

ERP 脑区功能分区与词类关系分析

yyx

2025-08-13

引言

本文件对事件相关电位（ERP）的 P200、N400 和 P600 成分进行分析，研究其在不同脑区和词类条件下的振幅和潜伏期。分析包括数据预处理、使用重复测量 ANOVA 进行统计分析，以及通过热图进行可视化。

数据加载

从 CSV 文件中加载 P200、N400 和 P600 成分的数据集。请根据您的环境更新文件路径。

```
data_p200 <- read.csv("/Users/yuanxiaoyu/Desktop/project/dataset/data_P200.csv")
data_n400 <- read.csv("/Users/yuanxiaoyu/Desktop/project/dataset/data_N400.csv")
data_p600 <- read.csv("/Users/yuanxiaoyu/Desktop/project/dataset/data_P600.csv")
```

```
# Extract unique positions for each ERP component
```

```
p200_positions <- unique(data_p200$position)
```

```
n400_positions <- unique(data_n400$position)
```

```
p600_positions <- unique(data_p600$position)
```

```
# Print the unique positions for verification
```

```
cat("Unique positions for P200:", p200_positions, "\n")
```

```
## Unique positions for P200: F3 F4 FZ C3 C4 CZ CP3 CP4 CPZ FC3 FC4 FCZ F5 FC5 F6 FC6 FT
```

```
cat("Unique positions for N400:", n400_positions, "\n")
```

```
## Unique positions for N400: F3 F4 FZ C3 C4 CZ CP3 CP4 CPZ FC3 FC4 FCZ F5 FC5 P3 P4 Pz
```

```
cat("Unique positions for P600:", p600_positions, "\n")
```

```
## Unique positions for P600: F3 F4 FZ C3 C4 CZ CP3 CP4 CPZ FC3 FC4 FCZ P3 P4 Pz P5 P6 F
```

```
# Function to reshape data to long format for amplitude (V)
```

```
reshape_long_uv <- function(df) {  
  data_long_uv <- df %>%  
    pivot_longer(  
      cols = ends_with("_V"),  
      names_to = "word_class",  
      values_to = "amplitude"  
    ) %>%  
    mutate(  
      word_class = case_when(  
        word_class == "common_noun_V" ~ "Common Noun",  
        word_class == "action_verb_V" ~ "Action Verb",  
        word_class == "typical_event_noun_V" ~ "Typical Event Noun",  
        word_class == "gerund_event_noun_V" ~ "Gerund Event Noun"  
      )  
    )  
  return(data_long_uv)  
}
```

```
# Function to reshape data to long format for latency (ms)
```

```
reshape_long_ms <- function(df) {  
  data_long_ms <- df %>%  
    pivot_longer(  
      cols = ends_with("_ms"),  
      names_to = "word_class",  
      values_to = "latency"  
    ) %>%  
    mutate(  
      word_class = case_when(  
        word_class == "common_noun_ms" ~ "Common Noun",  
        word_class == "action_verb_ms" ~ "Action Verb",  
        word_class == "typical_event_noun_ms" ~ "Typical Event Noun",  
        word_class == "gerund_event_noun_ms" ~ "Gerund Event Noun"  
      )  
    )  
  return(data_long_ms)  
}
```

```
# Reshape each dataset
```

```
data_p200_uv <- reshape_long_uv(data_p200)
```

```

data_p200_ms <- reshape_long_ms(data_p200)

data_n400_uv <- reshape_long_uv(data_n400)
data_n400_ms <- reshape_long_ms(data_n400)

data_p600_uv <- reshape_long_uv(data_p600)
data_p600_ms <- reshape_long_ms(data_p600)

```

函数定义

定义 ERP 对应的脑区

```

# Define brain regions for each ERP component
define_brain_regions_by_erp <- function() {
  brain_regions <- list(
    "P200" = list(
      "Frontal" = c("F3", "F4", "FZ", "F5", "F6"),
      "Frontocentral" = c("FC3", "FC4", "FCZ", "FC5", "FC6"),
      "Frontotemporal" = c("FT7", "FT8"),
      "Central" = c("C3", "C4", "CZ"),
      "Centroparietal" = c("CP3", "CP4", "CPZ"),
      "Occipital" = c("O1", "O2")
    ),
    "N400" = list(
      "Frontal" = c("F3", "F4", "FZ", "F5", "F7"),
      "Frontocentral" = c("FC3", "FC4", "FCZ", "FC5"),
      "Central" = c("C3", "C4", "CZ"),
      "Centroparietal" = c("CP3", "CP4", "CPZ"),
      "Parietal" = c("P3", "P4", "Pz"),
      "Occipital" = c("O1", "O2")
    ),
    "P600" = list(
      "Frontal" = c("F3", "F4", "FZ"),
      "Frontopolar" = c("FP1", "FP2"),
      "Frontocentral" = c("FC3", "FC4", "FCZ"),
      "Central" = c("C3", "C4", "CZ"),
      "Centroparietal" = c("CP3", "CP4", "CPZ"),
      "Parietal" = c("P3", "P4", "Pz", "P5", "P6"),
      "Temporal" = c("T7", "T8")
    )
  )
  return(brain_regions)
}

```

电极位置映射到脑区

```
# 将电极位置映射到脑区
map_electrodes_to_regions <- function(data, erp_name) {
  brain_regions <- define_brain_regions_by_erp()
  erp_regions <- brain_regions[[erp_name]]

  # 创建位置到脑区的映射
  position_to_region <- data.frame(
    position = character(),
    brain_region = character(),
    stringsAsFactors = FALSE
  )

  for (region_name in names(erp_regions)) {
    positions <- erp_regions[[region_name]]
    temp_df <- data.frame(
      position = positions,
      brain_region = region_name,
      stringsAsFactors = FALSE
    )
    position_to_region <- rbind(position_to_region, temp_df)
  }

  # 合并数据
  data_with_regions <- data %>%
    left_join(position_to_region, by = "position") %>%
    filter(!is.na(brain_region)) # 移除未分类的电极

  return(data_with_regions)
}
```

按脑区聚合数据

```
# 对脑区进行平均，减少条件数量
aggregate_by_brain_region <- function(data, measure_col, erp_name) {
  data_with_regions <- map_electrodes_to_regions(data, erp_name)

  # 按脑区平均
```

```

if (measure_col == "amplitude") {
  aggregated_data <- data_with_regions %>%
    group_by(sample_name, word_class, brain_region) %>%
    summarise(
      avg_amplitude = mean(amplitude, na.rm = TRUE),
      n_electrodes = n(),
      .groups = "drop"
    )
} else {
  aggregated_data <- data_with_regions %>%
    group_by(sample_name, word_class, brain_region) %>%
    summarise(
      avg_latency = mean(latency, na.rm = TRUE),
      n_electrodes = n(),
      .groups = "drop"
    )
}

return(aggregated_data)
}

```

运行 ERP 分析

```

# 运行 ERP 分析
run_erp_analysis <- function(data, measure, erp_name, positions) {
  cat("\n", rep("=", 60), "\n")
  cat(" 分析", erp_name, " 成分的", ifelse(measure == "amplitude", " 峰值", " 延迟"), "\n")
  cat(rep("=", 60), "\n")

  # 过滤指定位置的数据
  data_filtered <- data %>%
    filter(position %in% positions) %>%
    filter(!is.na(if(measure == "amplitude") amplitude else latency))

  cat(" 原始数据点数:", nrow(data_filtered), "\n")
  cat(" 被试数:", length(unique(data_filtered$sample_name)), "\n")
  cat(" 电极位置数:", length(unique(data_filtered$position)), "\n")
  cat(" 词类数:", length(unique(data_filtered$word_class)), "\n")

  # 聚合到脑区级别
  aggregated_data <- aggregate_by_brain_region(data_filtered, measure, erp_name)
}

```

```

cat("\n聚合后的数据:\n")
cat(" 数据点数:", nrow(aggregated_data), "\n")
cat(" 脑区:", paste(unique(aggregated_data$brain_region), collapse = ", "), "\n")
cat(" 词类:", paste(unique(aggregated_data$word_class), collapse = ", "), "\n")

# 转换为因子
aggregated_data$sample_name <- as.factor(aggregated_data$sample_name)
aggregated_data$word_class <- as.factor(aggregated_data$word_class)
aggregated_data$brain_region <- as.factor(aggregated_data$brain_region)

# 检查数据完整性
n_regions <- length(unique(aggregated_data$brain_region))
n_word_classes <- length(unique(aggregated_data$word_class))
expected_per_subject <- n_regions * n_word_classes

complete_check <- aggregated_data %>%
  group_by(sample_name) %>%
  summarise(
    n_obs = n(),
    expected = expected_per_subject,
    complete = (n_obs == expected),
    .groups = "drop"
  )

complete_subjects <- complete_check$sample_name[complete_check$complete]
cat(" 完整数据的被试数:", length(complete_subjects), "\n")

# 如果完整数据的被试太少，尝试放宽条件
if (length(complete_subjects) < 15) {
  cat(" 完整数据的被试较少，尝试使用至少有 80% 数据的被试...\n")
  partial_complete_subjects <- complete_check$sample_name[complete_check$n_obs >= 0.8]
  cat(" 至少 80% 数据的被试数:", length(partial_complete_subjects), "\n")

  if (length(partial_complete_subjects) >= 15) {
    complete_subjects <- partial_complete_subjects
  }
}

# 过滤数据
final_data <- aggregated_data %>%
  filter(sample_name %in% complete_subjects) %>%
  droplevels()

cat(" 最终分析的被试数:", length(unique(final_data$sample_name)), "\n")

```

```

cat(" 最终数据点数:", nrow(final_data), "\n")

# 计算描述性统计
if (measure == "amplitude") {
  descriptive_stats <- final_data %>%
    group_by(word_class, brain_region) %>%
    summarise(
      mean_amp = mean(avg_amplitude, na.rm = TRUE),
      sd_amp = sd(avg_amplitude, na.rm = TRUE),
      n = n(),
      .groups = "drop"
    )
  cat("\n描述性统计 (振幅 V):\n")
  # 修改: 显示所有行
  print(descriptive_stats, n = Inf)
} else {
  descriptive_stats <- final_data %>%
    group_by(word_class, brain_region) %>%
    summarise(
      mean_lat = mean(avg_latency, na.rm = TRUE),
      sd_lat = sd(avg_latency, na.rm = TRUE),
      n = n(),
      .groups = "drop"
    )
  cat("\n描述性统计 (潜伏期 ms):\n")
  # 修改: 显示所有行
  print(descriptive_stats, n = Inf)
}

# 运行 ANOVA
tryCatch({
  cat("\n正在运行重复测量 ANOVA...\n")

  if (measure == "amplitude") {
    anova_result <- ezANOVA(
      data = final_data,
      dv = avg_amplitude,
      wid = sample_name,
      within = .(word_class, brain_region),
      detailed = TRUE,
      type = 2
    )
  } else {
    anova_result <- ezANOVA(

```

```

    data = final_data,
    dv = avg_latency,
    wid = sample_name,
    within = .(word_class, brain_region),
    detailed = TRUE,
    type = 2
  )
}

cat("\nANOVA 结果:\n")
anova_table <- anova_result$ANOVA
print(anova_table)

# 解释显著性结果
cat("\n显著性结果解释:\n")
significant_effects <- anova_table[anova_table$p < 0.05, ]
if (nrow(significant_effects) > 0) {
  for (i in 1:nrow(significant_effects)) {
    effect <- significant_effects$Effect[i]
    p_val <- significant_effects$p[i]
    f_val <- significant_effects$F[i]
    cat(sprintf("- %s: F = %.3f, p = %.3f (显著)\n", effect, f_val, p_val))
  }
} else {
  cat("- 没有发现显著效应 (p < 0.05)\n")
}

# 球形性检验
if (!is.null(anova_result$`Mauchly's Test for Sphericity`)) {
  cat("\n球形性检验:\n")
  mauchly_table <- anova_result$`Mauchly's Test for Sphericity`
  print(mauchly_table)

  sphericity_violations <- mauchly_table[mauchly_table$p < 0.05, ]
  if (nrow(sphericity_violations) > 0) {
    cat("\n球形性校正 (Greenhouse-Geisser):\n")
    print(anova_result$`Sphericity Corrections`)
  }
}

return(list(
  data = final_data,
  anova = anova_result,
  descriptive = descriptive_stats,

```



```

        erp_name = erp_name,
        measure = measure
    ))

}, error = function(e) {
    cat("ANOVA 失败:", e$message, "\n")
    cat(" 尝试简化分析...\n")

    return(run_simplified_analysis(final_data, measure, erp_name))
})
}

```

简化分析

```

# 简化分析（当完整 ANOVA 失败时）
run_simplified_analysis <- function(data, measure, erp_name) {
    cat("\n运行简化分析 - 主效应检验:\n")

    # 词类主效应
    if (measure == "amplitude") {
        word_class_data <- data %>%
            group_by(sample_name, word_class) %>%
            summarise(mean_val = mean(avg_amplitude, na.rm = TRUE), .groups = "drop")

        brain_region_data <- data %>%
            group_by(sample_name, brain_region) %>%
            summarise(mean_val = mean(avg_amplitude, na.rm = TRUE), .groups = "drop")
    } else {
        word_class_data <- data %>%
            group_by(sample_name, word_class) %>%
            summarise(mean_val = mean(avg_latency, na.rm = TRUE), .groups = "drop")

        brain_region_data <- data %>%
            group_by(sample_name, brain_region) %>%
            summarise(mean_val = mean(avg_latency, na.rm = TRUE), .groups = "drop")
    }

    # 词类效应
    cat("\n--- 词类主效应 ---\n")
    tryCatch({
        word_anova <- ezANOVA(
            data = word_class_data,
            dv = mean_val,

```

```

        wid = sample_name,
        within = word_class,
        detailed = TRUE
    )
    print(word_anova$ANOVA)
}, error = function(e) {
    cat(" 词类效应分析失败:", e$message, "\n")
})

# 脑区效应
cat("\n--- 脑区主效应 ---\n")
tryCatch({
    region_anova <- ezANOVA(
        data = brain_region_data,
        dv = mean_val,
        wid = sample_name,
        within = brain_region,
        detailed = TRUE
    )
    print(region_anova$ANOVA)
}, error = function(e) {
    cat(" 脑区效应分析失败:", e$message, "\n")
})

return(list(
    data = data,
    erp_name = erp_name,
    measure = measure,
    simplified = TRUE
))
}

```

可视化函数

```

# 可视化函数
create_erp_plots <- function(analysis_result) {
    if (is.null(analysis_result$data)) return(NULL)

    data <- analysis_result$data
    erp_name <- analysis_result$erp_name
    measure <- analysis_result$measure

    # 创建热图

```

```

if (measure == "amplitude") {
  plot_data <- data %>%
    group_by(word_class, brain_region) %>%
    summarise(mean_val = mean(avg_amplitude, na.rm = TRUE), .groups = "drop")

  p1 <- ggplot(plot_data, aes(x = word_class, y = brain_region, fill = mean_val)) +
    geom_tile() +
    scale_fill_gradient2(low = "blue", mid = "white", high = "red",
                        name = "amplitude( V)" ) +
    theme_minimal() +
    labs(title = paste(erp_name, "amplitude"),
         x = "word", y = "region") +
    theme(axis.text.x = element_text(angle = 45, hjust = 1))
} else {
  plot_data <- data %>%
    group_by(word_class, brain_region) %>%
    summarise(mean_val = mean(avg_latency, na.rm = TRUE), .groups = "drop")

  p1 <- ggplot(plot_data, aes(x = word_class, y = brain_region, fill = mean_val)) +
    geom_tile() +
    scale_fill_gradient(low = "lightblue", high = "darkblue",
                       name = "latent(ms)" ) +
    theme_minimal() +
    labs(title = paste(erp_name, "latent"),
         x = "word", y = "region") +
    theme(axis.text.x = element_text(angle = 45, hjust = 1))
}

return(p1)
}

```

运行分析

执行完整的 ERP 分析。

```

run_complete_erp_analysis <- function() {
  # 存储所有结果
  results <- list()

  # P200 分析
  cat(" 开始 P200 分析...\n")
  results$p200_amplitude <- run_erp_analysis(data_p200_uv, "amplitude", "P200", p200_pos)
  results$p200_latency <- run_erp_analysis(data_p200_ms, "latency", "P200", p200_pos)
}

```

```

# N400 分析
cat("\n开始 N400 分析...\n")
results$n400_amplitude <- run_erp_analysis(data_n400_uv, "amplitude", "N400", n400_pos)
results$n400_latency <- run_erp_analysis(data_n400_ms, "latency", "N400", n400_pos)

# P600 分析
cat("\n开始 P600 分析...\n")
results$p600_amplitude <- run_erp_analysis(data_p600_uv, "amplitude", "P600", p600_pos)
results$p600_latency <- run_erp_analysis(data_p600_ms, "latency", "P600", p600_pos)

return(results)
}

# 运行完整分析
cat(" 开始 ERP 脑区功能分区与词类关系分析\n")

```

开始ERP脑区功能分区与词类关系分析

```
cat(rep("=", 80), sep = "", "\n")
```

=====

```
all_results <- run_complete_erp_analysis()
```

开始P200分析...

##

=====

分析 P200 成分的 峰值

=====

原始数据点数: 2240

被试数: 29

电极位置数: 20

词类数: 4

##

聚合后的数据:

数据点数: 676

脑区: Central, Centroparietal, Frontal, Frontocentral, Frontotemporal, Occipital

词类: Action Verb, Common Noun, Gerund Event Noun, Typical Event Noun

完整数据的被试数: 28

最终分析的被试数: 28

最终数据点数: 672

##

描述性统计 (振幅 V):

A tibble: 24 x 5

| ## | word_class | brain_region | mean_amp | sd_amp | n |
|----|-----------------------|----------------|----------|--------|-------|
| ## | <fct> | <fct> | <dbl> | <dbl> | <int> |
| ## | 1 Action Verb | Central | 1.40 | 0.579 | 28 |
| ## | 2 Action Verb | Centroparietal | 1.26 | 0.461 | 28 |
| ## | 3 Action Verb | Frontal | 1.96 | 0.926 | 28 |
| ## | 4 Action Verb | Frontocentral | 1.62 | 0.781 | 28 |
| ## | 5 Action Verb | Frontotemporal | 1.54 | 0.671 | 28 |
| ## | 6 Action Verb | Occipital | 1.99 | 1.53 | 28 |
| ## | 7 Common Noun | Central | 1.54 | 0.704 | 28 |
| ## | 8 Common Noun | Centroparietal | 1.39 | 0.574 | 28 |
| ## | 9 Common Noun | Frontal | 2.13 | 1.07 | 28 |
| ## | 10 Common Noun | Frontocentral | 1.75 | 0.847 | 28 |
| ## | 11 Common Noun | Frontotemporal | 1.62 | 0.702 | 28 |
| ## | 12 Common Noun | Occipital | 2.34 | 1.58 | 28 |
| ## | 13 Gerund Event Noun | Central | 1.44 | 0.707 | 28 |
| ## | 14 Gerund Event Noun | Centroparietal | 1.35 | 0.479 | 28 |
| ## | 15 Gerund Event Noun | Frontal | 1.93 | 0.853 | 28 |
| ## | 16 Gerund Event Noun | Frontocentral | 1.59 | 0.758 | 28 |
| ## | 17 Gerund Event Noun | Frontotemporal | 1.66 | 0.648 | 28 |
| ## | 18 Gerund Event Noun | Occipital | 1.96 | 1.40 | 28 |
| ## | 19 Typical Event Noun | Central | 1.53 | 0.813 | 28 |
| ## | 20 Typical Event Noun | Centroparietal | 1.38 | 0.529 | 28 |
| ## | 21 Typical Event Noun | Frontal | 2.08 | 0.987 | 28 |
| ## | 22 Typical Event Noun | Frontocentral | 1.72 | 0.801 | 28 |
| ## | 23 Typical Event Noun | Frontotemporal | 1.64 | 0.626 | 28 |
| ## | 24 Typical Event Noun | Occipital | 1.96 | 1.35 | 28 |

##

正在运行重复测量ANOVA...

##

ANOVA结果:

| ## | Effect | DFn | DFd | SSn | SSd | F | p |
|------|-------------------------|-----|-----|-------------|-----------|------------|--------------|
| ## 1 | (Intercept) | 1 | 27 | 1941.370705 | 302.87488 | 173.064892 | 2.944521e-13 |
| ## 2 | word_class | 3 | 81 | 2.683488 | 37.04751 | 1.955710 | 1.272114e-01 |
| ## 3 | brain_region | 5 | 135 | 46.966588 | 139.66508 | 9.079563 | 1.833765e-07 |
| ## 4 | word_class:brain_region | 15 | 405 | 2.275831 | 51.45503 | 1.194197 | 2.729238e-01 |
| ## | p<.05 | | | | | | |
| ## 1 | * 0.785212885 | | | | | | |
| ## 2 | 0.005027837 | | | | | | |
| ## 3 | * 0.081255795 | | | | | | |
| ## 4 | 0.004267303 | | | | | | |

##

显著性结果解释:

- (Intercept): F = 173.065, p = 0.000 (显著)

```

## - brain_region: F = 9.080, p = 0.000 (显著)
##
## 球形性检验:
##           Effect          W          p p<.05
## 2           word_class 0.749412732 1.916595e-01
## 3           brain_region 0.011461204 3.194962e-17      *
## 4 word_class:brain_region 0.000070722 2.088247e-06      *
##
## 球形性校正 (Greenhouse-Geisser):
##           Effect          GGe          p[GG] p[GG]<.05          HFe
## 2           word_class 0.8570305 0.1372271016          0.9550238
## 3           brain_region 0.3812060 0.0005097295          * 0.4094118
## 4 word_class:brain_region 0.5197275 0.3045440414          0.7508316
##           p[HF] p[HF]<.05
## 2 0.1302937307
## 3 0.0003527491      *
## 4 0.2890754441
##
## = = = = =
## 分析 P200 成分的 延迟
## = = = = =
## 原始数据点数: 2240
## 被试数: 29
## 电极位置数: 20
## 词类数: 4
##
## 聚合后的数据:
## 数据点数: 676
## 脑区: Central, Centroparietal, Frontal, Frontocentral, Frontotemporal, Occipital
## 词类: Action Verb, Common Noun, Gerund Event Noun, Typical Event Noun
## 完整数据的被试数: 28
## 最终分析的被试数: 28
## 最终数据点数: 672
##
## 描述性统计 (潜伏期 ms):
## # A tibble: 24 x 5
##   word_class      brain_region mean_lat sd_lat      n
##   <fct>          <fct>          <dbl> <dbl> <int>
## 1 Action Verb    Central            177.   22.5    28
## 2 Action Verb    Centroparietal     176.   27.6    28
## 3 Action Verb    Frontal            178.   18.1    28
## 4 Action Verb    Frontocentral      176.   16.0    28
## 5 Action Verb    Frontotemporal     180.   23.5    28
## 6 Action Verb    Occipital          198.   52.9    28
## 7 Common Noun    Central            182.   22.9    28

```

```

## 8 Common Noun Centroparietal 185. 32.6 28
## 9 Common Noun Frontal 177. 15.4 28
## 10 Common Noun Frontocentral 181. 19.1 28
## 11 Common Noun Frontotemporal 182. 27.1 28
## 12 Common Noun Occipital 207. 52.3 28
## 13 Gerund Event Noun Central 192. 25.0 28
## 14 Gerund Event Noun Centroparietal 183. 29.1 28
## 15 Gerund Event Noun Frontal 181. 22.2 28
## 16 Gerund Event Noun Frontocentral 185. 24.0 28
## 17 Gerund Event Noun Frontotemporal 175. 24.8 28
## 18 Gerund Event Noun Occipital 199. 44.0 28
## 19 Typical Event Noun Central 181. 20.9 28
## 20 Typical Event Noun Centroparietal 176. 28.6 28
## 21 Typical Event Noun Frontal 177. 17.3 28
## 22 Typical Event Noun Frontocentral 179. 27.5 28
## 23 Typical Event Noun Frontotemporal 185. 27.2 28
## 24 Typical Event Noun Occipital 195. 49.7 28
##
## 正在运行重复测量ANOVA...
##
## ANOVA结果:
##
##          Effect DFn DFd          SSn          SSd          F
## 1 (Intercept) 1 27 22651815.244 107921.6 5667.065665
## 2 word_class 3 81 3397.776 47482.7 1.932071
## 3 brain_region 5 135 35142.213 270915.8 3.502341
## 4 word_class:brain_region 15 405 7332.419 153396.9 1.290608
##
## p p<.05 ges
## 1 6.432890e-33 * 0.975046111
## 2 1.309306e-01 0.005826941
## 3 5.222927e-03 * 0.057154885
## 4 2.042895e-01 0.012490290
##
## 显著性结果解释:
## - (Intercept): F = 5667.066, p = 0.000 (显著)
## - brain_region: F = 3.502, p = 0.005 (显著)
##
## 球形性检验:
##
##          Effect          W          p p<.05
## 2 word_class 0.8068209977 3.560665e-01
## 3 brain_region 0.0153224303 7.884823e-16 *
## 4 word_class:brain_region 0.0000390991 1.147264e-07 *
##
## 球形性校正 (Greenhouse-Geisser):
##
##          Effect          GGe          p[GG] p[GG]<.05          HFe          p[HF]
## 2 word_class 0.8703328 0.13989271 0.9718583 0.1328341

```

```

## 3          brain_region 0.4072329 0.03624888          * 0.4407385 0.0324016
## 4 word_class:brain_region 0.5611206 0.24660115          0.8382868 0.2187126
##   p[HF]<.05
## 2
## 3          *
## 4
##
## 开始N400分析...
##
##  = = = = =
## 分析 N400 成分的 峰值
##  = = = = =
## 原始数据点数: 2192
## 被试数: 28
## 电极位置数: 20
## 词类数: 4
##
## 聚合后的数据:
## 数据点数: 672
## 脑区: Central, Centroparietal, Frontal, Frontocentral, Occipital, Parietal
## 词类: Action Verb, Common Noun, Gerund Event Noun, Typical Event Noun
## 完整数据的被试数: 28
## 最终分析的被试数: 28
## 最终数据点数: 672
##
## 描述性统计 (振幅 V):
## # A tibble: 24 x 5
##   word_class      brain_region mean_amp sd_amp      n
##   <fct>          <fct>          <dbl> <dbl> <int>
## 1 Action Verb    Central            -0.777  0.303    28
## 2 Action Verb    Centroparietal     -0.356  0.963    28
## 3 Action Verb    Frontal            -1.02   0.404    28
## 4 Action Verb    Frontocentral      -0.810  0.298    28
## 5 Action Verb    Occipital          -1.04   0.705    28
## 6 Action Verb    Parietal           -0.825  0.664    28
## 7 Common Noun    Central            -0.840  0.363    28
## 8 Common Noun    Centroparietal     -0.342  0.857    28
## 9 Common Noun    Frontal            -1.05   0.432    28
## 10 Common Noun   Frontocentral      -0.837  0.399    28
## 11 Common Noun   Occipital          -1.34   0.883    28
## 12 Common Noun   Parietal           -0.773  0.656    28
## 13 Gerund Event Noun Central            -0.766  0.396    28
## 14 Gerund Event Noun Centroparietal     -0.261  0.913    28
## 15 Gerund Event Noun Frontal            -1.04   0.437    28
## 16 Gerund Event Noun Frontocentral      -0.854  0.461    28

```



```

## 17 Gerund Event Noun Occipital      -1.03  0.939  28
## 18 Gerund Event Noun Parietal       -0.789 0.595  28
## 19 Typical Event Noun Central       -0.787 0.424  28
## 20 Typical Event Noun Centroparietal -0.296 0.828  28
## 21 Typical Event Noun Frontal       -0.978 0.355  28
## 22 Typical Event Noun Frontocentral -0.868 0.437  28
## 23 Typical Event Noun Occipital     -1.01  0.820  28
## 24 Typical Event Noun Parietal     -0.791 0.539  28
##
## 正在运行重复测量ANOVA...
##
## ANOVA结果:
##              Effect DFn DFd          SSn          SSd          F          p
## 1      (Intercept)    1  27 443.0107133  98.24521 121.749335 1.650956e-11
## 2      word_class     3  81  0.6363281  10.05887  1.708030 1.718779e-01
## 3      brain_region   5 135 42.6385974 113.64519 10.130144 2.962728e-08
## 4 word_class:brain_region 15 405  1.8094354  32.04078  1.524768 9.293445e-02
##    p<.05          ges
## 1      * 0.635595728
## 2      0.002499066
## 3      * 0.143744026
## 4      0.007073647
##
## 显著性结果解释:
## - (Intercept): F = 121.749, p = 0.000 (显著)
## - brain_region: F = 10.130, p = 0.000 (显著)
##
## 球形性检验:
##              Effect          W          p p<.05
## 2      word_class 9.048792e-01 7.659873e-01
## 3      brain_region 2.489941e-03 1.093996e-24      *
## 4 word_class:brain_region 6.818583e-06 7.703450e-12      *
##
## 球形性校正 (Greenhouse-Geisser):
##              Effect      GGe      p[GG] p[GG]<.05      HFe
## 2      word_class 0.9350430 0.1756158751      1.0545432
## 3      brain_region 0.3520937 0.0003740032      * 0.3747543
## 4 word_class:brain_region 0.3835270 0.1762352450      0.4991470
##      p[HF] p[HF]<.05
## 2 0.1718779262
## 3 0.0002671154      *
## 4 0.1554795626
##
## =====
## 分析 N400 成分的 延迟

```

```

## = = = = =
## 原始数据点数: 2192
## 被试数: 28
## 电极位置数: 20
## 词类数: 4
##
## 聚合后的数据:
## 数据点数: 672
## 脑区: Central, Centroparietal, Frontal, Frontocentral, Occipital, Parietal
## 词类: Action Verb, Common Noun, Gerund Event Noun, Typical Event Noun
## 完整数据的被试数: 28
## 最终分析的被试数: 28
## 最终数据点数: 672
##
## 描述性统计 (潜伏期 ms):
## # A tibble: 24 x 5
##   word_class      brain_region mean_lat sd_lat    n
##   <fct>          <fct>          <dbl> <dbl> <int>
## 1 Action Verb    Central            388.   35.0   28
## 2 Action Verb    Centroparietal     391.   31.1   28
## 3 Action Verb    Frontal            395.   34.5   28
## 4 Action Verb    Frontocentral      387.   40.7   28
## 5 Action Verb    Occipital          394.   36.1   28
## 6 Action Verb    Parietal           390.   30.1   28
## 7 Common Noun    Central            389.   29.5   28
## 8 Common Noun    Centroparietal     383.   22.9   28
## 9 Common Noun    Frontal            404.   39.2   28
## 10 Common Noun   Frontocentral      405.   33.4   28
## 11 Common Noun   Occipital          396.   34.3   28
## 12 Common Noun   Parietal           393.   33.0   28
## 13 Gerund Event Noun Central            383.   30.9   28
## 14 Gerund Event Noun Centroparietal     386.   31.1   28
## 15 Gerund Event Noun Frontal            397.   35.1   28
## 16 Gerund Event Noun Frontocentral      382.   31.7   28
## 17 Gerund Event Noun Occipital          403.   39.7   28
## 18 Gerund Event Noun Parietal           387.   20.2   28
## 19 Typical Event Noun Central            387.   28.8   28
## 20 Typical Event Noun Centroparietal     397.   26.4   28
## 21 Typical Event Noun Frontal            400.   32.0   28
## 22 Typical Event Noun Frontocentral      386.   39.2   28
## 23 Typical Event Noun Occipital          392.   46.1   28
## 24 Typical Event Noun Parietal           397.   29.6   28
##
## 正在运行重复测量ANOVA...
##

```

```

## ANOVA结果:
##
##          Effect DFn DFd          SSn          SSd          F
## 1          (Intercept)    1  27 1.033433e+08 150861.4 1.849559e+04
## 2          word_class     3  81 2.939027e+03 103335.0 7.679271e-01
## 3          brain_region    5 135 1.195429e+04 234028.9 1.379171e+00
## 4 word_class:brain_region 15 405 1.402532e+04 234968.3 1.611637e+00
##
##          p p<.05          ges
## 1 7.797763e-40      * 0.993050662
## 2 5.152956e-01      0.004047507
## 3 2.359755e-01      0.016261066
## 4 6.760973e-02      0.019024639
##
## 显著性结果解释:
## - (Intercept): F = 18495.591, p = 0.000 (显著)
##
## 球形性检验:
##
##          Effect          W          p p<.05
## 2          word_class 0.4136388541 3.909680e-04      *
## 3          brain_region 0.1378778831 7.436106e-06      *
## 4 word_class:brain_region 0.0008371423 2.624547e-02      *
##
## 球形性校正 (Greenhouse-Geisser):
##
##          Effect          GGe          p[GG] p[GG]<.05          HFe          p[HF]
## 2          word_class 0.6306228 0.4626059          0.6767040 0.4706838
## 3          brain_region 0.5713090 0.2561761          0.6459992 0.2531379
## 4 word_class:brain_region 0.5670781 0.1173852          0.8513573 0.0813531
##
##          p[HF]<.05
## 2
## 3
## 4
##
## 开始P600分析...
##
##  = = = = =
## 分析 P600 成分的 峰值
##  = = = = =
## 原始数据点数: 2264
## 被试数: 29
## 电极位置数: 21
## 词类数: 4
##
## 聚合后的数据:
## 数据点数: 784
## 脑区: Central, Centroparietal, Frontal, Frontocentral, Frontopolar, Parietal, Tempora
## 词类: Action Verb, Common Noun, Gerund Event Noun, Typical Event Noun

```

完整数据的被试数: 27

最终分析的被试数: 27

最终数据点数: 756

##

描述性统计 (振幅 V):

A tibble: 28 x 5

| ## | word_class | brain_region | mean_amp | sd_amp | n |
|-------|--------------------|----------------|----------|--------|-------|
| ## | <fct> | <fct> | <dbl> | <dbl> | <int> |
| ## 1 | Action Verb | Central | 0.659 | 0.271 | 27 |
| ## 2 | Action Verb | Centroparietal | 0.621 | 0.221 | 27 |
| ## 3 | Action Verb | Frontal | 0.881 | 0.358 | 27 |
| ## 4 | Action Verb | Frontocentral | 0.754 | 0.262 | 27 |
| ## 5 | Action Verb | Frontopolar | 1.30 | 0.675 | 27 |
| ## 6 | Action Verb | Parietal | 0.890 | 0.345 | 27 |
| ## 7 | Action Verb | Temporal | 1.29 | 0.730 | 27 |
| ## 8 | Common Noun | Central | 0.708 | 0.361 | 27 |
| ## 9 | Common Noun | Centroparietal | 0.655 | 0.313 | 27 |
| ## 10 | Common Noun | Frontal | 0.992 | 0.425 | 27 |
| ## 11 | Common Noun | Frontocentral | 0.818 | 0.408 | 27 |
| ## 12 | Common Noun | Frontopolar | 1.15 | 0.565 | 27 |
| ## 13 | Common Noun | Parietal | 0.919 | 0.410 | 27 |
| ## 14 | Common Noun | Temporal | 1.39 | 0.817 | 27 |
| ## 15 | Gerund Event Noun | Central | 0.731 | 0.310 | 27 |
| ## 16 | Gerund Event Noun | Centroparietal | 0.745 | 0.324 | 27 |
| ## 17 | Gerund Event Noun | Frontal | 0.980 | 0.553 | 27 |
| ## 18 | Gerund Event Noun | Frontocentral | 0.847 | 0.413 | 27 |
| ## 19 | Gerund Event Noun | Frontopolar | 1.22 | 0.651 | 27 |
| ## 20 | Gerund Event Noun | Parietal | 1.04 | 0.478 | 27 |
| ## 21 | Gerund Event Noun | Temporal | 1.14 | 0.587 | 27 |
| ## 22 | Typical Event Noun | Central | 0.656 | 0.203 | 27 |
| ## 23 | Typical Event Noun | Centroparietal | 0.619 | 0.229 | 27 |
| ## 24 | Typical Event Noun | Frontal | 1.03 | 0.470 | 27 |
| ## 25 | Typical Event Noun | Frontocentral | 0.753 | 0.223 | 27 |
| ## 26 | Typical Event Noun | Frontopolar | 1.30 | 0.627 | 27 |
| ## 27 | Typical Event Noun | Parietal | 0.992 | 0.454 | 27 |
| ## 28 | Typical Event Noun | Temporal | 1.29 | 0.899 | 27 |

##

正在运行重复测量ANOVA...

##

ANOVA结果:

| ## | | Effect | DFn | DFd | SSn | SSd | F | p |
|------|--|-------------------------|-----|-----|-------------|----------|-------------|--------------|
| ## 1 | | (Intercept) | 1 | 26 | 670.8739854 | 62.92899 | 277.1810648 | 2.191949e-15 |
| ## 2 | | word_class | 3 | 78 | 0.2149171 | 13.12449 | 0.4257571 | 7.350795e-01 |
| ## 3 | | brain_region | 6 | 156 | 40.1358924 | 57.15486 | 18.2579953 | 5.331208e-16 |
| ## 4 | | word_class:brain_region | 18 | 468 | 2.3215364 | 38.55023 | 1.5657480 | 6.466851e-02 |

```

##      p<.05          ges
## 1      * 0.796164329
## 2      0.001249711
## 3      * 0.189414539
## 4      0.013336024
##
## 显著性结果解释:
## - (Intercept): F = 277.181, p = 0.000 (显著)
## - brain_region: F = 18.258, p = 0.000 (显著)
##
## 球形性检验:
##              Effect              W              p p<.05
## 2              word_class 7.603784e-01 2.386440e-01
## 3              brain_region 5.744274e-03 1.533574e-16      *
## 4 word_class:brain_region 1.324546e-08 9.893855e-15      *
##
## 球形性校正 (Greenhouse-Geisser):
##              Effect              GGe              p[GG] p[GG]<.05              HFe
## 2              word_class 0.8666938 7.072081e-01              0.9715447
## 3              brain_region 0.4215858 5.675837e-08              * 0.4707821
## 4 word_class:brain_region 0.3239569 1.628261e-01              0.4281730
##              p[HF] p[HF]<.05
## 2 7.294827e-01
## 3 1.163394e-08      *
## 4 1.400022e-01
##
## =====
## 分析 P600 成分的 延迟
## =====
## 原始数据点数: 2264
## 被试数: 29
## 电极位置数: 21
## 词类数: 4
##
## 聚合后的数据:
## 数据点数: 784
## 脑区: Central, Centroparietal, Frontal, Frontocentral, Frontopolar, Parietal, Tempora
## 词类: Action Verb, Common Noun, Gerund Event Noun, Typical Event Noun
## 完整数据的被试数: 27
## 最终分析的被试数: 27
## 最终数据点数: 756
##
## 描述性统计 (潜伏期 ms):
## # A tibble: 28 x 5
##   word_class      brain_region mean_lat sd_lat      n

```

```

##      <fct>                <fct>                <dbl> <dbl> <int>
##  1 Action Verb           Central                624.   20.7   27
##  2 Action Verb           Centroparietal          607.   40.7   27
##  3 Action Verb           Frontal                 630.   30.1   27
##  4 Action Verb           Frontocentral           621.   28.1   27
##  5 Action Verb           Frontopolar             612.   39.0   27
##  6 Action Verb           Parietal                607.   23.2   27
##  7 Action Verb           Temporal                622.   30.7   27
##  8 Common Noun           Central                633.   36.1   27
##  9 Common Noun           Centroparietal          620.   35.6   27
## 10 Common Noun           Frontal                 636.   33.6   27
## 11 Common Noun           Frontocentral           633.   30.5   27
## 12 Common Noun           Frontopolar             614.   34.6   27
## 13 Common Noun           Parietal                604.   25.4   27
## 14 Common Noun           Temporal                624.   29.5   27
## 15 Gerund Event Noun     Central                632.   30.0   27
## 16 Gerund Event Noun     Centroparietal          615.   36.1   27
## 17 Gerund Event Noun     Frontal                 623.   31.6   27
## 18 Gerund Event Noun     Frontocentral           628.   28.1   27
## 19 Gerund Event Noun     Frontopolar             612.   31.6   27
## 20 Gerund Event Noun     Parietal                602.   19.1   27
## 21 Gerund Event Noun     Temporal                625.   30.6   27
## 22 Typical Event Noun    Central                626.   27.3   27
## 23 Typical Event Noun    Centroparietal          601.   26.5   27
## 24 Typical Event Noun    Frontal                 630.   35.6   27
## 25 Typical Event Noun    Frontocentral           639.   37.6   27
## 26 Typical Event Noun    Frontopolar             613.   35.2   27
## 27 Typical Event Noun    Parietal                610.   21.8   27
## 28 Typical Event Noun    Temporal                620.   28.5   27
##
## 正在运行重复测量ANOVA...
##
## ANOVA结果:
##              Effect DFn DFd              SSn              SSd              F
## 1      (Intercept)      1  26 2.906909e+08 188917.8 4.000662e+04
## 2      word_class       3  78 3.215953e+03 111141.9 7.523247e-01
## 3      brain_region     6 156 6.602130e+04 123566.5 1.389174e+01
## 4 word_class:brain_region 18 468 1.171347e+04 280371.4 1.086238e+00
##              p p<.05              ges
## 1 5.671273e-43      * 0.997584043
## 2 5.242900e-01      0.004547358
## 3 1.267782e-12      * 0.085739842
## 4 3.628389e-01      0.016366195
##
## 显著性结果解释:

```

```
## - (Intercept): F = 40006.622, p = 0.000 (显著)
## - brain_region: F = 13.892, p = 0.000 (显著)
##
## 球形性检验:
##
##          Effect          W          p p<.05
## 2          word_class 4.036204e-01 4.424585e-04 *
## 3          brain_region 6.201440e-02 9.271210e-07 *
## 4 word_class:brain_region 5.481176e-06 1.033522e-03 *
##
## 球形性校正 (Greenhouse-Geisser):
##
##          Effect      GGe      p[GG] p[GG]<.05      HFe
## 2          word_class 0.6432045 4.720925e-01      0.6937925
## 3          brain_region 0.5980684 2.189746e-08      * 0.7056399
## 4 word_class:brain_region 0.4750410 3.738576e-01      0.7286838
##          p[HF] p[HF]<.05
## 2 4.810437e-01
## 3 1.591911e-09      *
## 4 3.696538e-01
```

生成可视化

为每个 ERP 成分的振幅和潜伏期生成热图。

```
cat("\n生成可视化图表...\n")
```

```
##
## 生成可视化图表...
```

```
plots <- list()
for (result_name in names(all_results)) {
  if (!is.null(all_results[[result_name]])) {
    plots[[result_name]] <- create_erp_plots(all_results[[result_name]])
  }
}
```

显示图表

显示所有生成的热图。

```
for (plot_name in names(plots)) {
  if (!is.null(plots[[plot_name]])) {
    print(plots[[plot_name]])
  }
}
```

}
}







