Stimulus congruency and response compatibility effects on posterior theta in the Eriksen task

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Bachelor Thesis

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Abstract

A central question in cognitive neuroscience is how the brain resolves conflicts between competing visual and motor inputs. From the perspective of the Affordance Competition Hypothesis, action-relevant stimuli simultaneously activate multiple motor plans that must be filtered and selected based on task demands.

In this study, a modified Eriksen Flanker Task was used to shed light on the contributions of stimulus congruency and response compatibility to cognitive control. Behavioural, time-frequency, and topographical EEG analyses focused on posterior theta band (4-8 Hz) activity. Fourteen participants performed a single version of the task while EEG data were recorded from parieto-occipital sites.

Reaction time and accuracy data revealed additive costs of visual and motor conflict, with the slowest and least accurate responses observed in incompatible-incongruent trials. EEG results showed increased posterior theta power incompatible-incongruent conditions, especially between 150-250 ms post-stimulus.

Our findings suggest that posterior theta reflects integrative mechanism for resolving visual and motor conflict. The results are consistent with a distributed model of cognitive control involving both visual filtering and motor competition.

Keywords: Cognitive control, Eriksen flanker task, response conflict, compatibility, congruency, posterior theta, EEG, time–frequency analysis, affordance competition, visual filtering, motor inhibition

Introduction

Cognitive control relates to the ability of an individual to regulate behavior in response to competing or conflicting information. One of the key mechanisms underlying cognitive control is the regulation of attention and motor responses, particularly when distractions or conflicting cues are present. The Eriksen Flanker Task (Eriksen & Eriksen, 1974) is widely used to study how individuals handle such conflicts.

In the Eriksen Task, participants are typically instructed to respond to a central target stimulus while ignoring surrounding flankers. Originally, the task was designed to examine the response conflict arising when flankers are associated with a different motor response than the target, a phenomenon known as stimulus-response compatibility. For example, when the target requires a left-hand response, but the flankers are linked to a right-hand response, performance drops due to competing response activation. In addition to this stimulus-response conflict, researchers have also investigated stimulus-stimulus congruency, which refers to the perceptual similarity between target and flankers. When flankers share the same identity as the target (e.g. HHH), the trial is incongruent, whereas perceptually different flankers (e.g. SHS) create additional conflict. Typically, responses are faster and more accurate when both stimulus-response and stimulus-stimulus information are congruent.

Understanding the neural mechanisms that support solving such conflicts has been a major focus in cognitive neuroscience. One key finding is the role of theta-band oscillations (4-8 Hz), namely brain rhythms associated with attentional adjustments and top-down control. Traditionally, midfrontal theta activity has been viewed as a standard of performance monitoring and conflict detection, signaling the need to adjust cognitive control (Nigbur et al., 2012). However, recent work has pointed to the potential role of posterior theta in filtering out irrelevant visual information and suppressing distractor interference (Van der Lubbe et al., 2025; Asanowicz et al., 2023). This suggests that different types of theta oscillations may reflect distinct cognitive control mechanisms: midfrontal theta for general performance monitoring, and posterior theta for attentional filtering and motor inhibition.

The Affordance Competition Hypothesis (ACH) may offer a useful framework to interpret these findings (Cisek, 2007; Cisek & Kalaska, 2010). ACH proposes that multiple possible actions are represented in the brain at the same time, competing for selection based on both sensory input and motor demands. In the Eriksen Task, incongruent flankers introduce irrelevant stimuli that can activate competing motor responses, particularly when their associated responses differ from the target. Thus, conflict arises both from the need to resolve ambiguous perceptual input and from the inhibition of task-irrelevant response activations. This relationship between perceptual filtering and motor control is central to cognitive conflict resolution in ACH.

Moreover, the Binding and Retrieval in Action (BRAC) framework proposes that cognitive control phenomena in sequential tasks, such as the Eriksen Task, arise not only from active suppression but also from episodic feature binding and retrieval processes (Frings et al., 2020). According to BRAC, features of the stimulus (S), response (R), and outcomes (E) are integrated into event files. When a feature repeats itself in subsequent trials, the entire event-file is retrieved, potentially influencing current processing through retrieval of previous perceptual and motor codes. This framework suggests that the immediate past shapes current action control in dynamic adjustments that are made trial-by-trial.

Despite the aforementioned, an important question remains regarding the specific function of posterior theta in the regulation of cognitive control. Previous work by Van der Lubbe et al. (2025) already provides an indication that posterior theta oscillations are sensitive to both stimulus incongruence and response incompatibility. However, it is not fully established whether posterior theta is more strongly engaged by visual conflict, motor conflict, or an integrated response to both types of interference. Clarifying this issue is crucial for understanding whether posterior theta primarily reflects attentional filtering of visual distractors, motor inhibition of incorrect answers, or both.

The present study aimed to address this by systematically investigating how posterior theta power varies as a function of stimulus congruency and response compatibility in the Eriksen Task. Specifically, the study examined whether posterior theta activity is modulated more by the presence of incongruent visual information or by the need to inhibit competing motor responses.

Based on existing literature and theoretical frameworks, it is hypothesized that posterior theta power will be higher in incongruent trials than congruent ones, reflecting the increased demand for suppressing visual distractors (Asanowicz et al., 2023). It is further hypothesized that posterior theta power will be higher in response incompatible trials compared to compatible trials, as these conditions require additional motor inhibition to override incorrect responses (Cavanagh & Frank, 2014). Finally, it is expected that there will be an interaction between stimulus congruency and response compatibility, indicating that the combination of visual and motor conflict imposes greater demands on cognitive control than either of them alone.

Methods

Participants

Fourteen right-handed participants (7 female, 7 male), aged 18 to 30 years (M = 22.36), took part in the study. All reported normal or corrected-to-normal vision. Participants were screened using a demographic form and the Annett Handedness Questionnaire (Annett, 1970) to confirm right-handedness, as handedness may influence EEG lateralization and motor patterns. Exclusion criteria included a history of neurological disorders, psychological conditions such as ADHD or depression, and dyslexia. No participants met these exclusion criteria.

Participants were recruited through the SONA participant pool at the University of Twente and received course credit for participation. Due to not enough people being recruited through this way alone, additional participants were recruited via convenience sampling. The final sample included individuals of various national backgrounds: German (n = 7), Romanian (n = 5), Dutch (n = 1), and Bulgarian (n = 1). All participants provided written informed consent prior to the study, which was approved by the Ethics Committee of the Faculty of Behavioural, Management and Social Sciences at the University of Twente.

Stimuli and Procedure

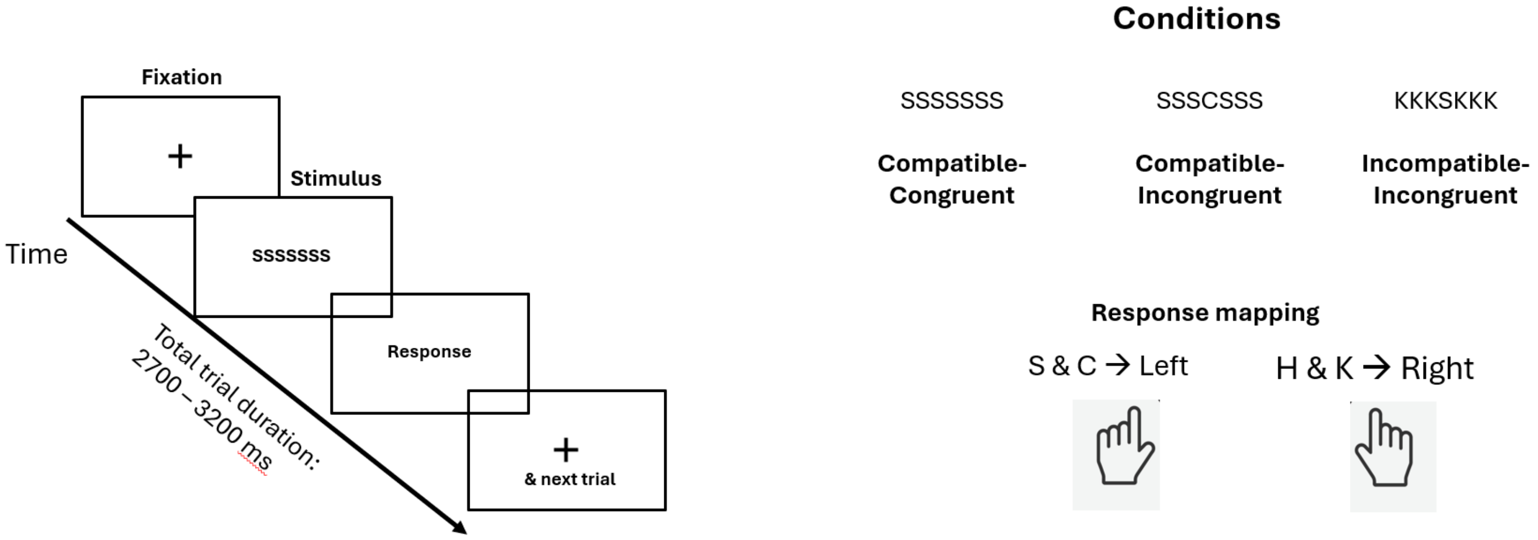
The experiment used a modified Eriksen task implemented in Presentation software. Stimuli consisted of seven-letter strings, with a central target letter (S, C, H, or K) flanked by three identical letters on each side. Depending on the condition, flankers could be compatible-congruent (e.g., SSSSSSS), compatible-incongruent (e.g., CCCSCCC, where both C and S require a left-hand response), or incompatible-incongruent (e.g., HHHSHHH, where H requires a right-hand response and S requires a left-hand response). The target letter determined the response: S and C required a left-hand response (left Ctrl key), while H and K required a right-hand response (right Ctrl key). These mappings remained fixed for all participants.

Each trial began with a central fixation cross presented for 500 ms, followed by the stimulus string (150 ms). Participants had a maximum of 1500 ms to respond. The intertrial interval varied randomly between 1000 and 1500 ms. Stimuli were displayed on a 24-inch LCD monitor (60 Hz refresh rate). Participants were seated approximately 60 cm from the screen in a dimly lit, sound-attenuated room.

Before the main task, participants completed a practice block of 24 trials to become familiar with the stimulus–response mappings and task timing. The main task consisted of 4 blocks of 80 trials (320 total), with all three experimental conditions randomized within each block. Prior to the task, participants also completed a baseline EEG recording (30 seconds eyes open, 30 seconds eyes closed, and guided saccades from the center of the screen to the left edge of the screen and back, 5 times, followed by the same instructions to the right side of the screen). Breaks were provided between blocks as needed. A schematic overview of the trial timeline, response mapping, and experimental conditions is presented in Figure 1.

Figure 1

Visual overview of the trial timeline and stimulus-response conditions.



Note: Each trial began with a fixation cross (500 ms), followed by a stimulus string (150 ms), a response window (max 1500 ms), and a randomized inter-trial interval (1000–1500 ms). Conditions varied by stimulus congruency and response compatibility: compatible-congruent (e.g., SSSSSSS), compatible-incongruent (e.g., CCCSCCC), and incompatible-incongruent (e.g., KKKSKKK). Responses were made with the left index finger for S and C, and with the right index finger for H and K.

EEG Recording

EEG data were recorded using a 32-channel ActiChamp system, with electrodes positioned according to the international 10-20 system. Recorded sites included: Afz, Af3, Af7, F5, F1, FCz, FC3, FT7, C5, C3, CP3, TP7, P5, P1, PO7, PO3, Oz, PO4, PO8, P6, P2, CP4, TP8, C6, C4, FC4, FT8, F6, F2, AF4, AF8, and CPz. Electrode impedance was kept below 10 kΩ. Data were referenced online to an implicit reference. EEG signals were sampled at 500 Hz without online filtering, and were subsequently filtered offline between 0.1-30 Hz using a fourth-order zero-phase Butterworth filter and a 50 Hz notch filter.

EEG Preprocessing

Preprocessing was performed using BrainVision Analyzer following an eight-step process. Continuous data were filtered (0.1–30 Hz) and cleaned using automated artifact detection. Segments were flagged if voltage gradients exceeded 50 μV/ms, if amplitude ranged over 200 μV, or if activity dropped below 0.1 μV for more than 100 ms. Artifacts were marked for exclusion from –200 ms to +200 ms relative to event onset.

Ocular artifacts were removed using Independent Component Analysis (ICA) with the Infomax algorithm. Components showing high correlation with vertical or horizontal EOG channels were identified, and the top 30% were removed based on squared correlation values. ICA was computed over a 322-second interval in 512 steps.

EEG data were then segmented into epochs from –1000 ms to +1000 ms relative to stimulus onset. Baseline correction was applied using the interval from –600 to –200 ms. Data were re-referenced to the average of 31 electrodes while retaining TP7 as a control.

Time-Frequency Decomposition

Time–frequency analysis was performed using a continuous wavelet transform with Morlet wavelets (parameter = 5). Frequencies ranging from 4 to 20 Hz were decomposed into seven logarithmically spaced layers. Spectral power was normalized as percent change relative to a –600 to –200 ms pre-stimulus baseline.

For theta band analysis, only Layer 1 of the frequency decomposition was used. This layer had a central frequency of 4.00 Hz, with effective filter boundaries of 3.33 to 4.67 Hz, corresponding to a narrow-band representation of early theta activity. The use of a single, low-frequency theta layer ensured a more restricted and targeted measure, minimizing overlap with other frequency bands and improving sensitivity to early conflict-related oscillatory activity.

The analysis focused on four post-stimulus time windows: 100–150 ms, 150–200 ms, 200–250 ms, and 250–300 ms. The choice of these windows was informed by prior studies reporting that posterior theta increases associated with conflict processing typically emerge between approximately 100 and 300 ms post-stimulus (Asanowicz et al.; van der Lubbe et al., 2025). The specific division into four consecutive 50 ms windows was selected to capture the temporal dynamics of theta power with higher resolution within this interval. Power values were extracted at posterior electrodes PO7 and PO8, where conflict-related theta effects have been consistently observed.

Statistical Analysis

The independent variables were stimulus congruency (congruent vs incongruent) and response compatibility (compatible vs incompatible). The dependent variables included behavioural measures, reaction time (RT) and percent correct (PC), as well as neural measures of percent change in theta power extracted from PO7 and PO8 within each time window.

All analyses were conducted in R using the readxl, tidyverse, ggplot2, ez, afex, and psych packages. Percent change in theta power was computed at posterior electrodes PO7 and PO8. For each time window, values were averaged per condition. Behavioral data (reaction time and percent correct) were cleaned and summarized using descriptive statistics and plotted via several relevant charts. Further analyses tested for main effects and interactions using repeated-measures ANOVAs.

Results

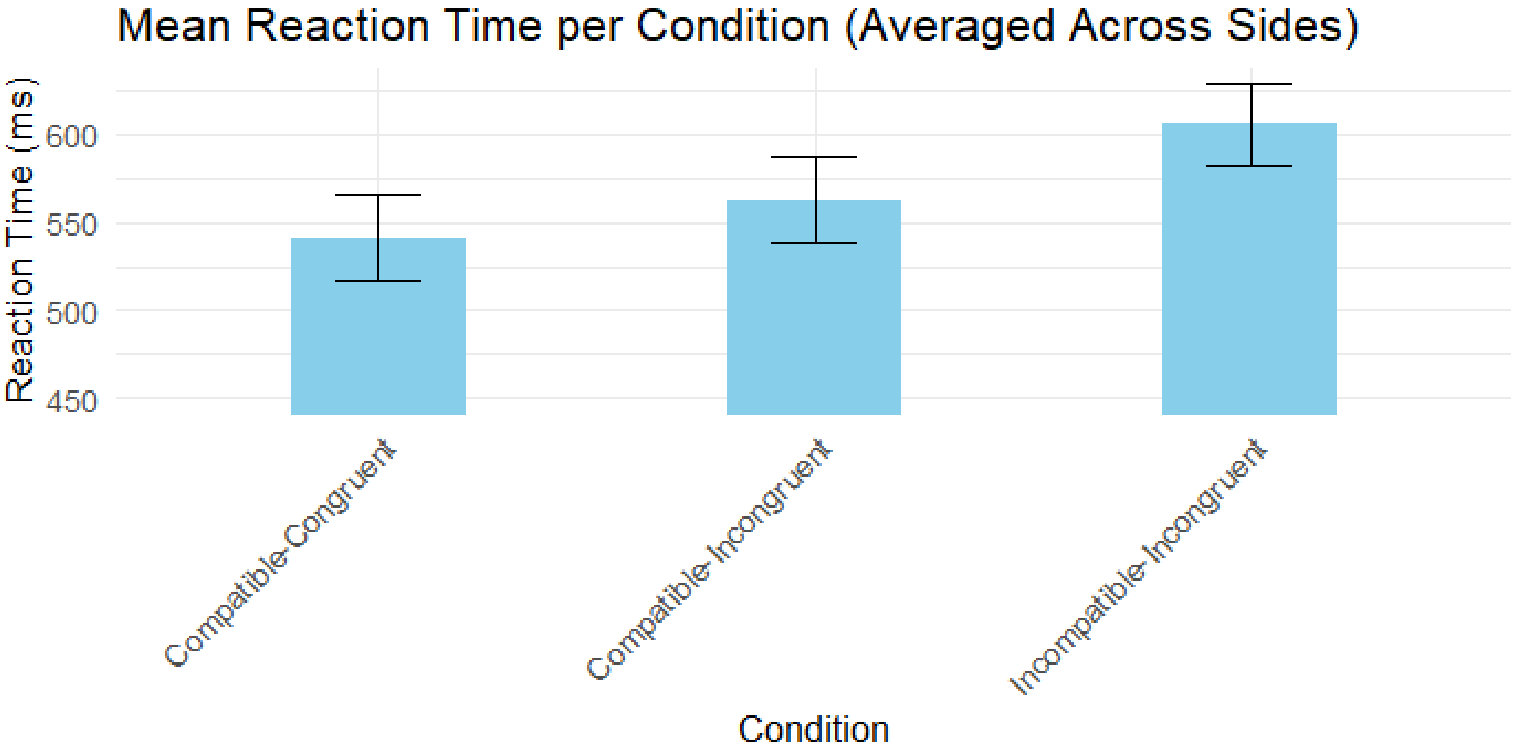
Behavioural Measures

Descriptive statistics for reaction time (RT) across the six experimental conditions are shown in Figure 2. Participants responded fastest in the compatible-congruent conditions and slowest in the incompatible-incongruent conditions, as expected.

Mean RTs ranged from approximately 540 ms to 612 ms, with the slowest responses observed in the incompatible-incongruent-left condition. There was a visible increase in RT with both stimulus incongruency and response incompatibility.

Figure 2

Mean reaction time (in milliseconds) for each experimental condition. Error bars represent standard error of the mean.



A 3 (Condition: congruent-compatible, incongruent-compatible, incongruent-incompatible) x 2 (Side: left, right) repeated measured ANOVA was conducted to examine the effects of stimulus-response condition and response side on RT. The main effect of Condition was significant *F*(1, 13) = 58.01, *p* < .001, indicating that RTs differed depending on the type of stimulus response conflict.

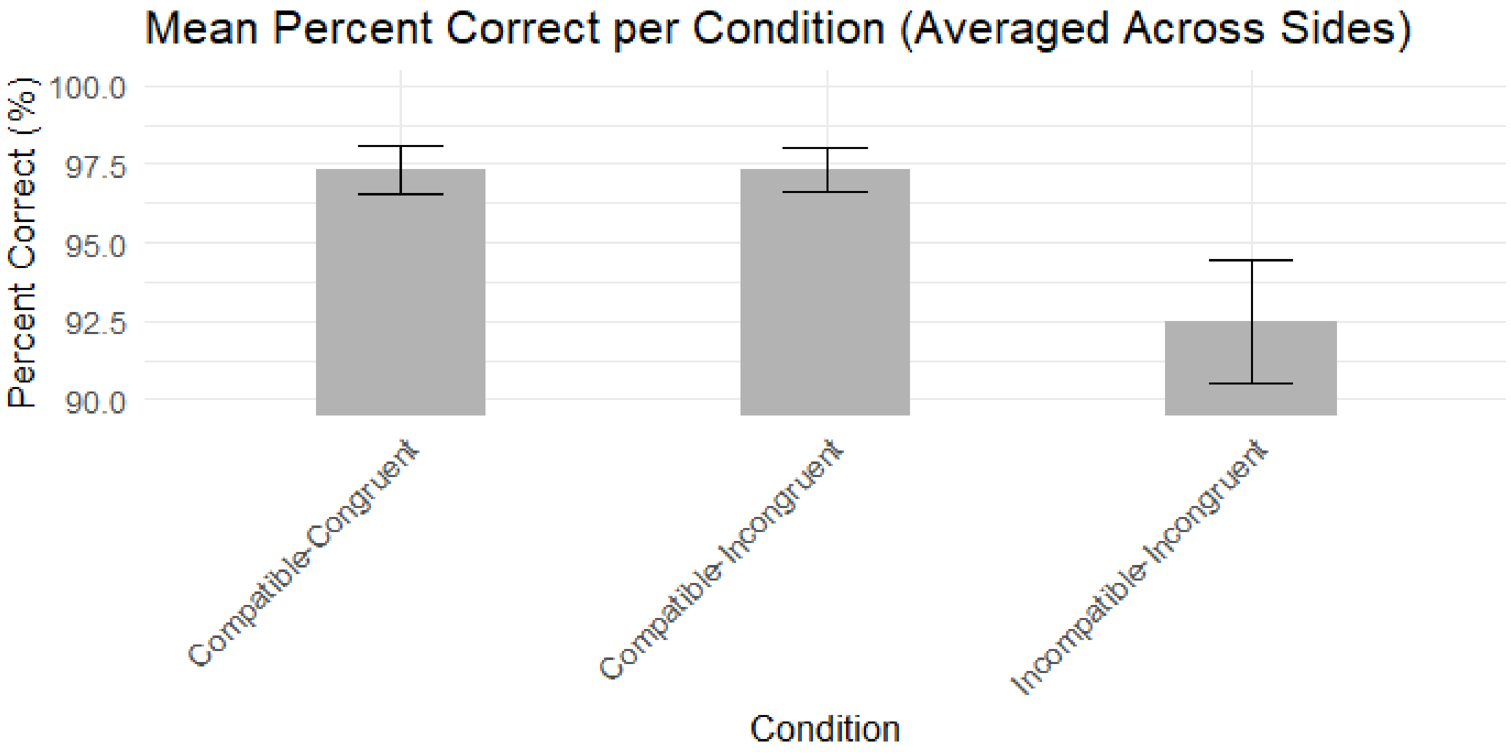
There was no significant main effect on Side, *F(*1, 13) = 0.01, *p* = .922, nor a significant Side × Condition interaction, *F*(1, 13) = 0.06, *p* = .813. These results suggest that reaction times were influenced by experimental condition but not by response side.

To further investigate the observed condition effect, three planned contrasts were conducted on the averaged RTs across response sides. The contrast between compatible-congruent and compatible-incongruent revealed a marginal effect t(13) = −2.32, *p* = .070, with participants responding approximately 21 ms slower in the IC condition. The contrast between compatible-incongruent and incompatible-incongruent was significant, t(13) = -4.72, *p* < .001, with an estimated RT increase of 43 ms in the incompatible-incongruent condition. The difference between compatible-congruent and incompatible-incongruent was also significant, t(13) = -7.05, *p* <.001, corresponding to a 65 ms increase in RT. These results indicate a clear additive cost of stimulus incongruency and response incompatibility on RT.

Accuracy data (percentage correct) are presented in Figure 3. Overall, performance was high across conditions, though slight variability was observed. Participants were most accurate in the compatible-congruent conditions, and less accurate in the incompatible-incongruent conditions

Figure 3

Mean percent correct for each experimental condition. Accuracy was highest in the compatible conditions and slightly lower in the incompatible incongruent conditions.



A 3 (Condition: Congruent-Compatible, Incongruent-Compatible, Incongruent-Incompatible) x 2 (Side: Left, Right) repeated-measures ANOVA was conducted on PC to examine the effects of stimulus congruency, response compatibility, and response side on task accuracy. The main effect of Condition was significant, *F(*2, 26) = 8.07, *p* = .00188, with a generalized eta squared of .174. Mauchly's test indicated that the assumption of sphericity was violated for this effect, W = 0.30, *p* = .001. Therefore, Greenhouse-Geisser corrected results are reported, *F*(1.18, 15.30) = 8.07, *p* = .00971. There was no significant main effect of Side, *F*(1, 13) = 0.90, *p* = .359, nor a significant Condition × Side interaction, *F*(2, 26) = 0.05, *p* = .950.

No significant differences were found between compatible-congruent and compatible-incongruent conditions, nor between left and right sides within any condition. These findings confirm that reduced accuracy is specific to conditions involving both stimulus incongruency and response incompatibility.

EEG Analysis

To explore the effects of stimulus congruency and response compatibility on posterior theta power, mean theta amplitudes were computed for each condition, electrode (PO7, PO8), and time-window (100-150 ms, 150-200 ms, 200-250 ms, 250-300 ms).

Across both electrodes, theta power was consistently lowest in the compatible congruent condition and highest in the incompatible incongruent condition. This pattern was especially pronounced between 150-200 ms, with the incompatible-incongruent condition peaking in both electrodes. When collapsing across electrodes, the Incompatible Incongruent condition reached an average peak theta increase of approximately 766%, compared to approximately 580% in the compatible-congruent condition. All conditions showed a rise in theta from the earliest time window to a peak in the 150-250 ms interval, followed by a slight decline by 250-300 ms.

As illustrated in Figure 4, mean theta power increased progressively across conditions, with the lowest values observed in the compatible-congruent condition, and the highest values in the incompatible-incongruent condition. Error bars indicated variability was greatest for the incompatible-incongruent trials.

Figure 5 additionally shows the distribution of percent change in theta power across the four post-stimulus time windows. The boxplots demonstrate that, in each time window, theta power was consistently higher in the incompatible-incongruent conditions compared to the other two. Notably, the 150-200 ms and 200-2500 ms windows showed the clearest separation of medians between conditions.

Figure 4

Line plot of percent change in theta over time per condition

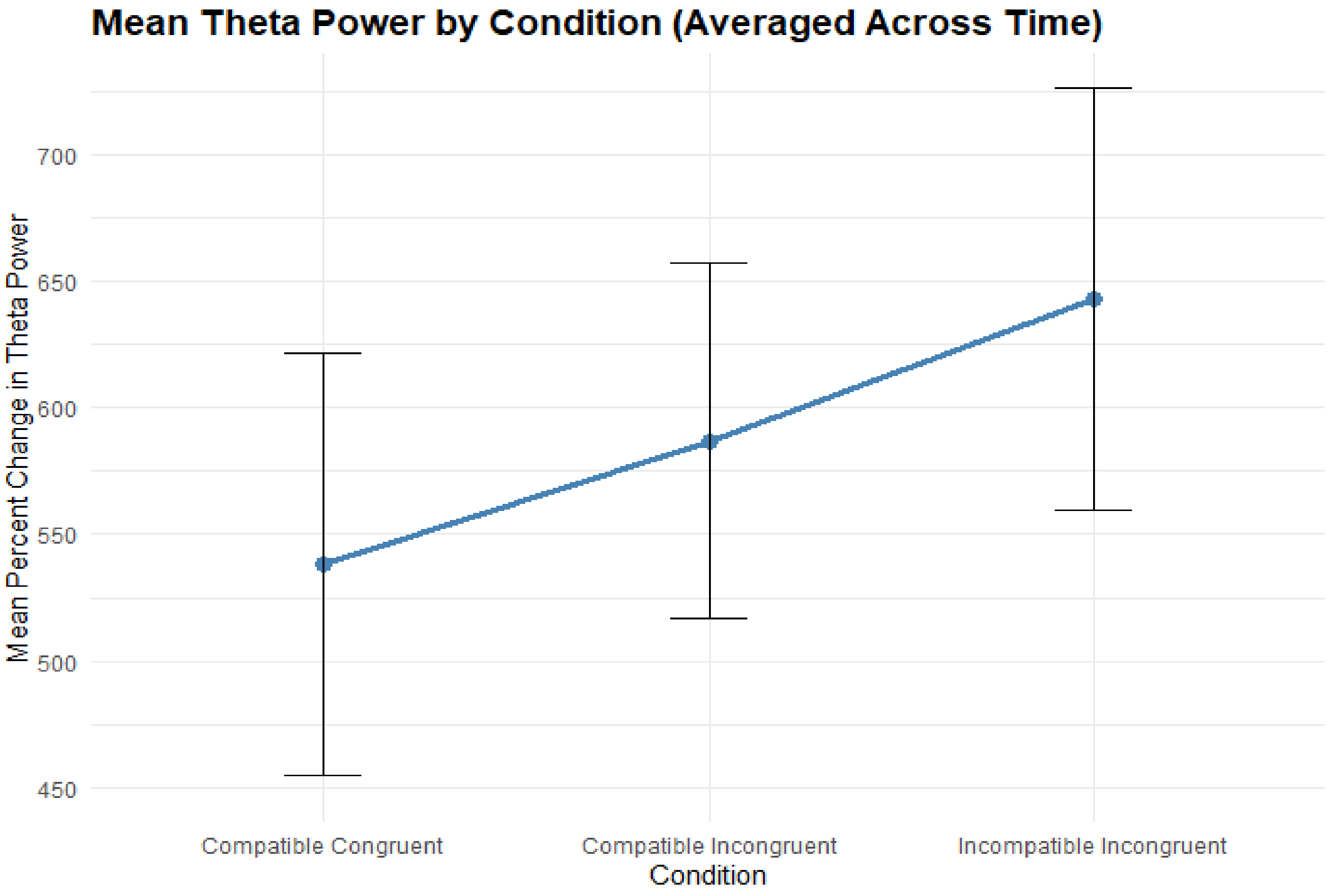
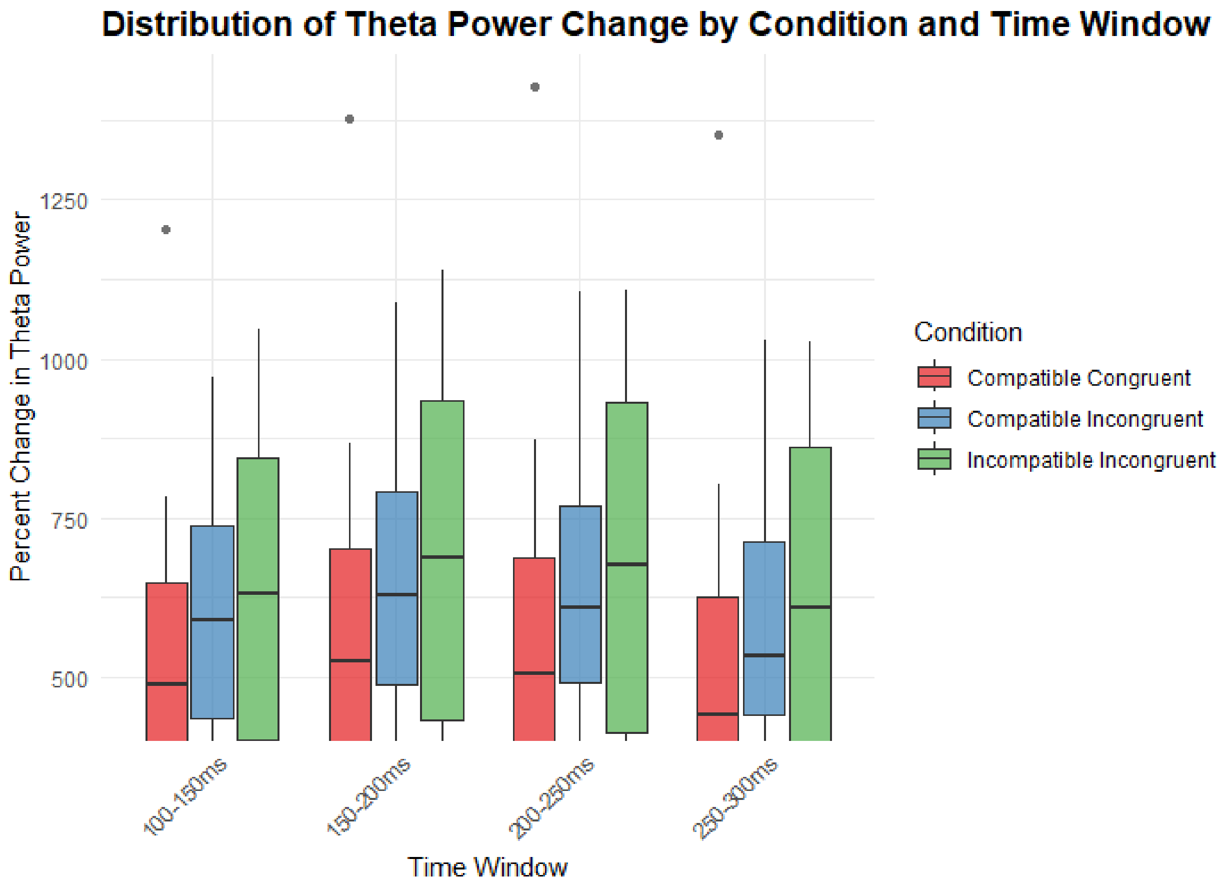


Figure 5

Boxplot of theta power increases by condition and time



EEG: Inferential Statistics (3 x 2 x 4 ANOVA)

A 3 (Condition: compatible-congruent, compatible-incongruent, incompatible-incongruent) × 2 (Electrode: PO7, PO8) × 4 (Time Window: 100–150 ms, 150–200 ms, 200–250 ms, 250–300 ms) repeated-measures ANOVA was conducted on the percentage change in theta power relative to baseline.

There was a significant main effect of Condition, *F*(1.54, 20.03) = 3.80, *p* = .050, indicating that theta power differed depending on the experimental condition. The main effect of Electrode was not significant *F*(1, 13) = 2.36, *p* = .148.

The main effect of Time Window was significant, $F(1.86, 24.16) = 17.00$, $p < .001$, suggesting a strong modulation of theta power over time. The Condition x Time Window interaction approached significance, $F(2.14, 27.80) = 3.07$, $p = .059$, indicating a possible trend that the effect of condition varied across time windows. No other two- or three-way interactions were statistically significant, though the three-way interaction between Condition, Electrode, and Time Window showed a trend, $F(2.19, 28.51) = 2.47$, $p = .098$.

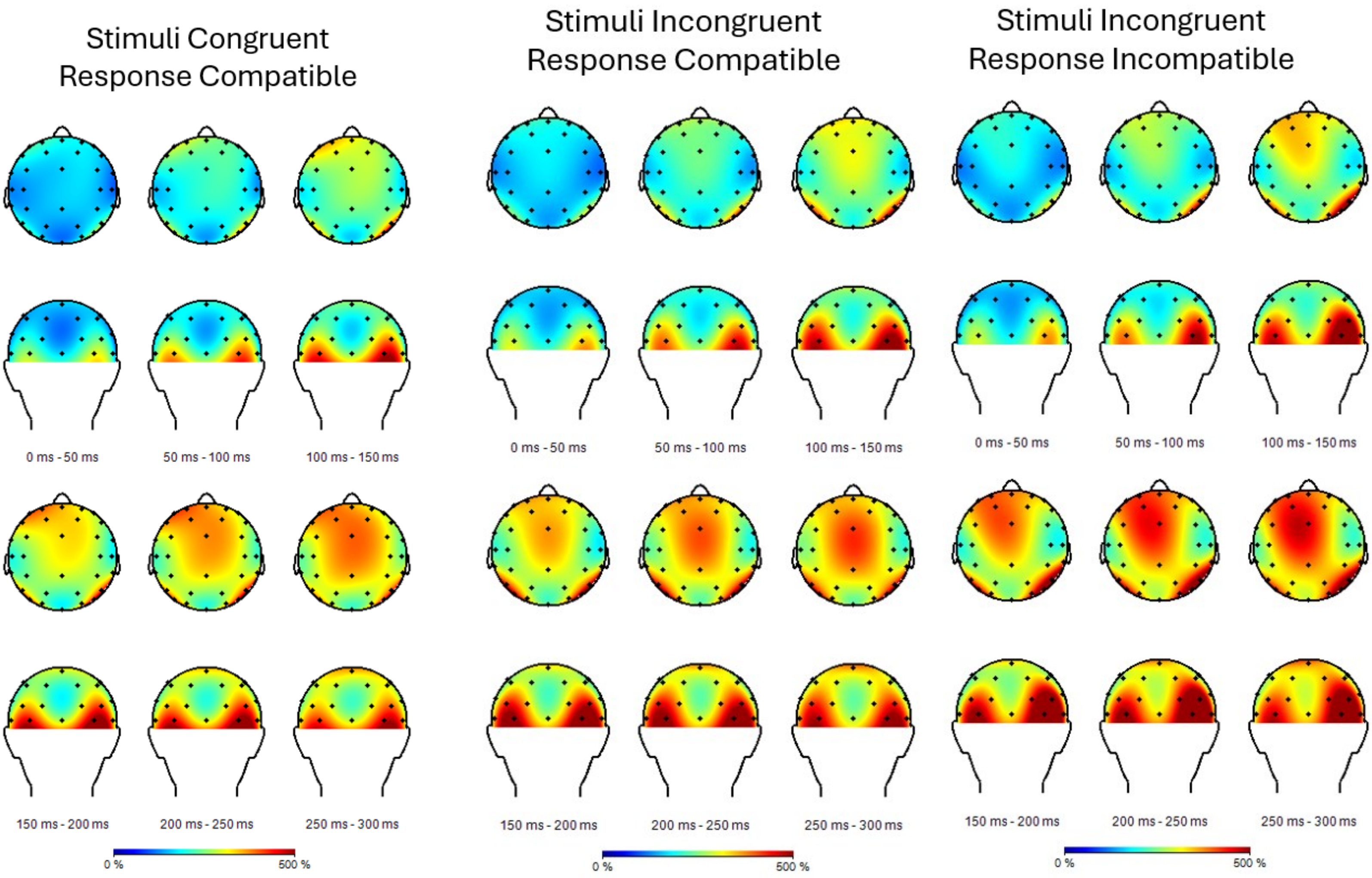
Separate analysis of the 100–150 ms time window revealed a main effect of Condition that approached significance, $F(1.63, 21.20) = 3.68$, $p = .051$. Neither the main effect of Electrode, $F(1, 13) = 2.57$, $p = .133$, nor the Condition × Electrode interaction, $F(2.00, 25.97) = 1.37$, $p = .273$, reached significance. Post-hoc pairwise comparisons (collapsed across electrodes) indicated that theta power was significantly higher in Incompatible Incongruent trials compared to Compatible Congruent trials ($p = .032$). No other pairwise contrasts were significant.

Topographical Distribution

To complement the time-resolved analysis, topography maps were generated for each condition by averaging theta power across all four windows. The maps clearly illustrate a posterior concentration of theta activity, which increases in intensity from the compatible-congruent to the incompatible-incongruent condition. The most prominent activation is observed in the incompatible-incongruent condition, as indicated in Figure 6.

Figure 6

Topographical maps of theta power in all conditions



Discussion

This study investigated the influence of stimulus congruency and response compatibility on posterior theta activity, reaction times, and percentage of tasks answered correctly in the Eriksen Task. Behavioural results replicated classic findings: reaction times and accuracy were strongly affected by both visual and motor conflict (Eriksen & Eriksen, 1974). Specifically, responses were slowest and least accurate in incompatible-incongruent conditions. In addition, incongruent stimuli and incompatible responses independently slowed reaction times and reduced accuracy relative to congruent and compatible conditions.

In line with these behavioural patterns, EEG results showed that posterior theta power was lowest in compatible-congruent trials and highest in incompatible-incongruent trials. Theta power increased over time, peaking between 150-250 ms post-stimulus. The observed Condition x Time Window interaction approached significance, indicating a modulation of conflict effects on theta. Notably, the topographical distribution of theta power confirmed a posterior focus, supporting its unique role from midfrontal theta in cognitive control.

Interpretation

These findings support the hypothesis that posterior theta oscillations are sensitive to both visual and motor forms of conflict, consistent with the idea that this rhythm reflects general control mechanisms (Asanowicz et al., 2023). The increase in theta during incongruent and incompatible trials suggests that posterior theta may facilitate the suppression of distractor-related activity and the inhibition of competing motor resources.

From the perspective of the Affordance Competition Hypothesis, the presence of incongruent flankers and incompatible responses can be interpreted as competing action plans that must be resolved before motor execution. The elevated theta power in these conditions may reflect the neural correlate of this competition process, particularly in sensory-motor integration areas.

Moreover, the Affordance Competition Hypothesis (Cisek, 2007) provides a useful framework for interpreting these findings. According to ACH, multiple potential actions are specified in parallel and compete for selection. The observed increases in posterior theta power during conflict trials may reflect neural processes that bias competition by suppressing representations of competing responses and enhancing selection of the appropriate motor plan. This interpretation aligns with the idea that posterior theta oscillations contribute to the solving of both perceptual and motor conflict during action selection.

Theoretical and Practical Implications

The current results expand the understanding of posterior theta as not just a passive aspect of visual filtering, but as an active control mechanism operating in both perception and motor function. This challenges the more exclusive association of posterior theta with attentional filtering and aligns with emerging perspectives that cognitive control is distributed across multiple regions and oscillatory rhythms (Cohen, 2014).

By systematically examining the distinct contributions of stimulus congruency and response compatibility, the present study helps point out the specific conflict types that modulate posterior theta activity. This refines our understanding of posterior theta as an integrative mechanism, likely involved in suppressing distractor-related perceptual input and inhibiting motor responses that are irrelevant. This specificity may enhance current models of conflict resolution, which often do not clearly distinguish the neural dynamics of different interference sources.

These insights may also have applied significance. Elevated frontal-central theta activity has consistently been observed in individuals with ADHD during resting-state EEG, and is widely interpreted as a marker of underarousal and impaired attentional regulation (Loo & Makeig, 2012). Although these findings originate from passive recordings, the same neural mechanisms underlying resting-state theta abnormalities are thought to contribute to task-related deficits in executive functions, such as conflict monitoring and response inhibition. Given that theta oscillations are also involved in adaptive cognitive control during conflict tasks, these abnormalities may reflect a broader dysregulation of control-related neural processes in ADHD.

Future Directions

Future research should replicate these findings in larger and more diverse samples to confirm whether the observed increases in posterior theta under visual and motor conflict generalize across populations. Given that the current study focused on condition-specific effects within a single-trial framework, subsequent work could incorporate manipulations of trial sequence or stimulus–response repetitions to directly examine whether posterior theta also reflects adaptive control mechanisms as predicted by the BRAC framework. Additionally, since we observed robust posterior theta modulation in high-conflict conditions, examining individual variability in this effect, particularly in populations with known attentional or control deficits, could clarify whether posterior theta serves as a stable neural marker for conflict sensitivity and regulation.

Moreover, while this study focused on condition-specific effects of stimulus congruency and response compatibility, the observed theta activity highlights the importance of further research into how cognitive control is dynamically regulated. For example, future studies could examine whether posterior theta power also reflects adjustments in control settings across successive trials.

Although sequential effects were not analyzed in the present study, the clear differentiation in theta power across conditions generates curiosity about whether posterior theta dynamics may also reflect such trial-by-trial adjustments. Previous work has linked frontal theta to adaptive control adjustments (Cavanagh & Frank, 2014), however, little is known about whether posterior theta also shows sequential sensitivity, perhaps reflecting dynamic visual filtering or updated action suppression following incongruent or incompatible trials.

Following this, future research could incorporate sequential designs or include condition transitions to examine whether posterior theta power adapts as a function of previous trial conflict.

Lastly, inspection of the topographical maps revealed that, while theta increases were maximal at posterior sites, there was also visible activity over frontocentral regions, suggesting possible frontal involvement in conflict processing. Although this study did not include connectivity analyses between multiple regions, future work could investigate the functional interactions between posterior and frontal regions. For example, connectivity measures based on the imaginary component of coherency (Nolte et al., 2004) could help clarify whether posterior theta reflects local processing or dynamic information exchange with prefrontal regions, as proposed by models of cognitive control.

Conclusion

This study provides evidence that posterior theta power is modulated by both stimulus incongruency and response incompatibility in the Eriksen Task. These findings further support the notion that posterior theta reflects an integrative control mechanism involved in filtering distractors and inhibiting competing motor plans. The results contribute to a more nuanced understanding of cognitive control and open further exploration for future research on the dynamics of visual and motor conflict resolution.

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Appendix

Appendix A

R Script for Data Analysis

```
# Load required libraries
library(tidyverse)
library(readxl)
library(psych)
library(ez)
library(emmeans)
library(ggplot2)
library(reshape2)
library(afex)
library(multcomp)

### SECTION 1: Load and Prepare RT & PC Data ###


# Read in Excel files
rt_data <- read_excel("RT2.xlsm", col_names = FALSE)
pc_data <- read_excel("PC2.xlsx", col_names = FALSE)

# Name columns and add participant IDs
```

```
col_names <- c(
  "compatible_congruent_left", "compatible_congruent_right",
  "compatible_incongruent_left", "compatible_incongruent_right",
  "incompatible_incongruent_left", "incompatible_incongruent_right"
)
colnames(rt_data) <- col_names
colnames(pc_data) <- col_names
rt_data$Participant <- factor(1:nrow(rt_data))
pc_data$Participant <- factor(1:nrow(pc_data))

# Convert to numeric and preprocess PC data
rt_data[, 1:6] <- lapply(rt_data[, 1:6], as.numeric)
pc_data[, 1:6] <- lapply(pc_data[, 1:6], function(x) {
  x <- as.numeric(x)
  ifelse(x > 1, x / 100, x)
})

# Reshape to long format
rt_long <- melt(rt_data, id.vars = "Participant", variable.name = "Condition", value.name =
        "RT")
pc_long <- melt(pc_data, id.vars = "Participant", variable.name = "Condition", value.name =
        "PC")
```

```
# Add factors

add_factors <- function(df) {

  df %>%

    mutate(

      Congruency = ifelse(grepl("incongruent", Condition), "Incongruent", "Congruent"),

      Compatibility = ifelse(grepl("incompatible", Condition), "Incompatible", "Compatible"),

      Side = ifelse(grepl("left", Condition), "Left", "Right"),

      Condition3 = case_when(

        grepl("compatible_congruent", Condition) ~ "CC",

        grepl("compatible_incongruent", Condition) ~ "IC",

        grepl("incompatible_incongruent", Condition) ~ "II"

      ),

      Congruency = factor(Congruency),

      Compatibility = factor(Compatibility),

      Side = factor(Side),

      Condition3 = factor(Condition3, levels = c("CC", "IC", "II"))

    )

}

rt_long <- add_factors(rt_long)

pc_long <- add_factors(pc_long)


### SECTION 2: ANOVAs and Planned Contrasts (RT & PC) ###
```

```
# Run 3x2 repeated-measures ANOVAs
anova_rt <- ezANOVA(
  data = rt_long,
  dv = .(RT),
  wid = .(Participant),
  within = .(Side, Condition3),
  type = 3,
  detailed = TRUE
)
anova_pc <- ezANOVA(
  data = pc_long,
  dv = .(PC),
  wid = .(Participant),
  within = .(Side, Condition3),
  type = 3,
  detailed = TRUE
)

print(anova_rt)
print(anova_pc)

# Average across Side
rt_avg <- rt_long %>%
```

```
  group_by(Participant, Condition3) %>%
  summarise(RT = mean(RT), .groups = "drop")
pc_avg <- pc_long %>%
  group_by(Participant, Condition3) %>%
  summarise(PC = mean(PC), .groups = "drop")

# Filter for complete cases
valid_ids <- function(df) {
  df %>%
    group_by(Participant) %>%
    summarise(n = n_distinct(Condition3)) %>%
    filter(n == 3) %>%
    pull(Participant)
}
complete_rt_avg <- rt_avg %>% filter(Participant %in% valid_ids(rt_avg))
complete_pc_avg <- pc_avg %>% filter(Participant %in% valid_ids(pc_avg))

# Contrast coding
for (df in list(complete_rt_avg, complete_pc_avg)) {
  df$Condition3 <- factor(df$Condition3, levels = c("CC", "IC", "II"))
  contrasts(df$Condition3) <- contr.sum(3)
}
```

```
# Linear models
lm_rt <- lm(RT ~ Condition3 + Participant, data = complete_rt_avg)
lm_pc <- lm(PC ~ Condition3 + Participant, data = complete_pc_avg)

# Planned contrasts
contrast_matrix <- rbind("CC vs IC" = c(1, -1, 0), "IC vs II" = c(0, 1, -1), "CC vs II" = c(1, 0, -1))
glht_rt <- glht(lm_rt, linfct = mcp(Condition3 = contrast_matrix))
glht_pc <- glht(lm_pc, linfct = mcp(Condition3 = contrast_matrix))

summary(glht_rt)
summary(glht_pc)

### SECTION 3: EEG Analysis ###

# Load and reshape all time-window EEG files
library(tidyr)
library(purrr)

files <- list(
  "100-150" = "V2_L1_100-150ms.xlsx",
  "150-200" = "V2_L1_150-200ms.xlsx",
  "200-250" = "V2_L1_200-250ms.xlsx",
```

```
  "250-300" = "V2_L1_250-300ms.xlsx"
)


eeg_data <- map2_df(files, names(files), function(file, win) {
  df <- read_excel(file)
  if (all(is.na(df[1,]))) df <- df[-1,]
  po_cols <- grep("^PO[78]-", names(df), value = TRUE)
  names(df)[1] <- "Participant"
  df %>%
    select(Participant, all_of(po_cols)) %>%
    pivot_longer(cols = -Participant, names_to = "Electrode_Condition", values_to = "Theta")
        %>%
    extract(Electrode_Condition, into = c("Electrode", "Condition"), regex = "(PO[78])-(.+)")
        %>%
    mutate(TimeWindow = win)
})


eeg_data <- eeg_data %>%
  mutate(
    Condition = recode(Condition,
                       "SCRC_L1" = "Compatible Congruent",
                       "SIRC_L1" = "Compatible Incongruent",
                       "SIRI_L1" = "Incompatible Incongruent"
```

```
    ),
    Side = ifelse(Electrode == "PO7", "Left", "Right"),
    across(c(Condition, Electrode, Side, TimeWindow), as.factor),
    Participant = factor(Participant)
  )

# EEG ANOVA
eeg_anova <- aov_ez(
  id = "Participant",
  dv = "Theta",
  within = c("Condition", "Electrode", "TimeWindow"),
  data = eeg_data,
  anova_table = list(correction = "GG", es = "pes")
)
print(eeg_anova)

# Post hoc contrasts
eeg_avg <- eeg_data %>%
  group_by(Participant, Condition) %>%
  summarise(Theta = mean(Theta, na.rm = TRUE), .groups = "drop")

lm_eeg <- lm(Theta ~ Condition + Participant, data = eeg_avg)
glht_eeg <- glht(lm_eeg, linfct = mcp(Condition = "Tukey"))
```

```
summary(glht_eeg)



### SECTION 4: PLOTTING ###


# RT Bar Plot

rt_summary <- complete_rt_avg %>%

  group_by(Condition3) %>%

  summarise(Mean = mean(RT), SE = sd(RT) / sqrt(n()), .groups = "drop")

rt_summary$Condition3 <- factor(rt_summary$Condition3,

                                levels = c("CC", "IC", "II"),

                                labels = c("Compatible-Congruent", "Compatible-Incongruent",
            "Incompatible-Incongruent")

)


ggplot(rt_summary, aes(x = Condition3, y = Mean)) +

  geom_bar(stat = "identity", fill = "skyblue", width = 0.4) +

  geom_errorbar(aes(ymin = Mean - SE, ymax = Mean + SE), width = 0.2) +

  coord_cartesian(ylim = c(400, NA)) +

  labs(

    title = "Mean Reaction Time per Condition",

    y = "Reaction Time (ms)",
```

```
    x = "Condition"
  ) +
  theme_minimal(base_size = 13) +
  theme(axis.text.x = element_text(angle = 45, hjust = 1))


# PC Bar Plot
pc_summary <- complete_pc_avg %>%
  group_by(Condition3) %>%
  summarise(Mean = mean(PC), SE = sd(PC) / sqrt(n()), .groups = "drop")
pc_summary$Condition3 <- factor(pc_summary$Condition3,
                                levels = c("CC", "IC", "II"),
                                labels = c("Compatible-Congruent", "Compatible-Incongruent",
            "Incompatible-Incongruent")
)


ggplot(pc_summary, aes(x = Condition3, y = Mean)) +
  geom_bar(stat = "identity", fill = "gray70", width = 0.4) +
  geom_errorbar(aes(ymin = Mean - SE, ymax = Mean + SE), width = 0.2) +
  coord_cartesian(ylim = c(75, 100)) +
  labs(
    title = "Mean Percent Correct per Condition",
    y = "Percent Correct (%)",
    x = "Condition"
```

```
  ) +
  theme_minimal(base_size = 13) +
  theme(axis.text.x = element_text(angle = 45, hjust = 1))
```

Note: This script was used to analyse the behavioural and EEG data. All analyses were conducted using R version 4.3.2 with packages such as ez, afex, emmeans, psych, tidyverse, and ggplot2.

Appendix B

Annett (1970) Handedness Questionnaire

Name:

Indicate the preferred hand:

	-2	**-1**	**0**	**+1**	**+2**
	Always left	*Mostly left*	*No preference*	*Mostly right*	*Always right*
Writing a letter					
Throwing a ball to hit a target					
To play a racket in tennis, squash etc					
What hand is up to handle a broom removing dust from the floor					
What hand is up to use a shovel					
Lighting matches					
Using scissors					
To told a wire to move it through the eye of a needle					
To distribute playing cards					
To hit a nail on the head					
To hold your toothbrush					
To remove the cover from a jar					

- 24 to 9 Left Handed

- -8 to +8 ambidextrous
- +9 to 24 Right Handed