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Eye tracking measures of uncertainty during perceptual decision making

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ABSTRACT

Perceptual decision making involves gathering and interpreting sensory information to effectively categorize the world and inform behavior. For instance, a radiologist distinguishing the presence versus absence of a tumor, or a luggage screener categorizing objects as threatening or non-threatening. In many cases, sensory information is not sufficient to reliably disambiguate the nature of a stimulus, and resulting decisions are done under conditions of uncertainty. The present study asked whether several oculomotor metrics might prove sensitive to transient states of uncertainty during perceptual decision making. Participants viewed images with varying visual clarity and were asked to categorize them as faces or houses, and rate the certainty of their decisions, while we used eye tracking to monitor fixations, saccades, blinks, and pupil diameter. Results demonstrated that decision certainty influenced several oculomotor variables, including fixation frequency and duration, the frequency, peak velocity, and amplitude of saccades, and phasic pupil diameter. Whereas most measures tended to change linearly along with decision certainty, pupil diameter revealed more nuanced and dynamic information about the time course of perceptual decision making. Together, results demonstrate robust alterations in eye movement behavior as a function of decision certainty and attention demands, and suggest that monitoring oculomotor variables during applied task performance may prove valuable for identifying and remediating transient states of uncertainty.

1. Introduction

Perceptual decision making describes the process of accumulating sensory evidence and using it to influence how we categorize, understand, and behave within the world (Green and Heekeren, 2009; Heekeren et al., 2008; Shadlen and Kiani, 2013). This process is exceedingly common in daily life; airport luggage screeners categorize objects as threatening or non-threatening, pathologists categorize histological features as normal or abnormal, and law enforcement officers categorize handheld objects as weapons or non-weapons (Brunyé et al., 2017; McCarley et al., 2004; Payne, 2001). In many cases, decisions are made under conditions of uncertainty, which can arise due to occlusion or distortion of the stimulus itself, or due to down-stream impacts of attention, memory, emotion, and/or decision criteria (Heekeren et al., 2008). Despite the ubiquity and importance of perceptual decision making, and the potential impact of uncertainty on task performance, surprisingly few studies have attempted to identify quantitative measures of decision uncertainty. The present study explores whether several measures derived from eye tracking might be sensitive to varying levels of uncertainty during a perceptual decision task.

1.1. Perceptual decision making and uncertainty

Gathering, combining, and interpreting information from the sensory systems is critical for understanding the world and motivating behavior. Several theories attempt to characterize the sensory, perceptual, cognitive, and behavioral processes involved in perceptual decision making. In one theory, decision making is considered a continuous process that transforms sensory information into categories (e.g., face/house) (Opris and Bruce, 2005). Evidence accumulates from sensory inputs, is integrated and compared with expectations and knowledge, and then a behavioral response is selected. This proposed serial progression from perception to action relies on diverse neural circuits including the visual system, reward system, cognitive system, and oculomotor system. Visual information, processed and interpreted by the cognitive and reward systems, guides the oculomotor system to shift gaze and gather information as needed. More recently, a relatively dynamic account of perceptual decision making has emerged (Heekeren et al., 2008). In this theory, four complementary and interactive systems are engaged. First, sensory systems, such as visual and tactile, gather and compare information. Second, perceptual uncertainty or

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difficulty is detected, motivating and constraining attention toward additional information gathering. Third, a cognitive system is used to compare accumulated information against knowledge, and prepare or execute a motor response. Finally, a performance monitoring system assesses outcomes and adjusts behavior accordingly. These four processes and their underlying neural circuitry are proposed to occur at least partially in parallel, and interactively over time.

Relevant to the current research, there are a few important points to realize about extant theories of perceptual decision making. First, current theories consider the importance of oculomotor processes to strategically shift attention and gather information from a scene; this is usually formalized through a role of the saccadic eye movement system and its underlying neural substrates. Thus, there is some suggestion that the perceptual decision making process engages and guides visual attention to accumulate information relevant to a decision. Second, these visual search processes appear to be contingent upon conditions of uncertainty, which should exert some reliable influence over oculomotor behavior as information is gathered from a stimulus. Third, while these theories tend to emphasize neural mechanisms underlying stages of the perceptual decision process, using tools such as functional magnetic resonance imaging, these tools may not be tractable for implementation in applied settings intending to monitor perceptual decision uncertainty during task performance. This is in contrast to eye tracking technology, which is increasingly available in lightweight, mobile, and even wireless form factors (Weibel et al., 2012).

1.2. Measuring decision uncertainty

Given the breadth and complexity of sensory, cognitive, and motor systems dynamically engaged during decision making, it is not surprising that researchers have examined it using a wide range of behavioral, physiological, and neurophysiological techniques. Using functional magnetic resonance imaging (fMRI), research demonstrates that particular portions of the left dorsolateral prefrontal cortex (DLPFC) are involved in perceptual decision making (Heekeren et al., 2004). For instance, when participants are tasked to distinguish faces versus houses, their ability to do so correlates with activity in the left DLPFC. The authors proposed that this brain region is engaged in perceptual decisions by computing differences between activation in face- and house-specific brain regions. Other research, using event-related electroencephalography (EEG), has demonstrated reliable changes in early and late event-related brain potentials related to discrimination of face and car stimuli (Philiastides et al., 2006; Philiastides and Sajda, 2006). Following stimulus onset, there was an early face-selective N170 component and a later component around 300 milliseconds; the authors proposed that the early component reflected the early perception of the stimulus, but the later component reflected the cognitive decision process. Interestingly, the late component was highly sensitive to variations in task difficulty, and correlated strongly with task accuracy and response times. These results suggest that EEG may hold promise for discriminating uncertainty states during perceptual decision making.

There are also fMRI data examining the impact of difficulty during perceptual decision making. For instance, one study used fMRI to monitor brain responses to the difficulty of a phonetic discrimination task (Binder et al., 2004). They found that low-level sensory information processing in the auditory cortex was related to decision accuracy, whereas frontal brain regions showed activity correlated with response uncertainty. Thus, both EEG and fMRI data suggest reliable spatiotemporal dissociations of brain activity related to sensory discrimination and decision-related processes. Overall, task difficulty seems to modulate both early and late phases of processing, and according to some theories may promote attention deployment to resolve transient states of uncertainty (Heekeren et al., 2008).

Regarding eye tracking, surprisingly few studies have explored how eye movements might be modulated by uncertainty while participants categorize a visual stimulus. As noted by Krajbich, this could be due to an assumption that eye movements are relatively restricted and low variability during single-stimulus perceptual categorization tasks (Krajbich et al., 2010). Indeed many studies and computational models have been devoted to characterizing eye movements during choice decisions, which involve the comparison of multiple stimuli along a variety of dimensions (Fiedler and Glockner, 2012; Krajbich and Rangel, 2011; Orquin and Mueller Loose, 2013). However, several decision-making theories make explicit mention of eye movements as an important contributor to evidence accumulation during decision making, without clearly differentiating between decisions made regarding single versus multiple stimuli. For instance, the drift diffusion model proposes that eye fixations are used to sample a stimulus to promote evidence accumulation (Krajbich and Rangel, 2011), and that eye movements reflect the active deployment and control of attention. This research, however, is largely constrained to tasks involving the comparison of two images, which necessitates relatively large saccadic eye movements between the stimuli. Thus, it is unknown whether similar oculomotor dependence on uncertainty states will emerge with a single and relatively constrained visual stimulus.

1.3. Oculomotor metrics of decision uncertainty

Though there is a paucity of research examining eye tracking during the perceptual decision making with a single stimulus, more generally several candidate eye tracking measures have been linked to decision making, uncertainty, and task difficulty. These include oculomotor metrics, such as fixation and saccade parameters, blinks, and alterations in phasic pupil diameter. We review each of these below.

1.3.1. Fixations

Eye fixations are momentary pauses of eye movements within a particular location that extend for a minimum duration (Duchowski, 2007). Fixations are thought to reflect the process of directing visual attention toward a stimulus to bring it into foveal vision, which is the highest resolution region of the retina and permits the greatest possible visual detail. During more difficult decisions, participants tend to show a higher number of fixations (Fiedler and Glockner, 2012; Krajbich et al., 2010). This research, however, is limited to comparing two or more visual alternatives. In contrast, when visually searching a single scene for a stimulus, increasing search task difficulty tends to decrease fixation frequency and increase fixation durations (Hooge and Erkelens, 1996; Jacobs and O'Regan, 1987), and also increase the duration of the first fixation on the scene (Zelinsky and Sheinberg, 1997). Thus, research is equivocal regarding the impact of difficulty on fixations: during choice tasks fixations increase in frequency with more difficult trials. In contrast, during single stimulus tasks fixation frequency decreases and duration increases during more difficult trials, perhaps to provide more time accumulating evidence from certain regions of a scene.

1.3.2. Saccades

Saccades describe the ballistic movements of the eyes between successive fixations, which produces a continually changing sequence of information projected onto the fovea (Liversedge and Findlay, 2000). Saccades can be characterized in a few ways, such as the distance between successive saccades, or saccade amplitude in degrees, and the speed of saccades in terms of average or peak velocity (in °/s). Saccadic amplitude and peak velocity tend to be related in power-law function, with relative saccade magnitude increases matched proportionately to relative peak velocity increases (Bahill et al., 1975; Di Stasi et al., 2013). In visual search contexts, saccadic amplitude tends to decrease when a search task becomes more difficult (Jacobs and O'Regan, 1987; Phillips and Edelman, 2008), such as when targets are more visually similar to distractors. Furthermore, an emerging body of research suggests that the peak velocity of saccades is a valuable index of difficulty-evoked arousal during visual tasks (for a review, see (Di Stasi