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Eye movements reveal epistemic curiosity in human observers

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ABSTRACT

Saccadic (rapid) eye movements are primary means by which humans and non-human primates sample visual information. However, while saccadic decisions are intensively investigated in instrumental contexts where saccades guide subsequent actions, it is largely unknown how they may be influenced by curiosity – the intrinsic desire to learn. While saccades are sensitive to visual novelty and visual surprise, no study has examined their relation to epistemic curiosity – interest in symbolic, semantic information. To investigate this question, we tracked the eye movements of human observers while they read trivia questions and, after a brief delay, were visually given the answer. We show that higher curiosity was associated with earlier anticipatory orienting of gaze toward the answer location without changes in other metrics of saccades or fixations, and that these influences were distinct from those produced by variations in confidence and surprise. Across subjects, the enhancement of anticipatory gaze was correlated with measures of trait curiosity from personality questionnaires. Finally, a machine learning algorithm could predict curiosity in a cross-subject manner, relying primarily on statistical features of the gaze position before the answer onset and independently of covariations in confidence or surprise, suggesting potential practical applications for educational technologies, recommender systems and research in cognitive sciences. With this article, we provide full access to the annotated database allowing readers to reproduce the results. Epistemic curiosity produces specific effects on oculomotor anticipation that can be used to read out curiosity states.

1. Introduction

Curiosity is defined as the intrinsic motivation to learn and acquire information, and plays a central role in intelligent behavior including in development, learning and exploration (Berlyne, 1954; Gottlieb, Oudeyer, Lopes, & Baranes, 2013; Oudeyer, Baranes, & Kaplan, 2013). Psychological theories formulated in the 1960s and 1970s distinguished between perceptual curiosity – a desire to obtain new sensory inputs – and epistemic curiosity – an interest in new knowledge or semantic information (Lowenstein, 1994). More recently, epistemic curiosity was associated with cortical and subcortical structures in human observers, including activation of reward-related structures (Kang et al., 2009), and memory enhancement through reward modulations of hippocampal mechanisms (Gruber, Gelman, & Ranganath, 2014).

An open question however concerns the links between curiosity and selective attention. Attention, along with working memory, is critical for learning and selective information processing (Cardoso-Leite & Bavelier, 2014; Gottlieb et al., 2013). In humans and non-human primates, visual attention and rapid eye movements (saccades) are the primary means by which subjects sample visual information, and are sensitive to value and motivation (Gottlieb, 2012; Gottlieb, Hayhoe, Hikosaka, & Rangel, 2014; Tatler, Hayhoe, Land, & Ballard, 2011). While a recent study has shown that personality measures of trait curiosity correlate with the numbers of saccades and numbers of regions explored during free-viewing of complex scenes (Risko, Anderson, Lanthier, & Kingstone, 2012), nothing is known about the links between eye movements and epistemic curiosity – interest in semantic information.

In this report we examined this question by tracking the eye movements of human observers while they were presented a series of trivia questions that created high or low epistemic curiosity states. Because curiosity can covary with other epistemic factors such as confidence and surprise, we asked subjects to provide

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independent ratings of the 3 subjective states. We tested the hypothesis that curiosity will influence eye movement control, and that these influences would be sufficiently specific to allow curiosity to be "read out" from eye movements using data mining algorithms. The results confirmed both predictions. We show that curiosity enhanced anticipatory eye movements toward the expected location of the answer and the dwell time on the answer after it was presented, without affecting other metrics of saccades or fixations. The ocular signatures of high or low curiosity, confidence or surprise were sufficiently specific so that a machine learning algorithm could discriminate these levels with above-chance accuracy across multiple individual observers.

2. Methods

2.1. Subjects

Twenty subjects (11 women) were recruited from the Columbia University community and were compensated for their participation at the rate of $15 per hour. All the experimental procedures were approved by The Institutional Review Board of Columbia University and written informed consent was obtained for each subject.

2.2. Procedure

During the experiments subjects were comfortably seated in a dimly lit room with their head stabilized by a chin-rest at a distance of 54 cm from a computer screen. Eye position and pupil size were measured at a sampling rate of 500 Hz using an Eye-link 1000 eye-tracking system configured for binocular tracking. Before data collection began, the subjects received a task description and performed a few practice trials that were not included in the data set.

In the first part of a session the subjects were required to perform a series of 120 trials in which they read and rated trivia questions and were subsequently shown the answer. The trials were evenly divided between 60 *one-question* trials in which the subjects received a single question, and 60 *two-question* trials, in which they saw two sequentially presented questions and could select the one for which they wished to see the answer. One and two-question trials were signaled in advance by, respectively, one or two "beeps" and were presented in randomly interleaved order in one trial block. A progress bar was displayed after every trial indicating the number of remaining questions.

As shown in Fig. 1 a trial began when the first question was displayed in the upper part of the screen and subjects were asked to rate their levels of curiosity and confidence using a scale of 1 (low) to 5 (high) (panel 1). On 2-question trials, this was followed by the presentation of the second question and its ratings (Fig. 1, panel 2), after which the subjects were prompted to select one question to which they wished to receive the answer using an up/down key press (Fig. 1, panel 3). The trial then progressed to the answer period during which we recorded eye movements as described below (Fig. 1, panels 4–5). After viewing the answer, the subjects received a final rating scale asking them to indicate their surprise in the answer (Fig. 1, panel 6; 1 low, 5 high). One-question trials were identical, except that only one question was displayed and, after giving their curiosity and confidence ratings, the subjects pressed a button to progress to the answer stage.

Our focus was on the subjects' eye movements during a 3 s period centered on answer presentation. To dissociate the anticipatory and reactive components of gaze we divided this period into a 1.5 s *anticipatory epoch* when a rectangular empty box appeared at the top of the screen indicating the forthcoming position of the answer (Fig. 1, panel 4), and a 1.5 s *answer period*, when the answer was displayed aligned to the left edge of the box (Fig. 1, panel 5). All letters (for the questions and answers) were displayed in black with a luminance lower than that of the background, and letter height was approximately 0.39 degrees of visual angle (DVA).

After completing the trivia questions, the subjects completed three questionnaires developed to assess personality traits (110 questions total). The first questionnaire measured the tendency to maximize external or internal sensations on a sensation seeking scale (Zuckerman, 1964). The second questionnaire was the Curiosity and Exploration Inventory II (Kashdan et al., 2009) which measures curiosity and exploration using 2 dimensions: interest for novelty, challenge and absorption (full engagement in specific activities). The third questionnaire analyzes novelty-seeking behaviors on four subscales based on the origin of the stimulation: internal or external to the body, and cognitive versus sensational (Pearson, 1970).

2.3. Data analysis

To study the impact of epistemic curiosity on eye movement patterns we measured eye position as a function of time during the answer period, as well as the number, amplitudes and peak velocities of individual saccades and the number and durations

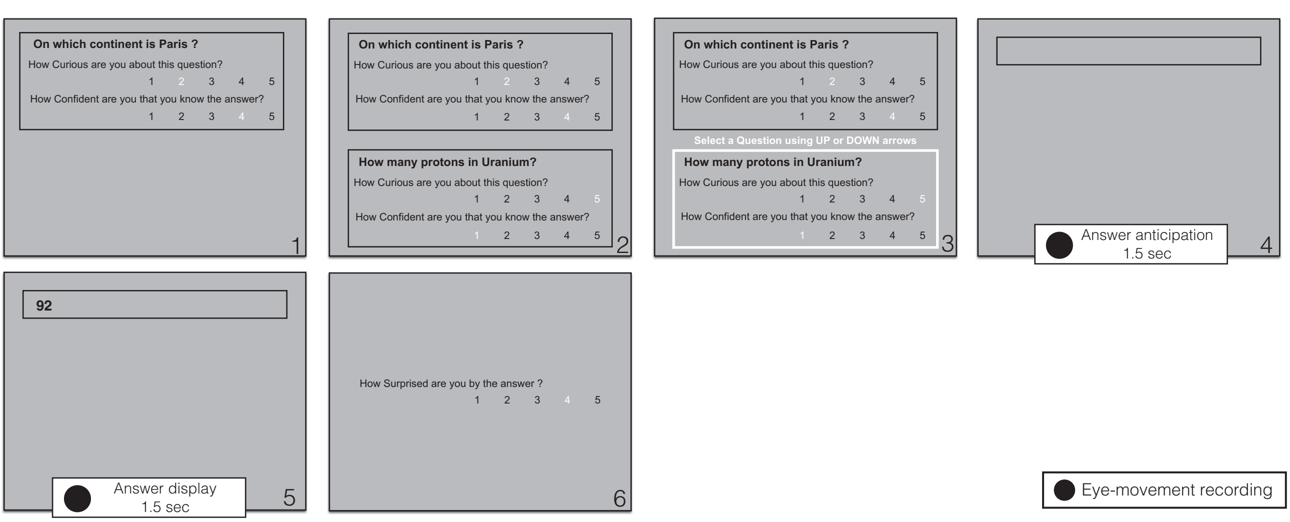

Fig. 1. Task design. The panels illustrate the sequence of events on a 2-question trial: (1) presentation of the first question and curiosity/confidence ratings, (2) presentation of the second question and its curiosity/confidence rating, (3) choice of question, (4) anticipation of answer, (5) presentation of answer, (5) surprise rating.