Primate Gaze Behavior Reflects Dynamic Decision-Making in Naturalistic Navigation

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Abstract:

Adaptive updating of beliefs in dynamically changing environments is essential for decision-making. While there is extensive research on static decision-making contexts, less is understood about closed-loop decision-making where actions directly influence visual perceptions. This study explores visual path integration and continuous decision-making in a 3D virtual reality (VR) setting, where primates, both monkeys and humans, navigate towards transiently indicated targets, presented either simultaneously or sequentially, with each offering identical rewards. The task required memory for target locations, updates of internal beliefs on self-position, and cost-effective navigational decisions. Our findings reveal a preference for proximal and centrally located targets, with a significant tendency to select the most recently indicated target, reflecting dynamic belief updates. Eye-tracking data suggest that gaze patterns prior to the second target's introduction can predict decision changes. Linear regression models confirm that these movements are indicative of the chosen target before its visibility, underscoring the importance of gaze dynamics in sensory integration and planning. Our results demonstrate how primate gaze behavior in a dynamic environment reflects adaptive decision-making process.

Keywords: Eye movement, Path integration, Decision-Making, Naturalistic behavior

Introduction

The adaptive updating of beliefs in response to dynamically changing sensory environments is a key component of effective decision-making. Extensive research has addressed decision-making in static contexts (Gold & Shadlen, 2007), yet continuous closed-loop decision-making where action reciprocally influences visual perception remains less explored (Yoo et al., 2021).

Real-world examples like path integration, where one's movement informs their spatial positioning, can provide a platform to explore the sequential decision making with a close-loop between action and perception (Etienne & Jeffery, 2004). Prior research suggests that eye movements can reflect internal beliefs by continuously tracking goal locations during natural navigation, even when no visible target is present (Lakshminarasimhan et al., 2020). Building on the previous ideas, we hypothesized that primates adjust their gaze to actively integrate the time-varying sensory information to guide future decision making. Our study investigates this through a virtual navigation task where two targets may appear simultaneously or sequentially, requiring primates to memorize and choose one to land on, as illustrated in Figure 1.

Results

Monkeys and humans engaged in a visual navigation task, using a joystick to steer towards transiently cued target locations. Two targets appeared either simultaneously or sequentially, while each target was associated with the same amount of reward (Figure 1). Subjects were free to choose a target to navigate.

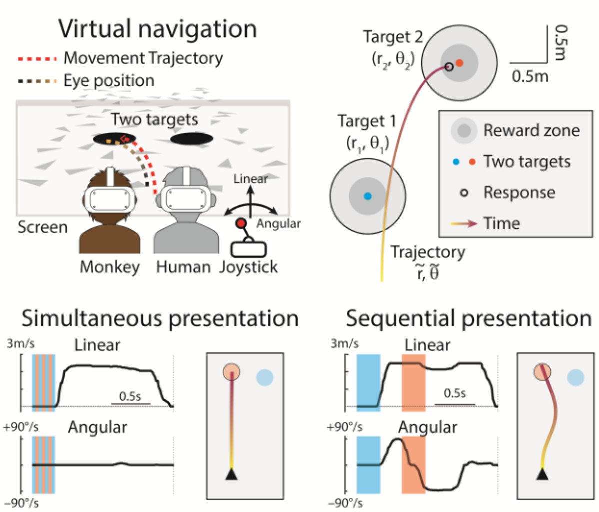

Figure 1: Naturalistic navigation in virtual environments with simultaneous and sequential target presentation.

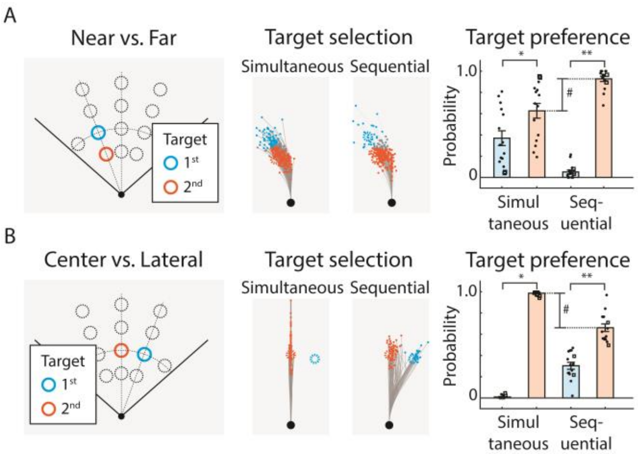

Figure 2: Target selection strategy under simultaneous and sequential presentations. (A) Target preference for two targets at equal angles but varying distances. Both humans and primates prefer the nearer target in both simultaneous (*P<0.05) and sequential presentations (**P<0.05), with an increased preference for the nearer target during sequential presentations (#P<0.05). (B) Target preference for targets at equal distances but at different angles. A strong preference for the central over the lateral target was observed (*P, **P<0.05), and a significant change-of-decision occurred when the central target was presented sequentially (#P<0.05). N = 15, including 13 humans and 2 monkeys. Paired t-test was used to calculate the significance.

The task required memory of the target location, updates of internal beliefs regarding self-position, and cost-effective navigational actions. Analysis of navigational strategies revealed that both humans and monkeys always preferred proximal and centrally located targets, and there was a noticeable tendency to select the most recently indicated target, as shown in Figure 2. This behavior indicates that primates can assess the cost toward the goal while dynamically updating their beliefs with new sensory information.

As previously reported (Lakshminarasimhan et al., 2020), eye movements continuously tracked the target location, even after the target was no longer visible (Figure 3). When subjects did not change their initial decision, their gaze consistently followed the location of the first target (Figure 3A). Conversely, when subjects decided to switch to a new target, their eyes quickly shifted to track this new target, reflecting a change of mind (Figure 3B). Intriguingly, we observed that eye movements prior to the introduction of the second target could predict a change in decision. To validate this hypothesis, we demonstrated that eye movements can accurately predict the position of the target chosen even before the second target appeared, thereby highlighting the role of gaze dynamics in sensory integration and future planning (Figure 3C).

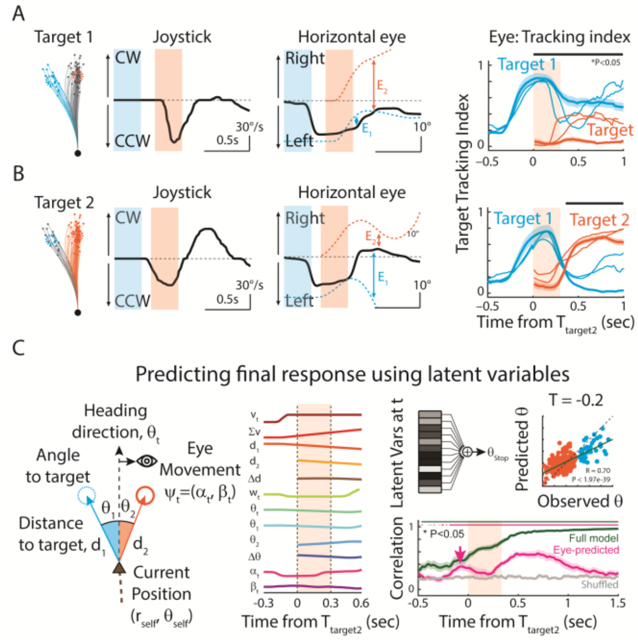

Figure 3: (A) Horizontal eye movements track target 1 (cyan) when the subject maintains the initial decision, but (B) track target 2 (orange) when the subject switches to a new target. The Target Tracking Index illustrates how closely eye movements follow the ideal tracking path for each target (N=15). (C) Latent variables can accurately predict the final response using a linear regression model, and a strong correlation between eye movement and response is evident even before the second target is introduced.

Our study shows that eye movements reflect the adaptive update of beliefs, emphasizing the role of eye movements during continuous, naturalistic navigation.

Acknowledgments

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