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How Does Aging Affect Decision-making? An Integrated Model Based on Neuroscience

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Abstract: With the global population rapidly aging, understanding how this demographic shift affects decision-making becomes paramount. This review examines the impact of aging on decision-making processes, recognizing the profound influence individual choices wield on personal and societal values. Previous studies in psychology and neuroscience have explored this intersection, yet a consensus remains elusive due to the different paradigms used in each experiment. This review proposes an innovative approach by introducing an integrated neurocomputational model by first breaking down the decision-making process and defining key terms such as reward, risk, and uncertainty, aiming to bridge existing gaps in understanding. It synthesizes empirical findings from psychological and neuroscientific perspectives, incorporating recent insights from neuroimaging research on age-related changes. The review concludes with future research recommendations, encouraging a deeper exploration of aging and decision-making through the lens of neuroscience.

Keywords: Aging, decision-making, neuroscience, computation model

1. Introduction

Each choice we make each day in different domains shapes our lives and the values of the whole society, and the major decisions made by people have a significant effect on their life direction and happiness level throughout their lifetime. Understanding how aging could affect the decision-making process of older adults is of great importance due to the factor that the world is aging rapidly, and the aging group is expected to grow at a rapid pace. Broader implications include aging group consumption decision-making pattern analysis or older adults's asset allocation choice study, as the elderly population represents the demographic group with the highest accumulation of societal wealth.

Previous studies on how aging affects the decision-making process in psychology and neuroscience perspectives elucidated the correlation between age and the decision-making process; however, a consensus on findings remains elusive. The potential sources of disparate outcomes are multifaceted: (1) varying experimental paradigms employed across studies for old and young groups comparison: the absence of standardized criteria for the decision-making process, and a deficiency in the classification and definition of incentives that influence decision-making as people may perceived the reward differently across their lifespan rather than the change of the whole decision-making process. (2) limited neuroscientific support: the majority of studies have elucidated the brain regions and neural mechanisms associated with decision-making and the functions and brain areas affected by age separately, the compounding effect of changes in neurotransmitters, neuron firing rate, and

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coding connectivity make the result less attractive. By that means, there is a deficiency in comprehensive understanding that can infer and predict the decisional changes brought about by aging. (3) The lack of an integrated model derives the whole decision-making process in a neuroscientific base: the decision-making process is complicated and involves different stages where circumstances and goals can quickly change dynamically. Moreover, there is relatively little in the way of a quantitative synthesis of age differences in the neural basis of decision-making under uncertainty so far.

In this review, instead of the conventional method of comparing behavioral and neural findings between the old and the young, an integrated model will be introduced to explain the intersection of decision-making and neural mechanisms in aging to guide the neurocomputational mindset to bridge the gaps in current literature. To begin with, the review divides the decision-making process into different categories and defines key terms and scope related to the whole process. The extensive empirical findings from psychological and neuroscientific perspectives in age-related decision-making would be synthesized, together with the recent development of neuroimaging research with novel insights into age-related changes in white matter and neural systems responsible for decision-making. Next, the neurocomputational model derived from empirical research will be displayed. Finally, future research recommendations regarding aging and decision-making based on neuroscience research will be discussed.

2. Decision-making process and key terms scope

There have been relatively few quantitative investigations of age variances in the neural underpinnings of decision-making. Based on the contrasting analysis of decision outcomes between older and younger individuals and the complexity of neural research in the context of aging, the following notable drawbacks emerge: the lab settings of the decision-making process for comparison studies are of various forms.

This section aims to analyze the decision-making process in each small component that can be represented by an integrated computational model, to technically define decision-making stages and valuation process, reward, context, and other cognitive influencing factors such as memory and social cognition, which could serve the further purpose of the neurocomputational intersection of aging and neural mechanism.

2.1. Different decision-making forms

Despite the significance of aging population decision-making studying and a large body of research comparing different decision-making results made by the elderly and the young, the results vary across paradigms and contrasts. Also, there is a lack of comprehensive investigation into the overall decision-making process in aging, which can be categorized into different forms and dissected into distinct sequential and hierarchically organized stages, where corresponding neural correlates can be identified.

In lab settings, decision-making processes are examined via standardized methodological practices (numeric reward, rigid experimental context). In real life, the decision-making process can be divided into different stages: information selection (memory, attention), dynamic context valuation (social cognition, and the different definitions of the terms value, reward, and utility, which will be discussed in the following session), risk and uncertainty trade-off, and multiple rounds decision making sometimes requires feedback valuation and information interpretation, new knowledge and the punishment learning from the environment, for example, reinforcement learning during the AI decision-making process to maximize the accumulated reward. The decision-making process is a complex process that recruits different neural circuits regarding different abilities. The valuation

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process and representation require cognitive ability (problem-solving, memory), affective ability (social cognition regarding choice, strategy flexibility), and the ability that has often been overlooked is transient brain connectivity (the capacity of brain networks to adapt and synchronize flexibly within a millisecond timeframe) [1], which is also affected by aging, to show the rich brain dynamics. The process then can be categorized into affective and motivational processing, sensorimotor processing (in which deficits should obviously compromise decisions), or cognitive processing.

Affective and motivation processing can be analyzed by the Affect-Integration-Motivation (AIM) framework [2], which proposes multiple pathways through which age-related anatomical and functional changes could contribute to age-related variations across different decision-making stages.

2.2. Valuation Process

Previous studies used simple numeric incentives in decision-making experiments. The results sometimes fail to explain the aging effect on decision-making since it is difficult to separate the contribution of altered decision-making ability due to aging and older people's different perceptions of "reward", and it also fails to capture the real underlying decision making motivation between the two groups. Some findings suggest that older people perceive the information differently. In other words, the sensitivity to the reward has been changed for the old. For example, in temporal discounting, old people generally have larger temporal discounts because they have less time in the future. Therefore, they tend to value the present more in their perception.

To control the effects of perception difference, the reward concept needs to be reconsidered; the term value would be a better option for assessment. Value is a functional concept that may not necessarily coincide with reward [3]. Therefore, it is necessary to look at the difference between value, reward, and utility; these distinctions are frequently obscured in experimental setups where participants aim to maximize straightforward numerical rewards [3]. What fundamentally impacts the decision-making choice is how much value is perceived and programmed by people's brains, then transformed into motivation signals in the reward system. Hence, it is essential to control the reward in the experiment, which can be perceived as the same value across ages, where the value can be measured in advance via self-report methods and questionnaires.

2.3. Decision-making context

Researchers frequently interchange the terms uncertainty, risk, and ambiguity [4]. However, in a goal-directed decision-making process, people make decisions under risk, and ambiguity should be discussed separately. In situations involving risk, the probabilities of various outcomes resulting from a choice can be objectively determined and quantified. However, in ambiguous situations, these probabilities may be either partially or entirely unknown, adding a layer of uncertainty to the decision-making process [5].

In that manner, it is reasonable to think, ambiguity might involve even more uncertainty relative to risk [6]. In some complex decision-making processes, which require multiple rounds of choice-making and information learning, ambiguity can be changed into a risk function of the individual learning experience [7]. Therefore, it is crucial to analyze and determine whether the situation involves risk or ambiguity in an integrated model as the level of uncertainty in the decision-making process varies, and the response of the old population and the young might be different.

2.4. Memory and social cognition

Memory and social cognition play pivotal roles in the decision-making processes of individuals. Memory is a valuable asset for storing past experiences and information, which provides a foundation for assessing the potential outcomes or shaping the anticipation of different choices. While social

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cognition, encompassing processes such as perspective-taking and understanding social cues, contributes significantly to decision-making.

The developmental process of aging is accompanied by several physical and mental changes, with some of the most significant ones relating to alterations in memory function. Studies have identified substantial declines throughout the adult lifespan in the capacity to create new episodic memories, process information rapidly, and engage executive processes [8].

In contrast, social cognition in older adults may exhibit a different pattern. The socioemotional selectivity theory [9], posits that older individuals prioritize emotional satisfaction and meaningful social relationships over the pursuit of novel information. This orientation may influence decision-making by emphasizing the importance of social and emotional considerations.

Changes in Integration for Social Decisions in Aging (CISDA), and recollection of past interactions with social companions can significantly impact decision-making in social contexts [10]. For instance, an individual might be reluctant to help older adults who fall on the street if he has been intentionally bumped by an older person.

In summary, both memory and social cognition significantly contribute to the decision-making process, albeit with different implications for older and younger individuals. While age-related changes in memory may impact older adults, social cognition remains a dynamic factor that influences decision-making across the lifespan.

3. Neuroscientific and psychological evidence of age-related changes

3.1. Current theory

To better understand the decision-making process, this research conducted a comprehensive analysis of theories from various perspectives in psychology and sociology. This was followed by a detailed examination of the neural bases related to the impact of age on decision-making processes.

Frontal aging hypothesis: The theory suggests that the frontal brain regions experience more significant deterioration due to aging, leading to greater declines in functions supported by the frontal lobe [11]. Further research based on this idea suggests that dorsolateral regions and their cognitive functions, such as executive function, are more susceptible to age-related decline compared to other frontal lobe regions, like the ventromedial prefrontal cortex and its associated functions, such as affective processing and social decision-making [12].

Theories of compensation: Typically, fluid abilities tend to decrease as individuals age, while crystallized abilities exhibit improvements even in old age. A strong correlation in the rates of change between fluid and crystallized abilities has been demonstrated; individuals experiencing more significant declines in fluid abilities also tend to exhibit smaller gains or even losses in crystallized abilities. This shared pattern in the changes of both fluid and crystallized abilities imposes limitations on compensation theories [13].

The loss prevention hypothesis posits that aging is accompanied by increasing losses (e.g., health, social partners, cognitive functions), prompting a shift in primary goal orientation from seeking gains to preventing losses [14]. It is noteworthy that consistent findings with socioemotional selectivity theory and the loss prevention hypothesis have been observed in incentive processing, value-based choice, and social decision-making. However, it remains unclear whether observed age differences result from an age-related shift in goals, organic brain aging (e.g., changes in brain structure and function), or a combination of both factors.

Neuromodulation theories: These theories point to age-related decline in the dopamine system as a key contributor to decision-making changes in aging, but also propose that declines in other neurotransmitter systems, such as serotonin [15], norepinephrine [16], and glutamate [2], can alter decision processing in aging.

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3.2. Neuroimaging findings

Behavioral research has shown differences in behavioural strategies in decision-making tasks over the course of aging, while the advancement of functional neuroimaging has progressively enabled the investigation into the neurofunctional foundations of these behaviours.

In general, examinations of brain volume through both cross-sectional and longitudinal studies indicate both linear and curvilinear alterations in grey matter volume. White matter volume similarly experiences curvilinear changes throughout the lifespan, with an increase until adulthood followed by a gradual decline in senescence. Modern investigations employing diffusion tensor imaging (DTI) have further disclosed age-related reductions in the connectivity of major white matter tracts, particularly marked declines observed in anterior and superior cortical regions [17]. Brain structure change analysis can sometimes be a poor proxy for age-related decision-making processes due to individual differences in neurotransmitter systems. Vivo dopamine imaging can be utilized to clarify the impact of dopamine on decision-making and propose methods for evaluating individual variations in the role of affective attentional focus [18]. Interpreting aging alterations in connectivity as detected by fMRI poses challenges due to methodological obstacles, including confounding factors such as vascular reactivity and head motion. These factors also exhibit variations in tandem with age, adding to the complexity of the analysis [19].

Few research has examined age-related changes in the presence of fundamental amino acid neurotransmitters, like glutamate and GABA, which are widespread in the brain, yet these neurotransmitters primarily contribute to more localized and specific circuit functions. (2) However, examinations using positron emission tomography (PET) in humans have uncovered a predominantly linear decrease in serotonin receptors in the cortex and in dopamine receptors (both D1-like and D2-like) in the prefrontal cortex and striatum throughout adulthood. Additionally, there is a linear decline in dopamine transporters in the striatum. However, the evidence for age-related alterations in presynaptic neurotransmitter availability, which is linked to synthesis capacity and vesicular storage, has been more varied [20].

In terms of risky concept interpretation, decision-making under risk and ambiguity were discussed separately, and compared in previous studies, the neural risk matrix implies specific brain regions correspond to the risky choice decision-making process, ventral striatum, anterior cingulate cortex, and anterior insula are responsible for risky choice promotion, modulate and inhibit, respectively [21]. The greater risk aversion is observed in older humans and highlights age-related alterations in brain connectivity. FMRI analyses demonstrated that, on the whole, aged rats exhibited higher functional connectivity compared to young rats, especially among brain regions associated with risky decision-making, such as the basolateral amygdala, orbitofrontal cortex, and ventral tegmental area [22].

Primary activations in behavioral risky decision-making were observed in the right insula through a meta-analysis [23], both sides of the dorsolateral prefrontal cortex (DLPFC), and the left orbitofrontal cortex (OFC). Circuits associated with both emotion regulation and the decision-making process were identified. However, in contrast to findings in the literature concerning young adults, the results indicate a unique pattern of hemispheric lateralization in older participants.

4. Computational model based on neuroscience

Empirical disparate evidence for age-related changes to brain regions within the decision network calls for a neurocomputational model for a better explanation of the aging effect on decision-making. This approach enables quantitative comparisons between model predictions and experimental data, facilitating a rigorous evaluation of model performance, and also allows for the integration of multiple levels of analysis, which perfectly fits the nature of the decision-making process. These models can

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integrate information across various levels of analysis as well as dynamic changes, incorporating neural, cognitive, and behavioural aspects into a unified framework for a more holistic understanding.

From the very initial stage of decision-making, the information is perceived by people through information selection, which recruits attention and memory. In numerous regions of the brain, particularly in the prefrontal cortex (PFC), neurons frequently exhibit intricate firing responses, seemingly integrating information from various sources such as cues, stimuli, contexts, rewards, and more. This phenomenon is referred to as mixed selectivity [3]. Secondly, during the valuation stage of decision making, cognitive function, such as memory (The hippocampus integrates the encoding, storage, and recall of memories, binding the spatiotemporal and sensory information that constitutes experience and keeping episodes in their correct context [24]), and cognitive map (deficiencies in goal-directed, model-based behaviour observed in older adults stem from challenges in representing the state spaces of cognitive tasks [25]). social cognition (In the social decision-making context, the ventromedial prefrontal cortex represents immediate anticipated rewards as individual utility, whereas the lateral frontopolar cortex represents group utility, and interaction information was updated by the anterior cingulate cortex and the temporoparietal junction [26]. Previous findings uncover that oxytocin might enhance prosocial behaviour by influencing social-value representations in the amygdala [27].) has been involved. Neurons in the orbitofrontal cortex (OFC) represent the likelihood of obtaining a reward, the level of effort required to attain a reward, and the time delay until the reward is delivered [28]. Then, the representation coded from the last step is programmed as motivational signs and transmitted to reward systems.

With the details discussed above, further effects of age-related change can be examined. In addition, the analysis of neuroscience spans different levels from macroscopic to microscopic, the smallest unit of neural analysis for computational modeling is a neuron. Suppose individual neurons are to the brain what letters are to an article. Neurons can be considered as letters, microcircuit motifs as words, and larger-scale architectural plans as sentences, and eventually, the article brain [29]. A substantial body of research has unveiled brain regions and brain structures related to age-related impacts on decision-making. Evidence shows that aging has a negative effect on anterior insula activation [2], anterior cingulate cortex (ACC), posterior parietal cortex (PPC), and lateral prefrontal cortex regions, specifically the lateral orbitofrontal cortex (OFC) and dorsolateral prefrontal cortex (DLPFC) [30]. Some studies have delved even further into the neurochemical level, exploring the neurotransmitter aspects, and have investigated the neural pathways implicated in the decision-making effects associated with age. There is an increasing recognition that aging affects different components of the dopamine system within individuals in a diverse manner, alongside considerable variability observed between individuals [18].

Chemically, both dopaminergic and noradrenergic neurons broadly but differentially innervate these regions, and can rapidly shift their firing rates in response to environmental opportunities and challenges [2]. In addition, the smallest unit can be further examined for the aging effect: neurons consist of three anatomically separate components: the cell body (soma), dendrites, and projecting axons. The brain's capacity to handle intricate information depends on a continuous provision of energy achieved through aerobic respiration facilitated by mitochondria [31].

Due to limitations in neural computation research at the neuronal level, the accuracy of neural computational models remains to be validated. Fortunately, experimental results from behavioural and psychological studies can assist in verifying the accuracy of neural computational models, thereby enhancing their precision and comprehensiveness.

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5. Future research suggestion

The specific study of decision-making patterns in older adults holds significant economic value and practical significance. Such kind of research is crucial for preventing decision errors in older individuals due to changes in decision-making abilities, thereby avoiding potential financial losses.

In current research on the influence of age on the decision-making process, significant progress has been made in identifying distinct brain regions associated with various functions using advanced neuroimaging techniques. There is also literature indicating the impact of age on neurotransmitters, providing further insights into the mechanisms through which age affects decision-making. With the maturity of algorithms and AI technologies, the integration of neuroimaging with AI, and the simulation of neural computational models using AI algorithms, conclusions can be extended to a more precise level, which could bring insights into individual-level analysis. This comprehensive approach allows for an in-depth exploration of the entire decision-making process with specific stimulation, including the impact at the level of neural circuits, neural systems, and neurons. Consequently, the protection of decision-making in older adults can be more effectively undertaken.

6. Conclusions

Age-related changes have been proven to be of significance in many implications. The age-related changes observed in various brain regions within the decision-making network necessitate the adoption of a neurocomputational model for a more thorough understanding. This model allows for quantitative comparisons and rigorous evaluations of performance while integrating information across multiple levels of analysis. From the initial stage of information perception to the valuation stage involving cognitive functions, social cognition, and neural computations, the complexity of decision-making involves intricate processes across different brain regions. The involvement of neurotransmitters and neural pathways further emphasizes the need for a comprehensive approach. While challenges exist in validating neural computational models at the neuronal level, leveraging empirical evidence from behavioral and psychological studies aids in refining their accuracy and enhancing overall precision. The intricate interplay of neural, cognitive, and behavioral aspects underscores the necessity of a holistic perspective to comprehend the multifaceted dynamics of decision-making across the lifespan.

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