Hierarchical Bayesian estimation of motor-evoked potential recruitment curves yields accurate and robust estimates

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Background

- Electromagnetic and electrical stimulation can modulate neural activity in the sensorimotor system.
- Stimulation of the brain and spinal cord causes muscles to produce motor-evoked potentials (MEPs).
- The recruitment curve illustrates the relationship between stimulation intensity and MEP size.

Problem: Sparse data due to experimental constraints poses a challenge for accurately estimating curves and their key parameters including threshold, S_{50}, slope, and saturation.

Approach: A new hierarchical Bayesian framework is introduced.

Methods

Recruitment Curve Estimation

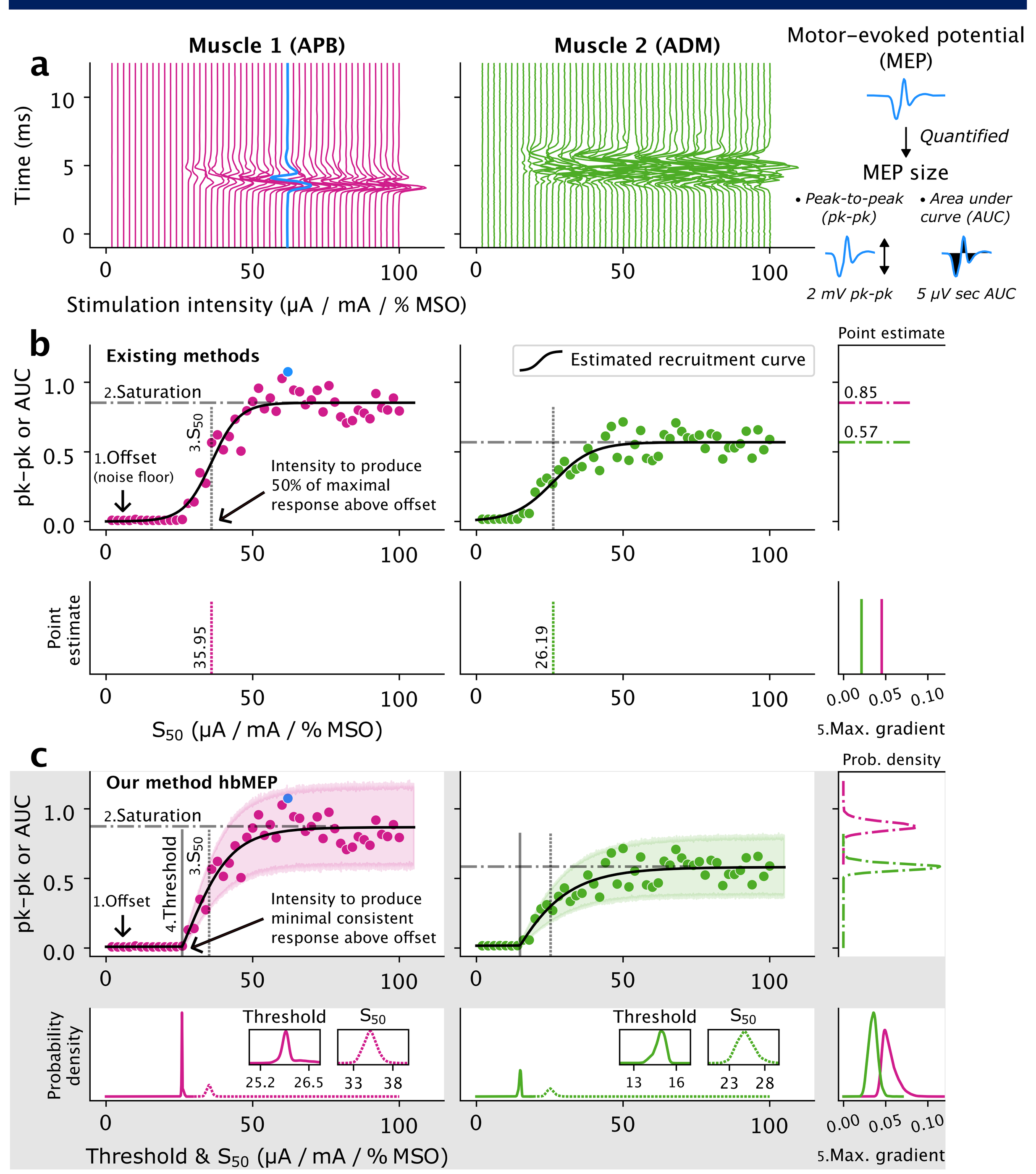

Fig. 1. Hierarchical Bayesian estimation of recruitment curves. **(a)** Motor-evoked potentials (MEPs). **(b)** Recruitment curves estimated using sigmoid function lack threshold estimate. **(c)** Estimated using new rectified-logistic function within a hierarchical framework. Shading represents 95% highest density intervals (HDI).

Synthetic Data Generation

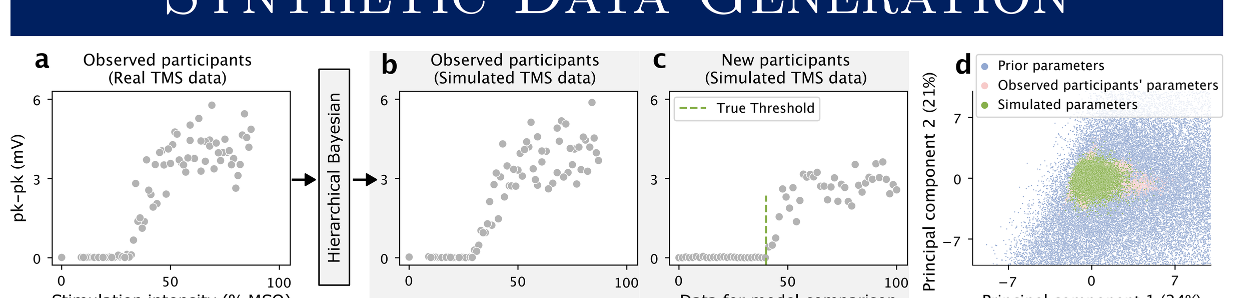

Fig. 2. Hierarchical model simulates high-fidelity synthetic TMS data. **(a)** Example participant from human TMS data. **(b)** Hierarchical model can replicate observed participant. **(c)** Example synthetic participant simulated conditioned on estimated population-level parameters for model comparison. **(d)** Principal component analysis plot shows large overlap between simulated data parameters (green) and parameters estimated from observed data (pink).

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Improved Accuracy

Supersedes the t-test

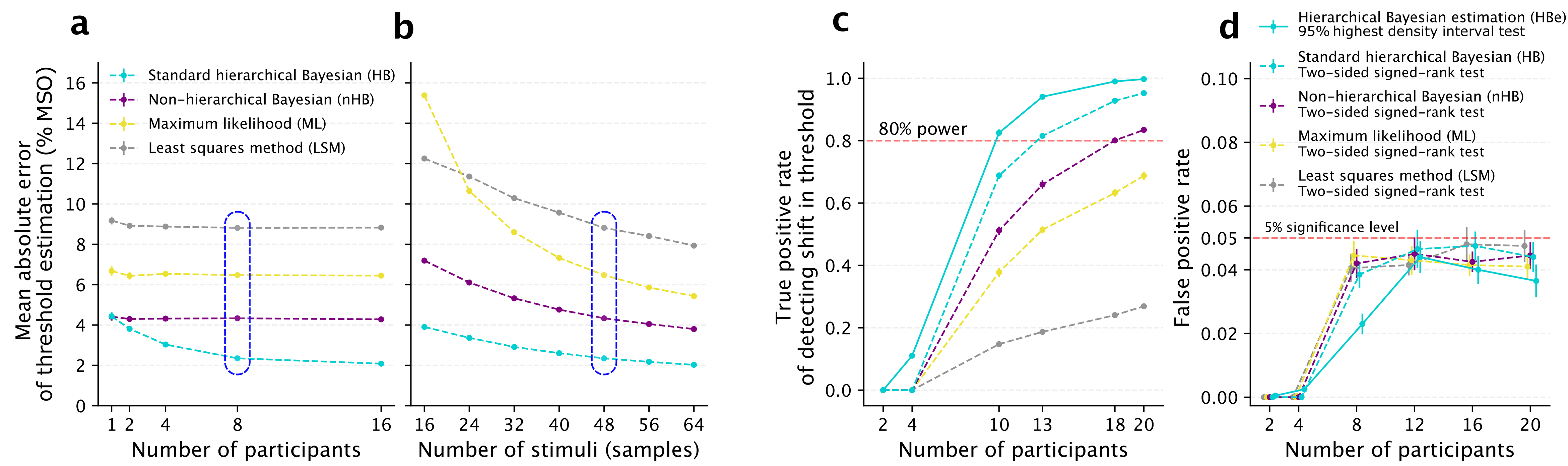

Fig. 3. **(a–b)** Standard hierarchical Bayesian model improves threshold estimation accuracy over non-Bayesian and non-hierarchical models on simulated data. **(c–d)** Bayesian estimation is more powerful when detecting a shift in the threshold compared to frequentist testing.

Improved Curve Estimation

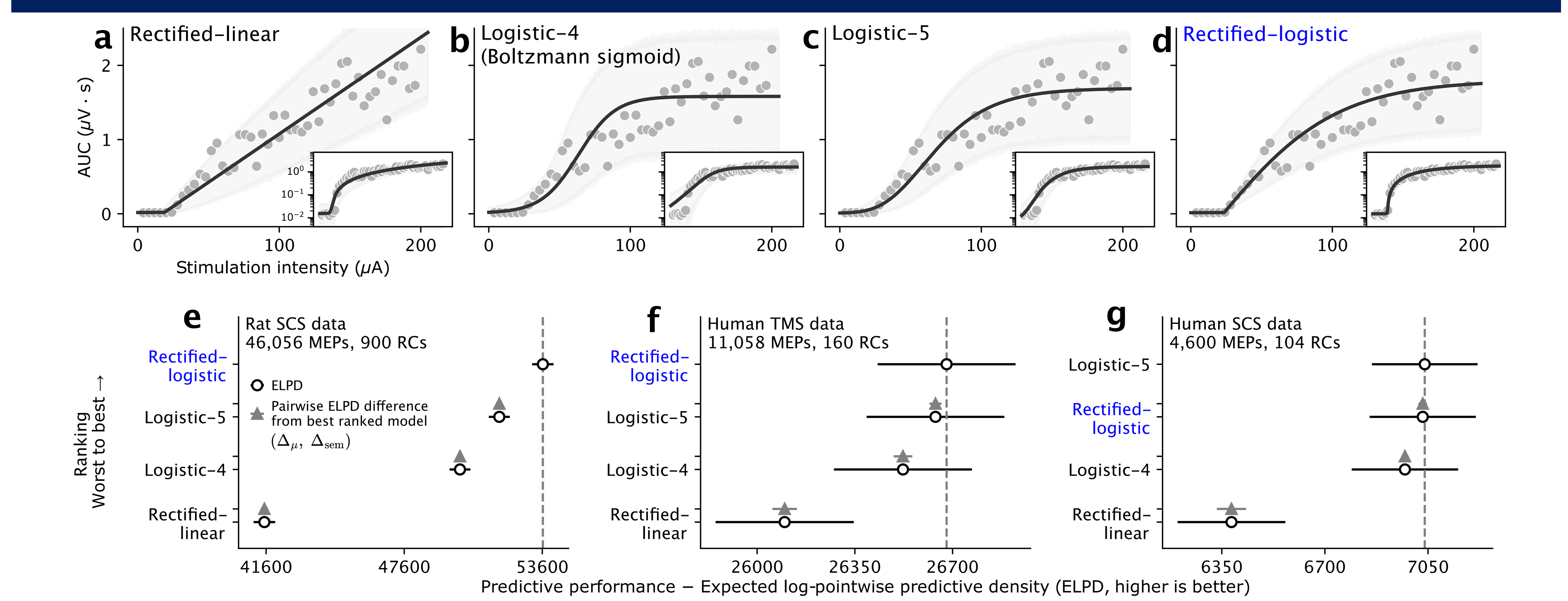

Fig. 4. Cross-validation on real Spinal Cord Stimulation (SCS) and Transcranial Magnetic Stimulation (TMS) data. Rectified-logistic function outperforms conventional logistic alternatives in predictive performance based on leave-one-out cross-validation [1], while having the unique advantage of estimating threshold, curvature and saturation.

Use Case: Detecting Change in Threshold

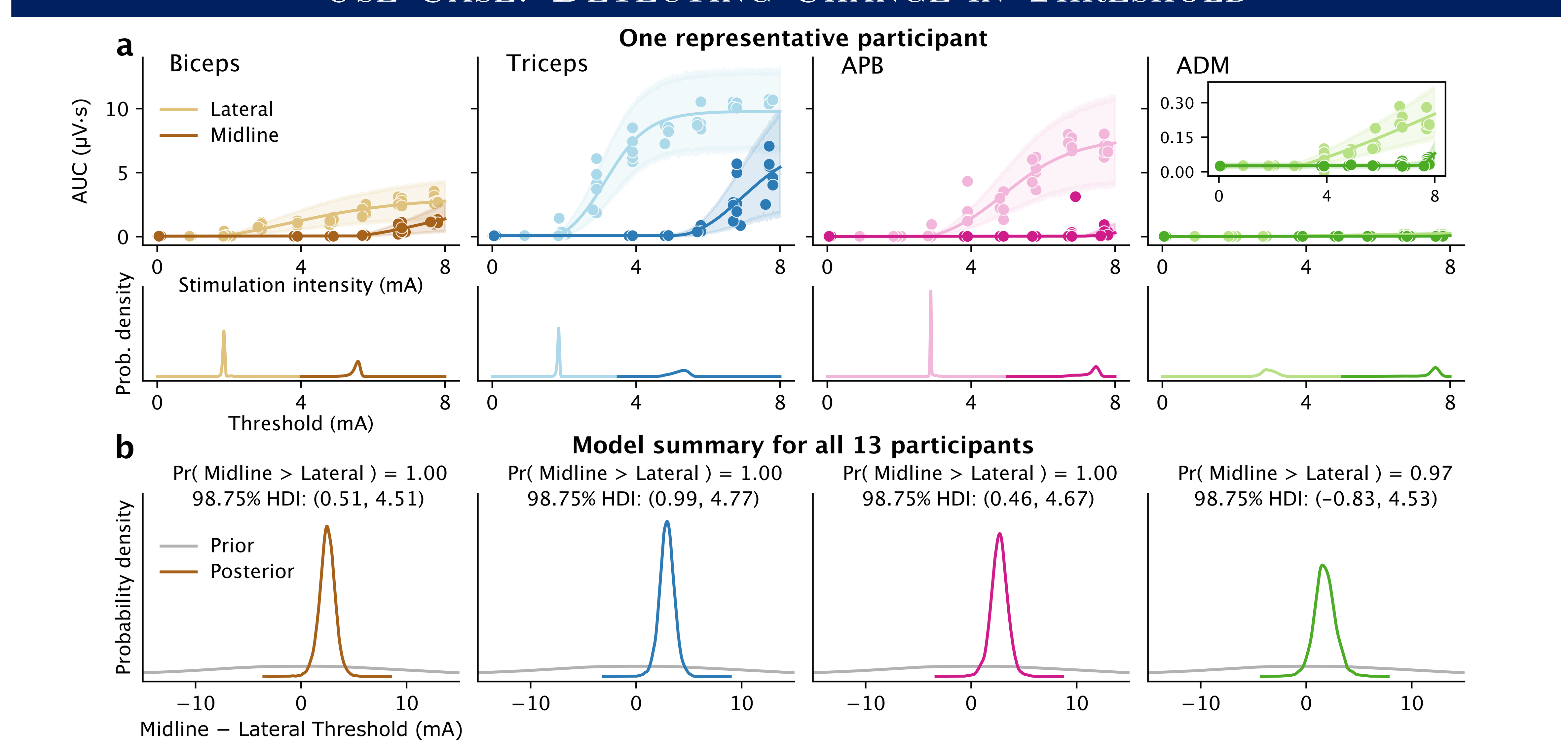

Fig. 5. Comparison of midline versus lateral stimulation thresholds on human epidural SCS data. **(a)** Example participant with lateral (light) and midline (dark) stimulation. Inset: zoom to show presence of threshold, despite small MEP size. **(b)** Difference between midline and lateral thresholds summarized by model across $N = 13$ participants suggests strong evidence in favor of lateral stimulation resulting in lower thresholds and being more effective, a known effect [2].

Fewer Stimuli Needed

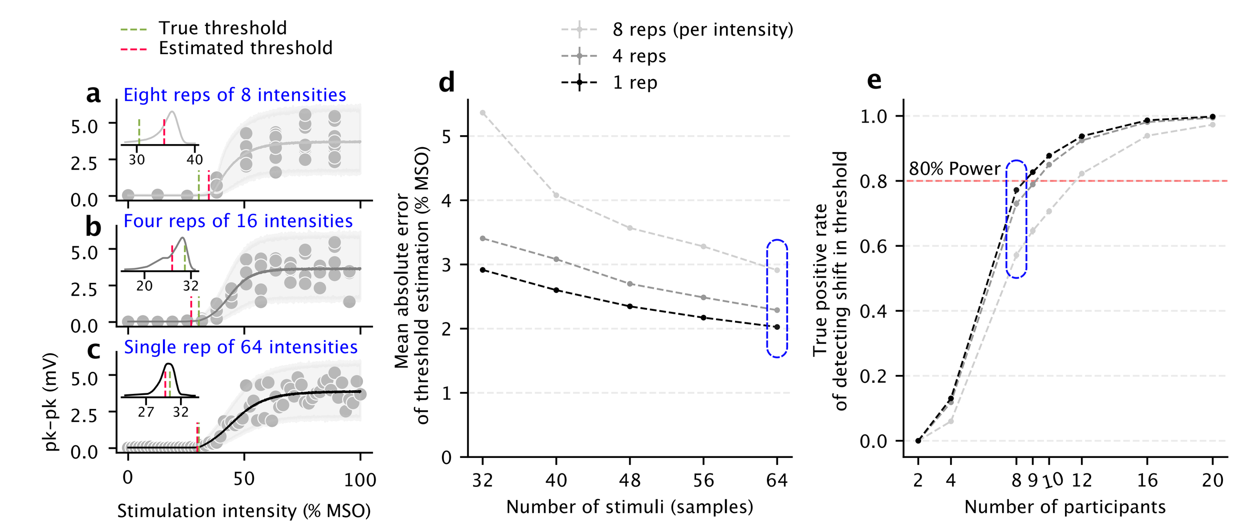

Fig. 6. Efficient threshold estimation is performed by sampling data evenly without repetitions. Example fits on simulated participant with total 64 equispaced stimuli and **(a)** eight repetitions, **(b)** four repetitions, and **(c)** a single repetition per intensity. **(d)** Single repetition produces lowest error for threshold estimation, regardless of the total number of stimuli. **(e)** For a fixed total of 64 stimuli, fewer repetitions require fewer participants to achieve 80% power when detecting shift in threshold from pre- to post-intervention phase.

Mixture Model for Outliers

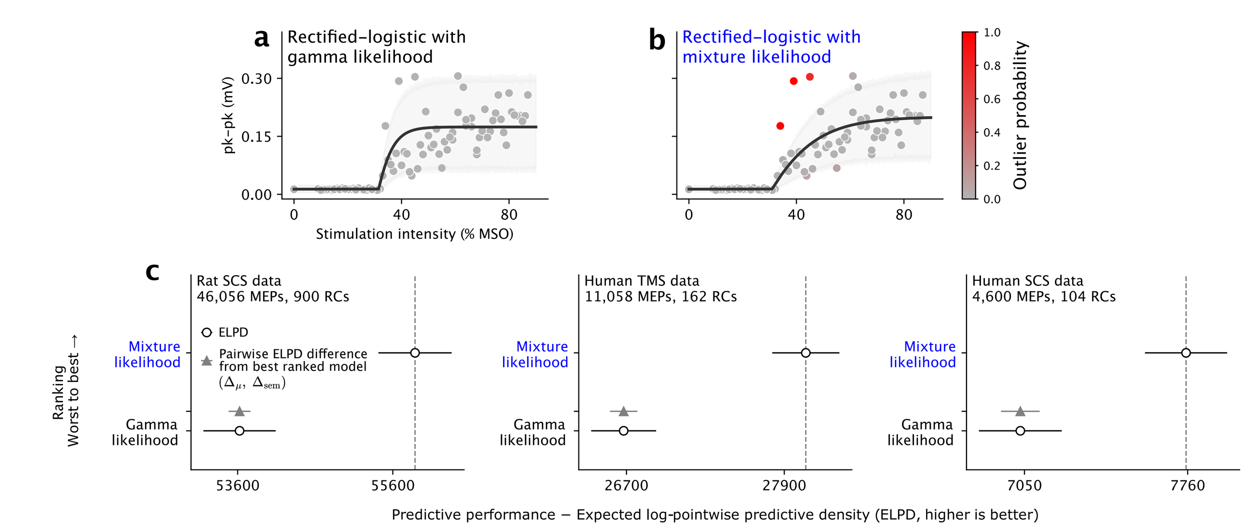

Fig. 7. Mixture model accounts for outliers and further improves predictive performance on all datasets. **(a)** Example overestimated growth rate due to the presence of outliers. **(b)** Mixture extension of the likelihood model is more robust to outliers. **(c)** Leave-one-out cross-validation.

Conclusion

- **Threshold estimation**: Rectified-logistic function allows estimation of motor threshold, which is independent of observed saturation, as opposed to S_{50} estimated with logistic functions.
- **Improved accuracy and power**: Partial pooling within a hierarchical framework provides more reliable and accurate estimates, which also translates into increased statistical power when detecting changes in threshold.
- **Reduced experimental burden**: The framework lowers experimental burden by reducing the number of stimuli required per participant while maintaining accuracy and simultaneously increasing the number of muscles across which these insights are obtained.
- **Validation across different stimulation modalities**: The framework is validated across spinal cord stimulation (SCS) and transcranial magnetic stimulation (TMS), highlighting its utility in different experimental contexts.
- **Future work**: This method can extend into an adaptive algorithm for efficient collection of data across multiple muscles during live SCS and TMS experiments.

References

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