Temporal Distance in Memory Shapes Gaze–Choice Dynamics across Primates

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INTRODUCTION

Previous work shows that macaque scan paths and gaze consistency during naturalistic viewing vary with event content (Wang et al., 2024), but what gaze represents during memory-based decisions remains unclear. Gaze may contribute to decision formation, reflect an emerging choice as a readout of the latent decision state, or combine both roles (Zylberberg et al., 2026). In temporal-order judgments, temporal distance (TD) varies across decisions, allowing us to ask whether the role of gaze in choice changes with temporal distance. Here, humans and macaques performed memory-based temporal-order judgments while eye movements were recorded. We asked: How does temporal distance shape gaze–choice dynamics across primates, and what does this reveal about the role of gaze in memory-based decisions?

CORE QUESTION

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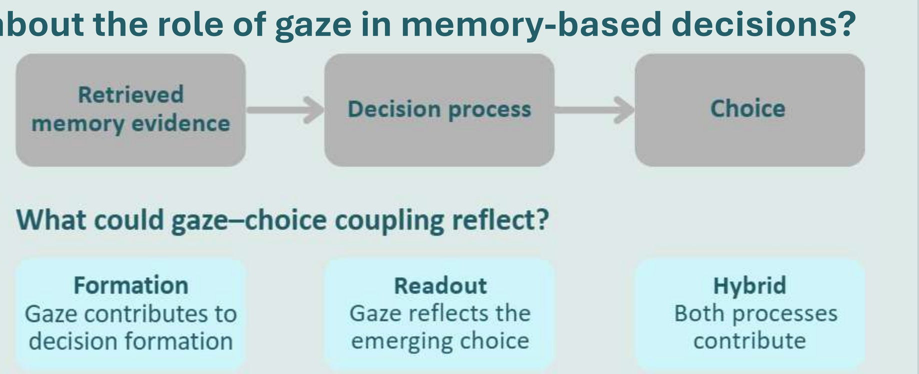


METHODS

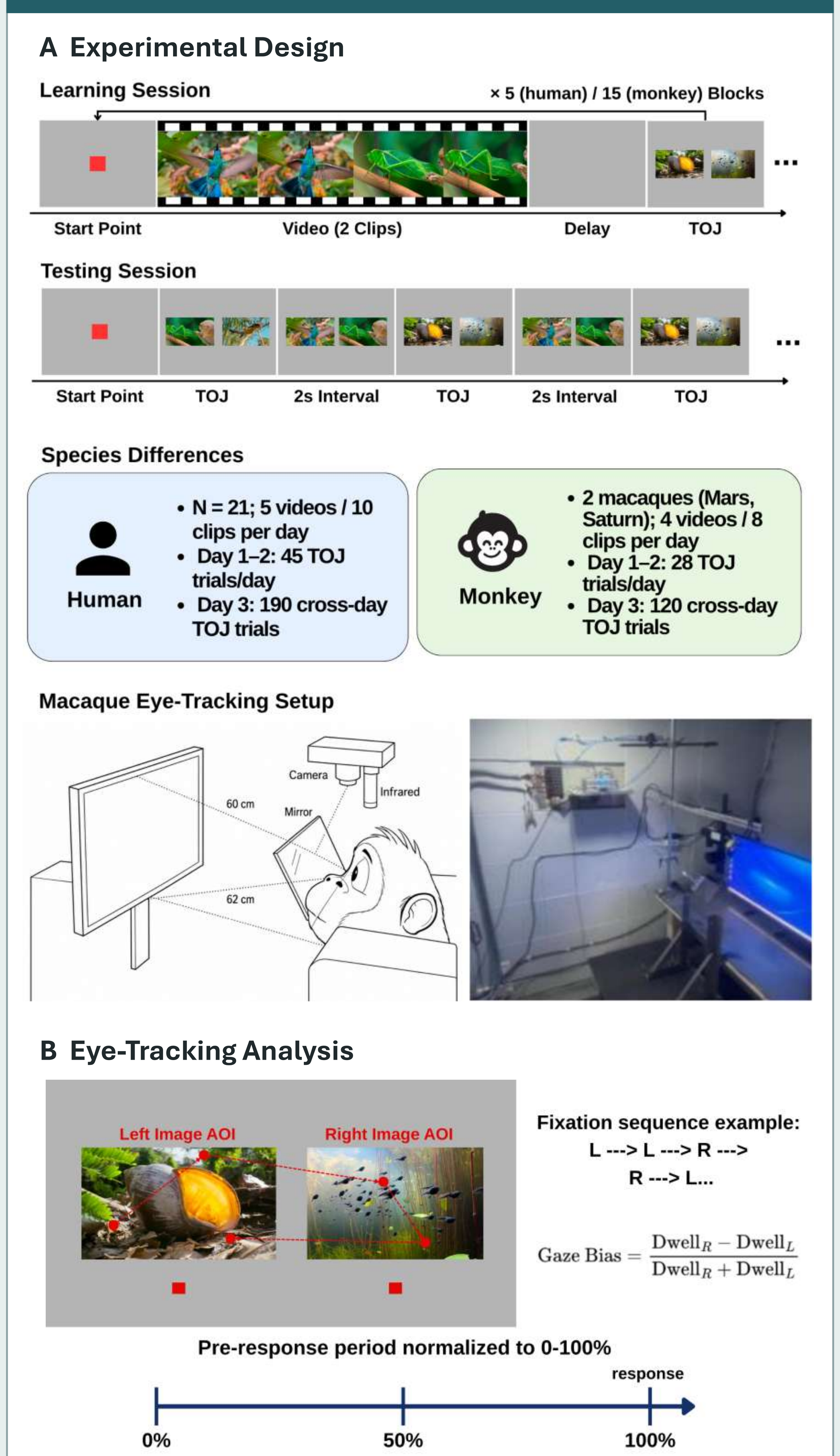


Figure 1. Experimental design and eye-tracking analysis. (A) Experimental structure. Human participants learned five videos per day across Days 1–2, with each video presented as two clips, and subsequently completed cross-day temporal-order judgments on Day 3. Macaques completed repeated daily learning and testing sessions using the same structure. Species-specific sample sizes, trial numbers and the macaque experimental setup are shown in the figure. **(B)** Fixations were classified according to whether gaze fell on the left image, right image, or outside the two image areas of interest (AOIs). Spatial gaze bias was calculated as the normalized difference in dwell time between the right and left image AOIs. For time-resolved analyses, the pre-response interval of each trial was normalized from 0–100%.

RESULTS

RESULT 1: GAZE IS SYSTEMATICALLY RELATED TO CHOICE

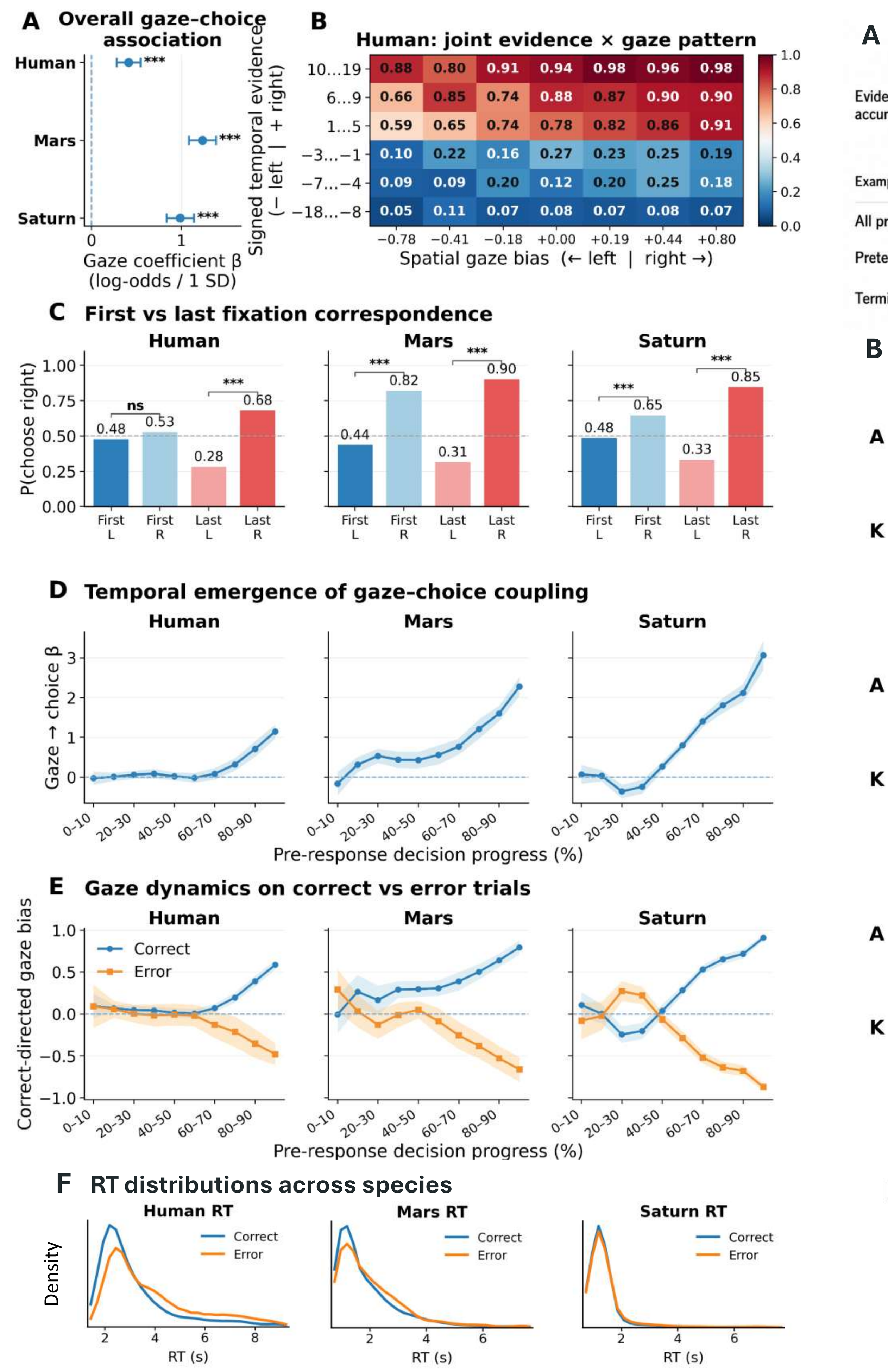
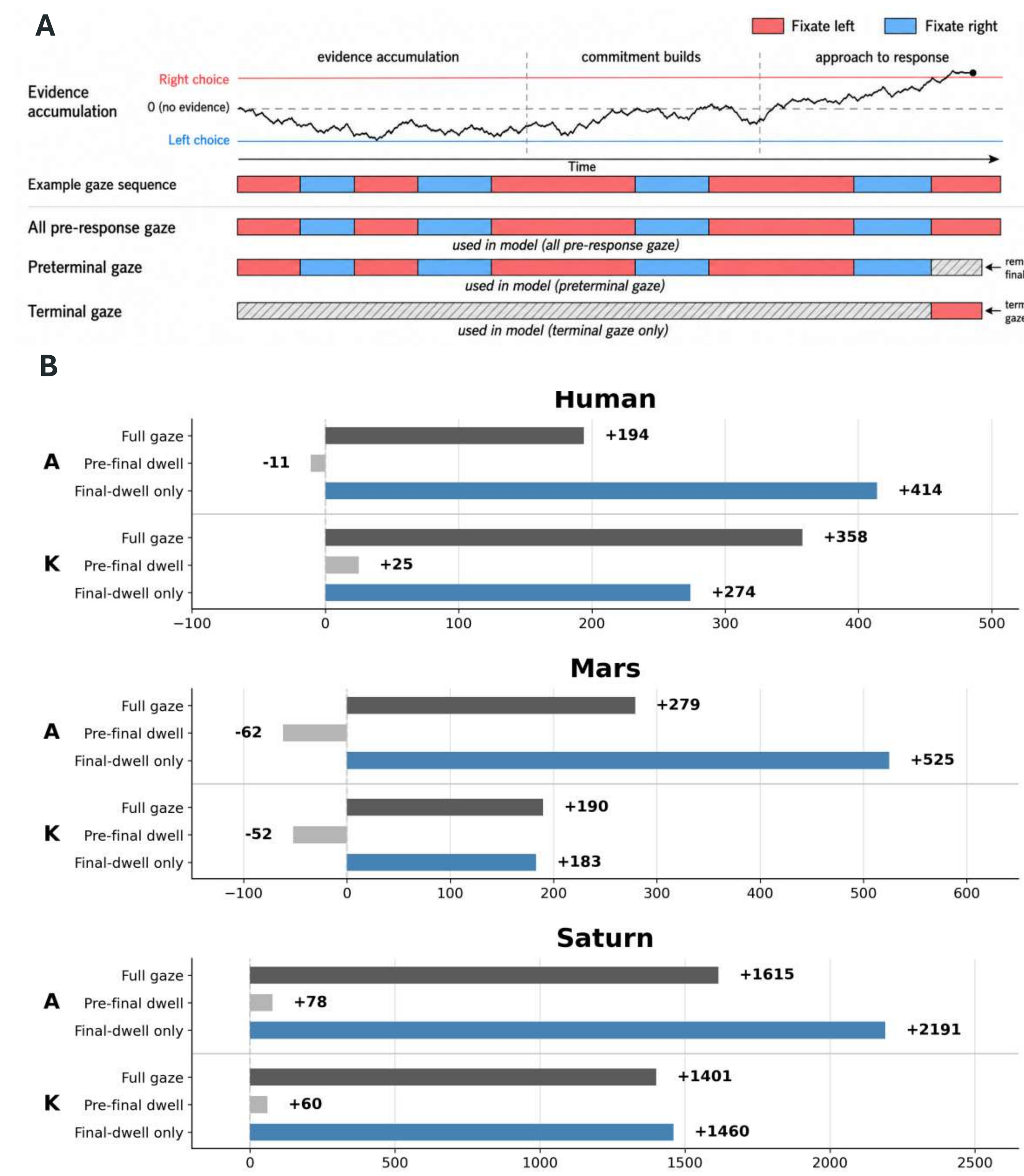


Figure 2. Temporal dynamics of gaze–choice coupling during memory-based temporal-order decisions in humans and macaques. (A) Logistic GEE models tested whether spatial gaze bias predicted rightward choice after controlling for signed temporal distance. Positive gaze coefficients were observed in humans and monkeys, indicating choice-related gaze beyond objective temporal evidence. **(B)** In humans, greater rightward gaze was associated with a higher probability of choosing the right option across TD levels. **(C)** First and last fixation analyses showed that last fixation was strongly associated with eventual choice in all three datasets, and first-fixation effects were significant in both macaques but weak in humans. **(D)** Time-resolved GEE models across ten normalized pre-response bins revealed predominantly late gaze–choice coupling in humans and earlier coupling in both macaques. **(E)** Gaze became increasingly aligned with the eventual choice on both correct and error trials. **(F)** RT distributions for correct and error trials are shown for humans, Mars, and Saturn.

RESULT 2: GAZE-MODEL ADVANTAGE IS CONCENTRATED IN THE FINAL DWELL



A - Additive: $v(t) = v_0 + \beta_{TD} TD_z + \beta_G G(t)$

K - Attentional weighting: gaze discounts unattended temporal evidence by θ

Figure 3. Final-dwell stress test of gaze-dependent accumulation models. (A) A schematic illustrates the aDDM evidence accumulation process and the three gaze-input models. The same pre-response gaze sequence was entered into the model in three ways: Full gaze used the entire gaze sequence; Pre-final dwell removed the final continuous image dwell before the response; and Final-dwell only retained that final dwell. **(B)** Model improvement was quantified as $\Delta BIC = BIC_{\text{no-gaze}} - BIC_{\text{gaze}}$, such that positive values indicate better fit of the gaze-dependent model relative to baseline. A denotes an additive gaze model, $v(t) = v_0 + \beta_{TD} TD_z + \beta_G G(t)$; K denotes an attentional-weighting model θ: fixing left: *v(t)=v0+d*(E_left -θ*E_right)*; fixing right: *v(t)=v0+d*(θ*E_left - E_right)*. Across humans, Mars, and Saturn, removing the final dwell greatly reduced the additive-model advantage. In contrast, using the final dwell alone still produced a strong improvement and even outperformed the full-gaze model in all three datasets. The K-family showed the same overall pattern. Together, these results indicate that the apparent benefit of gaze-dependent accumulation models is dominated by response-terminal gaze rather than being distributed uniformly across the pre-response period.

RESULT 3 — TEMPORAL DISTANCE SHAPES GAZE–CHOICE DYNAMICS

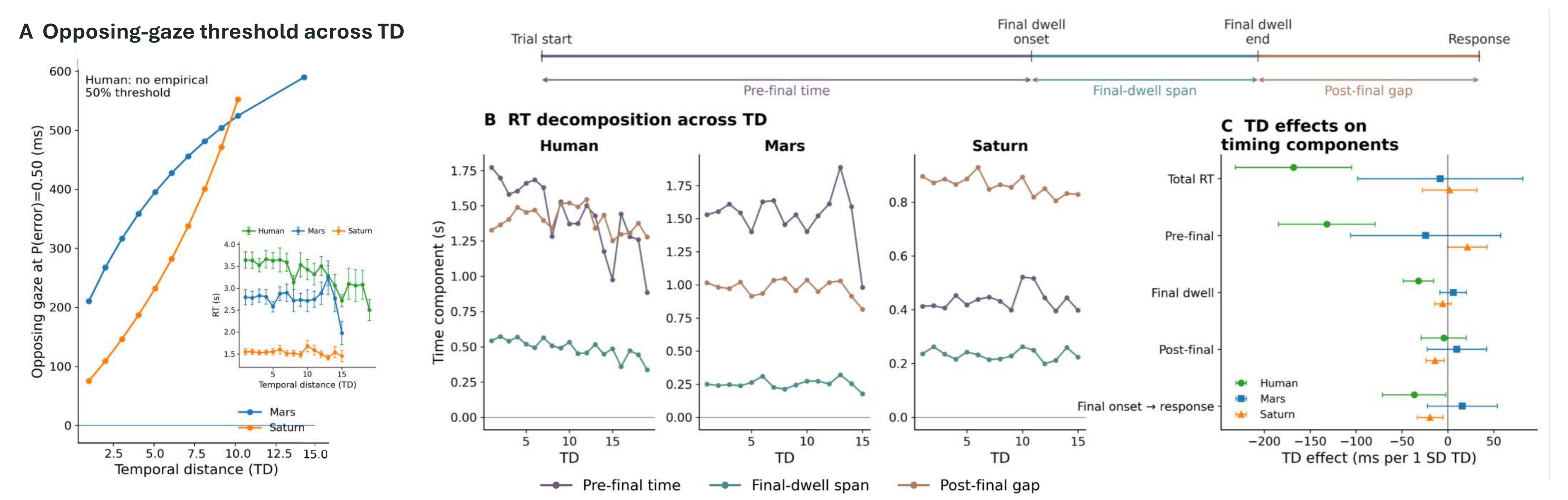


Figure 4. Temporal distance modulates gaze–choice coupling. (A) Each point shows the level of opposing gaze bias required to bring predicted error probability to 50% at each TD level. In both macaques, stronger TD required increasingly stronger opposing gaze, indicating that the gaze–choice relationship depended on temporal distance. Humans did not reach the 50% error threshold within the observed gaze range. Inset shows RT as a function of temporal distance for humans, Mars, and Saturn. **(B)** RT was separated into pre-final time, final-dwell duration, and the interval between final-dwell offset and response. In humans, stronger TD mainly shortened the period before the final chosen-item dwell, whereas timing effects were smaller and less systematic in the macaques. **(C)** GEE estimates of TD effects on total RT and each timing component. TD-related timing changes were more pronounced in humans than in macaques, with the largest human effects concentrated in total RT and pre-final time. This pattern suggests that increasing TD primarily shortened the period before entry into the terminal chosen-gaze state in humans.

DISCUSSION

- **A shared late choice signal across species.** Across humans and macaques, gaze became increasingly aligned with the eventual choice. Error trials showed the same late choice alignment, suggesting that gaze increasingly reflects the emerging decision state rather than objective temporal evidence alone.
- **Gaze-model advantage is concentrated in the final dwell.** Across humans and macaques, removing the final dwell substantially reduced the advantage of gaze-dependent accumulation models, and final-dwell-only gaze retained strong model improvement. This suggests that much of the apparent gaze-dependent accumulation signal is concentrated near the response.
- **Temporal distance differentially shaped decision dynamics across species.** Human RT decreased more clearly with increasing TD, but RT changes were smaller in the macaques. RT decomposition showed that the human TD effect was concentrated primarily in pre-final time, with weaker effects on final-dwell and post-final timing. In contrast, macaque timing was less systematically affected by TD, although larger TD required progressively stronger opposing gaze to drive predicted error probability toward 50%.
- **Cross-species patterns suggest different balances between decision formation and readout.** Human gaze appears predominantly readout-like, with late-emerging choice coupling and TD-related timing changes occurring mainly before the final chosen dwell. Macaques show similarly strong late gaze–choice coupling, but also clear earlier coupling, suggesting a more hybrid role, with gaze potentially contributing more to decision formation.

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