Supplemental Material

Midfrontal theta and pupil dilation parametrically track subjective conflict (but also surprise) during intertemporal choice

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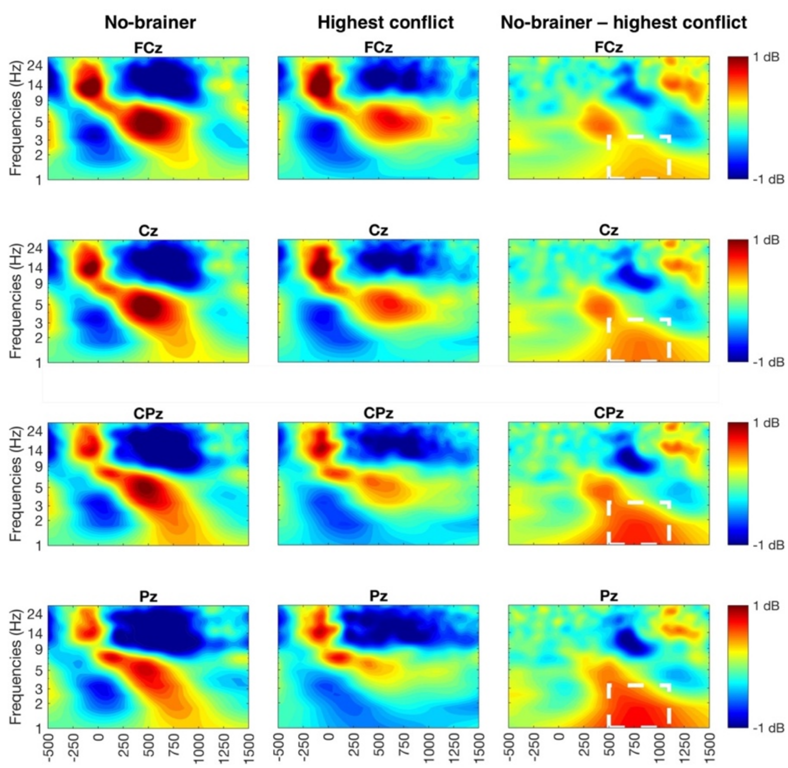
No-brainer decisions are associated with increase delta power

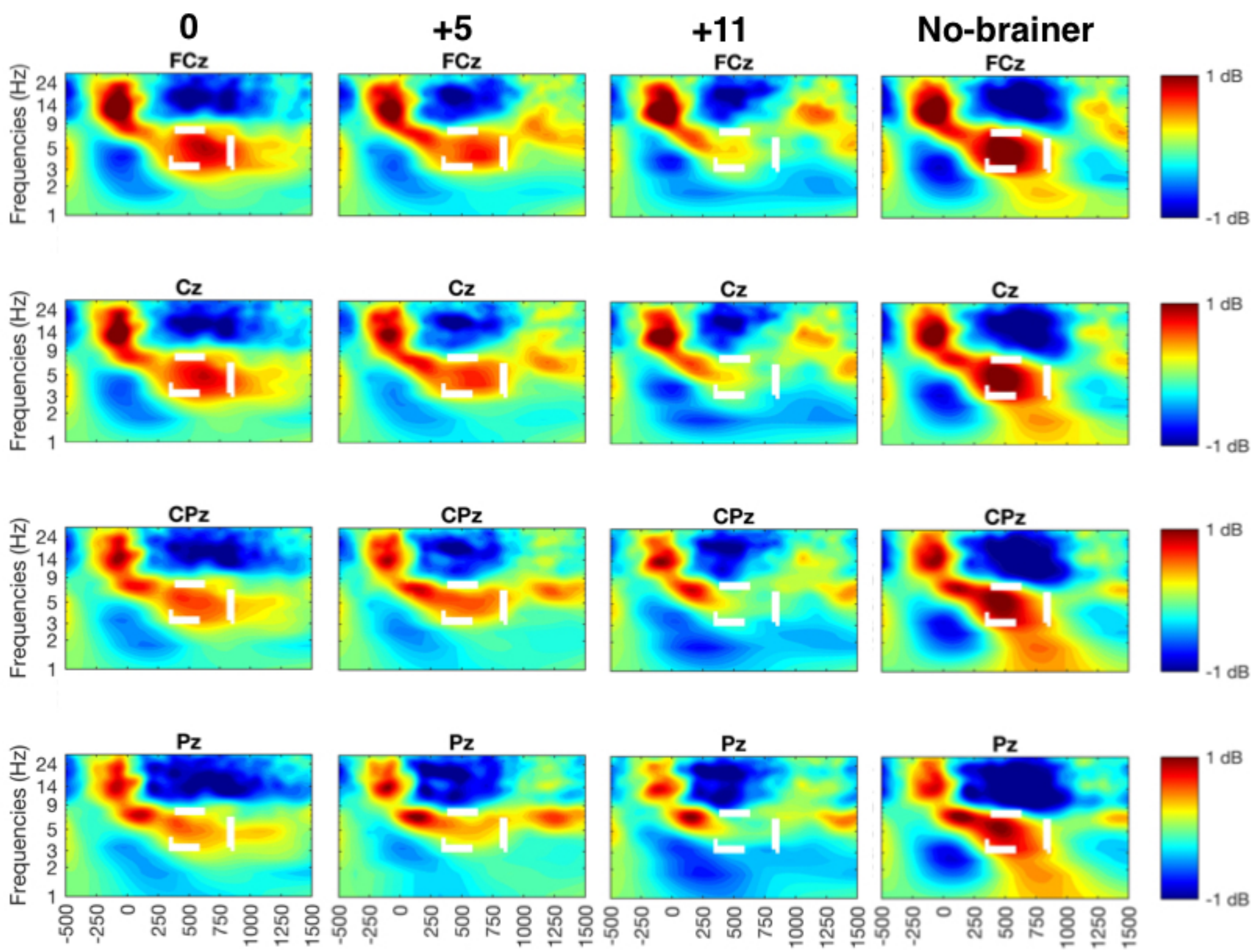
We ran exploratory analyses to probe the time-frequency dynamics associated with no-brainer decisions. We found that no-brainer choices were associated with not only increased midfrontal (FCz) theta power (reported in the main text), but also posterior (Pz) delta (1.0–3.2 Hz) power from 500 to 1100 ms (Supplementary Fig. 1). Electrode site (FCz, Cz, CPz, Pz) and condition (decision type: no-brainer vs. highest conflict) interacted significantly ($b = 0.001$, $SE = 0.0003$, $t(1152) = 4.17$, $p < .001$, $r = .12$). At FCz, no-brainer choices had more delta power than the highest conflict choices ($b = 0.002$, $SE = 0.001$, $t(251) = 3.03$, $p = .003$, $r = .19$), and this power difference between the two choices was even greater at Pz ($b = 0.006$, $SE = 0.001$, $t(249) = 7.70$, $p < .001$, $r = .44$).



Supplementary Fig. 1. Delta power enhancement at four midline electrodes (FCz, Cz, CPz, Pz) after stimulus presentation over posterior electrodes, collapsed over different intertemporal delays (10, 30, and 60 days), Increased delta power (1.0–3.2 Hz) was observed between 500 to 1100 ms after stimulus presentation. Left column shows power for no-brainer choices; middle column shows power for highest conflict choices (value difference = 0); right column shows the no-brainer minus highest conflict conditions contrast.

Total power, phase-locked (evoked) power, non-phase-locked (induced) power
In the main text, we presented only the time-frequency plots at electrode FCz (midfrontal site). Here, we present the total power plots at central and posterior sites where theta-band oscillatory dynamics have typically been observed during cognitive control and performance monitoring tasks (Supplementary Fig. 2).

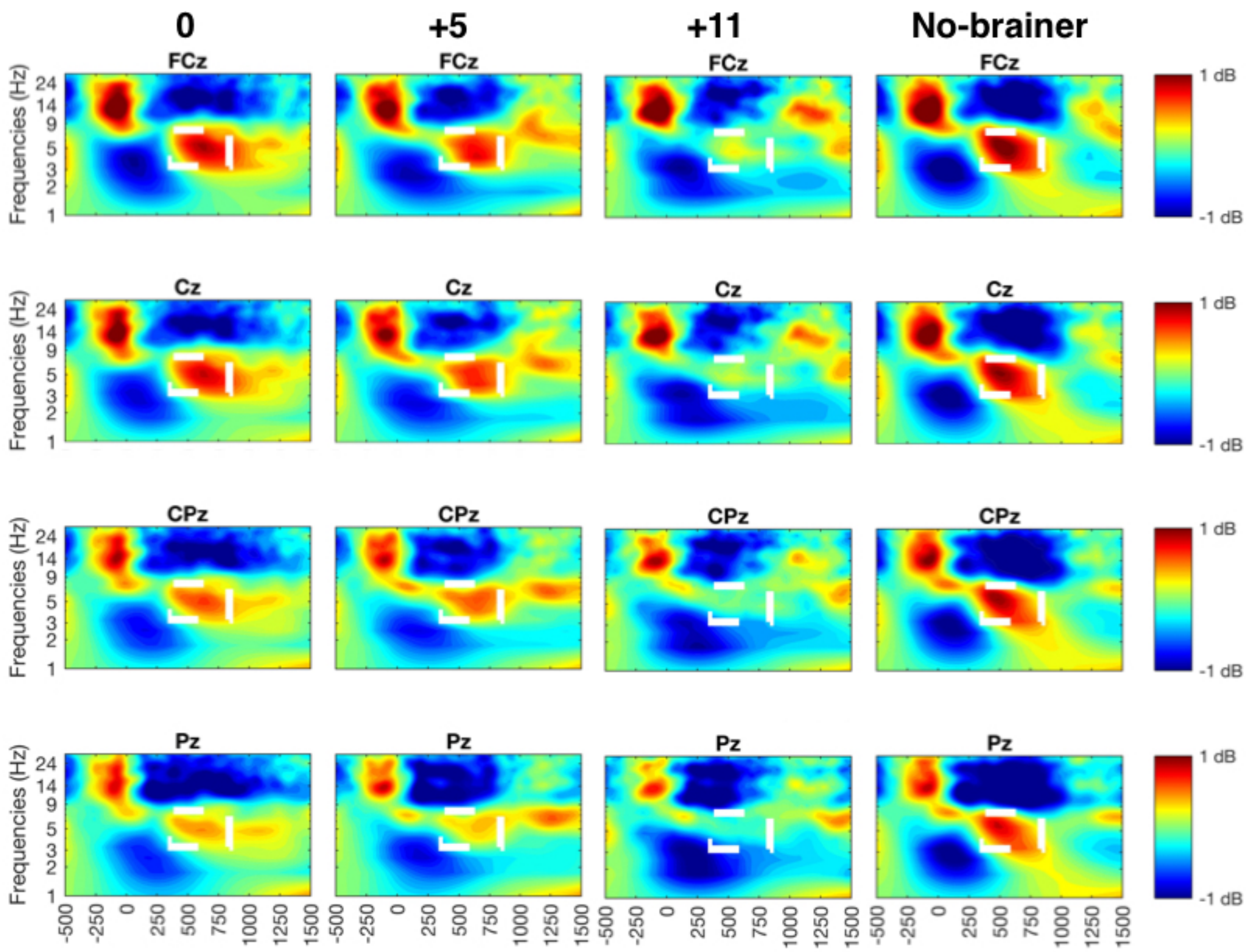
Total power



Supplementary Fig. 2. Total time-frequency power (3.2–7.7 Hz; 340 to 840 ms) at four midline electrodes (FCz, Cz, CPz, Pz) after stimulus presentation collapsed over different intertemporal delays (10, 30, and 60 days). Only value differences for 0, +5, +11 and no-brainer decisions are shown.

Non-phase-locked power

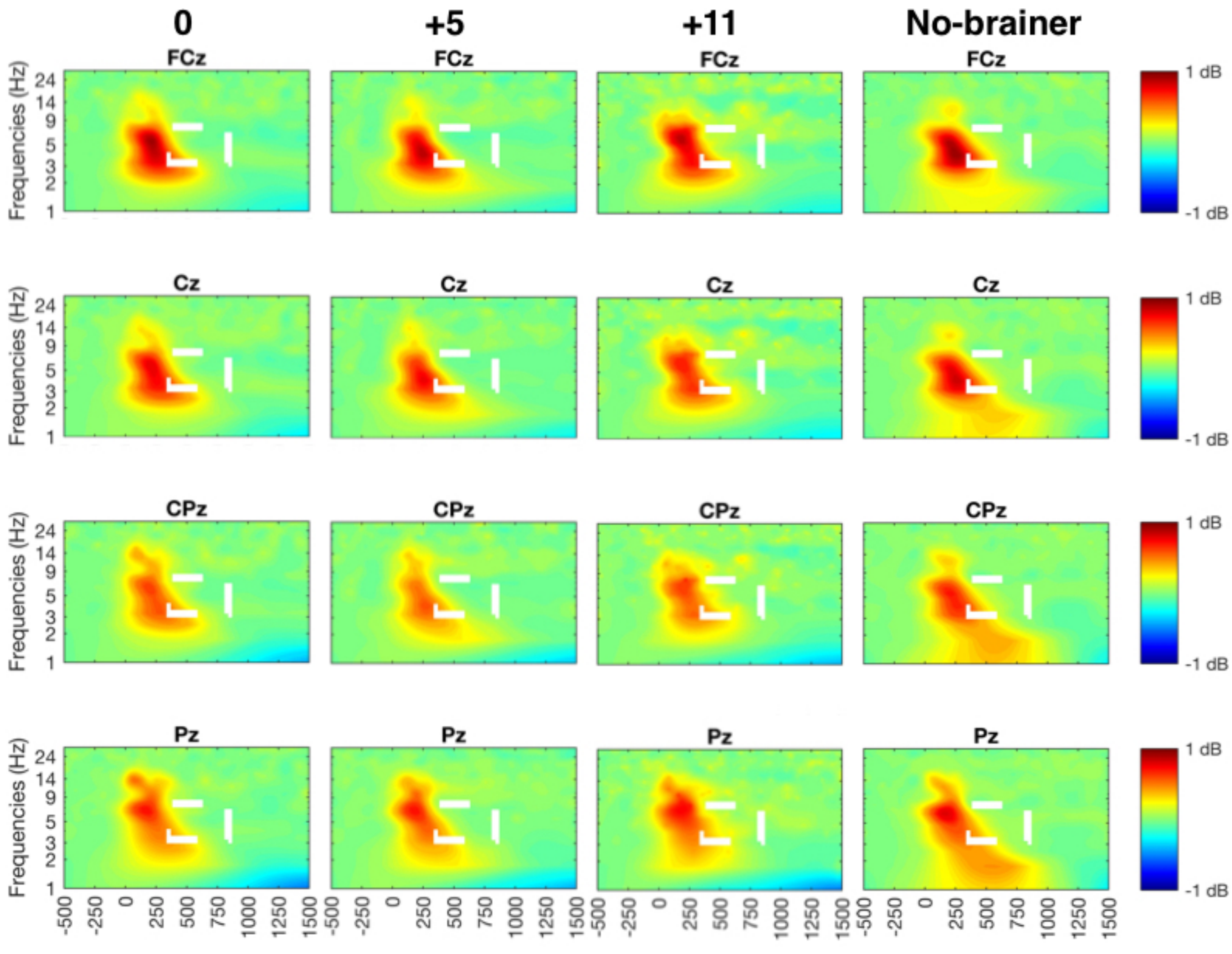
Given that we currently understand relatively little about the neurophysiology of non-phase-locked (induced) power, we report the non-phase-locked power results only for the sake of completeness. Value difference was curvilinearly related to non-phase-locked midfrontal theta power (FCz: quadratic $b = -0.39$, $SE = 0.07$, $t(1185) = -5.56$, $p < .001$, $r = .16$), indicating that non-phase-locked theta power (3.2–7.7 Hz; 340 to 840 ms) decreased as it became increasingly clearer that one reward had a higher subjective value than the other (Supplementary Fig. 3). The effect size for this finding is comparable to that of the total power findings reported in the main text (quadratic $b = -0.26$, $SE = 0.05$, $t(1181) = -5.60$, $p < .001$, $r = .16$). After controlling for decision time ($b = -0.81$, $SE = 0.19$, $t(101) = -4.28$, $p < .001$, $r = .39$), the quadratic relationship became weaker but remained significant ($b = -1.04$, $SE = 0.41$, $t(588) = -2.52$, $p = .012$, $r = .10$).



Supplementary Fig. 3. Non-phase-locked (induced) time-frequency power (3.2–7.7 Hz; 340 to 840 ms) at four midline electrodes (FCz, Cz, CPz, Pz) after stimulus presentation collapsed over different intertemporal delays (10, 30, and 60 days). Only value differences for 0, +5, +11 and no-brainer decisions are shown.

Phase-locked power

Value difference was curvilinearly related to phase-locked midfrontal theta power (FCz: quadratic b = 0.03, SE = 0.01, t(1191) = 2.33, p = .020, r = .07), indicating that phase-locked theta power (3.2–7.7 Hz; 340 to 840 ms) decreased as it became increasingly clearer that one reward had a higher subjective value than the other (Supplementary Fig. 4). However, the effect was very weak (p = .02, r = .07) relative to the total power and non-phase-locked power effects. After including decision time (b = 0.006, SE = 0.03, t(81) = 0.18, p = .857, r = .02), the quadratic relationship became non-significant (b = –0.003, SE = 0.08, t(586) = –0.04, p = .966, r = 0).



Supplementary Fig. 4. Phase-locked (evoked) time-frequency power (3.2–7.7 Hz; 340 to 840 ms) at four midline electrodes (FCz, Cz, CPz, Pz) after stimulus presentation collapsed over different intertemporal delays (10, 30, and 60 days). Only value differences for 0, +5, +11 and no-brainer decisions are shown.

EEG and pupil effects for subjective value of the delayed option

In the main text, we reported only the quadratic models because we had hypothesized a curvilinear effect between value difference (subjective conflict) and the neurophysiological measures. Here, we report the linear models (without the quadratic term, and controlled for decision time) that test for the effects of the subjective value of the delayed option. Essentially, these models are testing the linear effect of value difference because value difference was computed by subtracting a constant (15, the immediate reward) from the subjective value of the delayed reward. We report the statistics below and provide ∆BIC values that compare the fit of the quadratic models with the respective linear models—more negative ∆BIC values indicate that linear models reported here might be a better fit than the quadratic models fitted in the main text.

For stimulus-locked theta power, there was a significant negative slope ($b = –0.17$, $SE = 0.04$, $t(1197) = –4.62$, $p < .001$, $r = .13$, $\Delta BIC = 16.62$), suggesting that as the subjective value of the delayed reward increased, midfrontal theta power decreased. For the stimulus-locked positive ERP, the relationship was negative ($b = –0.63$, $SE = 0.15$, $t(1195) = –4.34$, $p < .001$, $r = .12$, $\Delta BIC = –2.22$). For peri-response theta power, the relationship was also negative ($b = –0.17$, $SE = 0.04$, $t(1205) = –4.82$, $p < .001$, $r = .14$, $\Delta BIC = 0.76$). Finally, there was no significant relationship between the peri-response conflict negativity and subjective value of the delayed option ($b = 0.59$, $SE = 0.40$, $t(291) = 1.45$, $p = .147$, $r = .08$, $\Delta BIC = –0.34$), and also no significant relationship for pupil dilation responses ($b = –0.19$, $SE = 0.11$, $t(1156) = –1.74$, $p = .082$, $r = .05$, $\Delta BIC = 3.28$). Overall, the findings are slightly inconsistent across different measures, and these linear effects are generally smaller than the quadratic effects reported in the main text. There is some evidence that stimulus-locked midfrontal theta power and positive potential decreased as the subjective value of the delayed option increased, but because all the ∆BIC values for most model comparisons are positive or close to 0, the quadratic models appear to fit the data better. Because we had not predicted these linear effects, these analyses are exploratory and we therefore suggest they be replicated in future studies.