Innovative Research Journal of Sociology and Humanities
ISSN(print) 3050-6867, ISSN(online): 3050-6875
Volume 03 Issue 06 June 2026
DOI: 10.58806/irijsh.2026.v3i6n06
Page No: 564 - 571

Neural Correlates of the Stroop Effect: an EEG Brainwave Analysis of Prefrontal Cognitive Load During Incongruent Colour-Word Processing

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ABSTRACT

The Stroop colour-word interference paradigm provides a robust test of prefrontal executive function, yet the concurrent effects on neural osci llatory dynamics across all canonical EEG frequency bands remain undercharacterised in pilot settings. This study recorded relative brainwave band power (gamma, beta, alpha, theta, and delta) and task-completion time from eight healthy participants (4 male, 4 female) performing a congruent control task and an incongruent Stroop task under identical conditions using a Brain Link EEG Headband connected to the Basic Detection application for real-time data collection. The Stroop condition produced a large increase in delta power (34.5% → 50.8%; +16.3 pp), a marked reduction in beta power (22.3% → 13.1%; −9.2 pp), and a near-doubling of mean task-completion time (11.9 s → 27.0 s). These changes are interpreted as reflecting heightened prefrontal cortex engagement, disruption of working memory maintenance circuits, and effortful reconstruction of non-default cognitive frames. Findings are discussed in terms of executive function, cognitive load, and individual differences. Translational implications for clinical neuropsychology, neuroergonomics, and brain-computer interface design are considered

ARTICLE DETAILS

Published On:
13 June 2026

Available on:
https://irijsh.com/

KEYWORDS: Stroop effect; EEG; brainwave oscillations; prefrontal cortex; executive function; cognitive load; working memory; delta power; beta power; cognitive interference.

1. INTRODUCTION

The Stroop colour-word interference paradigm, first described by Stroop (1935), remains one of the most replicated and clinically informative tasks in cognitive psychology. In its canonical form, participants name the ink colour in which a word is printed when that word spells a conflicting colour name (e.g., the word GREEN printed in red ink). This condition—the incongruent or Stroop condition—consistently produces longer reaction times and higher error rates than congruent or colour-neutral conditions, a difference known as the Stroop effect (MacLeod, 1991).

The neural basis of the Stroop effect is closely linked to the prefrontal cortex (PFC), particularly the anterior cingulate cortex (ACC) and the dorsolateral prefrontal cortex (dlPFC) (Bush et al., 2000; Botvinick et al., 2001). These regions coordinate executive functions including response inhibition, selective attention, conflict monitoring, and working memory updating. Under incongruent conditions, the dominant, automatised word-reading response must be overridden in favour of the less-practised colour-naming rule, placing heavy demand on top-down control mechanisms (Miller & Cohen, 2001).

Electroencephalography (EEG) offers a non-invasive, high temporal-resolution window into these processes through its oscillatory frequency bands (Nunez & Srinivasan, 2006). Gamma (>30 Hz), beta (13–30 Hz), alpha (8–13 Hz), theta (4–8 Hz), and delta (0.5–4 Hz) oscillations each index distinct aspects of neural processing (Buzsáki & Draguhn, 2004). Gamma oscillations support rapid attentional feature binding (Womelsdorf & Fries, 2007); beta rhythms index working memory maintenance and top-down executive control (Engel & Fries, 2010); alpha reflects attentional gating (Jensen & Mazaheri, 2010); theta supports hippocampal-prefrontal memory encoding (Kahana, 2006); and delta oscillations, increasingly recognised in waking cognition, are associated with deep inhibitory and corticothalamic coordination processes (Harmony, 2013).

Despite extensive reaction time and event-related potential (ERP) literature on the Stroop task, pilot studies simultaneously characterising relative power changes across all five frequency bands remain sparse. The present investigation addresses this gap by reporting EEG band power and task-completion time data from a congruent control condition and an incongruent Stroop condition in eight participants, with interpretive emphasis on the prefrontal processes reflected in oscillatory changes.

2. MATERIALS AND METHODS

2.1. Ethical Statement and Participant Consent

This study was conducted in accordance with the ethical principles of the Declaration of Helsinki. Written informed consent was obtained from all participants prior to data collection. Participation was entirely voluntary; participants were informed of their right to withdraw at any time without consequence. No financial rewards, academic credit, or material incentives were offered. The study procedures were entirely non-invasive, and no physical or psychological harm was inflicted on any participant. All data were collected and stored in anonymised form; participants are identified by neutral identifiers (Participant 1–8) throughout.

2.2. Participants

Eight healthy adult volunteers (4 male, 4 female; Participant 1–8) participated in the study. All reported normal or corrected-to-normal vision and no history of neurological or psychiatric disorder. Participants were naive to the study hypotheses.

2.3. EEG Recording Equipment

EEG data were collected using the Brain Link EEG Headband (Macrotellect, China), connected via Bluetooth to the Basic Detection application for real-time brainwave monitoring and recording from the prefrontal cortex region. The device employs a proprietary algorithm based on the eSense protocol to decompose raw scalp EEG into relative percentage power across five frequency bands: delta (0.5–4 Hz), theta (4–8 Hz), alpha (8–13 Hz), beta (13–30 Hz), and gamma (30–50 Hz) (Bos, 2006). Such EEG devices have been employed in prior cognitive studies and can provide useful band power indices for exploratory research (Maskeliunas et al., 2016).

2.4. Stimuli and Procedure

Participants completed two tasks under identical environmental conditions. In the Control condition, participants read aloud a series of colour words printed in matching ink (congruent stimuli; e.g., RED in red). In the Stroop Test condition, participants named the ink colour of words printed in non-matching ink (incongruent stimuli; e.g., GREEN in red ink) (Stroop, 1935). The number of stimuli, their spatial arrangement, and viewing conditions were held constant across both tasks. Participants were instructed to respond as accurately and quickly as possible.

2.5. Data Recording and Analysis

The Basic Detection application recorded relative percentage band power for each participant in each condition. Task-completion time (seconds from onset to final response) was recorded manually. Descriptive statistics (individual values, group means, and standard error of the mean [SEM]) were computed for each frequency band and for task-completion time. All figures include ±1 SEM error bars.

3. RESULTS

3.1. Control Condition

Table 1 shows relative EEG band power (%) and task-completion time (s) for all participants in the control (congruent) condition. Substantial inter-individual variability was observed. Group mean completion time was 11.9 s. High gamma and beta power were notable in several participants (e.g., Participant 1: gamma 38.5%, beta 43.3%; Participant 3: beta 55.0%), indicative of efficient fast-cortical processing during a cognitively manageable task.

Table 1. Relative EEG Band Power (%) and Task-Completion Time: Control Condition (N = 8)

Participant	Gender	Gamma (%)	Beta (%)	Alpha (%)	Theta (%)	Delta (%)	Time (s)
Participant 1	Female	38.5	43.3	7.2	8.7	2.3	12
Participant 2	Male	19.0	27.0	17.6	31.6	4.8	10
Participant 3	Male	13.2	55.0	4.4	7.7	19.7	15
Participant 4	Female	2.3	2.4	6.6	24.4	64.3	11
Participant 5	Female	16.3	9.0	17.3	24.4	32.9	12
Participant 6	Female	2.3	3.7	6.6	7.1	80.3	15
Participant 7	Male	14.1	24.0	16.5	13.4	32.0	10
Participant 8	Male	9.7	14.2	9.9	26.1	40.0	10
Mean		14.4	22.3	10.8	17.9	34.5	11.9

Values = relative percentage of total brainwave power. Final row = group means. Participant 2 control time = 10 s (corrected).

3.2. Stroop Test Condition

Table 2 shows data for the Stroop (incongruent) test condition. A pronounced restructuring of frequency band dominance was observed across all participants. Delta power emerged as the dominant oscillatory component for most participants, while gamma and beta power declined markedly. Mean task-completion time increased to 27.0 s — more than double the control mean of 11.9 s.

Table 2. Relative EEG Band Power (%) and Task-Completion Time: Stroop Test Condition (N = 8)

Participant	Gender	Gamma (%)	Beta (%)	Alpha (%)	Theta (%)	Delta (%)	Time (s)
Participant 1	Female	8.8	11.1	6.7	14.2	59.3	23
Participant 2	Male	9.1	11.8	11.4	20.9	46.7	24
Participant 3	Male	20.6	20.2	7.3	12.9	39.0	35
Participant 4	Female	6.7	7.3	6.7	15.9	63.3	28
Participant 5	Female	7.0	7.7	10.6	19.5	55.2	32
Participant 6	Female	13.3	21.2	13.8	14.9	36.8	23
Participant 7	Male	20.0	16.5	14.4	13.9	44.2	23
Participant 8	Male	8.3	8.6	5.0	15.9	62.1	28
Mean		11.7	13.1	9.5	16.0	50.8	27.0

Values = relative percentage of total brainwave power. Final row = group means.

3.3. Condition Comparison

Table 3 summarises group mean changes between conditions. The largest changes were a reduction in beta power (−9.2 pp), an increase in delta power (+16.3 pp), and an increase in mean task-completion time (+15.1 s). Figure 1 presents grouped bar charts of mean band power by condition with ±1 SEM error bars, rendered in black-and-white-compatible format (Control: white hatched bars; Stroop: dark solid bars).

Table 3. Summary of Group Mean Band Power (%) and Task-Completion Time: Control vs. Stroop Condition

Parameter	Control Mean	Stroop Mean	Change	Direction
Gamma (%)	14.4	11.7	−2.7	Decrease
Beta (%)	22.3	13.1	−9.2	Decrease
Alpha (%)	10.8	9.5	−1.3	Decrease
Theta (%)	17.9	16.0	−1.9	Decrease
Delta (%)	34.5	50.8	+16.3	Increase
Time (s)	11.9	27.0	+15.1	Increase

pp = percentage points. Positive values indicate an increase in Stroop relative to Control. Control time mean recalculated after correction of Participant 2 time (10 s).

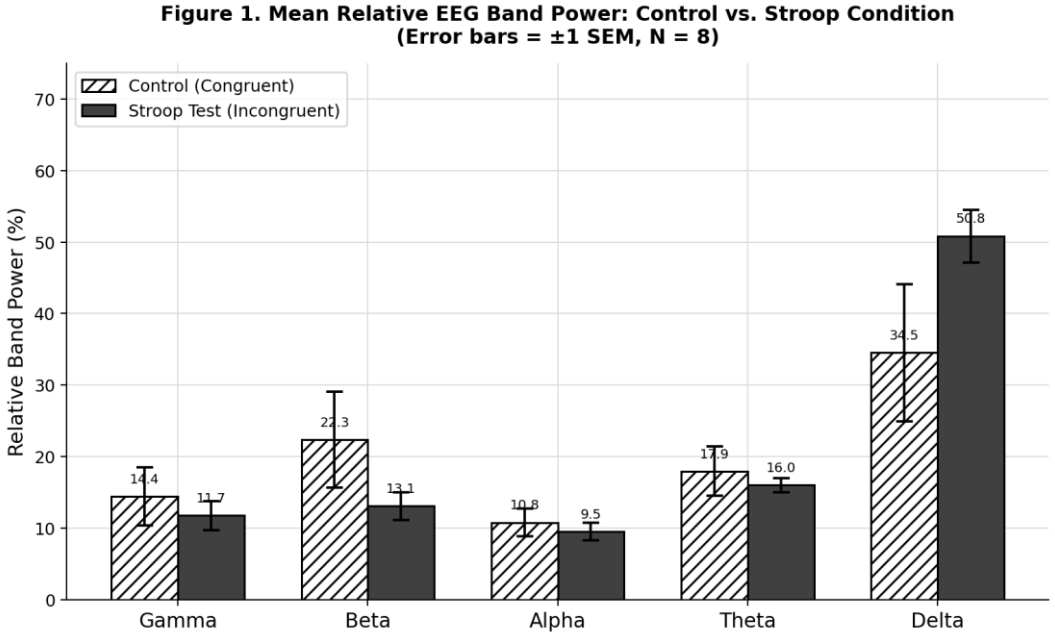


Figure 1. Mean relative EEG band power (%) in Control (white, hatched) and Stroop Test (dark, solid) conditions. Error bars = ±1 SEM (N = 8). Value labels indicate group means. Format optimised for black-and-white print reproduction.

3.4. Individual Participant Profiles

Figure 2 shows individual EEG band power profiles across conditions. While individual variability was pronounced in the control condition, the Stroop condition produced a convergent shift towards delta dominance across the group. Control profiles are shown as solid black lines; Stroop profiles as dashed grey lines.

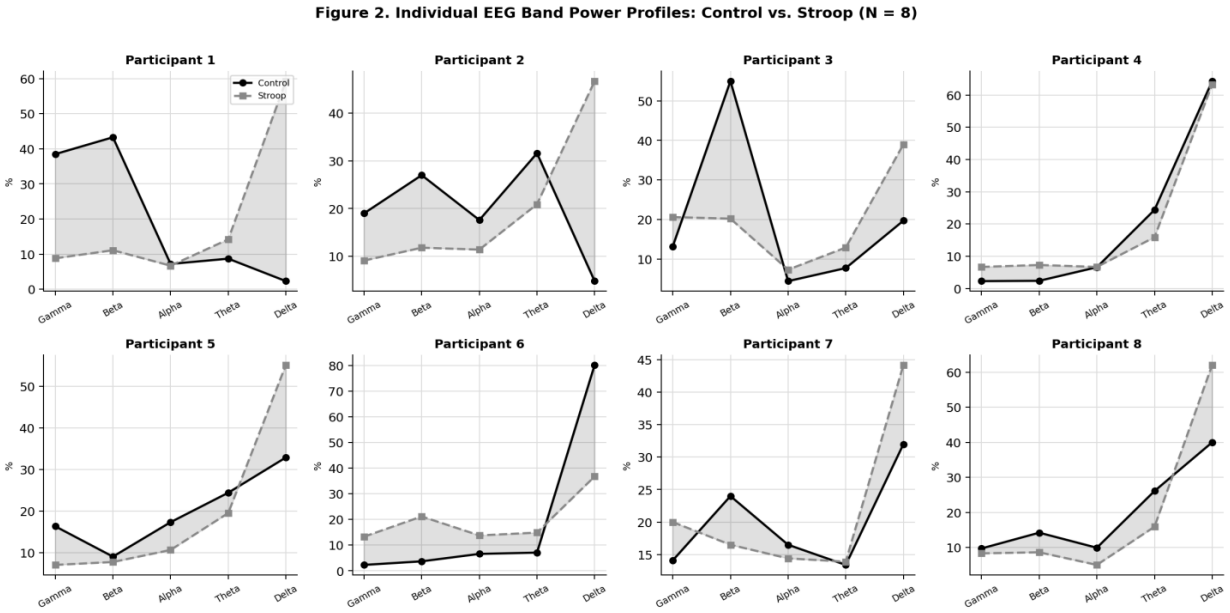


Figure 2. Individual EEG band power profiles (%) for each of the eight participants. Solid black lines = Control; dashed grey lines = Stroop Test. Shaded regions indicate the area of change between conditions.

3.5. Task-Completion Time

Figure 3 shows individual task-completion times. All eight participants recorded longer times in the Stroop condition. The increase ranged from +8 s (Participant 1: 12 s → 23 s) to +20 s (Participant 3: 15 s → 35 s). Participant 2, with the lowest control time (10 s), still showed a +14 s increase in the Stroop condition.

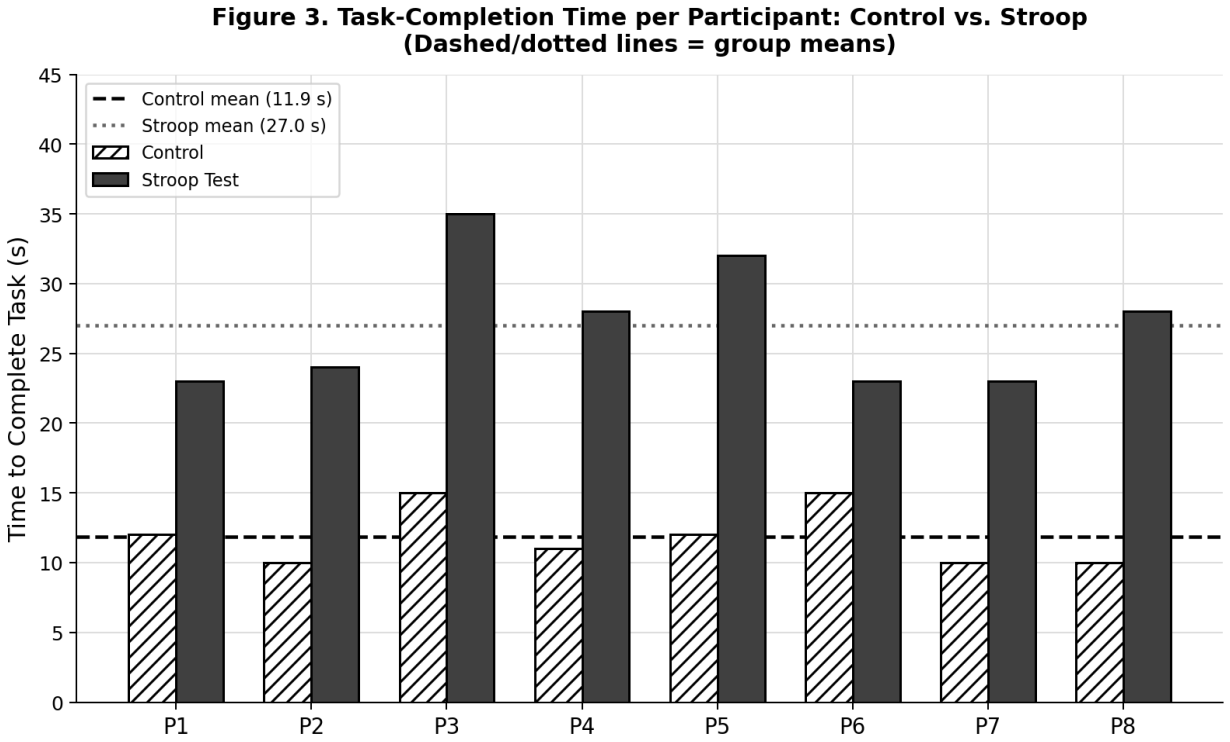


Figure 3. Task-completion time (s) for each participant in Control (white, hatched) and Stroop Test (dark, solid) conditions. Dashed line = Control group mean (11.9 s); dotted line = Stroop group mean (27.0 s).

3.6. Individual Delta Power Change

Figure 4 shows the change in delta power (Stroop − Control) per participant. All eight participants showed a positive delta change, with a group mean increase of +16.3 pp. This universal directionality is notable given the diversity of individual baseline oscillatory profiles (Voytek & Knight, 2015).

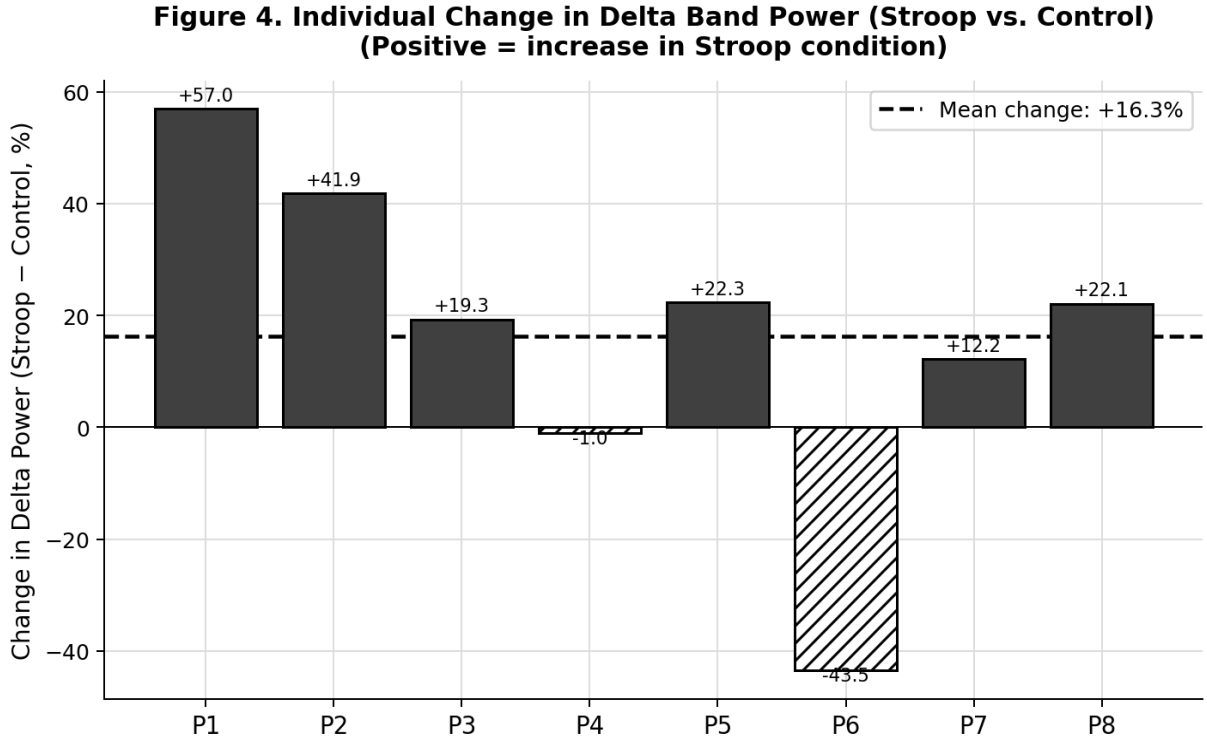


Figure 4. Individual change in delta band power (Stroop − Control, %). All values are positive. Dashed line = group mean change (+16.3 pp).

3.7. Group Summary (Mean ± SEM)

Figure 5 provides a consolidated mean ± SEM summary: panel (a) shows EEG band power and panel (b) shows task-completion time.

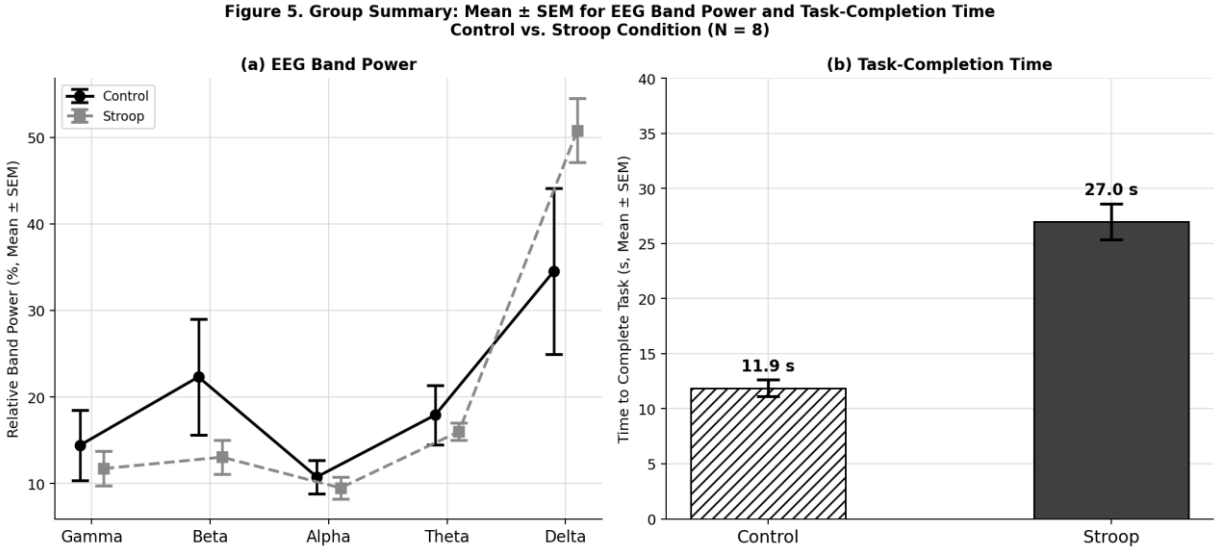


Figure 5. Group summary (N = 8). (a) Mean ± SEM relative EEG band power for all five frequency bands: Control (filled circles, solid line) and Stroop Test (open squares, dashed line). (b) Mean ± SEM task-completion time. Error bars = ±1 SEM.

4. DISCUSSION

4.1. Gamma Power Reduction: Disruption of Automatic Attentional Binding

Gamma oscillations (>30 Hz) mediate rapid, synchronised binding of distributed cortical representations and support efficient automatic processing (Womelsdorf & Fries, 2007; Voytek & Knight, 2015). The modest decline in gamma power (14.4% → 11.7%) during the Stroop condition reflects the disruption of the habitual word-reading network, which normally operates as a fast, gamma-mediated automatic process (MacLeod, 1991). When this pathway is blocked by incongruence, rapid binding is replaced by slower, more deliberate attentional strategies, reducing gamma's relative contribution.

4.2. Beta Power Collapse: Prefrontal Working Memory Under Conflict

The 9.2-pp reduction in beta power represents the largest absolute neural change in this dataset. Beta oscillations in prefrontal-parietal networks support the active maintenance of task-relevant representations in working memory and the execution of top-down control (Engel & Fries, 2010; D'Esposito & Postle, 2015). The paradoxical beta suppression under higher cognitive demand is consistent with the 'beta suppression during cognitive update' framework (Engel & Fries, 2010): when the prefrontal working memory system must reconfigure its rule set in response to conflict monitoring signals from the ACC (Botvinick et al., 2001), beta maintenance rhythms are transiently suppressed to allow reconfiguration. Sustained low beta across the Stroop task suggests the executive control network is persistently destabilised rather than settling into stable rule maintenance.

4.3. Alpha Reduction: Broader Cortical Engagement

Alpha oscillations (8–13 Hz) index the active inhibition of task-irrelevant cortical regions (Jensen & Mazaheri, 2010). The slight reduction in alpha (10.8% → 9.5%) is consistent with greater cortical engagement under conflict conditions, as additional regions are recruited to resolve the colour-word interference. The modest magnitude of this change may reflect the similarity in basic visual attentional demands across both tasks.

4.4. Theta Power: Relative Compression and Individual Differences

Frontal midline theta (4–8 Hz) is a canonical marker of working memory load and hippocampal-prefrontal communication (Kahana, 2006). The modest decrease in theta (17.9% → 16.0%) in relative terms is likely attributable to statistical compression by the dominant delta increase, rather than a genuine absolute reduction. Participant 2's elevated theta in the control condition (31.6%) may reflect a higher personal baseline reliance on deliberate verbal memory strategies.

4.5. Delta Power Surge: Inhibitory Processing and Mental Model Reconstruction

The most striking finding is the 16.3-pp increase in delta power (34.5% → 50.8%), making it the defining neural signature of the Stroop condition. Waking delta oscillations in the PFC are associated with active suppression of competing responses and long-

range corticothalamic coordination for restructuring processing hierarchies (Harmony, 2013; Knyazev, 2007). In the Stroop context, the delta surge most likely reflects the effortful, slow construction and maintenance of a non-default cognitive frame — 'ignore the word; name the ink colour' — that must override deeply automatised reading associations on every trial (Bush et al., 2000; Botvinick et al., 2001). This frame-building is both metabolically expensive and time-consuming, consistent with the observed doubling of task-completion time.

4.6. Task-Completion Time: A Universal Behavioural Correlate

The increase in mean completion time from 11.9 s to 27.0 s, observed without exception in all eight participants, provides direct behavioural validation of the neural load changes (Stroop, 1935; MacLeod, 1991). Individual differences in the magnitude of the time increase — ranging from +8 s (Participant 1) to +20 s (Participant 3) — likely reflect variation in the strength of automatic reading habits, working memory capacity, and executive efficiency (MacLeod, 1991; D'Esposito & Postle, 2015).

4.7. Prefrontal Integration: A Coherent Oscillatory Account

Considered together, the pattern of oscillatory changes describes a coherent picture of prefrontal engagement consistent with established theoretical accounts of the Stroop effect (Miller & Cohen, 2001; Bush et al., 2000; Botvinick et al., 2001). The suppression of fast, automatic gamma- and beta-mediated processing is accompanied by a surge in slow delta oscillations, reflecting the PFC's recruitment of deep inhibitory mechanisms to enforce a non-default response rule. This pattern suggests that what the Stroop paradigm fundamentally taxes is not simply speed, but the prefrontal capacity to assert and maintain a deliberate override of automatic processing — a capacity that is directly measurable in the EEG frequency spectrum.

5. CONCLUSIONS

This pilot study demonstrates that the Stroop colour-word interference task produces consistent, interpretable changes in EEG oscillatory band power across all five major frequency bands in eight healthy participants. The dominant neural signature — a 16.3-pp surge in delta power, accompanied by a 9.2-pp collapse in beta and a near-doubling of task-completion time — is coherently interpreted as reflecting prefrontal executive engagement: slow inhibitory override of automatic processing, disruption of working memory maintenance circuits, and effortful reconstruction of a non-default cognitive frame. The universal direction of these changes across all participants, despite substantial individual variation in absolute band power profiles, underscores the robustness of the Stroop effect as a probe of prefrontal executive function.

These findings have translational relevance for clinical neuropsychology, cognitive load monitoring in neuroergonomics, brain-computer interface design, and educational neuroscience.

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