Effectiveness of different computational models during the Tacit Communication Game

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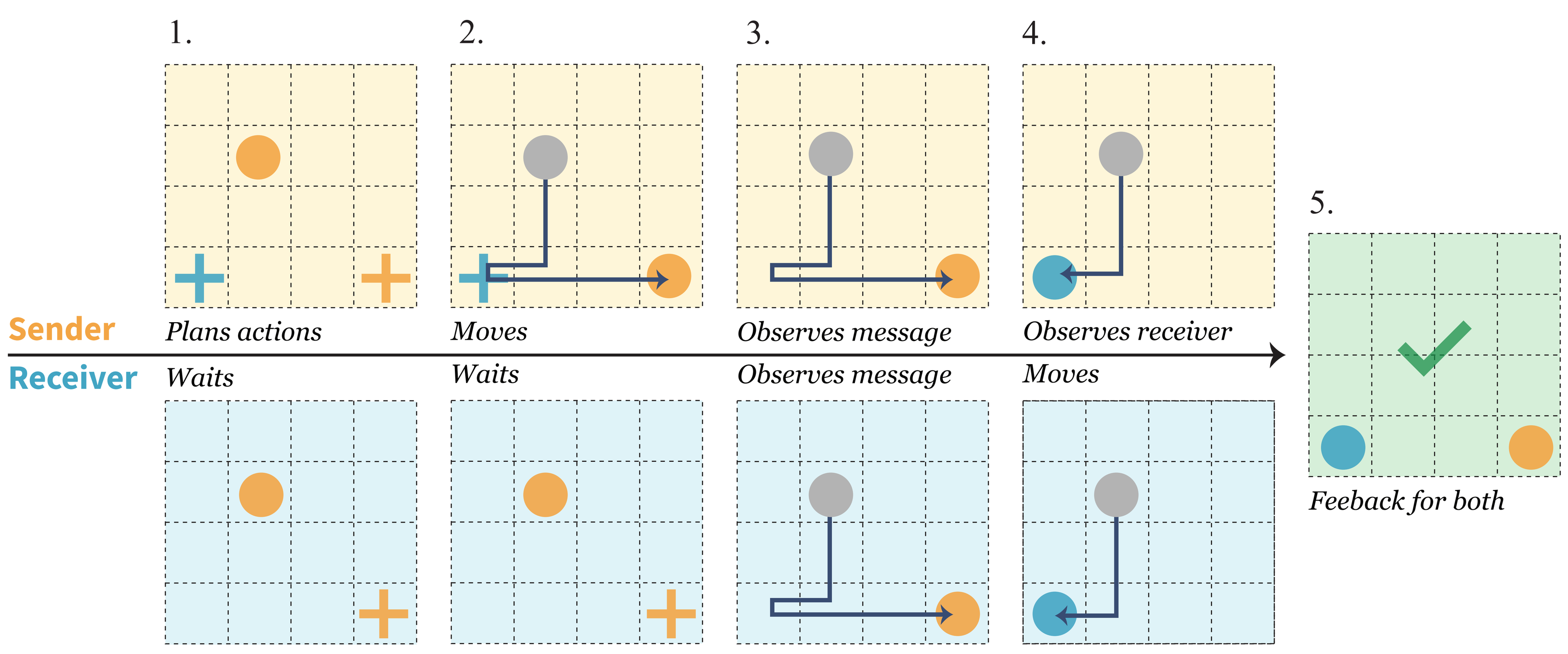
Introduction

- **Background -** Human language-based communication involves both spoken words and prosody to direct the recipient to the important parts of the message [1].
- **Research question -** How do humans communicate in novel environments without a common language?
- **Proposed mechanism -** Here we propose that **for effective communication surprising events/prediction errors can be used intentionally to signify the salient part of the message by deviating from established expectations.**
- **Approach:**
  - As a testbed for non-language-based communication, we utilized Tacit Communication Game (TCG) and develoed a novel computational model (Surprsie model) to implement the suggested mechanism.
  - To assess the performance of the Surprise model, we compared it to the Belief-based Model using data collected from 31 pairs of participants who played the TCG.
  - We investigated Pupil dilation and EEG data to quantify the evidance for the Surprise model.
  - Lastly, we conducted a separate experiment to further validate the effectiveness of different computational models by simulating two senders based on the Surprise model and the Belief-based model, respectively.

Experimental task: Tacit Communication Game



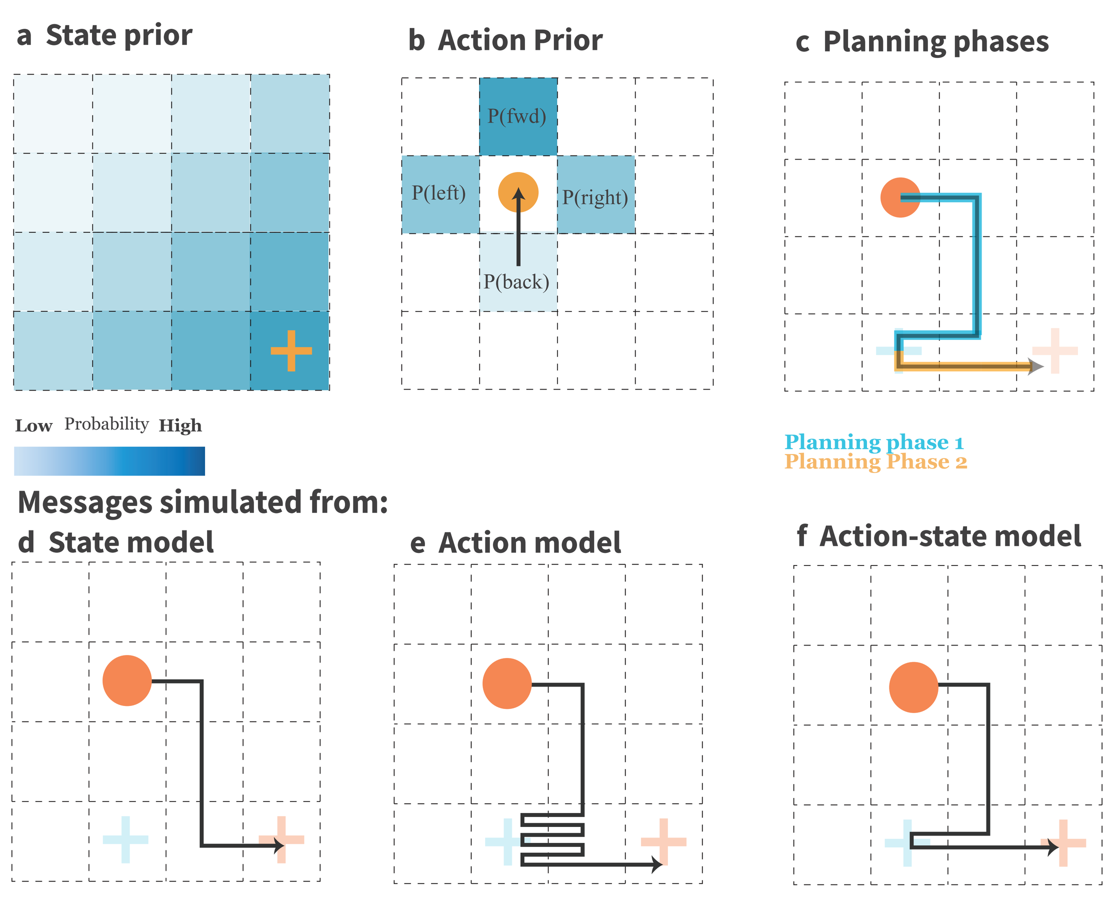
The Tacit Communication Game is played on a square game board displaying the goal positions of both players (Blue cross for the receiver and orange cross for the sander) to the Sender. The Sender's objective is to create a trajectory (the "message") from her starting position to her own goal state, effectively conveying the Receiver where his goal location is. The Receiver, in turn, moves his token to the position he believs his goal state to be.

Computational models -Surprise and Belief-based models

The Surprise model employs intuitive priors based on movement kinetics (Action priors) and goal orientation (State priors) to construct messages, maximizing surprise at the Receiver's goal state.

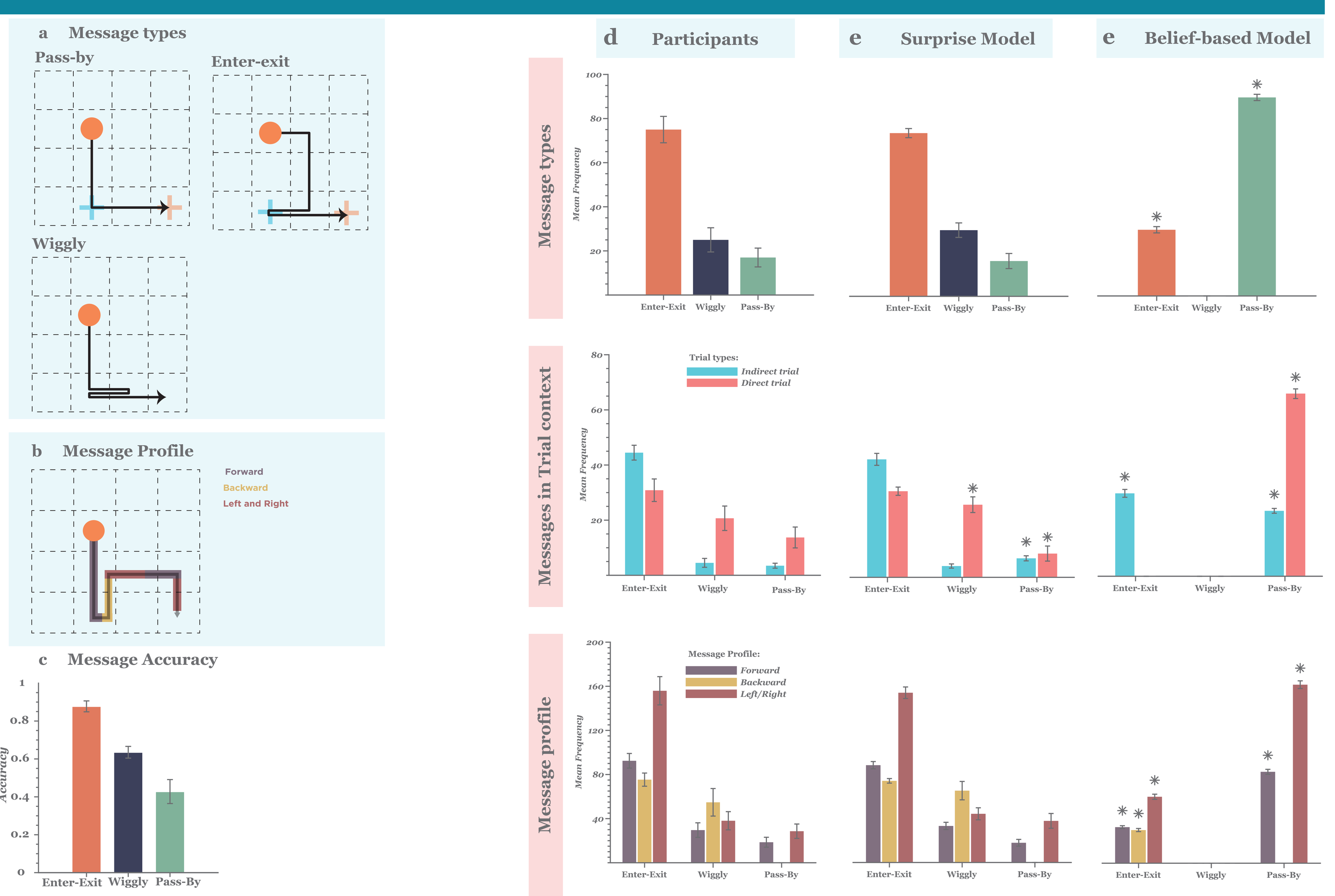
- **Action priors** ensure that probabilities are ordered in the following way:
  $p(f) > p(l) = p(r) > p(b)$
- **State Priors** provide general sense of where sender is heading. If s is one step further away from Sender's goal than s', then
  $p(s) < p(s')$ $\quad p(s) = 1/d \times p(s')$, with $d >= 1$
- **Combinied state-action priors:**
  $$p(a) = \frac{p(m)\times p(s'|s, m)}{\sum_{j=1}^{m=4} p(m)\times p(s'|s, m)}$$
- **Information-theoretic surprise:**
  $h(a) = -\log(p(a))$
- **Expected value** $ev_{a_i|s_i} = -\log(p(a_i) \times \epsilon^i r(s_i))$

Eventually, these expected values are transformed to the action probabilities.



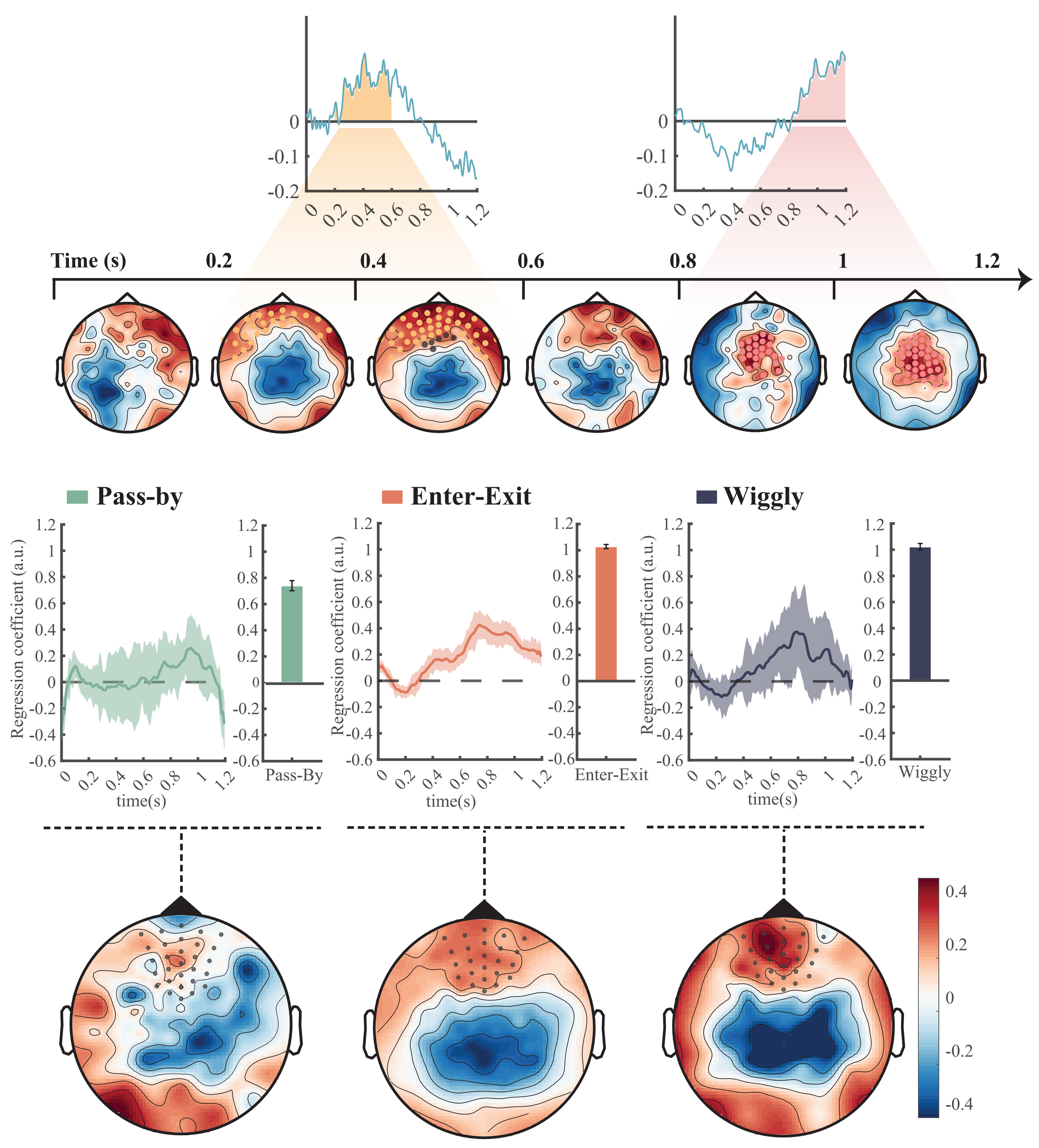
The Belief-based model stores all possible goal-location and message sets (L, M) in memory. In each trial, the sender observes her and the receiver's goal locations (ls, lr) and sends a message (m∈M). The receiver observes the message and selects a location (l∈L) as the goal. The model forms a belief distribution over all game board states. Message selection involves an exhaustive search through possible messages for a goal configuration, updating message-specific beliefs based on the receiver's goal success [2].

Model-free analysis of behavioural data and model evidence



We evaluated two computational accounts using participant-generated and model-simulated messages, focusing on three indices: *Message Type Frequencies, Message Profile Frequencies*, and *Message Frequencies across trial contexts*.
Comparing human-generated indices to the Surprise model, Bayes factors ($BF_{01} > 1$) strongly suggest similarity. However, compared to the Belief-based model, all Bayes factors ($BF_{01} < 1$*) indicate differences.

Model-based analysis of EEG data



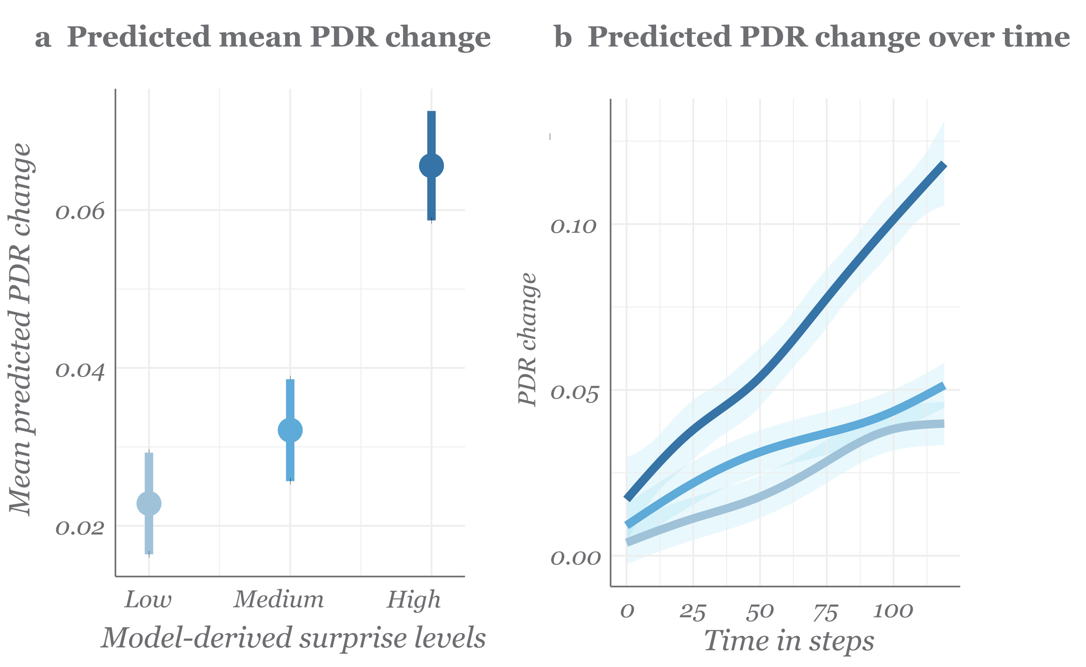
We hypothesized that receivers' identification of goal locations through deviation from expectations could manifest as neuronal encoding of surprise.

To study surprise's impact on EEG signals, we employed a model-based regression approach [3].

We identified two clusters of electrodes and time intervals exhibiting notable sensitivity to surprise. The initial cluster showed positive responses in frontal electrodes (0.4-0.8 seconds), while the second occurred in frontal-central electrodes (0.8-1.2 seconds).

Moreover, high surprise messages like "Entex-exit" and "Wiggly" showed stronger correlation with EEG signals from Central-frontal electrodes, compared to less surprising messages.

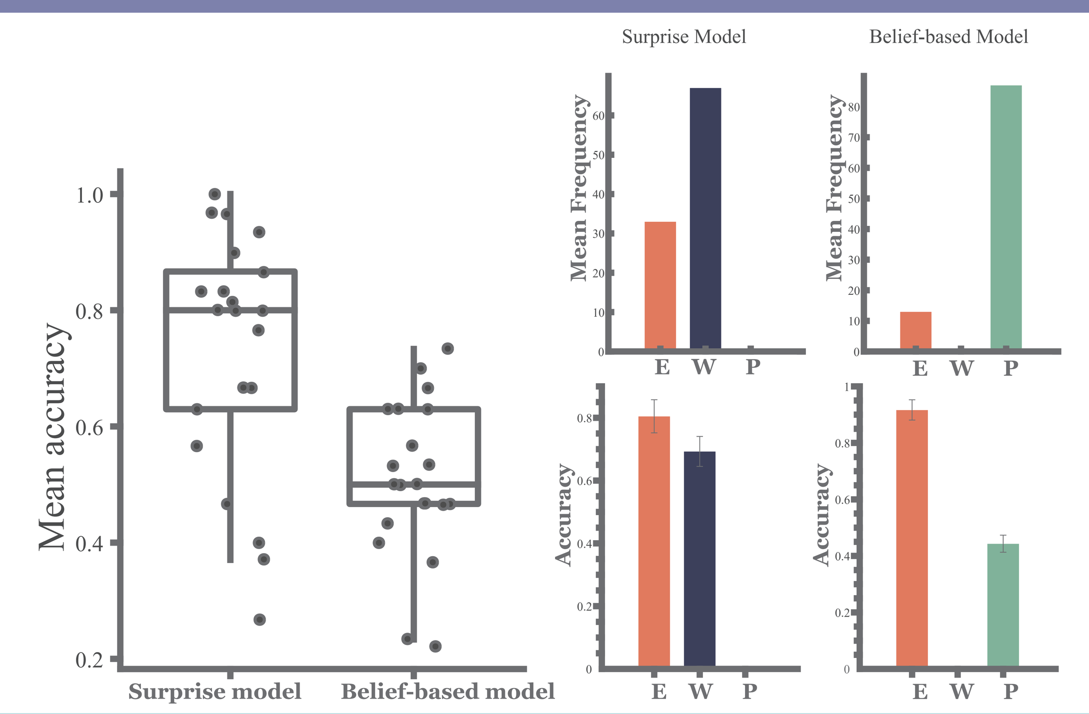
Model-based analysis of PDR data



Based on the role of the Locus coeruleus in detecting surprising changes in the environmental dynamics [4] and its effect on the pupillary dilation responses [5] we expect that the model's step-by-step surprise will be correlated with the step-by-step PDRs. The data showed correlation between model-derived surprising values and pupil dilation ($p<.001$), confirming that uncertainty in the environment can indeed affect the pupil size.

Effectivness of computational models with human senders

To examine the effectiveness of two different Computational models under experimentally controlled conditions, we simulated two Senders based on different models, and participants (n = 22) played only the Receiver in this game.
Participants exhibited significantly better performance when playing with the Sender simulated by the surprise model relative to the Belief-based model.
This finding suggests that creating surprise events is an effective communicative approach in non-verbal environments.



Conclusions

The results suggest that in the absence of common language, individuals intentionally use surprise and prediction errors to convey important information, providing a unique perspective on adaptive communication strategies. This differs from the traditional understanding of prediction errors in learning and decision-making [6]. By studying these implications, we can gain insights into human cognition and how our brains process information during communication. It may also improve therapies for communication disorders and offer fresh perspectives on the neural basis of language and non-verbal communication. Additionally, incorporating this understanding into communication technologies and AI could lead to more efficient non-verbal interfaces and enhance human-computer interactions, considering the significance of subtle cues and signals.

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Acknowledgments

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