts the reward, and thus reinforcing behaviors that are rewarded, which is crucial for adaptive behavior and learning. Dopamine-producing neurons in the ventral tegmental area (VTA) are responsive to addictive substances, uncertain rewards, and cues associated with rewards [16]. This makes them a possible shared neural basis for both gambling addiction and substance use disorders [16]. Damage to the medial prefrontal cortex can result in poor monitoring of behavioral outcomes and error prevention [8]. Inhibiting VTA dopamine neurons can impact risky decision-making and impulsivity [16].

4. Discussion

Sensory information from different sensory modalities propagates efferently to the central nervous system and integrates at different levels of the brain. Compatible mappings of sensory modalities lead to more effective cognitive processing than incompatible sensory-motor mappings in language production. Cortical and subcortical brain regions engage in cooperative interactions, forming complex networks for information processing, including early signals of choice in subcortical structures, which challenges the cortex-specified hierarchy previously assumed. Superior colliculus receives sensory information in an organized topographical manner and projects to different layers, with a particular emphasis on the prevalence of ascending outputs, which suggests a closer integration with forebrain circuits and the role of superior colliculus in attention and decision-making. Attention is a crucial mechanism in sensory processing involving both top-down and bottom-up processes, filtering out information and improving sensory information processing efficiency. PPC and PFC are crucial brain regions directing attention based on neural activity. Attention is linked to nervous system activation and executive control circuits in decision-making tasks. Perception of sensory information helps understand context during decision-making and cognitive tasks. Sensory inputs can trigger memories and evoke emotions, which in turn can inform decision-making by providing insights from past experiences. Sensory input and action interact dynamically in the perception-action cycle, involving various brain regions and cognitive functions, including the integration of emotional experiences with other cognitive processes to form perceptions. Decision-making is a complex cognitive process involving multiple brain regions and networks, including the prefrontal cortex, basal ganglia, and parietal cortex. Additionally, the brain's reward system, particularly the role of opioids and dopamine, plays a crucial role in influencing decision-making processes and adaptive behavior, with dopamine-producing neurons in VTA being responsive to addictive substances and cues associated with rewards, potentially contributing to gambling addiction and substance use disorders.

5. Conclusion

The literatures in this paper collectively highlight the complexity of decision-making processes in the brain, emphasizing the integration of sensory information, memory, emotions, and reward systems in shaping our choices and behaviors. Understanding these intricate processes is crucial for fields ranging from neuroscience to psychology and has practical applications in various aspects of human life. Future studies could dive deeper into the neural mechanisms of decision-making using advanced neuroimaging techniques such as fMRI and EEG to investigate how specific brain regions interact during decision-making process. Research from neuropharmacology's perspective can also be done to provide insights into decision-making deficit such as addiction and impulse control disorders. Research could be done as well on understanding how individual differences, such as personality traits, prior experiences, or genetic factors, influence sensory processing and impact decision-making. Understanding how sensory inputs guide cognition and decisions in humans can provide insights into neural technology field as well. This could involve brain-computer interfaces (BCIs) that provide real-time sensory feedback in individuals and making complex decisions using a computer connected to the brain. Deep learning algorithms that create decision-making models by predicting and optimizing decision outcomes are also built upon the study of decisions in humans.

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