Strange Simulation: Optimizing Multilevel Models of Infant Brain–Behavior Dynamics During the Strange Situation

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Introduction

- The Strange Situation (SS) elicits attachment-related changes in infant distress, exploration, and caregiver seeking across baseline, stranger, separation, and reunion episodes (Ainsworth et al., 1978). Limited work has employed simultaneous EEG recording *in the moment* of attachment related stress.
- Averaging EEG activity during each SS episode may obscure meaningful moment-to-moment brain–behavior dynamics *within* infants as attachment-related events occur.
  - Developmental EEG data are highly nested, noisy, and variable across infants, and may be further constrained by complex models and modest sample sizes
- Multilevel models can separate within-infant fluctuations from between-infant differences, but findings may depend on task coding, sample size, sampling density, signal quality, and model complexity.

The Present Study

- Using pilot-informed simulated data, we tested:
  - Time- versus episode-coded representations of the SS.
  - Within-infant frontal alpha–engagement coupling.
  - Effects of sample size, sampling density, and noise on model recovery.
  - Bias introduced when within- and between-infant EEG effects are not separated.

Results

Figure 1. Episodes of Separation & Reunion Across the Strange Situation

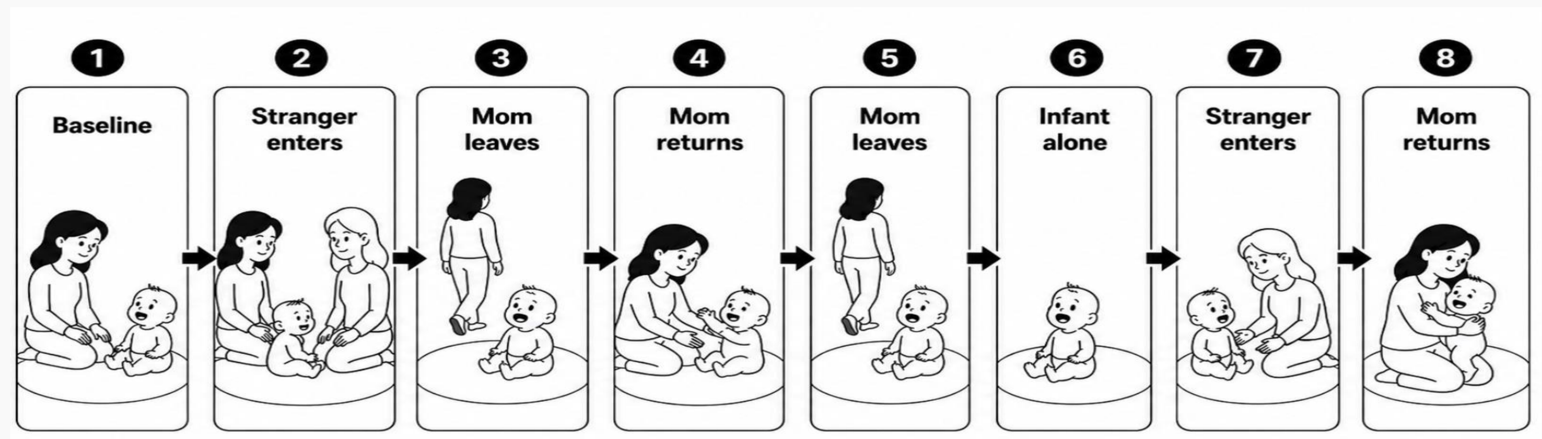

Table 2. Comparison of Time-Coded and Episode-Coded Model Families

Model	−2 Log Likelihood	AIC	BIC	df	Δ−2LL vs comparison	p (LRT)
T4 (Best Time Model)	2597.70	2603.70	2608.00	5	—	—
E4 (Best Episode Model)	2125.28	2143.28	2156.20	12	472.42 (vs. T4)	< .001**
T6 (Final Time Model)	2607.00	2613.00	2617.30	7	—	—
E6 (Final Episode Model)	2133.44	2151.40	2164.30	16	473.56 (vs. T6)	< .001**

Note: for the purposes of illustrating the model comparisons, results displayed are based on a simulated dataset with n=30

- Within-infant EEG–behavior coupling was robust across model families: time-coded model, $\beta = 2.77$, $SE = 0.16$, $p < .001$; episode-coded model, $\beta = 1.76$, $SE = 0.12$, $p < .001$.
- Episode effects remained large after accounting for EEG: Separation: $\beta = -3.62$, Stranger: $\beta = -1.47$, and Reunion: $\beta = -0.86$, all $p < .001$.
- EEG–behavior coupling did not differ reliably across episode types: Episode × EEG test: $\chi^2(3) = 0.75$, $p = .86$.

Key Takeaways

- Episode-coded models outperformed time-coded models
  - Time-coded models captured gradual decline across the task, but *underestimated* shifts based on attachment-related episode transitions.
- Within-infant EEG–behavior coupling was reliably recovered, even under *moderate noise* at N ≥ 60.
- Increasing *within-episode sampling density* (increasing time bins per episode) improved power *more efficiently* than increasing sample size alone.
  - Sampling density within each infant can be just as important as total sample size.
- Omitting person-mean centering inflated Type I error by conflating within-infant and between-infant effects.

Methods

Sample & Analytic Plan

- **Data Simulation Design**
  - Simulation conditions varied across three design dimensions:
    - Sample size: 30, 60, or 100 of infants ages 9 to 30 months
    - Sampling density: 3, 10, or 30 observations per episode.
    - Signal-to-noise ratio: Low, moderate, or high.
- **Multilevel Structure**
  - Repeated EEG and behavioral observations (Level 1) were nested within infants (Level 2).
  - **Random intercepts:** individual differences in average engagement
  - **Random slopes:** individual differences in change and EEG–behavior coupling
  - **Person-mean centering:** separated momentary within-infant EEG fluctuations from between-infant differences in average EEG
- **Model Comparison**
  - Two model families were compared: **time-coded**: gradual change across the task (i.e., reflecting accumulating stress/fatigue) & **episode-coded**: shifts across qualitatively differing episodes (i.e., baseline, stranger, separation, and reunion)
  - Models were evaluated using likelihood-ratio tests, AIC, BIC, power, parameter recovery, and Type I error.

Measures

- **Frontal alpha power.** Simulated EEG was informed by pilot data collected using wireless BrainVision liveAmp system & other stationary infant EEG data from the same ages. Alpha power was defined as 6–9 Hz and modeled across repeated within-episode time bins.
- **Behavioral engagement.** A continuous 0–10 composite was created based off of a standardized behavioral coding scheme to capture infant affect, vocalizations, movement, proximity-seeking, distress, and withdrawal. Higher scores reflected more positive engagement.
- **Strange Situation.** Eight structured episodes included baseline play, stranger entry, caregiver separations, infant-alone periods, and caregiver reunions (Ainsworth et al., 1978).

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Discussion & Future Directions

- This project extends traditional time-varying EEG models by jointly representing continuous change over time and qualitative socioemotional shifts across Strange Situation episodes.
- Modeling both dimensions provides a clearer test of how attachment-related contexts shape within-infant brain–behavior dynamics and between-infant differences in regulatory patterns.
- Overall, the strongest inferences came from models that matched the task structure, multilevel data structure, and expected within-person dynamics.

Limitations

- Findings are based on simulated data & depend on the assumptions built into the generative model.
  - Noise, missingness, and episode complexity were simplified relative to real infant EEG data.
- Higher-order effects were more difficult to recover under small-N conditions, speaking to real-world challenge of developmental EEG and multimodal protocols

Future Directions

- Apply these modeling decisions to empirical mobile EEG Strange Situation data, incorporate daily attachment diaries as another context of infant-caregiver attachment and regulation

Reference list can be provided upon request