

The involvement of the striatum in decision making

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Introduction

We continuously face decisions in our daily lives: “Which breakfast cereal?” “Should I exercise? Yes, but which exercise? Soccer or yoga?” “Should I take a vacation? Maybe after this grant deadline.” “Should I drink another glass of whisky to calm me down? Another cup of coffee to wake me up?” Decisions are driven by external (eg, the size and the delay of potential rewards/losses) and internal factors (eg, reflective-controlled and reflexive-automatic behaviors¹), as well as genetic

Decision making has been extensively studied in the context of economics and from a group perspective, but still little is known on individual decision making. Here we discuss the different cognitive processes involved in decision making and its associated neural substrates. The putative conductors in decision making appear to be the prefrontal cortex and the striatum. Impaired decision-making skills in various clinical populations have been associated with activity in the prefrontal cortex and in the striatum. We highlight the importance of strengthening the degree of integration of both cognitive and neural substrates in order to further our understanding of decision-making skills. In terms of cognitive paradigms, there is a need to improve the ecological value of experimental tasks that assess decision making in various contexts and with rewards; this would help translate laboratory learnings into real-life benefits. In terms of neural substrates, the use of neuroimaging techniques helps characterize the neural networks associated with decision making; more recently, ways to modulate brain activity, such as in the prefrontal cortex and connected regions (eg, striatum), with noninvasive brain stimulation have also shed light on the neural and cognitive substrates of decision making. Together, these cognitive and neural approaches might be useful for patients with impaired decision-making skills. The drive behind this line of work is that decision-making abilities underlie important aspects of wellness, health, security, and financial and social choices in our daily lives.

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influences (eg, prefrontal dopamine systems²) or psychopathology.

Poor decision making in individuals may be due to inadequate analysis of choices or an excessively risky (or overly cautious) approach, and can have deleterious consequences for health, safety, and financial well-being. Better understanding of decision-making skills, intact or impaired, is crucial. This can be shown by the example of tobacco smoking. Consider the impact of understanding why one person has never smoked a cigarette, whereas another has smoked one or two and then stopped, or another has smoked for some time and then stopped, and yet another who continues to smoke and then suffers the consequences of brain plasticity changes that subsequently underpin what develops into the damaging psychological and physical behavior of substance use disorders. This is just an example, but a similar logic can be applied to behavioral addiction (eg, pathological gambling): why one person keeps taking risks at gambling until his/her welfare is at stake. Another example is why one person with depression or who has had a stroke complies with recommended lifestyle changes and/or medical advice (eg, exercises, reduces alcohol intake, eats healthily, participates in social activities), as compared with another person who does not comply even though that person's health and life are at stake. There is thus a broad range of diseases in which long-term behavioral and lifestyle changes are needed, requiring decision-making skills.

The aim of this article is to discuss decision-making skills and their associated neural substrates. We emphasize the influential role of the prefrontal cortex and striatum in such skills. We also review the cognitive and motivational processes involved in decision making that are known to be impaired in various clinical populations, especially substance use disorders, behavioral addiction, and schizophrenia. We highlight the need to further characterize these cognitive processes and neural substrates in order to promote development of therapeutic strategies. Indeed, approaches may target both brain *and* behavior in order to guide patients away from a maladaptive trajectory, and toward a healthier lifestyle.

Processes of decision making and the role of the striatum

Decision making has been studied mainly in the context of economics and marketing and from a group perspec-

tive.³ The recent emergence of neuroeconomics and neuromarketing has opened research areas into how the human brain makes, for example, financial decisions.⁴ Of course, the decisions we make also have significant impact on our mental and physical health, and they can be studied with experimental tasks and neuroimaging techniques.

Making decisions involves several cognitive and motivational processes, such as attention, reward seeking, impulsivity, and risk taking. These processes can be viewed as being part of two systems that interact when making a decision: there is the “hot” emotional system that values immediate rewards and the “cool” rational system that values both immediate and delayed rewards. Decision making can thus be defined as a multicomponent cognitive and emotional process served by a dynamic multilevel neural circuitry receiving and projecting amodal signals, and continuously regulating and reassessing ongoing self- and other-feedback. This circuitry integrates and synchronizes information within cortical and subcortical networks, with the prefrontal cortex and striatum as putative conductors (eg, see refs 4-10).

Within this framework, characterizing and promoting decision making can strengthen the degree of integration at both cognitive and neural levels, taking into account external factors (eg, social environment). For instance, strategies promoting positive decision making include identifying ways to rebalance the reward values of unhealthy and healthy options by strengthening frontal inhibitory and cognitive control for those individuals who wish to reach their goals for lifestyle changes (eg, to exercise; to quit or reduce smoking, gambling, or drinking; to eat healthily) but who have repeatedly failed.¹¹ However, the challenge is to identify the best way to guide adaptive behaviors and brain plasticity in order to promote the functions underlying decision making on an individualized basis that can lead to real-life benefits.

In order to guide such adaptive behaviors, the neural network needs to be well described. As mentioned above, decision-making skills entail several cognitive and motivational processes, involving a complex neural network. However, there are some key players, especially the prefrontal cortex and striatum. The prefrontal cortex and striatum are highly interconnected¹² and frequently coactivate during motivational processes.^{13,14} Distinct parts of both the ventral and dorsal striatum have been associated with different decision-making

processes in healthy adults.¹⁴⁻¹⁶ Furthermore, rewards are influential in decision making and appear to particularly activate the striatum.¹⁷ Interestingly, having choices appears to be inherently rewarding.¹⁸ Studies have shown that making choices as well as having choices (eg, perception of control) are rewarding and elicit activity in the striatum. For instance, greater activity in the striatum was found in subjects who obtained rewards from choosing among several options than in subjects who obtained the same rewards without choices;¹⁹ likewise in subjects who received instrumentally delivered rewards compared with those who received rewards passively.^{20,21}

When decision-making skills are impaired

Decision making can be affected by maladaptive behaviors and/or maladaptive neural networks. Decision-making-related behaviors (eg, accepting a first [or “another last”] cigarette) and cognitive functions (eg, reward seeking, impulsivity, self-control, risk taking, attention) can be associated with symptoms (eg, craving) of certain medical conditions (eg, tobacco use disorders). Impaired decision making has been reported in various disorders, including substance use disorders, behavioral addictions, and schizophrenia (*Table I*).

Substance use disorders

Studies have repeatedly reported that patients with substance use disorders differ from healthy subjects in decision-making skills, and these behavioral differences have been associated with different patterns of activity in various brain regions, but especially in the ventral striatum. Methamphetamine users display risky decision making,^{22,23} which has been associated with the prefrontal cortex and striatum.²⁴ For example, methamphetamine users took more risks in the Balloon Analog Risk Task and displayed greater activity in the ventral striatum and weaker activity in the right dorsolateral prefrontal cortex than healthy controls.²³ Anticipation of money reward also elicited activity in the ventral striatum in patients with cocaine use disorders²⁵ and in heavy cannabis users.²⁶ Patients with tobacco use disorders also show impulsivity and risky decision making.^{27,28} As mentioned above, rewards seem to be influential in striatal activity, and this has also been observed in patients with substance use disorders.²⁹⁻³⁵ For in-

stance, striatal activity in response to monetary reward decreased in smokers with anticipation of smoking.³² More recently, Wilson and colleagues studied individual perception of reward and its link to the striatum in deprived nicotine smokers.³³ They observed that smokers who displayed the weakest activity in the ventral striatum during monetary rewards were less keen to refrain from smoking for monetary reinforcement. Likewise, patients with alcohol use disorders show risky decision making,³⁶ which seems to involve striatal activity. For example, patients with alcohol use disorders were more impulsive³⁴ and displayed weaker activity in the ventral striatum during anticipation of monetary reward.^{34,35} Similar findings were observed in healthy subjects when exposed to alcohol. Gilman and colleagues found that alcohol infusion elicited activity in the striatum when healthy social drinkers made risky choices rather than safer choices.³⁷ Interestingly, the four studies reporting greater impulsivity in patients with substance use disorders than in healthy controls showed reduced activity in the ventral striatum,^{29,31,34,35} whereas the two studies observing no difference in impulsivity between groups indicated increased activity in the ventral striatum^{25,26} (*Table I*).

Behavioral addiction

Risky decision making is considered a characteristic behavioral phenotype of pathological gambling, which involves striatal activity. Abnormal decision making and associated activity in the striatum in patients with pathological gambling appear similar to that observed in patients with substance use disorders.³⁸ For instance, activity in the ventral striatum during reward anticipation was inversely correlated with impulsivity level in patients with alcohol use disorders as well as in patients with pathological gambling.^{34,39,40} This might not be surprising, as both diagnoses share symptoms: these patients continue to engage in behavior that brings maladaptive rewards, despite negative consequences, tolerance, and withdrawal.⁴¹

Schizophrenia

Some data suggest that patients with schizophrenia display deficits in decision making, as assessed with the Iowa Gambling Task.⁴² They also seem to be more impulsive than healthy controls in the Delay Discounting

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task⁴³ and make hasty decisions in the Beads Task.^{44,45} Furthermore, it has been reported that hasty decisions in patients with schizophrenia are associated with reduced activity in the right ventral striatum during final decision making.⁴⁶ First-degree relatives also display abnormal hasty decisions,⁴⁷ whereas individuals with an at-risk mental state do not seem to display abnormal hasty decisions, but they do show reduced activity in the right ventral striatum when making final decisions as compared with healthy subjects.⁴⁸

Other

Other clinical populations display risky decision making, including those with borderline personality disorders,⁴⁹⁻⁵¹ compulsive hoarding,⁵² and acquired lesions in the prefrontal cortex.⁵³⁻⁵⁷ Involvement of the striatum associated with risky decision making has yet to be studied in these populations. Patients with Parkinson

disease with impulse control disorders also show risky decision making.⁵⁸ For instance, these patients took more risks in the Balloon Analog Risk Task, and this was associated with lower activity in the ventral striatum than in patients with Parkinson disease without impulse control disorders.⁵⁹

Some populations show abnormally cautious decision making, including individuals with major depression,⁶⁰⁻⁶² generalized anxiety disorders,⁶³ and healthy individuals with high trait anxiety.⁶⁴ Patients with traumatic brain injury also seem to display abnormally cautious risk taking as shown, for instance, in the Balloon Analog Risk Task.⁶⁵ Again, further investigations are needed to better describe impaired and intact decision-making skills and its associated neural substrates in these populations.

Regardless of whether poor decision-making skills are a cause or consequence of some disorders, ways to promote and rehabilitate individual decision making in

	Behaviors	Striatal activity
Substance use disorders	<ul style="list-style-type: none"> ↑ Risk taking in the BART in tobacco use disorders²⁸ ↑ Risk taking in the risk task²² and BART²³ in methamphetamine use disorders ↑ Impulsivity in the DDT^{27,31} and MID task²⁹ in tobacco use disorders ↑ Impulsivity in the MID task in alcohol use disorders^{34,35} No difference in the MID task in cocaine use disorders²⁵ No difference in the MID task in cannabis use disorders²⁶ No difference in the card-guessing task in tobacco use disorders³³ 	<ul style="list-style-type: none"> ↑ Activity in the R/L VS during the BART in methamphetamine use disorders²³ ↓ Activity in the L VS during the DDT³¹ and in the R/L VS during the MID task in tobacco use disorders²⁹ ↓ Activity in the R VS³⁴ and the L VS³⁵ during the MID task in alcohol use disorders ↑ Activity in the R/L VS during the MID task in cocaine use disorders²⁵ ↑ Activity in the R VS during the MID task in cannabis user disorders²⁶ ↓ Activity in the R/L DS during the card-guessing task in tobacco use disorders³³ ↓ Activity in the VS during anticipation of juice reward in tobacco use disorders³⁰
Behavioral addiction	<ul style="list-style-type: none"> Impaired decision-making in the IGT⁴⁰ 	<ul style="list-style-type: none"> ↓ Activity in the R VS during the card-guessing task³⁹
Schizophrenia	<ul style="list-style-type: none"> ↑ Hasty decision-making in the Beads Task⁴⁴⁻⁴⁷ ↑ Impulsivity in the DDT⁴³ Impaired decision-making in the IGT⁴² 	<ul style="list-style-type: none"> ↓ Activity in the R VS during the Beads Task⁴⁶

Table 1. Behaviors and striatal activity in substance use disorders, behavioral addiction, and schizophrenia, as compared with healthy subjects. BART, Balloon Analog Risk Task; DDT, Delay Discounting Task; DS, dorsal striatum; IGT, Iowa Gambling Task; L, left; MID, Monetary Incentive Delay Task; R, right; VS, ventral striatum

line with one's goal (eg, to quit smoking) would have tremendous medical, social, and economical impact.

Future perspectives: how can we promote decision-making skills?

An ultimate goal for future work is to characterize, promote, and eventually rectify the developmental trajectory of decision making on an individual basis in order to improve the health and welfare of patients. One challenge is to integrate various disciplines, as decision making is at the intersection of medicine, human sciences, neurosciences, economics, and marketing. Also, in order to promote certain behaviors (eg, to reject offers of cigarettes), we need ways of improving cognitive functions (eg, to reduce reward [tobacco] seeking) and/or modulating associated neural substrates (especially in the prefrontal cortex and striatum). These changes may ultimately be translated into clinical benefits (eg, to reduce or quit smoking). Thus, we need to develop better cognitive paradigms and approaches that will modulate prefrontal and striatal activity in other regions and networks.

Approaches to promote cognitive functions involved in decision making

One important aspect is to adapt the laboratory-based knowledge of decision making to real-world situations. Indeed, experiments should go beyond controlled laboratory experiments into real-life situations to translate basic findings into real-life benefits. A crucial, yet often neglected, aspect when measuring human brain responses to emotions, impulsivity, desires, and so on (processes involved in decision making) is the ecological validity. Decision making, such as in accepting or rejecting an offer of a cigarette, probably operates differently in real-life than it does in laboratory settings. There are well-established paradigms for decision making^{66,67} that can be adapted to include various real-world rewards. For instance, Takahashi⁶⁸ studied self-interest impulses with the Ultimatum Game, offering monetary and cigarette rewards to patients with tobacco use disorders and healthy individuals. Patients with tobacco use disorders rejected most unfair offers of money (as did healthy individuals), but they accepted unfair offers of cigarettes. Paradigms should also include potential influences from the environment and social network

(eg, peer pressure to smoke). The emerging field of immersive virtual reality will probably contribute to a better characterization of behaviors and cognitive functions in various clinical populations, including those with substance use disorders,^{69,70} behavioral addiction,⁷¹ and schizophrenia.⁷² We need complex paradigms that imitate real-life situations, but we also need paradigms that will dissect and isolate the various processes involved when making a decision, from attentional processes to motivation, evaluation, selection, and anticipation. Characterization of cognitive processes in decision making is of clinical interest. For instance, smoking outcomes were predicted by motivational cues^{73,74} and discounting of delayed rewards.⁷⁵ It has been reported that patients with tobacco use disorders who displayed greater discounting of monetary rewards were less likely to maintain smoking abstinence during a 28-week cognitive-behavioral therapy.^{76,77}

Approaches to promote brain activity involved in decision making

There are ways to modulate brain activity, including behavioral methods (eg, neurofeedback) and, more recently, techniques of noninvasive brain stimulation. Noninvasive brain stimulation, such as repetitive transcranial magnetic stimulation (rTMS) and transcranial direct-current stimulation (tDCS), can modulate human cognitive functions in vivo.⁷⁸ rTMS is a technique that enables noninvasive modulation of brain activity through the application of relatively focal, repeated magnetic fields. tDCS induces excitability shifts that are presumably due to subthreshold neuronal membrane depolarization caused by alterations in transmembrane proteins and electrolysis-related changes in hydrogen ion concentration. Both rTMS and tDCS can induce neural inhibitory and/or excitatory changes that can outlast the period of stimulation, depending on stimulation parameters. In brief, these techniques of noninvasive brain stimulation can modulate the function of a brain network; thus, the effects upon brain circuitry are causative to the subsequently observed behavioral outcomes. These noninvasive brain stimulation techniques have modulated cognitive functions involved in decision making,⁷⁹ including reward seeking,^{80,81} risk taking,^{82,83} impulsivity,^{84,85} and attentional processing of salient⁸⁶ and emotional information.^{87,88} They may have the potential to promote decision-making skills

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in clinical populations.⁸⁹ Some proof-of-concept studies modulated decision-making processes in patients, such as those with substance use disorders,⁹⁰⁻⁹² pathological gambling,⁹³ and obsessive compulsive disorders.⁹⁴ For instance, Hayashi and colleagues⁹⁰ studied the effects of rTMS applied over the left dorsolateral prefrontal cortex in patients with tobacco use disorders. They found suppressed tobacco craving and impulsivity for monetary rewards as measured by the Delay Discounting Task. In another study, the effects of tDCS over the dorsolateral prefrontal cortex were tested in patients with tobacco use disorders who wished to quit smoking.⁹² The number of cigarettes smoked and decision-making processes were studied. Decision-making skills of self-interest impulses and risk taking using the Ultimatum Game⁶⁸ and the Risk Task,²² respectively, with rewards of money and cigarettes, were measured. Main findings included a decrease in the number of cigarettes smoked and an increase in rejection rates of cigarette offers, but not monetary offers, in the Ultimatum Game, suggesting that the effects of tDCS might be reward sensitive. There was no significant change found in the Risk Task with regard to either reward.

Most protocols using rTMS and tDCS targeted the dorsolateral prefrontal cortex. Because of brain anatomy, the striatum cannot be directly targeted with non-invasive approaches. However, as the prefrontal cortex and striatum are highly interconnected, it has been hypothesized that targeting the prefrontal cortex with noninvasive brain stimulation may modulate striatal activity. Indeed, targeting the dorsolateral prefrontal cortex with rTMS induced dopamine release in the caudate nucleus,⁹⁵ as well as in the anterior cingulate and orbitofrontal cortex.⁹⁶ In a recent study, we applied tDCS over the dorsolateral prefrontal cortex of healthy adults

during magnetic resonance spectroscopy. We found that in comparison to sham stimulation, active stimulation elevated N-acetyl aspartate in the prefrontal cortex, and glutamate and glutamine in the striatum.⁹⁷ It would be interesting to test whether noninvasive brain stimulation can reduce deficits in decision-making skills by modulating activity in the prefrontal cortex and striatum in patients with impaired decision making, as it has been shown that striatal activity has clinical impact. For instance, activity in the ventral striatum predicted treatment outcomes and substance intake in patients with cannabis use disorders,⁹⁸ cocaine use disorders,⁹⁹ and methamphetamine use disorders.¹⁰⁰ Also, activity in the ventral striatum elicited during a card-guessing gambling task with monetary reward and punishment has been correlated with gambling severity in patients with pathological gambling.³⁹

Conclusions

Together, these strategies should aid in characterizing the cognitive and neural architecture involved when we make decisions. We need to explore ways to enhance the ecological validity of our paradigms of decision making in order to ease the transition from laboratory settings into real-life situations. Also, as with any other cognitive and neural functions, decision-making abilities develop and change throughout life, which should be further taken into account in future studies. For instance, activity in the dorsal striatum was elicited during immediate and delayed rewards in older, but not in younger, healthy individuals.¹⁰¹ This will also further aid in the development of prevention methods and it will address ambitious questions, such as *Why do some individuals and not others eat healthily, drink moderately, and exercise?* □

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La participación del estriado en la toma de decisiones

La toma de decisiones ha sido ampliamente estudiada en el contexto de la economía y desde una perspectiva grupal, pero aun se conoce poco acerca de la toma de decisiones individual. En este artículo se comentan los diferentes procesos cognitivos involucrados en la toma de decisiones y en sus sustratos neurales asociados. Los supuestos conductores en la toma de decisiones parecen ser la corteza prefrontal y el estriado. El deterioro en las destrezas para la toma de decisiones en varias poblaciones clínicas se ha asociado con actividad en la corteza prefrontal y en el estriado. Se destaca la importancia del fortalecimiento del grado de integración de los sustratos cognitivos y neurales con el fin de mejorar nuestra comprensión acerca de las destrezas para la toma de decisiones. En términos de paradigmas cognitivos, hay una necesidad de mejorar el valor ecológico de las tareas experimentales que evalúan la toma de decisiones en varios contextos y con recompensas; esto ayudaría a traducir los aprendizajes de laboratorio en beneficios en la vida real. En términos de los sustratos neurales, el empleo de técnicas de neuroimágenes ayuda a caracterizar las redes neurales asociadas con la toma de decisiones. Recientemente la modulación de la actividad cerebral, tanto en la corteza prefrontal como en las regiones conectadas (por ejemplo, el estriado), mediante estimulación cerebral no invasora también ha dado luces acerca de los sustratos neural y cognitivo en la toma de decisiones. A la vez, estas aproximaciones cognitivas y neurales podrían ser útiles para pacientes con deterioro en las destrezas para la toma de decisiones. El denominador común detrás de esta línea de trabajo es que las destrezas para la toma de decisiones están a la base de importantes aspectos del bienestar, la salud, la seguridad y las elecciones financieras y sociales en nuestra vida diaria.

L'implication du striatum dans la prise de décision

La prise de décision a été largement étudiée dans le contexte économique et du point de vue du groupe, mais la prise de décision individuelle est encore mal connue. Nous analysons ici les différents processus cognitifs impliqués dans la prise de décision et les substrats neuronaux associés. Les déclencheurs éventuels de la prise de décision se situeraient dans le cortex préfrontal et le striatum. Dans différentes populations cliniques, une altération des capacités de prise de décision s'associe à une activité du cortex préfrontal et du striatum. Nous soulignons l'importance de renforcer le degré d'intégration des substrats cognitifs et neuronaux afin de mieux comprendre les capacités de prise de décision. En termes de modèles cognitifs, il faut améliorer la valeur écologique des applications expérimentales qui évaluent la prise de décision dans différents contextes et avec des récompenses, ce qui aiderait à traduire les apprentissages expérimentaux en bénéfiques dans la vie réelle. En termes de substrats neuronaux, la neuroimagerie permet de caractériser les réseaux neuronaux associés à la prise de décision ; plus récemment, la modulation de l'activité cérébrale, comme dans le cortex préfrontal et les régions connectées (par ex le striatum), par une stimulation cérébrale non invasive a aussi mis en lumière les substrats neuronaux et cognitifs de la prise de décision. Conjointement, ces approches cognitives et neuronales pourraient être utiles aux patients dont les capacités de prise de décision sont altérées. En fil conducteur de ce travail, l'aptitude à la prise de décision sous-tend des aspects importants du bien-être, de la santé, de la sécurité et des choix financiers et sociaux dans nos vies quotidiennes.

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