Supplementary Material

Reliable and Efficient TMS-EEG Using Ultra-Thin Active Electrodes

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TEP Time Courses

Figure S1 corresponds to Figure 1 in the main manuscript and presents a topographical overview of TEPs using the passive instead of the active reference electrode.

Signal Consistency

Figure S2 corresponds to Figure 2 in the main manuscript, but uses passive instead of active referencing. In Figure S2A, we analyzed all available neighboring electrode pairs across both electrode types, resulting in 15 pairs per subject and a total of N = 150 pairs, each separated by approximately 2.1 cm. For early TEPs (15–80 ms post-stimulus), we observed a median concordance correlation coefficient (CCC) of 0.95 with an interquartile range (IQR) of [0.90, 0.99]. For late TEPs (80–350 ms), the median CCC was 0.95 [0.89, 0.98].

In Figure S2B, we assessed signal consistency within passive electrodes by analyzing diagonal neighbors (N = 100, d ≈ 3.0 cm), yielding a CCC of 0.94 [0.88, 0.97] for early and 0.94 [0.90, 0.97] for late TEPs. Figure S2C shows the analysis of horizontal neighbors within passive electrodes (N = 50, d ≈ 4.2 cm), resulting in a CCC of 0.86 [0.68, 0.94] for early TEPs and 0.90 [0.82, 0.94] for late TEPs.

Finally, due to the topography of the active electrode layout, only horizontal neighbor comparisons were feasible (Figure 2D). Here, the CCC was 0.88 [0.74, 0.95] for early TEPs and 0.88 [0.78, 0.93] for late TEPs.
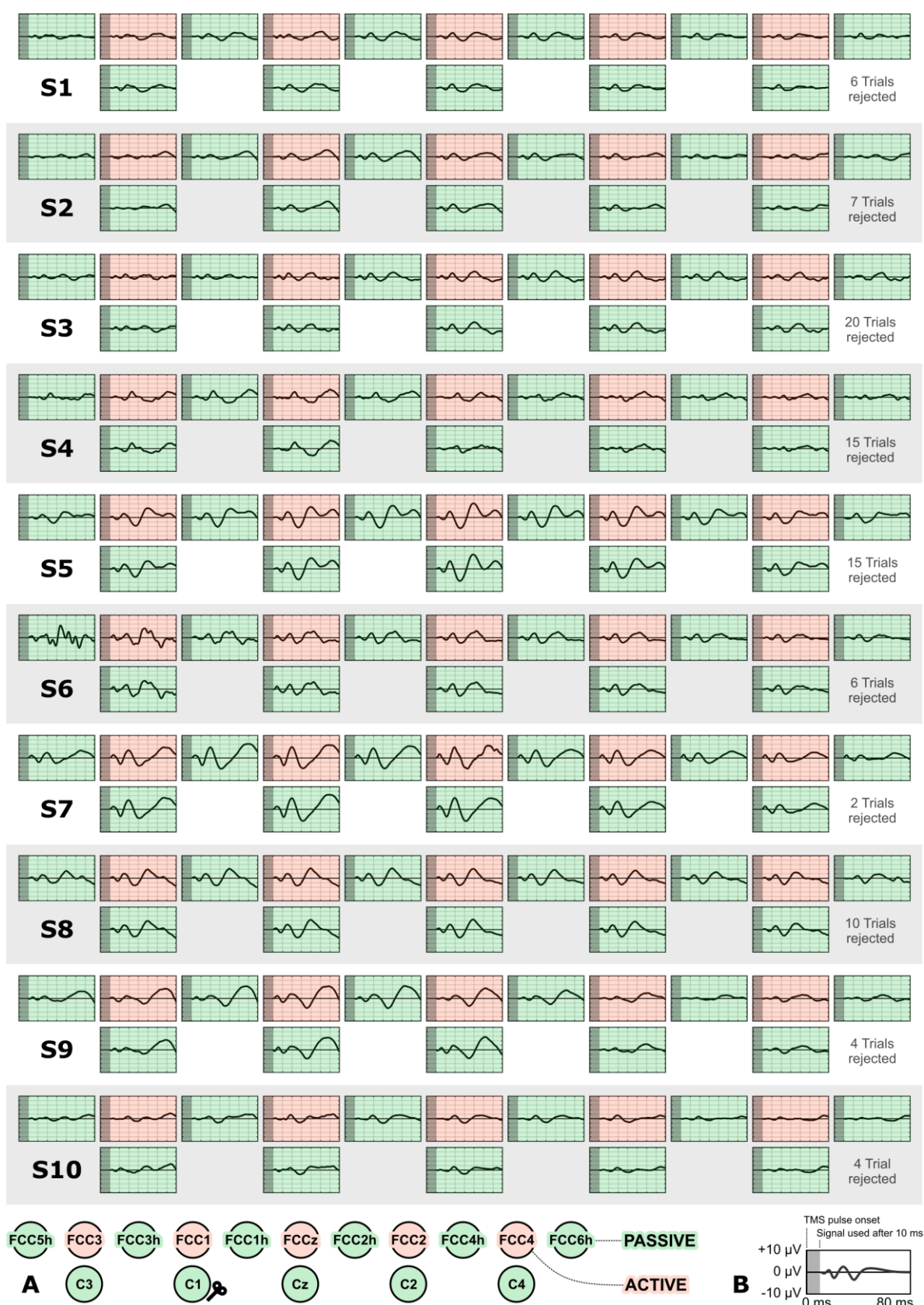
Figure S1: Topographical view of TEPs (10 to 80 ms) for all subjects (S1–S10), Electrode montage (A), and axes (B). Light green and red shading indicate passive and active electrode type, respectively. Coil location was above C1 as indicated.
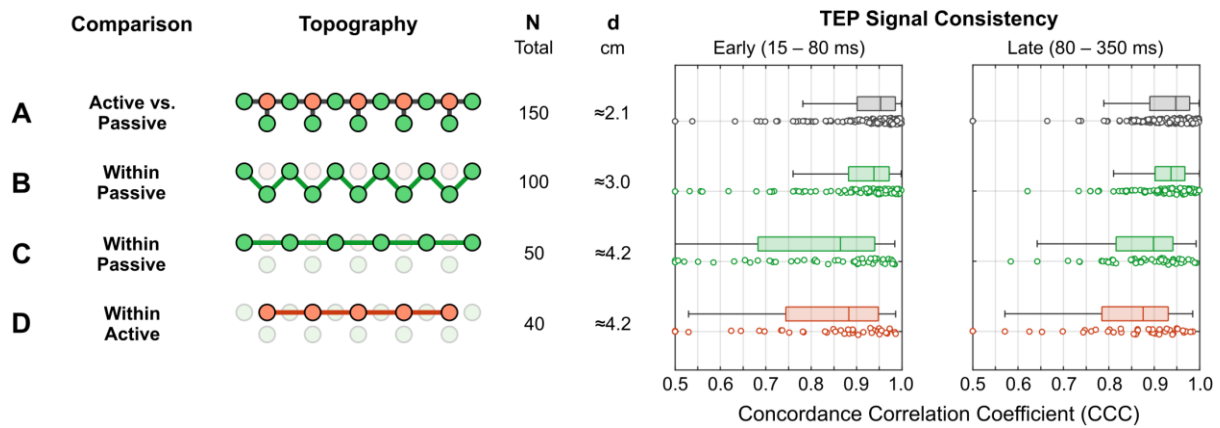
Figure S2: Signal consistency analysis across different electrode configurations (active: red, passive: green). (A) Active vs. passive electrodes, (B) within passive electrodes – diagonal pairs, (C) within passive electrodes – horizontal pairs, and (D) within active electrodes – horizontal pairs. N: total number of electrode pairs across all subjects. d: approximate distance between electrode pairs.

Amplitude Variability

We analyzed TEP amplitudes (root mean square, RMS) using passive instead of active referencing for early (15–80 ms) and late (80–350 ms) TEPs using linear mixed-effects models. In both time windows, TEP amplitude decreased significantly with increasing distance from the stimulation site (early: $\beta = -0.11$, $p < 0.001$; late: $\beta = -0.083$, $p < 0.001$). Electrode type (active vs. passive) had no significant effect (early: $\beta = -0.07$, $p = 0.35$; late: $\beta = -0.10$, $p = 0.14$). The models revealed substantial between-subject variability (random-effect standard deviation of 0.55 for early, 0.86 for late TEPs), exceeding the residual variability (0.37 and 0.35, respectively), indicating relevant inter-individual differences in overall TEP amplitude.

Figure S3, corresponding to Figure 3 in the main manuscript, provides a qualitative visualization of the TEP amplitudes across the anterior row of the electrode montage. A clear amplitude gradient with increasing distance from the stimulation site (C1) is visible for both early and late components. For clarity, we normalized amplitudes for each subject by the average RMS across all channels.
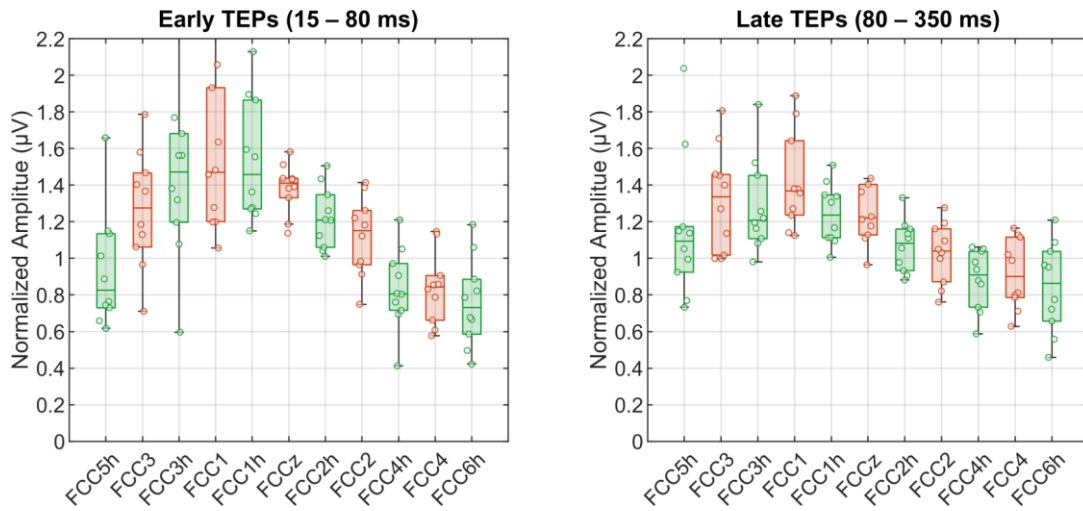
Figure S3: Normalized TEP amplitudes across montage anterior row, from left (FCC5h) to right (FCC6h). Red: active electrodes; green: passive electrodes.

Convergence of Averages

Figure S4, corresponding to Figure 4 in the main manuscript, shows the convergence of averages for early and late TEPs toward the full-trial average across all available trials, using passive instead of active referencing. Active and passive electrodes exhibit nearly identical convergence behavior. Early TEPs converge more rapidly, reaching a median CCC of 0.8 after 20 trials, whereas approximately 40 trials are needed for late TEPs. Likewise, a median CCC of 0.9 is achieved after 30 trials for early TEPs, but it takes around 60 trials to reach the same level for late TEPs.
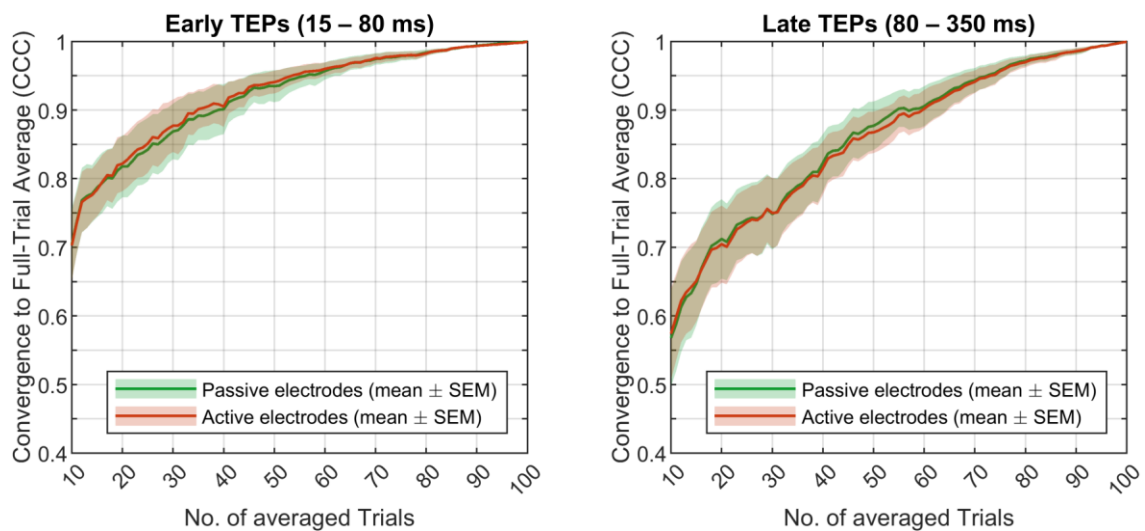

Figure S4: Convergence to the full-trial average for early TEPs (left) and late TEPs (right). The solid line represents the mean, and the shaded area indicates the standard error of the mean (SEM). Passive and active electrodes are shown in green and red, respectively.