Neural circuitry of judgment and decision mechanisms

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Abstract

Tracing the neural circuitry of decision formation is a critical step in the understanding of higher cognitive function. To make a decision, the primate brain coordinates dynamic interactions between several cortical and subcortical areas that process sensory, cognitive, and reward information. In selecting the optimal behavioral response, decision mechanisms integrate the accumulating evidence with reward expectation and knowledge from prior experience, and deliberate about the choice that matches the expected outcome. Linkages between sensory input and behavioral output responsible for response selection are shown in the neural activity of structures from the prefrontal-basal ganglia-thalamo-cortical loop. The deliberation process can be best described in terms of sensitivity, selection bias, and activation threshold. Here, we show a systems neuroscience approach of the visual saccade decision circuit and the interaction between its components during decision formation.

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1. Introduction

Decision processing is perhaps the central function of the brain, matching motor responses to sensory inputs on the basis of experience and gain value. The decision process involves the integration of neural representations of sensory input, action planning and execution with the expected outcome and reward. Decision processing links motor responses to sensory stimuli in a flexible and adaptive manner that takes into account projections about future outcome and reward. The neural basis of this linkage is presently one of the most intensively researched questions in cognitive systems neuroscience. In this review, we consider recent research that bears on this question focusing on data obtained from nonhuman primates in the context of oculomotor decisions.

To make a decision, our brains use their cognitive and sensory abilities for making associations across time between sensory stimuli and behavioral responses [42,160]. When the decision process is examined from a sensory perspective, visual modality appears to play an important role in many types of decisions [96]. In general, primates rely heavily on vision in controlling their behavior and consequently visual input is particularly important in decision making. Nevertheless, our decisions may also involve tactile information [120,121], sounds [67] as well as chemical senses [119,152]. However, regardless of the sensory modality, decision mechanisms use some common principles, including the formation of preference based on the associations between sensory evidence, reward value and prior experience. Therefore, the understanding of how ensembles of neurons process sensory stimuli and how the flood of neuronal signals is transformed into voluntary behavior is central to the advancement of neuroscience research [93,100].

What is a decision? One way to think about decision making is as a process that transforms continuously sensory data into simple discrete categories, yes–no, go/nogo. Decision making is a “bottle-neck” type of mechanism that selects from the multitude of internal and external degrees of freedom, those few that are expressed in behavior. A fitting illustration of the decision mechanism is the spiral shaped snail shell described in Fig. 1A. This ‘spiral’ concept captures nicely the sequential feature of cognitive processing (including decision making) that begins with the input of sensory signals from external environment, continues within the thalamo-cortical loops in the brain, and ends with the selection of optimal choice as behavioral output. To make voluntary choices, the decision maker’s brain uses specialized neuronal circuits that analyzes and interprets the influx of sensory information, integrates such information with knowledge from previous experience, weights the expected outcomes (utility) and selects the option that maximizes the expected utility. In the present review, we discuss some new insights into the neural correlates of decision making in monkeys and humans by looking at the decision circuitry and its dynamic interactions among sensory, reward, cognitive, and motor systems during the elaboration of decision (Fig. 1B).

2. Neural circuitry of visual motor decision making

We are focusing here on visuomotor decisions because much is known about decisions in the visual modality [96], and also because what we learn from visuomotor decisions should be easily generalized to other modalities. The formation of a visuomotor decision is a complex process that occurs during a sequential processing of information; it starts in the visual system and ends with the activation of ocular muscles. Thus, a decision circuit links together systems processing sensory, reward, cognitive, and motor signals. Each system component is doing its job in interaction with the neighboring systems. Let us look closely at each individual system participating in the processing of decision.

2.1. Visual system

The processing of visual stimuli coming from eye’s retina through the lateral geniculate nuclei (LGN) begins in the primary visual area (V1) of the cortex and continues in the secondary, tertiary, and higher visual areas in the parietal and temporal lobes [35,73]. The complex network between visual areas is further organized into two main processing streams: (i) the ventral visual stream that passes into the inferior temporal (IT) cortex; and (ii) the dorsal visual stream passing...
through the middle temporal (MT; also known as area V5) visual area into posterior parietal cortex [32,92]. Neurons in area MT respond best to stimuli moving in one direction [2,97], while parietal neurons respond to visual motion such as optic flow [76], and to static visual stimuli as a function of their location in several spatial reference frames (for review, see Refs. [5,26]). Visual signals from both dorsal and ventral streams are conveyed to prefrontal cortex where these signals are integrated for the spatial and temporal organization of behavior [36,108]. A major source of reward related signals seems to be the dopamine (DA) mediated innervations of the prefrontal cortex and other (parietal and temporal) cortical areas from a group of cells located in VTA (for review, see Refs. [134,143,155,162]). Similar reward related projections are sent from the nearby SNc to the caudate nucleus [89]. These dopaminergic neurons have ideal properties for providing the signal that guides the acquisition of goal (as a desired end state) related information [68,134–136]). Initially, they give a burst of activity to unpredicted rewards, and as time goes by, they also become activated by cues that predict the rewards. If a reward is withheld, dopaminergic neurons are inhibited. These properties indicate that dopamine influx into the PFC and caudate nucleus may modulate the signals that bias the decision process. A schematic description of the reward system is presented in Fig. 2B.

2.3. Cognitive system

An important part of the brain, namely the prefrontal ‘executive’ mechanism, is thought to be responsible for the implementation of higher-order cognitive judgment and decision making [93,98]. Thus, the privileged location of prefrontal cortex at the apex of sensory-to-motor processing hierarchy [41] may provide the flexible and rule-driven interface between accumulating sensory evidence and the selection of optimal response [160]. Thus, a context sensitivity to decisions (i.e., being able to flexibly reconnect sensory signals and motor signals on the basis of contextual information) might be the contribution of the cognitive system to the decision-making process. The ‘executive’ system has been divided by some into several functional and anatomical components [7,34,52,93,142]. Such functional ‘fractionation’ appears to be paralleled by the anatomical organization of the frontal cortico-thalamo-basal ganglionic loops into: dorsolateral prefrontal, orbitofrontal, limbic, oculomotor, and motor components [3,8,57,124].

Dorsolateral prefrontal cortex (dlPFC) is the integrative center’ of high order cognitive processing in the brain and plays a central role in the executive control of behavior [11,40,51,93,165]. The processing subserved by dlPFC has been characterized in terms of working memory (online maintenance of items for immediate use), by mediating the linkage of sensory stimulus and response across time [39,40]. Two dlPFC areas with a primary role in visuomotor decision making are the prefrontal area 46 around principal sulcus and the frontal eye fields (FEF). FEF represents a visual processing stage at which the location of salient stimuli becomes explicit and is read out into a behavioral command that guides subsequent action [19,20]. Neural activity associated with visually guided eye movements was
also found in the supplementary eye fields (SEF; [123,133]). Their hypothesized role is in self-generated saccade production, conditional motor learning, object perception, volition and behavior monitoring (for review, see Ref. [130]). A schematic description of the cognitive system is presented in Fig. 2C.

2.4. Saccadic eye movement system

Visual signals originating in primary visual area V1 reach LIP, FEF and SEF via several extrastriate visual areas [35]. In addition, certain extrastriate areas with retinotopic visual field organization (such as area MT) project topographically onto FEF [132]. Lateral FEF which is responsible for generating short saccades receives afferents from areas that represent central vision, while medial FEF which is responsible for generating longer saccades is innervated by areas that represent peripheral vision [19,20,50]. FEF and other cortical eye fields (SEF and LIP) send both direct and indirect projections (via basal ganglia) to the intermediate layers of superior colliculus (SC; for review, see Refs. [66,147]). The frontal and parietal eye fields can affect saccadic eye movements only by engaging the “saccade generator” circuitry in the pons and brainstem, both directly (via routes that bypass SC) and indirectly via the SC [85,138,147,148]. Like all eye movements, saccades triggered by the frontal and parietal eye fields depend on the brainstem’s neural integrator [31]. Moreover, electrical stimulation of brain structures that generate the command to shift gaze (such as the FEF or the superior colliculus), elicits an eye movement if the electrical current and its frequency are high enough [19,146]. A schematic description of the oculomotor system is presented in Fig. 2D.
3. Neural correlates of decision making

Successive populations of neurons carry a large variety of signals that are correlated with external sensory events, internal mental states or impending behavioral responses. These signals are encoded, decoded, and remapped at several stages of the perception to action cycle in order to select the most appropriate course of action [40,41,98,107,140]. Decision formation is based on a set of steps that include: (i) accumulation of sensory evidence [111,141], (ii) integration of sensory signals, reward expectation and cognitive information [18,87,106], (iii) weighing of the options by comparisons between a subject’s expected reward and prior experience [128,149], and finally, (iv) selection of behavioral response [131]. The flow of decision signals is depicted in Fig. 3.

3.1. Accumulation of sensory evidence

Any decision making process (regardless of its modality or complexity) is based on some evidence (gain) about the options. Thus, the time course of evidence accumulation should be dependent upon the amount and rate of information gain [33,56,63]. We choose as focus for our review the ‘classic’ perceptual decision experiments of Newsome et al. [17,80,141]. The justification for our choice is in the completeness and consistency of their work; they have examined decision related activity in key neural structures of the dorsal visual stream, prefrontal cortex, and superior colliculus using the same “moving dots” paradigm. Moreover, decision-related processing (as it has been argued by Newsome, Shadlen, and others) is revealed by two features of LIP and FEF activity: (1) dependence on percent coherence in the sensory stimulus, and (2) an upward trend in neural activity over time.

In the motion discrimination task of Newsome et al. (shown in Fig. 4A) monkeys were trained to decide whether the direction of motion was toward one of the two choice targets that appeared on either side of the coherent dot stimulus. After viewing such coherent dot motion, at the end of the trial, monkeys reported their judgment by making an eye movement to the appropriate target. One of the targets was placed in the neuron’s response field (RF) while the other target was positioned away from RF, at the opposite location. The neurons in several cortical areas of the dorsal visual processing stream were recorded while the monkeys performed this task [16,80,124,141].

How is the accumulation of sensory evidence reflected in the activity of dorsal visual stream neurons? Examining the activity of MT neurons Newsome et al. found that when a directionally selective cell fires more vigorously (Fig. 4B, left panel), the monkey is more likely to make a decision in favor of the preferred direction of that cell [17]. Such a relationship to the eventual perceptual decision was evident within 50 ms from the response onset and persisted throughout the presentation of stimulus. They tested then how subthreshold currents injected in MT columns influence decision formation, and noted that visually and electrically induced directional signals interact with each other according to a winner-takes-all algorithm (i.e., one or the other signal wins) when the two competing signals have nearly opposite preferred directions, or follow distributed coding schemes (each signal “votes” for its preferred direction and the outcome is a weighted summation of the two or more signals) at smaller angular separations [99,125]. On the other hand, microstimulation of MT columns was shown to affect decision’s speed by either increasing or decreasing the rate of sensory evidence accumulation, corresponding to faster or slower decision times, respectively. Thus, microstimulation “quickened decisions” (injected and natural signals cause a faster accumulation) in favor of preferred direction and slowed decisions (injected and natural signals cause a slower accumulation) in favor of the opposite direction [33]. These experiments indicate that sensory information accumulates until a decision threshold is reached [58].

In parietal cortex, neurons that carry ‘high-level signals’ have spatially selective activity (i.e., neural activity modulated by the spatial location of visual target) required to identify salient visual targets or to guide saccadic eye movements [26,27,54]. Lateral intra-parietal (LIP) neuronal activity, like that in MT, began early in the motion viewing period and had a larger response when the direction of motion was toward the RF than when the motion was away from the RF (Fig. 4B, central panel). Since motion signals
are presented continuously, the decision result appears to be formed by accumulating each piece of evidence over time. The time course of neural response shows that when the coherence of dots increases, the buildup or decay trends are steeper and the decisions are faster (Fig. 4C; [118,141]). Thus, looking at the slopes of activity increase/decrease in Fig. 4C, we note that the accumulation of sensory evidence agrees with the speed-accuracy condition (i.e., accurate decisions correspond to longer reaction times than the faster and less accurate decisions). The similarity between LIP and dIPFC activity patterns highlighted by Chafee and Goldman-Rakic [23] suggests that these two cortical areas share common circuits to: (i) process accumulated sensory evidence, (ii) store such sensory information in working memory, or, (iii) read out relevant information in perceptual decisions.

Fig. 4. Description of evidence accumulation process. (A) Temporal sequence of behavioral events in a motion discrimination task. The monkey gazed at the fixation point for 350 ms. Then two targets appeared, one of which was in the neural response field (RF, shaded). After 200–300 ms, the random dot kinematogram appeared between the targets and outside the RF. The direction of motion was toward one of the two targets. Motion strength was varied from trial to trial by adjusting the percentage of coherently moving dots. After 1 s, the random dots were turned off, leaving only the fixation point and targets. After 0.5–2.0 s, the fixation point was extinguished, signaling the monkey to indicate its choice by shifting its gaze to one of the targets. The monkey was rewarded for choosing the target along the direction of random dot motion, or randomly when there was no net motion (0% coherence). T1 and T2, saccade targets; RF, receptive field. (Reprinted with permission from Shadlen and Newsome [141]). (B) Neuronal activity in MT, LIP and PFC during motion discrimination task. The cartoon at the top indicates whether the monkey’s behavioral response was an eye movement into or out of the response field. Rasters and PSTHs are aligned to the onset of motion, which is then followed by a motion-viewing period. These neurons modulated their activity early in the motion-viewing period and in accordance with the monkey’s direction judgment and pending eye movement. Responses were more enhanced and more profoundly depressed when the motion strength was greater. Adapted with permission from Shadlen and Newsome [141], Kim and Shadlen [80], and Mazurek et al. [90]. (C) Population response from LIP neurons during the direction discrimination task. The average firing rate is plotted as a function of time during the motion-viewing and delay periods. Solid and dashed curves are from trials in which the monkey judged direction toward and away from the RF, respectively. Error trials are not shown. Both the time course and magnitude of the response are affected by the strength of random-dot motion, particularly during the motion-viewing period. Adapted with permission from Shadlen and Newsome [141].
FEF and dorsolateral prefrontal cortical neurons have a mixture of high-level oculomotor and weaker visual signals reflecting the strength and direction of motion (Fig. 4B right panel; [80]). Such mixture of visual signals may represent the conversion process of accumulated visual motion signals into a ‘categorical decision’ about the direction of movement. So far, we know that several brain areas show decision related activity similar to what is observed in LIP, including prefrontal cortex and superior colliculus [72,80]. It is unknown whether any or all of these areas are responsible for integration of the evidence from MT, or to what degree their responses simply reflect this process. However, we hypothesize that such integration occurs along the dorsal pathway, between LIP and prefrontal cortex. In fact, some evidence indicates that signals from both dorsal and ventral visual streams are integrated (accumulated over time) in prefrontal cortex [108]. Bruce [18] has shown that FEF signals represent an integrative process of visual and oculomotor signals. Along the same idea, the microstimulation experiments of Gold and Shadlen [48,49] beautifully show that FEF oculomotor signals responsible for saccadic eye movement deviations reflect the accumulated motion information that guided the monkey’s choices on the discrimination task. Gold and Shadlen [49] further note that neurons from FEF involved in accumulating motion information do not represent specific actions but rather behavioral rules (pro-or anti-saccades). Pro-saccades are the saccades made to the location of the target, while the anti-saccades are saccades to the opposite location of the visual target.

3.2. Integration of reward value in decision making

The prefrontal cortex plays a central role not only in integrating visuospatial information of relevant targets [18,108], but also information about future events, actions, and the outcome of these actions. Therefore, the signals carried by neurons in prefrontal cortex [87,162], anterior cingulate cortex [143], posterior parietal cortex [106], posterior cingulate cortex [91], and basal ganglia [61] are modulated by reward expectation. Reward expectation (or value) is an important constraint in the shaping of an animal’s behavior [145]. According to Herrnstein’s matching law, an animal’s choice is biased to the option that maximizes reinforcement probability [64,65]. It is hypothesized that the signals that bias decisions come from a group of DA cells located in VTA and SNc [1364]. These dopaminergic cells have phasic responses that depend on reward probability and tonic responses signaling reward uncertainty [37]. The convergence of dopaminergic projections to prefrontal cortex tells us that DA signals are used for cognitive purposes [164].

How is reward expectation integrated in decision formation? Leon and Shadlen [87] found many prefrontal cells with reward related enhancement throughout the memory period but not much enhancement was found in the FEF (probably because FEF cells are more related to the preparation aspect of eye movement). Such enhancement, in the lateral PFC, was thought to represent the coding and monitoring of motivational context [163]. Thus, the mixture of neural signals representing spatial working memory and reward expectation appears to be an integrative feature of most prefrontal neurons. Also, the modulation by reward was reported in the activity of neurons in the LIP [106], supplementary eye fields [4], and other cortical areas. In LIP, Rorie and Newsome [122] reported that information concerning reward magnitude exerts a simple additive bias on the neural mechanisms participating in the formation of perceptual decisions. Therefore, the modulation of most neocortical and neostriatal activity by midbrain’s dopaminergic signals should provide a bias to the decision process.

How is reward expectation bias reflected in decision formation? A possible answer to this question was provided by Lauwereyns et al. [84] who have identified in the caudate nucleus neurons that create a spatially selective response bias dependent on the expected reward (gain). In their experiment, monkeys performed a visually guided saccade task with an asymmetrical reward schedule in which the animal was rewarded for a correct saccade to only one out of two possible target positions. The discharge rate of caudate neurons increased selectively right before the expected appearance of a relevant visual target. A plausible interpretation of these results is that the bias in the caudate nucleus favors a particular spatial response when it is associated with a high reward value, but not when it is associated with a low reward value [79]. Such bias could be propagated downstream in the oculomotor loop from caudate nucleus onto the pars reticulata of substantia nigra, and then onto superior colliculus [66]. Neurons in SC have a movement field at the position with a higher reward value and can augment presaccadic processes involved in saccade initiation [75].

3.3. Comparison of knowledge from prior experience with an expected reward

The weighing of the options requires ongoing comparisons between a subject’s reward expectation and the knowledge from prior experience [128]. Even in the absence of sensory information, prior estimates of the probabilities of options can be used to select a particular course of action. For example, Carpenter et al. have shown that knowledge of prior probabilities can influence decision making [22,114]. In their experiments, human subjects were required to saccade to a stimulus that could appear at more than one possible location. The saccades to targets presented at highly probable locations occurred with shorter latency than the saccades elicited by targets at unlikely locations. These and other recent experiments established that prior knowledge of the likelihood of a future event could influence the speed of visual saccadic decision making [33,75,95,137].

How is prior knowledge used in decision formation? Sugrue and Newsome [149] found that LIP neurons keep
track of past reward history. And the relationship between firing rate and the experienced value (defined as the weighted average of reward history) is independent of the motor response relationship to the firing rate. Recently, they found that animals and humans employ a linear integration over reward history to estimate the relative value of found that animals and humans employ a linear integration over reward history to predict the future events from over reward history to estimate the relative value of memory may prospectively predict the future events from past history. On the other hand, if the prior probabilities that describe the environment change, the decision mechanism needs to ‘update’ its prior knowledge. Neurons in basal ganglia might provide specialized mechanisms to extract such information. For example, the activity of midbrain dopaminergic neurons might carry a ‘post-decisional error signal’ indicating whether the decision made by the animal yielded more or less reward than expected. To perform online comparisons between a subject’s expected reward and the knowledge from prior experience, the brain may use the prefrontal-basal ganglia-thalamo-cortical loops.

3.4. Selection of behavioral response

The crucial step in decision formation is the selection of optimal behavioral response. The implementation of a selection mechanism usually requires a winner-takes-all (WTA) algorithm. Such selection mechanism should depend on the “relative salience” of the competitors weighted so as to provide appropriate “dominance” [115]. In selecting a behavioral response, the primate brain has available the prefrontal-basal ganglia-thalamo-cortical loops that have the right architecture for decision making. The structures of basal ganglia are ideally configured to select on the basis of input salience. Distributed prefrontal cortical loops through the basal ganglia can provide an independent control over multiple output channels [3,69]. This independent control, therefore, suggests the need for multiple parallel selections, each arbitrating between a pool of competitors [115]. Basal ganglia, with the caudate nucleus as input and the pars reticulata of substantia nigra as output, are in the privileged position to resolve the conflict problem over access to limited oculomotor and cognitive resources, by selecting between competing inputs from different regions of prefrontal, parietal, and temporal cortical areas. It is possible that the division of basal ganglia in limbic, associative and motor domains could reflect the presence of a functional selection hierarchy [115].

Selecting a visual stimulus to direct gaze requires comparing stimulus attributes across the visual field [127]. The existence of retinotopic maps makes it possible for local interactions to implement such comparisons. A saccadic eye movement is produced when the neurons at one location within the movement maps become sufficiently active [18]. Visual processing, then, makes sure that only one site within a movement map becomes activated. This is done when the neurons signaling the preferred target location develop enhanced activation while the neurons responding to other locations are attenuated. Saccade production is regulated via inhibitory projections from SNr to the SC and FEF via thalamus [66]. The inhibitory control signals in the FEF and SC may originate in SNr [53].

A schematic description of the response selection loop is presented in Fig. 5. The representation of visual stimuli stored in working memory are processed in prefrontal cortex and frontal eye fields (FEF), both of which project strongly to neostriatum, especially the caudate nucleus. These inputs are reconfigured in neostriatum in relation to the evaluative inputs about the significance of options. As a result, a certain target is selected for potential activation. Processing through pallidonigral-subthalamic circuitry leads to a ‘differential activation’ of the selected choice, which is forwarded to the cerebral cortex and to the pattern generators in the brainstem [55]. It is noteworthy that neurons in caudate nucleus [79,84], thalamus [82,166], SNr [83], and SC [71] carry signals that are influenced by decision contingencies and outcomes. SNr neurons responsible for inhibition respond preferentially to the stimuli associated with reward [126].

Fig. 5. Response selection loop. Schematic description of the prefrontal cortical and basal ganglia circuitry used in the selection of behaviorally relevant response. Visual stimuli (sensory input) carrying information about target’s spatial location reach the prefrontal cortex after several intermediate processing stages. Cognitive information regarding choice options and representations stored in working memory are processed in prefrontal cortex and frontal eye fields (FEF), both of which project strongly to neostriatum, especially the caudate nucleus. These inputs are reconfigured in neostriatum in relation to the evaluative inputs about the significance of options, derived from substantia nigra pars compacta and the reward system. As a result, a certain option (target, response) is selected for potential activation. Processing through pallidonigral-subthalamic circuitry leads to a differential activation of the selected choice, which is forwarded to the cerebral cortex and to the pattern generators in the brainstem. Adapted from Graybiel [55] with permission.
A common feature in the FEF and SC nodes of the decision circuit is the presence of a buildup/prelude activity pattern [19,72]. The premovement (‘buildup’) activity in FEF begins with a few spikes, increases slowly and culminates with the onset of saccade [19]. The FEF cell in Fig. 6, that was recorded in a color match-to-sample (MTS) task, shows this pattern.

**Fig. 6.** Buildup activity of a FEF neuron during the target selection process. (A) Diagram of the color match-to-sample (MTS) saccade task. A centrally presented sample is on for 750 ms and must be remembered for a brief variable “delay” period (100–500 ms) before the match/non-match pair appear. Furthermore, after the peripheral stimuli appear the monkey is required to further delay his response for a brief variable “wait” period (200–1000 ms) until the fixation light is extinguished. (B and C) Responses of a FEF visuomovement neuron in the MTS task. Data are aligned with the extinction of the central fixation light, that is the saccade go signal. The gradient strip (grey color) represents the last 1000 ms of the variable “wait” epoch used for decision making (target selection). The raster lines for trials where the match stimulus was in the cell’s response field (RF) are red and the trials where the stimulus was opposite to the RF (xRF) are green. Notice that the buildup activity begins well prior to the saccades in the RF trials, but not in the xRF trials. Data recorded by I. Opris, H. R. Friedman and C.J. Bruce.
decision task with two options (red and green targets), provides an example of such buildup activity. If neural activity in the prefrontal cortex represents the decision making, then this activity should reflect the formation of monkey’s preference for one of the options. A decision signal reflecting such preference should increase over time (buildup response) when the subject is required to choose the preferred target, or decrease (decay response) when the subject is required to choose the non-preferred target. Thus, when the neuronal threshold is reached, a behavioral response is selected [59,129]. In addition, neural activity representing the decision should be independent from lower level sensory and motor processes.

How is the processing of response selection accomplished? Distinctions are often made between the processes suberving target selection, the allocation of attention and the processes suberving motor response selection (Schall [127]). Let us look at each individual process.

3.4.1. Target selection

A target selection process determines the target to be selected from multiple targets presented simultaneously in the visual world, and the appropriate response for the next eye movement [129]. Recent results indicate that a subset of neurons in the dorsolateral prefrontal cortex show a visuospatial mnemonic process that is related to the selection of visual spatial target [74]. Consistent with this (target selection) interpretation of the delay period activity, Opris et al. [102] found that prefrontal cortical activity and saccade target selection are causally related. Thus, the electrically injected current (applied during the delay epoch of a delayed spatial MTS saccade task) in the prefrontal cortical loop, interacts with the signals responsible for target selection, overwriting the selected target, and consequently biases saccade choices either towards the receptive/movement field (RF/MF) or away from RF/MF (Fig. 7). The selection mechanism followed a winner-takes-all algorithm (in which either of the signals representing the target or the distractor wins) at larger target separation or a vector averaging (in which each signal is equally weighted and the direction of elicited saccade is between the two targets) at smaller separations.

3.4.2. Attention allocation

When a salient stimulus pops up in the visual field, the brain can selectively direct visual attention to that location without an overt movement of the eyes or head. In such instance, the allocation of attention was possible without the selection of a response. Testing the attention allocation hypothesis in monkeys, Hasegawa et al. [59] have shown that the response of prefrontal neurons of monkeys could differentiate between target and distractors from the very beginning of their response. These cells provided a clear distinction between attention allocation and response selection, since the monkey was not allowed to express its choice until after a given delay. In a different task, Lebedev et al. [86] trained monkeys to remember one location while attending to a different location. They reported that delay period activity was more often related to spatial attention (as the final location of the target) than to working memory (as the remembered location of the target). Such clever and carefully balanced experimental designs, therefore, can distinguish attention allocation from response selection or spatial memory.

3.4.3. Motor response selection

The salient stimuli presented in the visual field may carry specific action instructions (go–nogo) or behavioral rules (hold or release a lever; pro- or anti-saccades). Based on such instructions/rules [160], the animal chooses the appropriate behavioral response. Neural correlates of such behavioral selection have been identified in the activity of frontal eye field neurons of monkeys during a visual search task [94,154] and in premotor cortex during a rule task [160]. In fact, Schall’s lab has shown that FEF neurons can distinguish between “visual selection” and motor processing stages in response selection [94]. According to these authors the time of target discrimination partitions the reaction time epoch into a ‘perceptual stage’ in which target discrimination takes place, and a ‘motor stage’ in which saccade programming and generation take place [153]. Consistent with the reaction time partition, Horwitz and Newsome [71,72] found in superior colliculus the types of signals (target selection and movement specification) hypothesized by Schall et al. As shown recently, SC neurons communicate with FEF [44] and the intra-parietal area [103] over a wide range of sensorimotor and cognitive functions, allowing the decision mechanism to select the movement before the action is initiated [46].

4. Dynamic interactions during decision elaboration

The systems processing decisions are highly interactive. Recent work highlights some of the cognitive interactions involving the prefrontal cortex [28,29,30], prefrontal and dorsal visual extrastriate cortices [78], the prefrontal cortex and basal ganglia [104], the frontal eye fields and superior colliculus [144], and the LIP and SC [103], as key nodes of the cognitive mechanism circuitry. When the activity of prefrontal neurons is recorded with several electrodes, the modulation described by the time course of coherent firing in groups of neurons may provide valuable clues about neuronal association in functional groups [1,139,158]. As decision elaboration unfolds in time, we hypothesize that the systems processing the integration of relevant signals and the selection of behavioral responses change their pattern of firing. The emerging pattern of buildup/decay in the correlated firing of the pairs of neurons sharing common inputs may be shown by joint scatter diagrams [144].
4.1. Correlated neuronal firing

How is correlated firing involved in decision formation? An example showing two interacting neurons in frontal cortex that were recorded simultaneously while a monkey performed an instructed GO–NOGO task is displayed in Fig. 8 [158]. The interaction of these neurons reflects two distinct trends in the coincidence time histograms that are...
meaningful for decision elaboration (but not pointed out). When the monkey performs the GO paradigm, the correlation dynamics exhibits a gradual buildup reflecting the accumulation of information for the GO choice, while when the animal performs in the NOGO paradigm, the correlation dynamics exhibits a gradual decay. This is an elegant illustration of how groups of co-firing neurons assemble together to perform a computational task or how
co-firing falls to zero when the neurons become functionally dissociated. Such neuronal grouping may use excitatory or inhibitory interactions. Recent findings reveal that the inhibitory prefrontal interneurons have the activity more tightly correlated than the excitatory ones and such correlation is short-ranged [28,29]. Also, the prefrontal inhibitory interaction is ‘gating’ the temporal flow of information that controls the cognitive operations [30] and likely plays an important role in decision elaboration.

4.2. Timing the onset of decision process

Which area of the brain initiates the decision process? We hypothesized that visuomotor decisions arise from functional interactions between ensembles of neurons in principal sulcus and FEF [101]. In contrast to our idea, Wallis and Miller [160] suggest that a perceptual bias arises in prefrontal cortex a few tens of ms earlier than in premotor cortex, but the selectivity of premotor cells was stronger and earlier than in the prefrontal cortex. If one takes into account that response selection may be processed within a basal ganglia-thalamic-cortical loop that sends to premotor cortex the selection result, this explains the timing difference. Along the same path of reasoning with Wallis and Miller who further hypothesized a degree of specialization in decision making, recent results suggest that SEF plays an earlier and more cognitive role in internally guided decision making processes for saccades [25], and precedes superior colliculus activity in a sensory decision-making task [12]. However, it is reasonable to assume that the initiation of visuomotor decision occurs along the prefrontal–parietal segment. In support of this view, we note that the presaccadic activity in FEF reaches a specific and constant threshold activation level before saccade initiation [58] and that FEF and LIP communicate to each other and with superior colliculus over a broad range of visual, cognitive and movement signals [23, 103,144].

5. Quantitative approach to decision making

The understanding of the quantitative facet of decision mechanism has two main roots: one is in signal detection theory (SDT) and the other is in the accumulator models of reaction times. Here, we briefly touch on the main features of the two approaches and then focus on their relevance to the neural modeling of the decision mechanism.

5.1. Signal detection theory and accumulator models

The main features of signal detection theory (SDT; [56]) are the sensitivity (performance limits provided by the senses) and the bias (limits arising from decision making strategies) measures. These features allow us to compare psychophysical sensitivity captured in the psychometric function and the neuronal sensitivity of MT neurons during motion signal detection [16]. In accumulator models, a choice response is triggered when the signal that represents the decision process grows over time to reach a threshold level [6,112,159]. Similar to the accumulator models are the classic random walk and the related diffusion models [10,109]. In these models, the decision making procedure can be formally described as a random walk (or diffusion process) in which the system “drifts” toward one of two opposite boundaries (thresholds), under the influence of noise [110,111]. These processes form the theoretical bases for a wide range of cognitive decision models that include sensory detection [156], perceptual discrimination [88], memory recognition [109], and higher level decisions [21,117].

The accumulation of evidence can be formally described by accumulator models or as random walk/diffusion processes. These models assume that decisions involve a mechanism that accumulates information over time from a starting point toward one of two boundaries, as shown in Fig. 9A. When one of the boundaries is reached, a response is initiated. The rate of information accumulation coined as ‘drift rate’ is determined by the quality of the extracted information. Consistent with the information accumulation feature [9,10], a dynamic version of signal detection theory (DST) describes the decision process with only three parameters: the first two are sensitivity (detectability) and bias (similar to those in SDT) while the third is a threshold bound (criterion) which is required to account for speed-accuracy trade off effects. The rising time to threshold, in fact, represents the deliberation time (decision time), a valuable parameter used to quantify the decision.

5.2. Psychological and biophysical description of information accumulation

To show the link between neuronal activity and the processing dynamics described by the psychological ‘diffusion model’ of decision, Ratcliff et al. [113] hypothesized that buildup/prelude neurons in SC and FEF are part of a mechanism that implements the accumulation of sensory evidence in a decision process. They compared neural firing rates to the paths of evidence accumulation for the diffusion process and found that collicular prelude/buildup activity closely follows the trajectory of the decision process described by a diffusion model. Mazurek et al. [90] instantiated the hypothesis that neurons in sensorimotor association areas compute the time integral of sensory signals from the visual cortex, suggesting that the decision is made when the integrated evidence reaches a threshold.

Another model uses nonlinear decision units with leakage (activation decay) to account for the biophysically plausible constraints (lateral inhibition, recurrent excitation) and to address some of the challenges (1. indefinite time course of information accumulation; 2. extension to several
alternatives) to existing diffusion, random walk and accumulator models [156]. The units representing different response alternatives accumulate activity from sensory input units, compete with one another through mutual inhibition and signal a response when they cross a fixed threshold. This model explains the linear slowing of reaction time as a function of the log of the number of alternatives, known as Hick’s law [157]. An illustration of the hypothesized information accumulation (in tasks using two, four and eight targets and asymmetrically rewarded) is presented in Fig. 9B. A prediction of Hick’s law suggests that the deliberation time and the criterion threshold may increase with the increase in the number of options if reward is asymmetrically given (one target receives more often than the others). Surprisingly, visually guided saccades do not follow the Hick’s law (i.e., reaction times do not increase with the number of alternatives; [83]), but this does not invalidate the law; it only shows its limitations.

In attempting to understand synaptic mechanisms of visual motion discrimination experiments of Shadlen and Newsome [141], Wang [161] has modeled a biophysically based recurrent cortical network by using spiking neurons. The model shows that slow synaptic reverberations mediated by NMDA receptors and winner-takes-all competition mediated by feedback inhibition generates an attractor (stable state) dynamics that is consistent with neurophysiological and psychophysical data from delayed discrimination experiments [118,141,161]. In this model, categorical decisions and memory storage are accomplished by attractor dynamics (exemplified by the analogy with a down-hill motion).

6. Summary and conclusion

The understanding of decision making circuitry has been greatly benefited by the contribution of Newsome, Shadlen, and others that have revealed key features of decision-related processing: (1) dependence on percent coherence in the sensory stimulus, (2) an upward trend in neural activity over time (in the delay epoch); (3) independence of decision signals from low level sensory and motor processes. The upward time-trend in the neural activity is seen in LIP and FEF activity without any sensory input (during the delay period of a memory-guided saccade task). Some caution is needed when interpreting the neural correlates of decision processing that have been described to date. Specifically, a relationship between neural signal intensity in oculomotor structures and visual motion coherence may reflect an increase in the strength of connections between visual sensory centers processing visual motion and motor centers processing saccade commands. It would then need to be further clarified whether this mechanism, achieved through training, constitutes a neural basis for decision making in the psychological sense of the term, which implies a flexible association of stimuli and responses on a trial by trial basis. Additional experimentation will be required to further clarify the dissociation between neural activity and sensory and motor variables that are integral to decision processing. Considerable progress in this direction has already been achieved by recent research into the neural basis of oculomotor decision making.

We reviewed a wide range of recent evidence concerning neural underpinnings of decision making and perceptual judgment from a circuitry perspective. The review was
intended to present the decision circuit as a unitary mechanism that coordinates dynamic interactions between sensory, reward, cognitive, and motor/oculomotor systems. In the sequencing of the elaboration process we considered several steps: (1) accumulation of sensory evidence, (2) integration of sensory information with reward expectation and knowledge from prior experience, (3) weighing of the options, and (4) selection of behavioral response. Although most of the reviewed experimental data comes from neurophysiological single unit recordings, we emphasized the significance of pair-wise recording in two distinct brain areas and the value of simultaneous multi-electrode recordings in the elucidation of decision circuitry. Such data are a necessary pre-requisite for tracing the decision circuitry. In fact, there is growing interest about how decision signals propagate through the multiple stages of the decision circuitry [81] and how such signals are coded, decoded, and re-mapped. Although, the rapid advancement in functional magnetic resonance imaging (fMRI) provides valuable information about the spatial extent of human decision making circuitry, it was beyond our scope to review fMRI literature. However, it is worth noting that converging evidence supports the view that human dorsolateral prefrontal cortex integrates sensory information over time and converts such information into a categorical decision about motion direction [62]. In fact, this experiment provides a successful replication in humans of the experiments done by Shadlen and Newsome [141] in monkeys. Finally, it is worth mentioning that recent insight into the decision processing will contribute to further understanding of the cognitive basis of behavioral control and the elucidation of executive dysfunction [14,15,47,105].

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