Covert attention is flexibly allocated in value-guided choice

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Abstract

Computational models of human decision making suggest that visual attention influences evidence accumulation from choice options, with non-fixated peripheral options being downweighted relative to the fixated option via a constant parameter. Such models negate the possibility that levels of covert attention might change across the course of a decision, shaped by information gathering and options encountered. We explicitly test how attention is allocated beyond gaze (i.e., covert attention) during value-guided choice using a probe-detection task. Participants (N = 31) completed a choice task, with simultaneous eyetracking recording, where they chose between differently valued patches to earn rewards. During each trial, probe letters were flashed briefly onscreen at each patch location, and probe report accuracy at each location was used as a measure of attentional deployment. Results showed that covert attention at peripheral locations was modulated by decision-relevant variables – such as their decision-relevance and relative value – and has downstream consequences for fixation-related choice biases. These findings indicate that attention to peripheral options is flexible rather than fixed.

Keywords: Decision-making; attention; value-guided choice

Introduction

How do we make decisions when faced with different options? Sequential sampling models posit that agents accumulate evidence for each choice option until a decision threshold is reached. Recent such models incorporate overt gaze as a proxy for visual attention; one particularly influential model is the attentional drift diffusion model (aDDM) and its extensions (Krajbich, Armel, & Rangel, 2010; Krajbich & Rangel, 2011; Yang & Krajbich, 2023), which propose that gaze determines evidence accumulated, such that non-fixated options are attentionally downweighted via a fixed decay parameter. Although these models have been useful for explaining choice and reaction time data, they draw an equivalence between fixation and visual attention. Contrary to this equivalence, work from animal (Cavanagh et al., 2019) and human (Perkovic et al., 2023) decision-making have suggested that covert attention beyond gaze may affect choice behavior.

Does covert attention to peripheral choice options merely involve constant attentional discounting? If not, how might covert attention be allocated during the decision process? To address these questions, we use a probe-detection task (Gaspelin, Leonard, & Luck, 2015; Dugué et al., 2015) to examine attentional allocation beyond overt gaze during value-guided decision-making. Our results showed that covert attentional allocation at peripheral locations is flexibly modulated by decision-relevant variables and has downstream consequences for attenuating fixation-related choice biases.

Experiment

Participants (N = 31, M_{age} = 23.6 years, 15 male, 16 female) completed a value-guided choice task which involved a secondary probe-detection task (Figure 1).

In this task, participants repeatedly chose between patches filled with colored dots (orange and cyan) that indicated the value of each option. One color was designated as the target color (counterbalanced between participants). Choosing the more valuable option (that is, the option that contained a higher proportion of target color dots) in each trial earned the participant gemstones, which determined their bonus payment (maximum £1.50).

On each trial, three patches were presented; two patches (relevant options) were filled with 100 colored dots each, and one patch was not filled with colored dots (irrelevant option; serving as the control location). Following 220 ms of looking at their first- or second-sampled option (counterbalanced between trials), participants were briefly presented with probe letters for 150 ms at each of the three patch locations (Figure 1e). The trial continued on as normal after probe presentation. Once participants selected a patch, they were asked to report the probe letters they detected (Figure 1f). Letter report accuracy did not affect trial reward outcome.

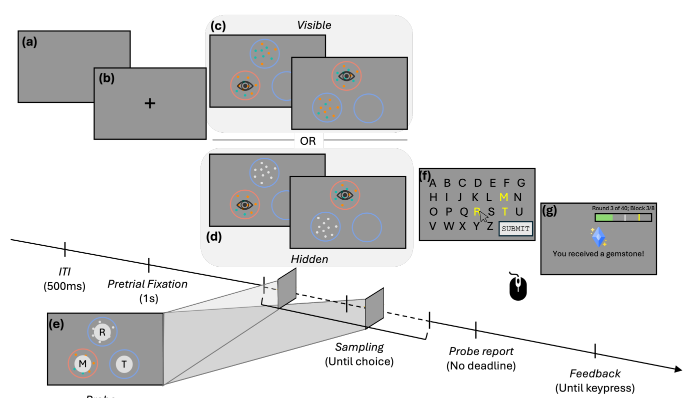

Figure 1. Participants completed a free-viewing value-guided choice task which involved a secondary probe-detection task. Figure depicts an example trial; see main text for details.

The visibility of the peripheral (unfixated) option (*visible* or *hidden*; see Figure 1c versus 1d) was varied between blocks within subjects, in a replication of the design used by Eum, Dolbier, and Rangel (2023). On *visible* trials, the contents of the decision-relevant patches remained onscreen regardless of which patch was currently fixated. On *hidden* trials, patch contents were gaze-contingent, such that only the content of the currently fixated decision-relevant patch was visible. To allow us to examine the effect of an option's relative value on the amount of covert attention allocated to it, we also varied the value difference (i.e., difference in proportion of target dots; 2 to 20%) between the two relevant options on each trial.

Participants completed two practice blocks of 20 trials with only the primary choice task (i.e., Figure 1 without components e and f), followed by two practice blocks of 20 trials which contained regular trials (as illustrated in Figure 1), followed by the main experiment which consisted of eight blocks of 40 regular trials (320 trials total).

Results

First, we found that covert attention at peripheral locations was modulated by the locations' choice-relevance. Participants were more likely to correctly detect probe letters that appeared at the choice-relevant unfixated option – as well as at the fixated option – relative to the unfixated choice-irrelevant option (Figure 2). Generalized linear mixed effects models (GLMM) with random subject intercepts showed that these main effects of probe location type and peripheral option visibility condition were significant regardless of probe timing (all $p < .001$). Controlling for the distance between the probe-letter and gaze location additionally revealed that less attention was allocated to peripheral options when they were not visible (significant visibility x probe location interaction for both probe timings, $p < .016$). Together, these results suggest that participants are covertly attending to the unfixated (relevant) location more than the third, irrelevant location.

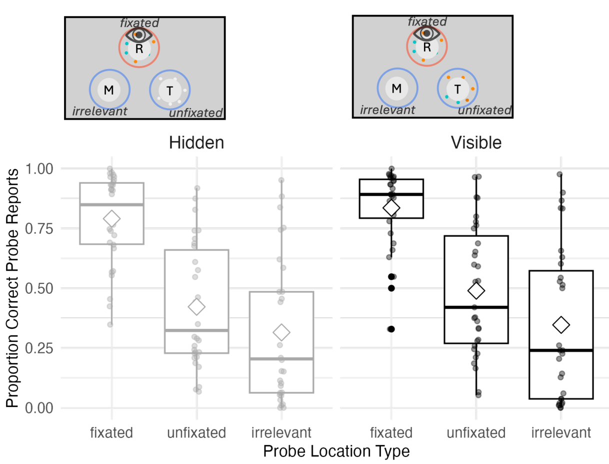

Figure 2. Probe report accuracy was affected by location choice-relevance and unfixated option visibility.

Second, we found that covert attention at a peripheral option was modulated by its relative value (i.e., difference in proportion of target-color dots relative to the fixated option). The likelihood of correct probe-letter report for the relevant unfixated option increased, as that option's relative value compared to the fixated option increased (Figure 3). This value modulation effect was significant (GLMMs with subject random intercepts; $p < .001$) and persisted ($p < .001$) in follow-up analyses controlling for distance between the probe-letter and gaze location. This finding suggests that attentional weighting to peripheral options is sensitive to relative value.

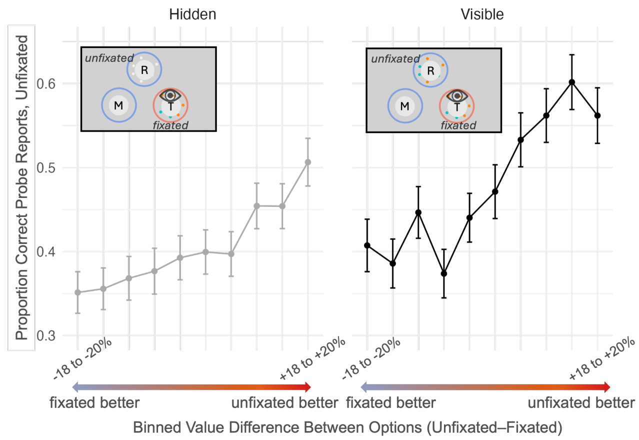

Figure 3. As the value (i.e., proportion of target-colored dots) of the unfixated option increased relative to the fixated option, people became more accurate at detecting the probe at that unfixated option.

Third, we found that covert attention had downstream consequences for choice behavior. Replicating previous work (Krajbich et al., 2010), we found a choice bias towards the last-fixated option (and hence, against the last-unfixated option), whereby people were less likely to choose an option that they were not fixating on at the time of choice, even controlling for relative value (GLMMs with option chosen as outcome; effect of last-fixated option controlling for relative value $p < .001$). Replicating results by Eum et al. (2023), this bias increased when peripheral visual information was hidden compared to when it was visible ($p < .001$). Beyond these replication results, we found that this choice bias was attenuated when the probe at the last-peripheral option was correctly detected ($p < .001$). This suggests that increased covert attention reduces the suboptimal choice bias against an unfixated option.

Conclusions

Our findings suggest that covert attention to peripheral options is flexible and sensitive to decision-relevant variables, such as the choice-relevance of a peripheral location and the value of that location relative to the currently-fixated option. Further, results show that covert attention allocation has downstream behavioral consequences, including attenuating fixation-related choice biases. The current study thus highlights the need for models of decision-making to consider the role of attention beyond gaze, and to characterize attentional weighting as flexible rather than fixed.

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References

Cavanagh, S. E., Malalasekera, W. M. N., Miranda, B., Hunt, L. T., & Kennerley, S. W. (2019). Visual fixation patterns during economic choice reflect covert valuation processes that emerge with learning. *Proc. Natl. Acad. Sci. U.S.A.*, *116*(45), 22795–22801. doi: 10.1073/pnas.1906662116

Dugué, L., McLelland, D., Lajous, M., & VanRullen, R. (2015). Attention searches nonuniformly in space and in time. *Proc. Natl. Acad. Sci. U.S.A.*, *112*(49), 15214–15219. doi: 10.1073/pnas.1511331112

Eum, B., Dolbier, S., & Rangel, A. (2023). Peripheral visual information halves attentional choice biases. *Psychological Science*. doi: 10.1177/09567976231184878

Gaspelin, N., Leonard, C. J., & Luck, S. J. (2015). Direct evidence for active suppression of salient-but-irrelevant sensory inputs. *Psychological Science*, *26*(11), 1740–1750. doi: 10.1177/0956797615597913

Krajbich, I., Armel, C., & Rangel, A. (2010). Visual fixations and the computation and comparison of value in simple choice. *Nat Neurosci*, *13*(10), 1292–1298. doi: 10.1038/nn.2635

Krajbich, I., & Rangel, A. (2011). Multialternative drift-diffusion model predicts the relationship between visual fixations and choice in value-based decisions. *Proc. Natl. Acad. Sci. U.S.A.*, *108*(33), 13852–13857. doi: 10.1073/pnas.1101328108

Perkovic, S., Schoemann, M., Lagerkvist, C.-J., & Orquin, J. L. (2023). Covert attention leads to fast and accurate decision-making. *Journal of Experimental Psychology: Applied*, *29*(1), 78–94. doi: 10.1037/xap0000425

Yang, X., & Krajbich, I. (2023). A dynamic computational model of gaze and choice in multi-attribute decisions. *Psychological Review*, *130*(1), 52–70. doi: 10.1037/rev0000350