Human Eye Movements as Indicators of Complexity

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Abstract. Perceiving and interacting with the world around us is a multimodal process that involves orienting our eyes, head, and body towards objects of interest. It is also a highly dynamic process during which the eyes continuously scan the visual environment to sample information. This active sensing allows us to overtly and rapidly react and adapt to survival-critical changes in the environment. At a more subtle and covert level, it also accompanies and supports cognitive processes that underlie planning, decision making and problem solving. This chapter discusses research advances on active sensing during cognitive tasks at varying levels of complexity and proposes that eye movements can provide direct, real-time insight into cognitive processes, at a fine spatial and temporal scale.

Our everyday life is characterized by problems that require cognitive competencies, ranging from simple decisions about what food to eat or which route to drive to complex problem solving in ill-defined and dynamic situations. Planning, deciding, and solving problems are key components of human nature, and our daily lives reflect an ongoing quest to master these competencies. A wide range of tests and tools have been developed that allow assessment of cognitive and executive functions in the relatively controlled environment of the laboratory as

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well as "in the real world" (Betsch et al., 2011; Diamond, 2012) and at varying levels of complexity (Funke & Spering, 2006).

Yet, experimental research on human thinking currently does not appropriately address real-world complexity. Studies largely focus on performance outcome, and tools that allow us to investigate underlying processes and mechanisms at a granular level are less accessible. With advances in machine learning, researchers have found that functional magnetic resonance imaging can reveal and quite literally track the cognitive stages that constitute a problem solving process (Anderson et al., 2016; Anderson et al., 2020). Even though these studies employ challenging video games, these are well-defined and relatively simple tasks requiring visual skills such as time-to-contact estimation or multiple-object tracking. Similarly, studies utilizing electroencephalography during problem solving tasks have largely focused on arithmetic or insight problem solving (e.g., Bowden et al., 2005; Dietrich & Kanso, 2010; Hinault & Lemaire, 2016).

By contrast, methods for assessing the cognitive stages that underlie solving real-world problems, ill-defined by nature (e.g., Dörner & Funke, 2017), are sparse. The more complex a task, the harder it is to assess problem solving steps, strategies, and performance within the constraints of an experimental laboratory. Perhaps it is indeed time for "problem solving research […] to give up methodological rigorism and to open the field once again for controlled introspection and single-case studies that describe the phenomena in a less restricted way" (Funke, 2014, p. 495). Even though methods such as thinking out loud might provide a rich qualitative data set, they are subjective by definition. Moreover, observers can only report thoughts that are accessible to them in any given moment. In this chapter, I will propose that human eye movements can serve a similar purpose to self-reports and sensitively reflect the strategies we develop and steps we take when we plan, decide, and solve problems. Even though research on eye movements during real-world decision making and problem solving is in its infancy, eye movements are emerging as a versatile tool to investigate cognitive processes (Ryan & Shen, 2020; Spering, 2022), including processes that occur outside of our immediate awareness (Hannula et al., 2007; Spering & Carrasco, 2015).

In the context of research on complex cognition, eye movements have at least four key advantages: (1) We move our eyes naturally and spontaneously and need little training or instruction to do so; (2) eye movements are highly sensitive, including to information that observers are not consciously aware of; (3) they are easy and relatively inexpensive to measure non-invasively; and perhaps most importantly, (4) eye movements are continuous and provide fine-grained spatial and temporal information.

Eye Movements as Metrics of Cognition: Prerequisites

When we view the world around us, our eyes move continuously. We employ an arsenal of different types of eye movements to fixate gaze on objects of interest, redirect gaze during activities such as reading or scene viewing, track objects that move, or compensate for image motion resulting from movements of our head and body. Eye movements across the vertebrate lineage are finely tuned to the image statistics of our natural environment and the demands of the tasks we face (Land & Nilsson, 2013; Land & Tatler, 2009). Humans make three to five eye movements per second, making it the most common movement primates engage in (Bargary et al., 2017). Yet, the extraocular muscles that move the eyes 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 system for the inference of cognitive processes. Humans use a combination of saccades (rapid gaze shifts to objects of interest), smooth pursuit (slow, continuous tracking of moving objects), vergence (movements to focus in depth/3D), and movements that compensate for self-motion, such as the vestibulo-ocular reflex (Leigh & Zee, 2015). These larger eye movements are interspersed with fixation, periods of relative rest, during which the eyes move within a small spatial range (Poletti & Rucci, 2016; Rolfs, 2009). Eye movements align the fovea (the area of highest photoreceptor density and, thus, highest visual acuity) with objects of interest and allow us to see the visual world in all its richness and spatial detail (Gegenfurtner, 2016). They support and guide isolated motor actions such as reaching or walking (de Brouwer et al., 2021; Matthis et al., 2018) and accompany everyday tasks ranging from making a sandwich to driving a car (Foulsham, 2015; Hayhoe, 2017; Hayhoe & Ballard, 2005; Lappi, 2016); they are also believed to contribute to high performance in sports (Vickers, 2016).

The discovery that cognitive processes, and specifically task instructions, influence eye movements was first reported by Russian vision scientist Alfred Yarbus (Tatler et al., 2010; Yarbus, 1967; see also Castelhano et al., 2009). Yarbus made several key observations: When viewing a scene, the eyes' initial fixation is preferentially directed at persons within the scene, more specifically, at their faces (Fletcher-Watson et al., 2008) and particularly the eye region (Kingstone, 2009). During longer viewing, gaze cyclically and repeatedly revisits the most important elements of a picture. In more recent years, eye movement responses have been formalized to serve investigating cognitive processes during visual search, reading, and scene viewing (Rayner, 2009). The utility of eye movements as sensitive indicators of cognitive processes relies on the following key assumptions: (1) Observers look at objects they are processing (Rayner & Liversedge, 2004), indicating that fixation locations allow us to deduce what sort of information about an object or a location is currently being processed (eye-mind hypothesis; Just & Carpenter, 1980); (2) fixation duration reflects processing time (Kaller et al., 2009; Vickers, 2016) such that the longer an object or a location is fixated, the more information is gathered and processed; (3) in tasks that involve object manipulation and dynamic interactions with the visual environment, eye movements precede actions (de Brouwer et al., 2021), thereby reflecting advanced planning of future task-related actions; (4) eye movements not only reflect cognitive states but contribute to them as well (Ryan & Shen, 2020; Spering, 2022).

Studies that consider eye movements as cognitive indicators typically rely on standard fixation and saccade metrics. The large majority of studies in this field uses fixation or dwell time, saccade endpoints, and the direction of saccades (e.g., forward, backward, alternating). Some studies report saccade kinematics, such as saccade latency (reaction time), peak velocity, amplitude, duration, or their vigor (a metric that calculates velocity as a function of amplitude); however, these metrics are still underutilized. Dynamic aspects such as smooth pursuit, vergence, or the vestibulo-ocular reflex are almost never reported. This is most likely due to the nature of the stimulus material, which is largely static and presented in 2D; moreover, observers are almost always seated in front of a computer with their head stabilized. Pupil dilation and blink rate are two relatively novel markers of cognitive task features and observer characteristics; they have the potential to shed light on longer-scale or sequential cognitive processes (Ebitz & Moore, 2019; Jongkees & Colzato, 2016; for a review, see Spering, 2022). In the following sections, I will discuss selected, representative studies showcasing the utility of eye movements in tasks that measure humans' cognitive competencies at different levels of complexity.

Eye Movements Reflect Humans' Adaptive Capability to Plan

In its broadest form, planning involves an intention or decision concerning what one is going to do. This process is comprised of a series of internal goals that are formulated and stored in memory and then retrieved to guide a behavior or achieve an action and compare it against an internal model of the environment. Eye movements can reveal planning at a very low processing level, i.e., they reflect steps of sensory information accrual (Gottlieb & Oudeyer, 2018). This step includes searching for and selecting an object as a target, weighting and integrating sensory information, and preparing for and executing an action. Congruently, much of the research in this area has been conducted with highly simplified tasks that break down the cognitive planning process to its lowest level: planning on or deciding where to look next. Notwithstanding the simplicity in their design, the results of these studies have important implications for studying more complex forms of planning as well. They reveal that eye movements tend to be directed at the most salient object (the one that stands out the most) in a visual scene (Fecteau & Munoz, 2006) and depend on statistical regularities as well as the expected reward associated with a target or location (for a review see Eckstein, 2011). Eye movements during natural scene viewing typically follow a stereotypical pattern of making a saccade to a novel object (exploration) and revisiting a previously fixated object (exploitation; Mirpour & Bisley, 2021). In this context, eye movements have often been shown to behave near-optimally, i.e., they scan a visual scene efficiently, taking into account natural scene characteristics as well as constraints of the visual system itself (Najemnik & Geisler, 2005). Moreover, the finding that eye movements can be made in anticipation of a visual event—before a target starts to move (Kowler, 2011), before it reaches a certain location in space (i.e., "look-ahead fixations", Mennie et al., 2007), or in prediction of a future action (Flanagan & Johansson, 2003; Fooken & Spering, 2020)—implies that eye movements play an important role in motor task planning. At a somewhat more complex level, during visual-guided navigation, observers rely on an internal map (or plan) of their surroundings. For example, when navigating a virtual maze, human eye movements are rapidly deployed to sequentially review the future path, reflecting internal plans in real time (Zhu et al., 2022).

Understanding information accrual as a building block of human planning is especially important in situations that are marked by uncertainty and that change dynamically over time. After all, we cannot plan, decide, or solve problems without knowing what information is available first. Eye movements reveal the nature of the information that is being gathered. They also reflect memory representations of object or scene characteristics (Ryan & Shen, 2020), and analyzing them over time can shed light on the relative influence of and balance between low-level visual and higher-level cognitive influences (Schütt et al., 2019).

Equipped with knowledge of these building blocks, we can move on to planning tasks that require executive functions. The Tower of Hanoi (or, in its variation, the Tower of London) is a goal-stacking task that requires transferring a number of balls or disks of different colors or sizes from one peg to another following stacking-order and movement rules. It constitutes a simple, static environment that requires a mental search through a space of possible solution paths. Assessing eye movements in this task and in similar scenarios can reveal optimality in the steps taken and overall task performance. For example, the analysis of dwell time on goal-space and work-space locations in this task reveals discrete planning phases

(Hodgson et al., 2000). Eye movements are initially concentrated on the goal space, reflecting the gathering and assessment of information to create an internal representation of the goal state. During a subsequent phase of solution elaboration, eye movements focus on the work space. Errors during this phase are associated with an overall lack of eye movements towards problem-critical locations (e.g., balls that had to be moved before others could be accessed). Similarly, Ayala and colleagues (2022) showed that sub-optimal eye movement patterns in early planning stages reflect poor information extraction from the task environment. Eye movements can also reflect the use of strategies, algorithms, and routines (Patsenko & Altmann, 2010) and indicate task demands (Nitschke et al., 2012), learning (Asato et al., 2006), and memory representations or dysfunctions (Droll & Hayhoe, 2007; Huddy et al., 2007). An exploration of eye movements (fixation duration and saccade amplitudes) during the Rubik's cube task linked switches from ambient to more focal viewing to different states of attentional processing (Guo et al., 2022).

To translate these findings from active engagement with artificial tasks to active sensing in the real world, researchers could capitalize on the emergence of mobile eye-tracking methods to characterize eye movements during ecologically valid scenarios (Ladouce et al., 2017). Real-world task planning, for example, includes time pressure, cost, risk, and social factors, and whether eye movements can reflect performance and performance-related factors in these complex, dynamic social situations remains to be investigated.

Eye Movements as a Window Into Decision Making

Decisions are ubiquitous, and just like for planning and problem solving, they can be simple and binary—whether to drive through a changing traffic light or whether to stop—only requiring selecting, discriminating, and weighing the accumulated sensory evidence, or much more complex. Value-based decisions—for example, which lunch option to choose, gym to join, or stock option to invest in—require identifying and deliberating expected costs and benefits. Eye movements have been used in both simple and more complex decision scenarios. They can indicate target selection and deliberation processes as well as performance monitoring (confidence; Ebitz & Moore, 2019). They can serve as an index of stimulus and task features such as uncertainty or value (Shadmehr et al., 2019). They signify and predict decision timing and temporal expectation (Seideman et al., 2018). They also indicate levels of cognitive control, for example, when a decision scenario involves inhibiting a response (Munoz & Everling, 2004). Notably, some of these more process-related outcome variables are derived not only based on where we look and for how long (i.e., endpoints and dwell time) but also on metrics such as saccade peak velocity. For example, the velocity of a saccade reflects decision accuracy as well as the confidence associated with that decision (Seideman et al., 2018). Confidence or decision certainty are also reflected in the pupil response, a nuanced measure that also indicates how beliefs about one's own decision change over time (e.g., Colizoli et al., 2018). The vigor of a saccadic eye movement, i.e., the time the movement takes relative to its amplitude, describes the strength, effort, or energy expenditure of a saccade. It has been related to the economic utility of a decision outcome, i.e., the interaction of the subjective reward value associated with a decision outcome, and the effort that has to be exerted to obtain this reward (Shadmehr et al., 2019). For example, when an observer deliberates between two choice alternatives that differ in value—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. As the decision process unfolds, vigor increases for the response alternative that is ultimately chosen. These results highlight the incredible potential of eye movements as markers of decision timing and of humans' ability to keep track of reward and effort over time. Similarly, the analysis of smooth pursuit eye movements harnesses the continuous nature of these movements. In a simulated decision task mimicking the real-world timing and requirements of baseball, Fooken and Spering (2020) found that the accuracy of pursuit and timing of saccades predicted how well observers ultimately did in this task, highlighting that eye movements not only reflect the decision outcome but potentially contribute to it as well.

Even though these studies demonstrate the impressive potential of eye movements as markers of decision processes, they all rely on relatively simple tasks. More recently, eye movements have been measured in multi-alternative, multi-attribute choice tasks that mimic requirements of selecting an item from a vending machine (Thomas et al., 2021). Findings obtained with simple tasks also appear to apply to tasks that involve moral decisions (Pärnamets et al., 2015). It is now important to apply these findings and principles to decision tasks embedded in contexts that change dynamically over time (Barendregt et al., 2022), reflecting real-world decisions that require adaptive behaviour.

Can eye Movements Reflect the Complexity of a Problem?

Problem solving, by definition, deals with situations in which steps toward the solution of the problem are not clear; in fact, the problem itself can be ill-defined. In its simplest form, a problem could be a riddle or a puzzle. In its more complex form, a problem lacks transparency, is polytelic (i.e., it might have to be approached from multiple, sometimes competing, perspectives to satisfy multiple subgoals), contains interacting components, and changes dynamically within an everchanging context (Dörner & Funke, 2017). In short: most global challenges (poverty, climate change, pandemics, racism, etc.) constitute complex problems.

It is easy to conceive that eye movements can measure simple problem solving. In fact, the first systematic studies on eye movements during cognitive tasks in general compared expert and novice chess players—with chess considered the *"drosophila"* of cognitive psychology—and identified distinguishable eye movement strategies that marked the success of experts (Chase & Simon, 1973; de Groot, 1978). Experts' eye movements tended to alternate more often between key pieces and fixate less on individual pieces, indicating that chess masters encode visual information in chunks rather than in individual units (Reingold et al., 2001). A larger visual span allows not only retaining more moves in visual short-term memory but also planning more moves ahead. These findings show that eye movements reflect the perceptual organization and internal representation of task-relevant information in situations that go beyond highly simplified visual search tasks. Similarly, eye movements reflect the acquisition of knowledge toward a solution (sometimes termed the "Aha" moment) in anagram problem solving tasks; a pattern of decreased fixations on distractor letters can even predict the point where the observer is ready to solve the task (Ellis et al., 2011). Recent studies have shown that the "Aha" moment is often preceded by a reduction in visual information accrual, evidenced by more frequent eye blinks and fewer eye movements into the problem space (Salvi et al., 2015).

Yet, none of these studies involve complex tasks or even dynamic changes to the solution space. Can eye movements indicate the complexity of a task, and of the thought process of a problem solver? The studies summarized in this chapter show that eye movements can indeed reveal the efficiency with which an observer gathers visual information across different levels of complexity, from binary and highly simplified search tasks to simple problems. Under uncertainty or lack of task transparency—one of the hallmarks of a complex problem—information gathering and integration becomes even more critical, and eye movements can be a valuable tool to help us understand sensory information accrual when information is sparse. Eye movements, especially pupil responses, also reflect task difficulty and the cognitive demands a task poses—characteristics that can be expected to become more pronounced with increasing task complexity. Eye movements could be analyzed in tasks that comprise multiple simultaneous goals, perhaps with a focus on which goals observers prioritize or identify as most task relevant.

To design tasks that allow investigating eye movements during complex problem solving we can look to research on human factors—of how humans interact with elements of their workplace or technical environment. Even though these tasks are not always complex, they are marked by features that contribute to task complexity, such as dynamics, uncertainty, urgency, and high risk. Eye movements have been analyzed in medical contexts, such as in surgeons in the operating room or radiologists during diagnostic pathology (e.g., Pauszek, 2023) or in the automotive industry and in drivers during multitasking (Ahlström et al., 2021). Even though the focus of this work has overwhelmingly been on person factors such as workload, vigilance, attention, and fatigue, or on object factors such as device usability and equipment design, these studies show that eye movements can reveal processes and outcomes in real-world dynamic social contexts. Moreover, virtual reality displays provide an opportunity to create immersive and ecologically valid scenarios and track eye, hand, and body movements simultaneously (Anderson et al., 2023).

In summary: even though eye movement studies do not yet capture and reflect the complexity of real-world problem solving scenarios, they provide insights into the fundamental building blocks of human cognition. Since the first systematic eye tracking studies on human cognition, our knowledge of the visual signals that guide human eye movements has increased dramatically. Cognitive psychologists can now harness this knowledge and disentangle the low-level visual drivers that draw our eyes to salient objects in a scene from the higher-level cognitive factors that determine strategies and processes underlying complex cognition.

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