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Eye Movements as a Window into Decision-Making

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Abstract

For over 100 years, eye movements have been studied and used as indicators of human sensory and cognitive functions. This review evaluates how eye movements contribute to our understanding of the processes that underlie decision-making. Eye movement metrics signify the visual and task contexts in which information is accumulated and weighed. They indicate the efficiency with which we evaluate the instructions for decision tasks, the timing and duration of decision formation, the expected reward associated with a decision, the accuracy of the decision outcome, and our ability to predict and feel confident about a decision. Because of their continuous nature, eye movements provide an exciting opportunity to probe decision processes noninvasively in real time.

1. INTRODUCTION

Decision: cognitive process of comparing and deliberating alternatives before a choice can be made

Perceptual decision: decision based on weighing sensory evidence

Value-based decision: decision based on weighing reward expectations

Choice: selection of an option, often through a motor action, when faced with two or more alternatives

Confidence: metacognitive ability to internally estimate the probability of a correct choice, given the evidence

Saccade: quick (high-velocity and short-duration) eye movement toward an object or location of interest

Perceiving the visual world is an active process that involves orienting the eyes, head, and body toward an object of interest. It is also a highly dynamic process during which the eyes continuously scan the environment to sample visual information. Many research disciplines—from developmental and cognitive psychology to computer science to art history—use eye movements to measure visual perception, object recognition, memory function, and other cognitive processes. This review focuses on the link between eye movements and decision-making.

We make decisions frequently throughout the day. Perceptual decisions are usually simple and binary—such as whether to drive through a changing traffic light or whether to stop. They require selecting, discriminating, and weighing the accumulated sensory evidence. Value-based decisions might be more complex and involve options with multiple attributes—for example, which lunch option to choose, gym to join, or stock option to invest in. They require identifying and deliberating expected costs and benefits. Perceptual and value-based decisions have been the focus of neuroscience for over three decades. Single-neuron and population recording studies of nonhuman primates have unraveled some of the brain circuits underlying the transformation of a sensory signal into a perceptual choice (Gold & Shadlen 2007; Najafi & Churchland 2018; Schall 2001, 2013) and the timing, accuracy, and confidence with which this choice is made (Shadlen & Kiani 2013). Nonhuman primate neurophysiology, human imaging, and neuropsychological studies have elucidated how value is represented in neuronal activity across different brain areas (Kennerley & Walton 2011, Padoa-Schioppa & Conen 2017, Platt & Glimcher 1999, Vaidya & Fellows 2020). In many of these studies, primates indicate their choice by moving their eyes in a preferred direction or location while neuronal activity is being recorded. For example, a classic paradigm involves asking monkeys to discriminate the motion direction of a stimulus (e.g., left versus right) by making a saccade in the perceived direction (to the left or right). In this task, saccade choice accuracy is related to neuronal activity in motion-sensitive brain areas (Newsome et al. 1989). More critically, choice accuracy is also predicted by activity in decision-related brain areas, making this a key task to elucidate aspects of perceptual decision-making (Levi & Huk 2020, Shadlen & Kiani 2013). Such tasks have contributed to detailed neuronal and computational models of decision-making that rely on the idea that neuronal activity itself acts as a decision signal and predicts upcoming choices (Glimcher 2001; Gold & Shadlen 2007; Najafi & Churchland 2018; Schall 2001, 2013; Shadlen & Kiani 2013).

More recently, neurophysiological studies have been complemented by behavioral eye movement studies that focus not only on where we look but also on the metrics of the movement itself. In these studies, eye movements are used as indicators of target selection, choice or deliberation processes, and performance monitoring (confidence), as well as indices of stimulus and task features such as uncertainty or value. Whereas traditional reaction-time measurements (e.g., of button presses or verbal responses) provide basic insights into the mental processes that mediate decision processes, eye movements can provide a much finer temporal resolution than reaction time can (Glaholt & Reingold 2011). They allow us to investigate not only the relation between neuronal activity and behavior but also how this relationship unfolds.

In cognitive psychology and neuroscience, the terms choice and decision are often used interchangeably. Both processes are commonly studied by evaluating simple actions or movements, such as button presses, saccadic eye movements, or pointing movements. Strictly speaking, a choice directly implies a response (or an action), whereas the decision is the process leading up to it. Definitional distinction of these terms can help categorize and evaluate the available evidence and identify gaps in our understanding of decision-making (Schall 2001, 2005, 2013). In this review, I attempt to refer to choices when I speak about the action itself and to decisions when I speak

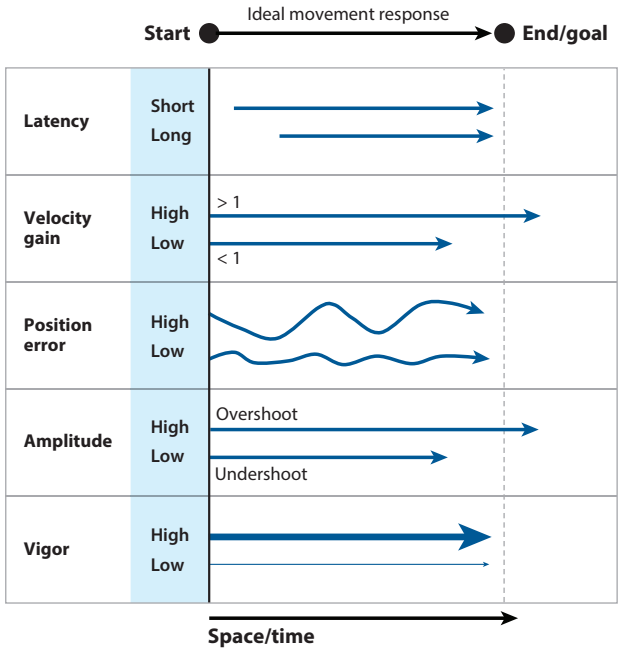

Figure 1

Selected eye movement metrics as a function of space or time shown relative to an idealized movement between a start time/position and an end time/position. The latency of a movement describes the time interval between stimulus onset and movement onset. The velocity gain of a pursuit movement describes the magnitude of the movement and how well the velocity of the eye matches the velocity of the target (defined as eye velocity divided by target velocity; a gain less than 1 means the eye moves slower than the target, and a gain greater than 1 means the eye moves faster than the target). The position error is the spatial accuracy and describes how well eye position matches target position. This measure can be described for pursuit or saccades (and microsaccades); for saccades it is more commonly described as the amplitude, which can either fall short of the target and undershoot (hypometric saccade) or overshoot (hypermetric saccade). Movement vigor is the time it takes for the movement relative to its amplitude; it describes the strength, effort, or energy expenditure of a movement.

about the deliberation process. I discuss studies that employ parameters of physical actions—for example, a movement's latency, amplitude, velocity, and vigor—as indicators of a decision's characteristics (**Figure 1**). This review is organized as follows.

I first introduce eye movement types along with a selective overview of underlying brain pathways. I then review experimental eye movement studies of human and nonhuman primates engaging in a variety of laboratory decision tasks. In five sections, I discuss studies that utilize eye movements as models of sensory evidence sampling and accumulation to maximize information gain (Section 3.1), as predictors of sensorimotor decision timing and temporal expectation (Section 3.2), as measures of response execution and inhibition (Section 3.3), as indicators of reward and value (Section 3.4), and as markers of decision certainty and confidence (Section 3.5). I propose new directions for future research that focuses on clinical populations, new technologies, or real-world tasks. Together with recent discoveries, these new directions can lead to insights into the function and dysfunction of decision processes across populations and applications and into the pathophysiology of diseases that affect decision-making.

Latency: the time period between the onset of a target, cue, or go signal and the start of a movement

Vigor: defined as saccade peak eye velocity (or saccade latency plus movement time) normalized by saccade amplitude

2. PRIMATE EYE MOVEMENTS ARE TUNED TO A DYNAMIC SENSORY WORLD

Fixation: the period between saccades when the eyes are relatively focused on an object or location

Smooth pursuit: continuous tracking response to moving objects of interest during which smooth periods are interspersed with catch-up saccades

Superior colliculus (SC): layered midbrain structure receiving direct retinal input and contributing to orienting movements and preceding cognitive processes, attention, and decision-making

Frontal eye field (FEF): visual and oculomotor area in prefrontal cortex contributing to visual processing, target selection, and generation of eye movements

Lateral intraparietal cortex (LIP): visual and motor area in parietal cortex involved in eye movement control and selection processes, attention, and decision-making

Because the resolution of peripheral vision is limited, eye movements are needed to align the eyes' foveae with visual objects or areas of interest, allowing researchers to examine these movements in detail. Different types of visually guided eye movements cooperate to achieve gaze alignment with a target (Leigh & Zee 2015). Saccades are high-velocity and short-duration movements that shift the eyes to a new spatial area of interest. During fixation, the eyes focus on a small area and make only miniature movements (Rolfs 2009). Smooth pursuit eye movements are continuous eye rotations often made in conjunction with saccades to track a moving object and hold it steady near the fovea. Even though these different gaze-aligning eye movements are usually prompted by different stimuli in the laboratory, they interact to achieve high-accuracy vision (Goettker & Gegenfurtner 2021, Orban de Xivry & Lefèvre 2007). We make about three to five eye movements per second, meaning that eye movements are the most common movement primates engage in (Bargary et al. 2017). Yet the extraocular muscles do not fatigue (Fuchs & Binder 1983), allowing us to move our eyes continuously. It is this continuity at high accuracy and precision that makes eye movements such an appealing model of sensorimotor behavior and allows us to infer cognitive processes.

In the context of decision-making, eye movement metrics such as the latency, amplitude, peak velocity or frequency of a saccade, and the position error or velocity gain of smooth pursuit (**Figure 1**), have been linked to the timing or accuracy of the choice. Some studies have defined specific eye movement parameters that signify decision processes. For example, saccade vigor (**Figure 1**) reflects the economic utility of a decision outcome, that is, the interaction of the subjective reward associated with a decision outcome and the effort that has to be exerted to obtain this reward (Shadmehr et al. 2019). Pupil dilation and blink rate are two relatively novel markers of decision-task features and have the potential to shed light on longer-scale or sequential decision processes. Under constant luminance, pupil diameter tends to be modulated by arousal and responds sensitively to a large range of decision-related processes, including value, effort, confidence, uncertainty, and surprise (Ebitz & Moore 2019); spontaneous eye blinks have been correlated with decision outcome and stimulus predictability (Jongkees & Colzato 2016).

The detailed knowledge of the brain mechanisms that control eye movements (for a detailed review, see, e.g., Krauzlis 2005, Lisberger 2015, Munoz & Coe 2011) allows us to link oculomotor neuronal activity to decision-related neuronal activity. In brief, a visual signal is sensed by the retina and relayed via the thalamus to primary visual cortex. Neurons in these brain areas encode stimulus features that will ultimately allow the observer to localize, categorize, and select a stimulus as the basis for the following choice. In parallel, the retina projects directly to the midbrain's superior colliculus (SC). Visual cortex and the SC have rich connections with a network of frontoparietal oculomotor areas such as the frontal eye field (FEF) and lateral intraparietal cortex (LIP), where sensory signals are integrated and transformed into a motor command to move the eyes. The motor command is adjusted and optimized in the cerebellum and passed on to motoneurons in brainstem nuclei that innervate the extraocular muscles.

Of interest for the current review is how the sensory signals that drive eye movements might be modulated by top-down decision signals. One prime candidate for the integration of sensory and decision signals is FEF, which contributes to the generation of saccades and pursuit. Independent of its role in generating eye movements, it is also involved in visual-cognitive functions such as visual search and target selection (Schall 2013, 2015). Similarly, the SC carries signals that correlate with choice accuracy in decision tasks and with related variables such as target uncertainty (Basso & May 2019); microstimulations in the SC can directly modulate decision outcome

(Herman et al. 2018). There is a general consensus that the FEF and SC are implicated in sensorimotor transformations through which visually driven activity changes affect eye movement metrics (Kimmel & Moore 2007, Stanford et al. 1996). Neuronal firing rates in these areas encode decision thresholds (Gold & Shadlen 2000, Stanford et al. 2010). However, the exact mechanisms of how decision processes might influence eye movement metrics are not yet fully understood.

Pupil constriction and dilation are driven primarily by brainstem projections to the Edinger–Westphal nucleus in the midbrain, which signals the pupillary sphincter muscle to contract. This circuit receives descending cortical inputs (via the locus coeruleus or the SC, for example) that might be responsible for cognitive modulation of pupil size (Joshi & Gold 2020). Both the locus coeruleus and the SC have been linked directly to pupillary changes via cortical inputs, for example, from FEF (Ebitz & Moore 2019, Lehmann & Corneil 2016), but the detailed pathways for this cortical modulation are unclear.

Spontaneous eye blinks are driven by activity in three motor systems (facial, oculomotor, and retractor bulbi systems; Delgado-García et al. 2003), but the exact circuitry underlying cognitive modulations of blinks is not known. Clinical studies indicate abnormalities in spontaneous blinks in disorders associated with dopamine dysfunction, such that reduced or increased dopamine activity is associated with low or high eye blink rates, respectively. Blinks appear to reflect dopamine receptor type 2 function (Groman et al. 2014), linked to decision thresholds in go/no-go circuits in the basal ganglia (Bahuguna et al. 2015). Correspondingly, blink rate correlates with performance in tasks associated with dopamine function, such as reward-driven learning or decision-making (Jongkees & Colzato 2016). In the following section I discuss how a systematic investigation of eye movement metrics in decision tasks can shed light on some of the unanswered questions in decision research.

3. EYE MOVEMENTS AS INDICATORS OF DECISION PROCESSES

3.1. Eye Movements as Models of Sensory Evidence Sampling and Accumulation

In its simplest form, choosing one item over another involves perceptually detecting or locating a target and then selecting it from among distractors. The underlying choice processes are usually automatic and happen outside our conscious awareness. This basic form of decision-making follows a stage model of human information processing (Sternberg 1969) that includes decoding a stimulus, retrieving information from memory, and deciding on the basis of the available information before producing an appropriate response. At a more fine-grained level, a decision process involves accumulating noisy sensory samples until an evidence threshold is reached, at which point the decision is considered final (Ratcliff & McKoon 2008). The information accrual process is driven by goals such as maximizing choice accuracy, timing, or reward (Gold & Shadlen 2007). Eye movements directly contribute to this optimization process by achieving high-acuity vision of objects or locations of interest. They also reflect the steps of sensory information accrual (Gottlieb & Oudeyer 2018)—ranging from which target is selected first to how evidence is weighed and integrated with prior knowledge and expectations to when the information accrual process is stopped, inhibited, or reassessed.

Simple perceptual decisions have been studied with the use of paradigms such as visual discrimination, target selection, and visual search. Visual search paradigms present multiple response alternatives and involve scanning or foraging the search array or image before settling on a response (Eckstein 2011). Visual search could be considered a sequence of choices (where to move next) leading to a final decision (target present or absent). Eye movement patterns are related to how successful observers are in finding the target and to when they stop the search. Which target is prioritized reflects how we process visual saliency, task and target information,

statistical regularities, and value (Eckstein 2011). Moreover, how we interact with real-world scenes through eye movements can give important insights into how we interpret the content of the image and why errors occur in target present/absent decisions (e.g., whether the image contains a malignant growth; Krupinski 2010, Wu & Wolfe 2019).

Oculomotor capture: the likelihood with which the first saccade toward a search display is made to a distractor, not the target

Salience: the subjective perceptual property of an object or stimulus (relative to its context) that attracts an observer's attention and orienting response

Typically, eye movement analyses during visual search have focused only on where we look and less on the spatiotemporal characteristics of saccades and fixations (Godwin et al. 2021). Considering each saccade during search as a read-out of a perceptual decision, it can be interesting to investigate situations in which the initial saccade is captured by a distractor, not the target (Theeuwes 2004). Features of saccades in such oculomotor-capture paradigms reveal target saliency and target probability information, in line with predictions of priority or salience models (Fecteau & Munoz 2006, Itti & Koch 2000). Initial saccade landing position and saccade latency reflect the similarity between target and distractor, the frequency with which a target appears, and the probability of a distractor appearing in a certain location within the search display. For example, saccades were less likely to land on distractors when they appeared in a location with high distractor (and low target) probability, and fixation duration at those locations was shorter. These findings indicate that saccade properties sensitively signal the probability of a target or distractor appearing at a certain location and the related process of disengaging the eyes from a location that has been identified as irrelevant (Sauter et al. 2021). Moreover, saccades can be attracted to nonsalient stimuli (or distractors) that signal the availability of reward, especially at short saccade latency; saccade accuracy scales with the magnitude of the reward (McCoy & Theeuwes 2016). It appears that the oculomotor system competitively integrates external salience and internal value information when deciding where to look (Meeter et al. 2010).

According to classic saliency models, already-fixated objects should be inhibited in order to drive efficient search until the target has been found. Neurophysiological studies have identified parts of the oculomotor decision network (e.g., areas FEF and LIP) as critical structures that keep track of refixations and determine where to look next (Mirpour & Bisley 2021, Mirpour et al. 2019). Despite behavioral and neurophysiological evidence for inhibition of return (Klein & MacInnes 1999, Mirpour & Bisley 2021), eye movements during search and free viewing often follow a pattern of making a saccade to a novel object (exploration) and revisiting a previously fixated object (exploitation). Refixations usually occur shortly after the first fixation, within one (intervening) saccade. Compared with saccades to novel locations, they are of longer duration (approximately >50 ms) and occur most frequently in areas of high salience and where objects similar to the target are located (i.e., in areas where it is easy to miss the target) (Zhang et al. 2021). It follows that refixations might serve an important purpose in reducing sensory uncertainty during visual search or foraging tasks. Eye movement metrics such as fixation patterns and potentially pupil size could further elucidate the factors that determine the trade-off between exploration and exploitation—at both the environment (e.g., scene complexity and predictability) and the individual (e.g., confidence, prior knowledge, or memory capacity) levels, emphasizing the importance of cognitive signals in guiding where we look.

How cognitive factors interact with salience is also reflected in findings that show a causal relation between fixation duration and choice outcome; that is, fixation duration on a response alternative is closely related to which object is ultimately chosen. Typically, the longer a response alternative is viewed (e.g., in a nonurgent choice task, such as a choice between different food items), the higher the likelihood that it will be selected, irrespective of its value (Armel et al. 2008, Pärnamets et al. 2015, Shimojo et al. 2003, Thomas et al. 2019). This process is presumably amplified by visual spatial attention to the fixated location or object (Cavanagh et al. 2014, Krajbich et al. 2010) and interacts with salience (Towal et al. 2013). In a reanalysis of four choice data sets from previous studies, in which observers had to select and rate or bid on an object out of a choice

set, Thomas and colleagues (2019) calculated the positive or negative gaze advantage for each trial, computed as the fixation time on the selected object relative to the total time spent fixating. They found that 98% of a large sample of observers had positive scores, indicating an overall positive relationship between gaze allocation and choice. Individual choice behavior could be predicted by a gaze-weighed linear accumulator model, which assumes accumulation of sensory evidence at a rate that is discounted for objects that are fixated for a shorter period of time. The authors propose that this model can also account for individual behavior in multialternative, multiattribute choices (Thomas et al. 2021), such as when selecting an item from a vending machine. Similar claims have been made for decisions involving moral questions (e.g., "murder is sometimes justifiable" versus "murder is never justifiable"). When observers' fixation duration was restricted in a gaze-contingent display, in which a (randomly predefined target) choice alternative was shown for longer than the other alternative, they were systematically biased toward this target. These findings show that gaze-dependent decision models, according to which observers choose what they fixate, apply even to high-level moral decisions (Pärnamets et al. 2015).

An interesting discussion point is that many of the studies reviewed above assume implicitly that information accumulated throughout a trial or search process is weighed uniformly in how it contributes to a choice. However, this is not the case: Observers instead commonly rely more heavily on sensory information acquired early (Levi & Huk 2020, Nienborg & Cumming 2009, Yates et al. 2017). Using pupil size measurements, Kawaguchi and colleagues (2018) showed that this early weighing of information is modulated by confidence. The animal was more biased toward early information when it was confident about its decision (dilated pupil) than when it was overall less confident (pupil constriction; Kawaguchi et al. 2018).

In summary, these findings shed light on aspects of sensory evidence accumulation, such as how visual and task features (e.g., salience and probability) are processed to guide initial target selection or the goal of a first saccade, how and why sensory information is revisited by refixations, and why acquired evidence is not necessarily weighed uniformly across the course of a trial or task. Eye movements can also affect choice processes and outcomes in constructive ways and need to be factored into models of sensory evidence accumulation (Li & Ma 2021).

3.2. Eye Movements as Indicators of Decision Timing and Temporal Expectation

Because of the relatively shorter latency of eye movements compared with that of button presses, eye movements can reveal just how fast a perceptual choice can be made. Standard center-out saccades are usually made at latencies of 200 to 250 ms (Bekkering et al. 1994), and express saccades can be initiated even faster, after approximately 100 ms, with the fastest saccades starting at approximately 75 ms (Fischer 1986). The fastest smooth tracking response, ocular following, has minimum latencies similar to those of the fastest express saccades (70–75 ms; Gellman et al. 1990). By contrast, button press responses to simple objects take approximately 300–350 ms (Bekkering et al. 1994), and responses to more complex scenes take even longer (450 ms on average) (Fabre-Thorpe et al. 2001). In a simple perceptual choice task, Kirchner & Thorpe (2006) showed two images of natural scenes and asked human observers to make a saccade to the image that contained an animal. Strikingly, observers were able to reliably saccade to the correct image after only 120 ms, implying that the image can be processed and categorized within less than 100 ms (considering a 20-ms delay for saccade preparation). These results show how fast the visual system can accumulate information to inform a choice.

These findings are congruent with results obtained with tasks specifically designed to investigate the temporal evolution of decision-making. When a stimulus is presented in a choice paradigm, neuronal activity begins to differ on the basis of whether the stimulus that falls into

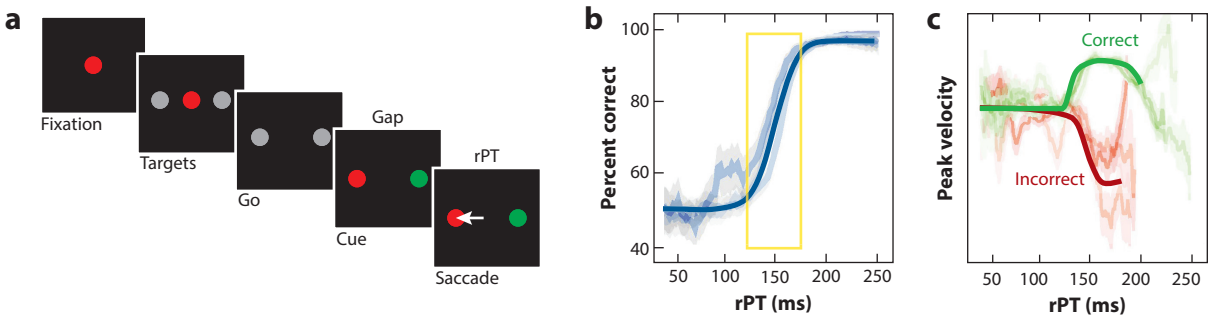

Figure 2

The urgent saccadic choice task (Stanford et al. 2010). (*a*) Time sequence of events in a rapid color discrimination task in which the target's color matches the fixation spot. The presentation of potential target locations is followed by the offset of fixation (go signal), compelling a response. Color cues are withheld for a variable amount of time (gap), determining task difficulty. Choices are indicated by a saccade. (*b*) Schematic of a tachometric curve (*bold blue*) plotted as a function of raw processing time (rPT), with three original data sets (*faint blue*) adapted from Seideman et al. (2018) (CC BY 4.0). The yellow box marks the rise time of the tachometric curve, as responses transition from choices (50% correct) to correct estimates (saturation of the tachometric curve), reflecting the time course of the perceptual decision. (*c*) Schematic of eye velocity as a function of rPT in trials with correct (*bold green curve*) and incorrect (*bold red curve*) choices. Each point on the velocity curve represents average peak velocity for many saccades as a function of rPT. Faint-colored data profiles are original data from three monkeys (adapted from Seideman et al. 2018). Original data have been scaled to correct for magnitude differences in individual eye velocity and aligned to the velocity peak for clarity.

the recorded neuron's receptive field is a cued target or distractor approximately 150 ms after cue presentation (Stanford & Salinas 2021). Just before a saccade is made, neuronal activity in areas such as FEF and LIP is unambiguously aligned with the upcoming choice (Glimcher 2001, Huk & Shadlen 2005, Schall & Hanes 1993, Stanford & Salinas 2021), establishing the link between neuronal activity and saccadic choices. But given that the time interval to evaluate response alternatives, to reach a decision, and to prepare a saccade is long (typically >500 ms), it is not possible to pinpoint the exact time when the decision is made. To investigate the temporal dynamics of this process, Seideman et al. (2018) utilized an urgent saccadic choice task in which monkeys were trained to make a rapid color discrimination between a target and a distractor. Importantly, the color cues revealing target and distractor identities were presented only after the monkey received the command to move, ensuring that the motor plan is already initiated when choice alternatives are evaluated (Stanford et al. 2010) (**Figure 2*a***). Perceptual processes are therefore determined solely by the raw processing time (rPT)—the amount of time during which the visual cue can be evaluated—and can be assessed independently of the motor processes related to making the choice. Tachometric curves (the percentage of correct choices per rPT bin) reveal that accuracy increased with increasing processing time. Moreover, it took approximately 150 ms for the cue to be read out (the timepoint at which the rise in performance is halfway between chance and asymptotic; **Figure 2*b***). The rapid transition from guesses to correct responses within approximately 50 ms indicates a short overall perceptual processing time and sensory information accumulation to reach a decision in this task, implying that the decision duration was approximately 50 ms.

Receptive field: area of sensory space (here, visual) that can elicit neuronal responses when stimulated

Recall that longer processing times are associated with a higher proportion of correct choices. Saccade peak velocity also varied as a function of processing time. Peak velocity was significantly higher (and saccade amplitude longer, endpoints less variable) in trials with correct choices than in trials with incorrect choices. Velocity profiles started to diverge at around the time at which perceptual processing transitioned from guesses to correct estimates (~125 ms; **Figure 2*c***). Together, these findings indicate that eye movement metrics are strongly driven by how perceptual information is accumulated and weighed. Differences in saccade metrics co-occur with the formation

of a decision. The overall timing that can be inferred here implies that perceptual decisions might be completed sooner than previously believed, between 50 and 100 ms after choice alternatives or relevant visual cue information is available. It could be argued therefore that some of the neuronal responses in areas FEF, LIP, and SC, interpreted as related to differentiating between decision alternatives, might instead be related to postdecisional evaluations, attentional shifts, or performance monitoring (Stanford & Salinas 2021; see also Huk et al. 2017, Katz et al. 2016).

Urgent choice tasks are also prevalent in real-world situations. Hitting a baseball is arguably one of the most difficult tasks to achieve in sports. Traveling at speeds of approximately 100 mph, a fastball arrives at the plate in less than 400 ms. Given a bat travel time of approximately 180 ms (Shaffer et al. 1993), this leaves a mere ~200 ms for the hitter to process visual trajectory information to decide whether to swing and where to intercept, essentially rendering this task an urgent choice task. Eye movements play a critical role during this process and are used to continuously track the ball until shortly before interception (Toole & Fogt 2021). In a laboratory simulation of the decision process required for baseball hitting, Fooken & Spering (2019, 2020) asked observers to view a 2D display with a ball moving toward a dedicated strike zone (**Figure 3*a***). Shortly after launch, the ball disappeared from view and observers had to extrapolate its trajectory in order to decide whether the trial was a hit or a miss. If they estimated a hit, observers had to rapidly intercept the ball within the strike zone (go trials); if they estimated a miss, observers had to withhold the interceptive hand movement (no-go trials). An analysis of observers' eye movements—a combination of smooth pursuit and saccades—revealed a close link between eye movement accuracy and go/no-go decision outcome, akin to findings of a link between neuronal activity in supplementary eye fields (SEFs) and decision outcome in a similar task (Kim et al. 2005). The position error of the smooth pursuit part of the response as well as the time at which observers made a saccade into the strike zone predicted decision outcome (go versus no-go) in this task (Fooken & Spering 2019). Moreover, the rate of targeting saccades during pursuit (the last saccade made before interception) started to differ between go and no-go decisions prior to hand movement onset, with higher saccade rates in go trials than in no-go trials (**Figure 3*b***). Similar to findings from the

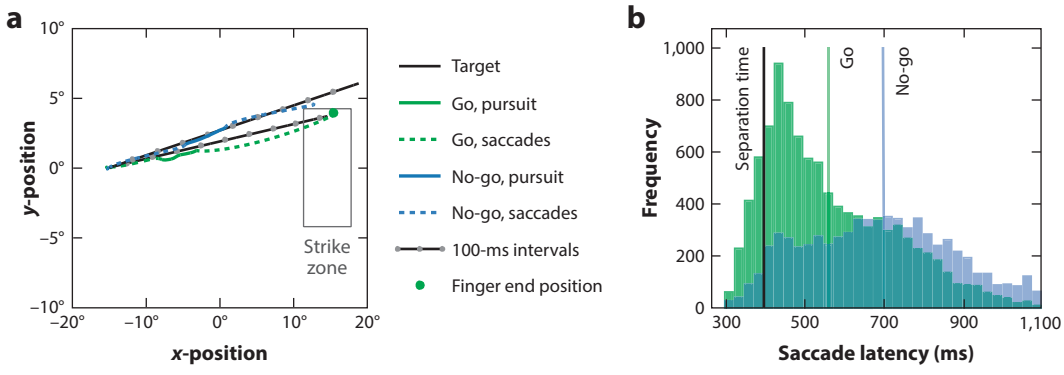

Figure 3

The rapid go/no-go interception task (Fooken & Spering 2019). (*a*) Observers tracked a ball moving toward a strike zone with their eyes. The ball was initially visible and then disappeared from view so that its trajectory had to be extrapolated to estimate a hit (manual intercept, finger end position in the strike zone) or miss (withhold interception). Feedback indicated the ball's true position and interception location. Eye and hand movements were recorded. The green single trace is from a representative correct go trial, and the blue trace is from a correct no-go trial. Intervals between dots on target trajectories (*straight lines*) indicate 100-ms intervals; here, the ball was visible for 200 ms. (*b*) Frequency of targeting saccades (last saccade made before interception) as a function of time-bin relative to target onset ($n = 45$; adapted from Fooken & Spering 2019). The vertical black line denotes the separation time as the mean time point at which frequency distributions for go and no-go trials started to differ significantly.

urgent saccadic choice task (Stanford et al. 2010), smooth pursuit properties provide a signature of the evolving decision process that precedes an interceptive choice response. Of note, findings by Fooken & Spering (2019, 2020) also point to a role of pursuit in enhancing go/no-go decisions, not unlike what has been reported for fixation duration and choice preference above (Thomas et al. 2019). Pursuit velocity (between the time of the initial and the final targeting saccades) was correlated with decision timing (i.e., a well-timed interception) on an individual observer basis. These findings indicate that eye movements not only differentiate between different decision outcomes but also are related to better-timed decisions.

Microsaccade: small-amplitude saccade made during fixation

When choice alternatives are presented sequentially and not simultaneously (i.e., rapid serial visual choice task), eye movements provide information about temporal expectations of events. When searching for an item in a display, observers are believed to activate a search template, a working-memory representation of target features. Recent studies have revealed that these search templates are not continuously active but are transiently and rapidly activated and deactivated before and after the onset of each search episode, tuned to the observer's temporal expectation of search. These findings were obtained by evaluating observers' microsaccades in response to a rapid serial visual presentation of colored disks presented during a delay preceding a search display (in which a target color had to be found; Olmos-Solis et al. 2017). Microsaccades were suppressed close to the time when the search display was anticipated. Their direction was biased toward task-irrelevant distractors that matched the target color, and these biases increased in strength as the appearance of the next search display grew closer. Microsaccade suppression and biases are indicators of observers' search template activation in expectation of the upcoming search display (Olmos-Solis et al. 2017) and therefore of the upcoming information-weighing process for target selection. Generally, response-related suppression of saccades or microsaccades (oculomotor freezing) appears to be linked to active response preparation and efficiency across modalities and tasks and provides a marker of temporal expectation (e.g., Abeles et al. 2020, Badde et al. 2020). This measure could therefore serve as a tool to track the time course of decision formation in classic choice tasks as well.

Blinks and pupil responses are other real-time indicators of decision processes that focus on the timing of when the decision is being made. Studies of the visual domain have already related the timing of blinks to information processing. Blinks occur at breaks in the information flow or immediately after a manual response has been given (Wascher et al. 2015). Blinks can be suppressed prior to predictable temporal events (Abeles et al. 2020, Hoppe et al. 2018), making blinks a potential marker of temporal uncertainty. Blinks might even enhance visual processing in a detection task (Ang & Maus 2020), indicating that blinks not only are a useful real-time measure of visual processing and temporal uncertainty but also might be functionally linked to performance.

In summary, in binary choice tasks, eye movement metrics directly reflect the transition from perceptual evidence evaluation to when a decision threshold is reached, within 50–100 ms after complete visual information is available. Results obtained in urgent choice tasks reveal that decisions might take only tens of milliseconds, much faster than previously believed. Similarly, eye movement signatures characterize different outcomes in real-world urgent choice tasks (such as a simulated baseball paradigm). Oculomotor freezing can indicate the dynamics of cognitive expectations during decision formation, and blinks provide a novel tool to further delineate the decision time course.

3.3. Eye Movements as Indicators of Response Inhibition

A binary choice might involve a process of inhibiting a planned or ongoing action. Eye movement and blink characteristics reflect how fast or how well the choice to inhibit a response is made.

McSorley & McCloy (2009) showed that saccades curve away from a nonselected object, and land progressively farther away from it, as the signal strength of a motion direction cue increases. For example, saccades following a direction cue with a strong motion signal were deviated away more strongly and landed farther away from the nontarget direction than did saccades following a weak motion signal direction cue. These findings reveal a signature of inhibition, scaling with signal strength, in saccade curvature and endpoints. They also show that oculomotor output can be continuously affected by a decision signal, even after the choice (e.g., saccade left or right) has been made. Decision formation affects eye movements even when the decision task does not involve an eye movement (Joo et al. 2018), emphasizing the tight link between decision-related activity and decision-unrelated oculomotor processes. Overall, these results point to a continuous interaction between decision signals and eye movement responses during action execution and inhibition.

Antisaccade: instructed saccade away from a cued or salient target, usually to a target 180° opposed

Countermanding, stop-signal, go/no-go, and antisaccade tasks are examples of paradigms that have been specifically developed to investigate action inhibition processes. In countermanding or stop-signal tasks, observers are asked to execute a speeded response, such as a button press or a saccade, to a go signal—for example, the disappearance of a fixation spot. In a small subset of trials, observers have to abort that response when a stop signal—for example, the reappearance of a fixation spot—is shown (Logan 1994). This task allows researchers to study the initiation and cancellation of planned movements and how movement consequences are monitored—processes that are mediated by neuronal activity in area FEF and in area SEF, respectively (Schall et al. 2000). Responses are believed to be the outcome of a competitive process between generating (go) and cancelling (stop) a movement. The stop-signal reaction time (or movement latency) quantifies the time needed to cancel a movement, and for saccades it is approximately 100 ms in monkeys (Hanes & Schall 1995) and 130 ms in humans (Hanes & Carpenter 1999). Saccade cancellation becomes increasingly harder as the delay between target onset and stop signal increases. During saccade cancellation, microsaccades are also suppressed (Godlove & Schall 2016). Therefore, saccade latency and rate of microsaccade suppression provide two possible measures of movement (or choice) cancellation in the saccade domain.

Even though pursuit and saccades differ in terms of movement characteristics such as speed and latency, the mechanisms underlying the release of and transition back to fixation (as in the stop-signal task) appear to be similar in both systems. Both movements are made at a shorter latency when the fixation spot is extinguished before the onset of the target (gap paradigm), and both movement latencies scale similarly with gap duration (Krauzlis & Miles 1996). Kornylo et al. (2003) directly compared stop-signal performance in saccades and in pursuit. Estimated stop-signal reaction times were overall shorter for pursuit than for saccades (50–60 ms in humans and 60–70 ms in monkeys). On the basis of these latencies, the authors argue that the inhibitory mechanisms for both systems are similar. The saccade system includes a point of no return (starting at the offset of omnipause neuron activity, which usually helps the eye maintain fixation and suppress saccades) placed up to 20 ms before the start of the saccade, but the pursuit system might not include such a ballistic interval. Therefore, the stop-signal reaction times might in fact be comparable across eye movement types when taking this interval into account.

Congruent with pursuit countermanding, Jarrett & Barnes (2003) found that anticipatory pursuit (made before the onset of an expected target) could also be stopped at will when an auditory cue is given. This finding is particularly interesting, given that anticipatory pursuit cannot be initiated at will. Finally, ongoing pursuit can be stopped and will then gradually transition to fixation. This gradual stopping is likely achieved through a combination of two elements: (*a*) an activation of the fixation (omnipause neuron) system and (*b*) the use of additional sensory information through online feedback (efference copy) or predictive mechanisms (Missal & Heinen 2017).

Spontaneous eye blink rate: frequency of eye blinks per time unit

Parkinson's disease: neurodegenerative disease primarily affecting the motor system, with cardinal symptoms tremor, bradykinesia, and postural instability; also affects sensory and cognitive abilities

In addition to countermanding activity in voluntary or visually driven movements, spontaneous eye blink rate, a marker of dopamine function, predicts how efficiently human observers are able to inhibit unwanted action tendencies in this task. In a standard version of the stop-signal task, Colzato and colleagues (2009) related the go-signal reaction time (indicator of response execution) and the stop-signal reaction time (indicator of response inhibition efficiency) to the rate of eye blinks. Whereas blinks were unrelated to response execution, they were positively correlated with response inhibition efficiency: Increased blink rate was associated with lower inhibition efficiency. Blinks might therefore serve as an additional indicator of inhibitory control. However, the assessment of eye movements in countermanding tasks merely links saccade latency, microsaccade inhibition, and blink frequency to task outcome, not to the choice inhibition process itself. Moreover, most studies rely on correlations and do not manipulate eye movement behavior (which would be admittedly difficult—but possible—for blinks) to investigate the constructive contribution of blinks to decision efficiency.

In the antisaccade task, observers must suppress a saccade toward a cued distractor (prosaccade) and instead voluntarily direct it toward an uncued target. This task has been used to evaluate the timing of saccade direction errors (in addition to saccadic latencies) as a measure of response inhibition (Munoz & Everling 2004). Direction errors can occur early in the trial as an express-latency (90–140 ms) reflexive response to the cued target, indicating that suppression might start (and fail) preemptively, before the peripheral visual target can even trigger a saccade command. Later direction errors (latency >140 ms) indicate that there is also a voluntary suppression mechanism that can override an erroneous (automated) prosaccade. The detailed timing of these different processes was revealed by saccade behavior in a compelled antisaccade task, in which observers had to start programming a saccade before knowing the direction of the correct response (Salinas et al. 2019). Analyzing observers' success rates as a function of rPT (analogously to **Figure 2*b***) reveals that the initial draw to the cued target yielded an almost 0% success rate (at 100 ms after cue onset), which was recovered when endogenous control took over (within an additional 40 ms).

These different temporal processes and error types reveal different forms of suppression that might be mediated by separate neuronal pathways (Coe & Munoz 2017). Prestimulus suppression could be controlled by direct cortical inputs from key frontal lobe areas (e.g., dorsolateral prefrontal cortex or area FEF) to intermediate layers of the SC. Suppression during a later stage might be distributed across different pathways providing SC input, including through the caudate nucleus in the basal ganglia, where signals for automatic, exogenously triggered prosaccades and voluntary, endogenously controlled antisaccades interact (Watanabe & Munoz 2009). The involvement of the SC is also supported by the finding that pupil dilation scales with saccade latency and errors, indicating a close relation between pupil size and saccade preparation. Pupil dilation is larger for short-latency antisaccades than for regular antisaccades, and it is larger for correct antisaccades and erroneous prosaccades than for correct prosaccades (Wang et al. 2015). The involvement of dopaminergic pathways, for example, through the basal ganglia, is supported by consistent observations of increased antisaccade errors in patients with Parkinson's disease (Waldthaler et al. 2021) (see the sidebar titled Decision Processes in Parkinson's Disease), a potential biomarker of impulse control disorders in these patients (Barbosa et al. 2019).

In sum, the ability to inhibit a response is a critical feature of choice processes in situations that require adaptation to changing contexts or goals. Saccade and pursuit latency and blink frequency during the stop-signal task reflect the cost and resource efficiency of response inhibition—saccades and pursuit are initiated later and are less correct when the inhibition process is challenging (e.g., due to long delays or low saliency). Saccade direction errors and pupil dilation in the antisaccade task reveal the characteristics and time course of inhibition mechanisms—an early automatic mechanism and a later voluntary one, mediated by different brain pathways—during

DECISION PROCESSES IN PARKINSON'S DISEASE

Dysfunction of the dopamine system in the brain is critically associated with decision competence and conditions such as Parkinson's disease (PD). Dopamine function is also involved in impulsivity, a psychological construct affecting how we evaluate risk and time (Simioni et al. 2012). Studies of eye movement reveal deficits in both aspects of impulsivity in PD. When trading off two choices with different reward magnitudes and probabilities in a simulated lottery task developed by Sharp and colleagues (2012), patients with unmedicated PD are risk averse for gains—an effect that was normalized by medication (Cherkasova et al. 2019). The same patients were also more driven by expected value or reward regardless of medication state. Eye movement measures (e.g., fixation duration) can quantify the relative use of reward and probability information (Cherkasova et al. 2018). Assessing eye movements in a time-critical go/no-go interception task (**Figure 3*a***), Fooken et al. (2021) found relatively preserved decision competence in patients with PD, but only as long as they did not rush their decision (indicated by targeting saccade timing; **Figure 3*b***). Together, these findings support the notion that abnormal impulsivity in PD is related to abnormal risk-taking behavior and to a tendency to make more errors when a decision is rushed. Eye movement indicators of decision can therefore inform neurobiological models of PD.

binary saccadic choice tasks. The stop-signal and antisaccade tasks bear some resemblance to the urgent saccadic choice task. In both types of tasks, vital stimulus or cue information has to be detected or interpreted when a motor plan is already ongoing, and an original movement plan (developed within 100 ms of cue onset) has to be either halted or inhibited (within an additional 40 ms) by voluntary mechanisms. These tasks therefore allow us to determine when automatic and voluntary mechanisms are engaged to control eye-movement-indicated choice behavior.

3.4. Eye Movements as Indicators of Reward and Value in Decision Tasks

In real-world economic decisions, such as whether to buy a house or continue renting, observers must choose from among multiple options with different subjective values. To understand how values are converted into choices, we must first understand how the brain encodes value. Just as eye movements can be used to read out decisions, eye movements also directly reflect the value or expected reward associated with a choice. Saccade and pursuit metrics, blink rate, and pupil size are all determined by activity in dopaminergic systems in regions that are also important for reward processing, such as the direct pathway connecting the basal ganglia (caudate nucleus and substantia nigra) to the SC (Hikosaka et al. 2014). This link between reward modulation and eye movement control implies that these metrics can sensitively signal how we process reward information.

It is well documented that expected reward leads to shorter saccade latency and higher peak velocity. Saccade velocity scales with the probability or expected rate of receiving a reward (Thura et al. 2014). Congruently, the value associated with a saccadic choice also modulates peak velocity as a function of amplitude, a metric known as saccade vigor (Shadmehr et al. 2019). When observers deliberate between two choice alternatives with different values—a smaller monetary reward paid out immediately or a larger reward paid out later—the eyes initially move with the same vigor to both options. But as the process continues, vigor increases for the response alternative that is ultimately chosen. Immediately after the choice (button press) is made, vigor drops, with a steeper rate of decline in trials in which the decision was made fast. This temporal evolution of vigor—its rise as the observer identifies a preferred option and its drop after the choice has been made—provides a marker of decision timing (Reppert et al. 2015). Moreover, observers tended to

make their last saccade before the button press to the alternative they chose later. The target of this last saccade reliably predicted the explicit choice in a given trial (for equivalent findings for targeting catch-up saccades during pursuit, see Fooken & Spering 2019) (**Figure 3*b***). Vigor also increases as a function of value difference between options and differentially scales with two aspects of economic utility—reward and effort: It increases with expected reward and decreases with anticipated effort (Shadmehr et al. 2019).

It appears that human observers are able to keep accurate track of reward and effort over time. When observers were asked to look at images that differed in reward (manipulated via image content) and effort (eccentricity between images), reward and effort history across previous trials affected saccade velocity and fixation or harvest duration (as a measure of how much reward is being collected) in following trials. A history of rewarding images led to increased vigor and decreased harvest duration; less time spent at a given image means more images can be viewed and more reward can be accumulated (Yoon et al. 2018). These findings show that saccade vigor reflects decision optimality (according to the marginal value theorem; Yoon et al. 2018), that is, maximizing the rate of gain associated with reward and effort of a current action, given the rate of gain in recent history.

Recent history of reward also modulates performance in antisaccade tasks. Saccades are more error prone if antisaccade trials are preceded by trials in which the target was associated with a high (versus no or low) reward (Preciado & Theeuwes 2018). This selection bias or capture driven by reward history was found mainly for short-latency saccades, indicating that reward predominantly modulates automatic control mechanisms, possibly by interacting with stimulus salience and overriding voluntary control mechanisms.

The value associated with a choice is also predicted by the frequency of blinks. For example, blink rate correlates with the outcome of value-based choices after reinforcement learning (Slagter et al. 2015) and predicts observers' strategies in assessing low-value versus high-value alternatives. Van Slooten and colleagues (2019) asked observers to view pairs of colored squares that were each associated with a different reward probability. Observers had to learn to select the most rewarding option and received feedback about whether they earned a reward. In a subsequent transfer phase, observers viewed the same options in novel pair combinations and had to again choose the most rewarding option, but without receiving feedback. Lower blink rate predicted higher choice accuracy during the learning phase, but only when the difference in expected value between options was large. The same data set also revealed that pupil size fluctuations tracked choice behavior and value beliefs (Van Slooten et al. 2018). Prior to making a value-based choice, pupil dilation reflected the value of the option to be selected. After receiving feedback, pupil dilation reflected uncertainty about the value of the most recent choice options, and pupil constriction reflected reward prediction errors. In addition to signifying the arousal associated with an expected reward, pupil dilation is also associated with riskier choices (Cherkasova et al. 2018). In summary, saccade metrics such as vigor and parameters such as blink rate and pupil size, determined by activity in dopaminergic systems, signal reward processing during decision-making. This link has important implications for our understanding of value-based decision-making in diseases associated with dopamine dysfunction.

3.5. Eye Movements as Markers of Decision Certainty and Confidence

When sensory information is insufficient, unreliable, or inconclusive, decisions are made under uncertainty. Most decisions we make are accompanied by a feeling of confidence that the decision is accurate—internally estimated probability of a correct choice (often equal to the estimated

probability of receiving a reward)—given the evidence (Pouget et al. 2016). Confidence can be overtly measured by soliciting a confidence rating at the end of a given trial, or it can be covertly and analytically derived. For example, in a drift-diffusion model describing performance in a two-alternative sensory discrimination task, in which evidence is accumulated over time until it reaches a decision threshold or boundary, decision confidence could be defined as the distance between the decision signal and the decision threshold (Kawaguchi et al. 2018, Kepecs et al. 2008). Seideman and colleagues (2018) defined decision confidence statistically as the probability of a correct choice, given the available sensory evidence—which in the case of their task is equivalent to information processing time (more processing time means more evidence). They considered saccade peak velocity to reflect the degree of certainty with which a decision is made because peak velocity was associated with choice accuracy and scaled as a function of processing time, meaning it increased with increasing evidence. The finding that saccade metrics reflect not only choice accuracy but also the statistical confidence in the choice implies that decision-making and confidence might rely on the same underlying mechanisms.

Pupil diameter reveals nuanced and dynamic information about the decision time course and is linked to how beliefs about one's own decision change over time (Colizoli et al. 2018, Urai et al. 2017). Throughout a decision process, the pupil is continuously dilated (de Gee et al. 2014). Several studies have investigated the relationship between pupil size and internal belief states about the decision, before and after feedback about the decision outcome has been received. For example, Colizoli and colleagues (2018) monitored pupil size while observers performed a motion direction discrimination task at different levels of task difficulty, resulting in different levels of uncertainty. Importantly, the authors introduced long and variable delays before and after response feedback to investigate the effect of reward anticipation and reward prediction error on pupil dilation. During both delay intervals, observers showed sustained pupil dilation. Larger increases in pupil size during the prefeedback interval were associated with larger decision uncertainty (Urai et al. 2017). Larger pupil size changes during the postfeedback interval were observed in trials in which feedback indicated that the given response was incorrect, suggesting that pupil size scales with prediction error and the perceived violation of the internal belief state. Input signals to the pupil therefore continuously signal uncertainty about the upcoming decision (prefeedback interval) and the comparison with feedback (postfeedback interval). Pupil dilation correlates with confidence in humans (Lempert et al. 2015) and monkeys (Kawaguchi et al. 2018). It also indexes the occurrence of surprising events (Preuschoff et al. 2011, Satterthwaite et al. 2007). A detailed analysis of the time of peak pupil dilation during a perceptual decision task can reveal the time course of information accumulation for perceptual and confidence judgments (Balsdon et al. 2020). This novel approach might allow researchers to link pupil dilation to information-seeking behavior as a function of confidence (see also Kawaguchi et al. 2018), thus revealing the time course of the interplay between current decision confidence and future evidence accumulation (for an example using manual tracking, see Locke et al. 2020).

In sum, tracking pupil size during decision-making not only scales with uncertainty and confidence but also might reveal the dynamics of evidence accumulation and how information seeking is adjusted on the basis of individual differences in metacognitive confidence or perceived uncertainty. This is especially important when considering demanding real-world tasks that commonly require a sequence of decisions, and in which confidence in the first decision might affect information accumulation in following decisions (Van den Berg et al. 2018) or in which evidence accumulation must be adapted to a changing environment (Murphy et al. 2021). The known link between pupil size and confidence might allow outcome predictions in multistep complex decision sequences.

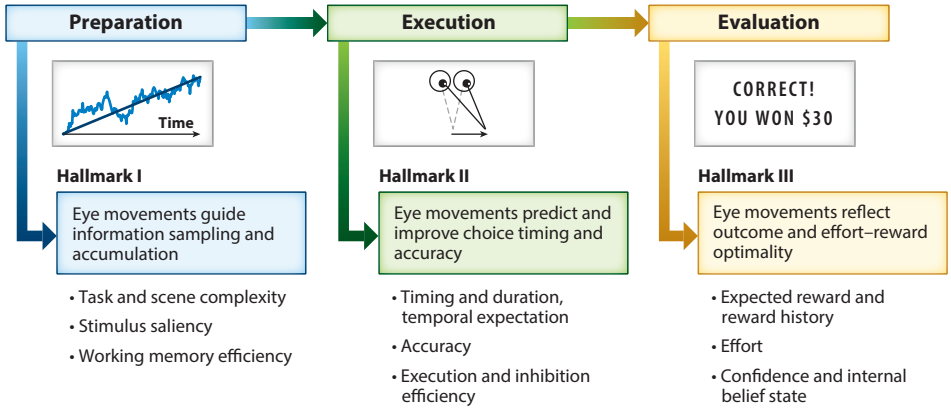

Figure 4

Decision-making framework and hallmark features reflected by eye movement metrics. In the preparation phase, eye movements signify information sampling and accumulation and reflect stimulus, task, and scene properties and how efficiently information is stored and retrieved from working memory. During and just before response execution, eye movements predictively scale with the timing and accuracy of the upcoming choice; they also reflect executive functions such as response inhibition. After a decision has been made, eye movements scale with the value of a decision and the subjective feeling of confidence; they also reflect the optimal integration of effort and reward.

4. CONCLUSION

Eye movements accompany and reflect the preparation, execution, and evaluation of behavior in decision tasks (**Figure 4**). They provide an exciting research tool with which to investigate the temporal evolution of decision processes and their accuracy and complement neurophysiological studies of decision-making. As indicators of decision component and task features, and as process tracers of cognitive functions and states, the use of eye movements integrates research directions across disciplinary silos in vision sciences, movement sciences, psychology, economics, computer science, and other related disciplines that target decision-making. This review is meant to stimulate novel eye-movement-based research on the mechanisms and processes of decisions and to help establish eye movements as an integral part of multidisciplinary decision-making research.

SUMMARY POINTS

1. Eye movement metrics add a continuous dimension to the discrete outcomes of decision tasks; they provide direct, real-time insight into the dynamics of deliberation processes at fine spatial and temporal scales.
2. Saccade metrics in urgent choice tasks reveal decision timing and duration. Perceptual decisions can take as little as 50 ms and are made within 50–100 ms of when complete visual information about choice alternatives and tasks is available.
3. The dynamics of smooth pursuit and the frequency of saccades track the time course of decision formation and the temporal expectation of future events.

4. Saccade endpoints, fixation duration, and saccade exploration–exploitation patterns reflect scene and task complexity and signify working-memory efficiency in visual search and related selection and decision tasks.
5. Choice preference is linked to fixation duration, and decision timing accuracy is linked to eye movement accuracy, indicating that eye movements not only reflect upcoming choices but might also contribute to them.
6. Saccade and pursuit latency and blink frequency reflect the efficiency with which a response can be inhibited, and saccade direction errors and pupil dilation reveal two separate inhibition mechanisms.
7. Saccade vigor scales with the expected reward and anticipated effort of a decision and tracks reward history, indicating that it reflects an optimal integration of reward and effort.
8. Saccade metrics and pupil dilation reflect decision confidence and internal belief states, linking eye movements not only to the process of making the decision but also to its predicted outcome.

FUTURE ISSUES

1. Eye movement measures have been applied mostly to studying decision-making in healthy, young adults. Given the impact of neurological and psychiatric diseases on decision-making, eye movements could be applied to pathological decision-making with the ultimate aim of developing neurobiologically plausible models of dysfunction as well as bedside decision tests.
2. The functional link between eye movements and decision outcome is underexplored. Relations have been reported for pursuit, blinks, and fixation duration, but few studies have systematically manipulated eye movements' effects on the timing and accuracy of decisions.
3. Researchers should take advantage of the rapid advance of eye-tracking technology to investigate eye movements during real-world decision tasks, such as gambling. Eye movements could also be used to indicate social and interpersonal factors in multiplayer economic decision tasks.
4. The eye movement and decision literature has focused mainly on saccades to stationary targets. Smooth pursuit has the added benefit of being sensitive to dynamic visual stimulation, allowing researchers to create decision tasks that reflect the natural, dynamic properties of our visual environment.

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