The Hierarchical Nature of Cognitive Control: EEG Evidence from Task Switching

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Abstract

One of the main research paradigms in cognitive control is task switching. Previous studies have found that switch costs are modulated by the hierarchical nature of cognitive control, but few studies have explored the dynamic neural mechanisms underlying this modulation process. The present study investigated the differences in switch costs across different hierarchical levels and their neural mechanisms using a nested cue-task switching paradigm. In the experiment, participants were required to complete two types of tasks at different hierarchical levels: the low-level task required participants to judge numerical magnitude (or parity), whereas the high-level task required first processing a certain semantic feature of the number (e.g., whether the current number was even) before making a magnitude judgment. Behavioral results showed that switch costs in the high-level task were significantly greater than those in the low-level task. Cue-locked EEG results revealed that the hierarchical effect first appeared in the P2 component, and the switch effect (difference between switch and repetition trials) was modulated by task hierarchy in the CNV component, reflecting greater selective attention and higher proactive control allocated to high-level tasks during the task goal reconfiguration stage. Target-locked EEG results demonstrated that the amplitude differences between switch and repetition trials in the high-level task were significantly larger than those in the low-level task in both the N2 and slow wave (SP) components, reflecting enhanced reactive control during the processes of inhibiting old task sets and reconfiguring new response sets. These findings provide new evidence for task set reconfiguration theory and the hierarchical nature of cognitive control.

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Hierarchical Control in Task Switching: Electrophysiological Evidence

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Abstract

Task switching represents one of the primary paradigms for investigating cognitive control. While previous research has demonstrated that switch costs are modulated by the hierarchical nature of cognitive control, few studies have explored the dynamic neural mechanisms underlying this modulation. The present study employed a nested cue-task switching paradigm to examine differences in switch costs across hierarchical levels and their underlying neural mechanisms. Participants performed two hierarchical tasks: low-level tasks required judging digit magnitude or parity, whereas high-level tasks required first processing a semantic feature (e.g., whether the current digit was even) before performing the magnitude judgment. Behavioral results revealed significantly greater switch costs for high-level tasks compared to low-level tasks. Cue-locked ERP results showed that hierarchical effects first emerged in the P2 component, with switch effects (switch minus repeat) on the CNV component being modulated by task hierarchy, reflecting enhanced selective attention and proactive control allocated to high-level tasks during the task goal reconfiguration stage. Target-locked ERP results demonstrated that the amplitude differences between switch and repeat trials for high-level tasks were significantly larger than for low-level tasks in both N2 and slow wave (SP) components, reflecting enhanced reactive control during inhibition of the old task set and reconfiguration of the new response set. These findings provide novel evidence for task-set reconfiguration theory and the hierarchical nature of cognitive control.

Keywords: cognitive control, task switching, switch costs, hierarchical control

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1. Introduction

Cognitive control refers to a goal-directed psychological process through which individuals flexibly mobilize cognitive resources to adjust behavior in a constantly changing environment (Miller & Cohen, 2001). Task switching is one of the most widely used paradigms for studying cognitive control (Shi & Zhou, 2004; Huang & Lin, 2009; Vandierendonck et al., 2010). Compared with task repetition, task switching produces longer reaction times and higher error rates, a phenomenon known as switch costs (Kiesel et al., 2010; Wylie & Allport, 2000; Wylie et al., 2009; Xie et al., 2020; Zhuo et al., 2021a, 2021b). Switch costs (task switching minus task repetition) are influenced by numerous factors, including preparation time (Altmann, 2019; Kiesel et al., 2010), task attributes (Woodward et al., 2003), task frequency (Jiang, 2018; Baene & Brass, 2013; Frober et al., 2018; Grzyb & Hubner, 2013; Monsell & Mizon, 2006; Rogers & Monsell, 1995), and response selection (Schuch & Koch, 2003). The two dominant theoretical accounts of switch costs are task-set reconfiguration theory and interference inhibition theory. Reconfiguration theory posits that switch costs arise because participants require additional time for endogenous, top-down control processes. This executive control process necessitates reconfiguring the new task —that is, resetting the relevant task parameters—and this resetting or reconfiguration process involves additional control demands (Mayr & Kliegl, 2000; Rogers & Monsell, 1995). In contrast, interference inhibition theory argues that switch costs do not stem from new task-set reconfiguration but rather from interference between previous and current task executions (Allport & Wylie, 1999; Meiran, 2008; Waszak et al., 2003; Wylie & Allport, 2000).

1.1 Proactive and Reactive Control in Task Switching

The Dual Mechanisms of Cognitive Control (DMC) framework proposes that cognitive control can be distinguished into proactive control and reactive control (Braver et al., 2007). Proactive control refers to top-down preparatory processes applied to upcoming tasks, which can be manipulated by altering the preparation time before target onset or cue properties. Studies using alternating-runs paradigms (Karayanidis et al., 2003, 2010), cue-task switching paradigms (Kieffaber & Hetrick, 2005; Nicholson et al., 2005; Swainson et al., 2006), and the Wisconsin Card Sorting Task (Barceló et al., 2000) have found that, compared with task repetition, task switching elicits a switch-related positivity at central and posterior scalp sites during cue presentation, likely reflecting this proactive control process. This switch positivity is modulated by cue validity (Nicholson et al., 2006; Karayanidis & Jamadar, 2014) and the interval between cue and target (Baene & Brass, 2013; Karayanidis et al., 2003; Kieffaber & Hetrick, 2005; Nicholson et al., 2005), and correlates with behavioral switch costs (Karayanidis et al., 2010). Additionally, research has found that both task switching and repetition elicit contingent negative variation (CNV) over frontal-midline regions after cue processing and before target presentation, a component potentially related to anticipatory attention (Brunia, 1999) or response preparation (Karayanidis & Jamadar, 2014). Further ERP evidence for proactive control in task switching comes from studies using cue-task switching paradigms, which have found larger P3 and late positive component (LPC) amplitudes during cue-locked task switching (Han et al., 2018; Kieffaber & Hetrick, 2005), reflecting preparation processes for corresponding tasks or rules during task or rule learning stages (Altmann, 2019; Kiesel et al., 2010).

Reactive control refers to the process by which individuals optimize target processing after target onset by minimizing interference from task-irrelevant information. Research has shown that in target-locked ERPs, task switching elicits more negative frontal and central N2 components and smaller parietal P3b amplitudes compared with task repetition (Karayanidis et al., 2003; Nicholson et al., 2005), reflecting reactive control during target processing, particularly under task-switching conditions. The N2 component over frontal and central regions typically reflects conflict monitoring and interference control (Folstein & Van Petten, 2008; Gajewski et al., 2008; Yeung & Cohen, 2006; Zhu et al., 2020). Nicholson et al. (2005) also found that task switching elicited larger N2 amplitudes than task repetition, reflecting greater response conflict during task switching (Gajewski et al., 2010). Following the N2 component, the P3b component shows a different pattern in target-locked ERPs: unlike cue-locked P3b, task switching elicits smaller target-locked P3b amplitudes than task repetition, manifesting as a switch negativity (Barceló et al., 2000; Kieffaber & Hetrick, 2005; Karayanidis et al., 2003, 2010; Nicholson et al., 2005). This switch negativity may reflect higher task demands and greater working memory load during task switching (Barceló et al., 2000; Karayanidis et al., 2003). Responding to switch trials requires updating the task set—that is, re-extracting new rules and stimulus-response (S-R) associations from working memory—making S-R associations less stable for switch than for repeat trials (Barceló et al., 2000; Waszak et al., 2003).

1.2 Hierarchical Nature of Task Switching

Hierarchical representations have been demonstrated across numerous cognitive processes, including perception (Hommel et al., 2000), working memory (Nie et al., 2017), and action execution (Rosenbaum et al., 1983). In daily life, tasks and actions typically consist of multiple steps that can be represented hierarchically (Lashley, 1951). For example, the task "making coffee" comprises a series of nested subtasks (grinding beans, brewing, etc.). Hierarchical representation is thus a psychological representation composed of nested components and subcomponents, where higher-level information influences lower-level subcomponents (Schneider & Logan, 2006). Hierarchical representation plays a crucial role in goal-directed behavior (Badre & Nee, 2018), as people can hierarchically categorize object attributes to reduce degrees of freedom within categories, enabling better and faster decision-making and responding under limited cognitive resources (Badre & Nee, 2018; Collins et al., 2014; Kleinsorge & Heuer, 1999). Kleinsorge and Heuer (1999) explored how dimensional quantity and hierarchical level affect switch costs using the dimensional organization of "task sets," proposing a hierarchical task-switching model. This model comprises three hierarchical levels: task judgment type, S-R mapping consistency, and response switching/repetition. Task judgment type represents the highest level, S-R mapping consistency the intermediate level, and response switching/repetition the lowest level. Using a combined cue-target paradigm, spatial cues presented above and below a central fixation indicated whether participants should judge the magnitude or location (left/right) of a central digit, while digit color indicated whether to use a consistent or inconsistent S-R mapping rule (e.g., for magnitude tasks, green indicated a consistent rule—left key for small, right for large—while red indicated an inconsistent rule). Response switching/repetition referred to whether the physical response key changed between consecutive trials. Results showed that switch costs were highest when task judgment type switched; when task judgment type repeated, switching S-R mapping rules produced larger switch costs than repeating them, but this effect was reduced when task judgment type switched. Furthermore, when both task judgment type and S-R mapping rules repeated, response switching produced switch costs, whereas response repetition reduced them. Thus, switch cost variation depends on both the number of dimensions requiring change and their hierarchical levels within the structure. The authors argued that when the top level of a hierarchical task set changes, all levels must be reset; conversely, when only the lowest level changes, only that level requires resetting. When individuals switch a particular level, they automatically switch all lower levels as well. Consequently, switch costs are smaller when both task judgment type and S-R mapping rules switch compared to when only task judgment type switches. In short, within a task set, what to do (task goal), how to do it (response rule), and action execution are represented hierarchically from high to low levels.

Recent studies have shown that elements of task sets, such as perceptual stimulus features or S-R rules, can also be represented hierarchically (Collins et al., 2014; Han et al., 2018, 2019). For instance, Collins et al. (2014) used a reinforcement learning task with stimuli that orthogonally combined color (red, yellow) and shape (triangle, circle) features, each mapped to four different response keys. Participants learned these associations through feedback. The researchers investigated whether participants could treat one dimension (e.g., color) as a high-level attribute and another (e.g., shape) as a low-level attribute, and if so, whether switch costs differed between high-level switches (e.g., red circle to yellow circle or yellow triangle) and low-level switches (e.g., red circle to red triangle), along with the underlying neural mechanisms. Behavioral results confirmed that participants spontaneously formed hierarchical representations of perceptual features, while ERP results showed that high-level switches elicited more negative late ERP components (450–609 ms) over parietal cortex than low-level switches, indicating that high-level switches consume more cognitive resources. Han et al. (2018) employed a cued task-switching paradigm, designating one perceptual dimension of a cue (letter R) as a high-level attribute (e.g., solid vs. hollow) and the other two as low-level attributes nested under the high-level attribute. Participants responded to subsequent target digits (1–9) according to rules specified by different cue attributes. Results showed that during the cue-locked phase, high-level rule switching elicited smaller N2 and larger P3 amplitudes than low-level rule switching, reflecting enhanced proactive control during rule learning; during the target-locked phase, high-level rule switching elicited more negative N2 and smaller P3 amplitudes, reflecting enhanced reactive control during task execution. Han et al. (2019) presented cues and tasks simultaneously and obtained similar results. Additionally, Li et al. (2019) used a nested task-switching paradigm with three hierarchical levels of digit judgment tasks, finding that upward switching (from low- to mid-level tasks) elicited more negative N2 amplitudes and sustained positivity than downward switching (from high- to mid-level tasks), reflecting different response inhibition and task reconfiguration processes.

Existing behavioral research demonstrates hierarchical representation of task sets and their elements (e.g., perceptual features and response rules), with higher-level switches incurring greater switch costs than lower-level switches (Collins et al., 2014; Han et al., 2018, 2019). However, existing ERP studies have yielded inconsistent conclusions due to different research foci. For example, Li et al. (2019) employed a nested three-level task to examine asymmetric switch costs across hierarchical levels—that is, cross-level switching in different directions—and found that increased cognitive control during low-to-high switching was associated with larger N2 amplitudes. Three other studies (Collins et al., 2014; Han et al., 2018, 2019) focused on hierarchical levels of perceptual dimensions or response rules. Collins et al. (2014) found that high-level perceptual dimension switching elicited more negative late waves over parietal cortex than low-level dimension switching, while Han et al. (2018, 2019) found that target stimuli under high-level response rule switching conditions elicited more negative N2 amplitudes than under low-level response rule switching. Like these two studies (Han et al., 2018, 2019), the present research explores hierarchical cognitive control and its neural mechanisms. However, our approach differs: Han et al. (2018, 2019) investigated hierarchical levels of response rule switching, comparing switch costs between two high-level rules (e.g., Rule 1: "If cue letter R is solid, select tasks based on color" vs. Rule 2: "If cue letter R is hollow, select tasks based on orientation") and two low-level rules (e.g., Rule 3: "If solid cue letter R is red, perform magnitude judgment" vs. Rule 4: "If solid cue letter R is green, perform parity judgment"). In contrast, our study examines hierarchical levels of task switching, comparing switch costs between two high-level tasks (e.g., Task 1: "Judge the parity of large numbers" vs. Task 2: "Judge the magnitude of odd numbers") and two low-level tasks (e.g., Task 3: "Judge digit magnitude" vs. Task 4: "Judge digit parity"). We specifically focus on the neural mechanisms underlying differential switch costs within different hierarchical levels. In short, while substantial behavioral research has revealed greater switch costs for high-level than low-level task switching, no study to date has used ERP technology to investigate the neural mechanisms of cognitive control elicited by task hierarchy itself—an essential element of task sets. Although some researchers have explored hierarchical levels of perceptual dimensions (Collins et al., 2014), response rules (Han et al., 2018, 2019), and asymmetric cross-level switching (Li et al., 2019), none have addressed task hierarchy.

1.3 Research Purpose and Hypotheses

This study aims to leverage the high temporal resolution of ERPs to explore the hierarchical nature of cognitive control and its neural mechanisms during task switching. Using a cue-task paradigm, we investigate whether proactive control related to cue processing and reactive control related to target processing are modulated by task hierarchy. If so, we examine which ERP components reflect this modulation and whether it manifests in components associated with conflict response inhibition and task-set reconfiguration (e.g., N2/P3), such that amplitude differences between switch and repeat trials are greater for high-level than low-level tasks. We designed a two-level task with hierarchical nesting (Li et al., 2019; Lu et al., 2017). In low-level tasks, participants judged digit magnitude or parity, whereas high-level tasks required identifying a stimulus attribute before performing the low-level task (Figure 1). Based on previous research on task switching and hierarchical control (Karayanidis et al., 2003, 2010; Kleinsorge & Heuer, 1999; Collins et al., 2014; Han et al., 2018; Li et al., 2019), we hypothesized: (1) Low- and high-level tasks differ in the number of dimensions requiring processing: low-level tasks process only one dimension, while high-level tasks process two semantic dimensions (e.g., magnitude and parity). Therefore, high-level tasks would elicit longer reaction times and higher error rates. During high-level task switching, both dimensions require switching, potentially increasing interference from the previous task and requiring longer task-set resetting time, resulting in larger switch costs for high-level than low-level tasks. (2) Previous ERP research using cue-task switching paradigms has shown that cue-locked task switching elicits smaller N2 and larger P3 amplitudes (i.e., switch positivity) compared with task repetition, whereas target-locked N2 and P3 amplitude differences between task switching and repetition show a reversed pattern (i.e., switch negativity). We hypothesized that both cue-locked switch positivity and target-locked switch negativity would be modulated by task hierarchy, manifesting in components reflecting proactive and reactive control (N2, P3, or slow potential, SP), such that amplitude differences between switch and repeat trials would be larger for high-level than low-level tasks. (3) According to Kleinsorge and Heuer' s (1999) hierarchical task-switching model, task goals are higher-level than S-R mapping rules, requiring greater cognitive control and potentially longer processing time. Therefore, hierarchical effects on task goals might appear later than those on S-R mapping rules, as reported in Han et al. (2018).

2. Method

2.1 Participants

Thirty right-handed volunteers (15 male; aged 18–23 years, mean age 19.3 years) from Jiangxi Normal University participated in the experiment. All participants had no history of psychiatric or neurological disorders, had normal or corrected-to-normal vision, and no color blindness. Two participants were excluded due to excessive EEG artifacts. Using G*Power software with a medium effect size ($p^2 = 0.25$), desired power ($1\text{-}\beta = 0.80$), and significance level ($\alpha = 0.05$), the required sample size was calculated as 24, confirming that our actual sample size was adequate. All participants provided written informed consent and received monetary compensation upon completion.

2.2 Materials and Design

We employed a nested cue-task switching paradigm (Badre & D' Esposito, 2007; Li et al., 2019) with two hierarchical task levels. Low-level tasks required participants to perform parity or magnitude judgments on digits (1–9, excluding 5), processing only one semantic feature per trial. High-level tasks required participants to first identify a digit attribute before performing the low-level task. For example, when judging the parity of numbers greater than 5, participants first confirmed whether the current digit exceeded 5; if so, they performed the parity judgment, otherwise they made no response (no-go trials). No-go trials occurred on approximately 16% of trials and, along with the first go trial following each no-go trial, served as filler trials and were excluded from statistical analysis. In high-level tasks, both semantic features (parity and magnitude) required processing, which could be orthogonally combined into four high-level task types: "parity judgment for numbers greater than 5," "parity judgment for numbers less than 5," "magnitude judgment for odd numbers," and "magnitude judgment for even numbers." To ensure that both attribute identification and semantic judgment switched during high-level task switching, two high-level tasks requiring the same semantic processing (e.g., parity judgment for numbers greater than 5 and parity judgment for numbers less than 5) were never included in the same experimental block.

Cues consisting of color-shape combinations corresponded to different task types, with high- and low-level tasks pseudorandomly intermixed within each block. Participants pressed the "F" key with their left index finger for odd or large numbers and the "J" key with their right index finger for even or small numbers. The mapping between cue attributes and response keys was counterbalanced across participants.

A 2 (transition type: task repetition, task switching) × 2 (hierarchical level: low, high) within-subjects design was used. Based on the relationship between consecutive trials, four experimental conditions were defined: low-level task repetition, low-level task switching, high-level task repetition, and high-level task switching, each comprising 85 trials. Additional conditions (e.g., switching from high- to low-level tasks) served as filler trials, with 85 trials each for high-to-low and low-to-high switches. No-go trials (115 trials) and their subsequent go trials (115 trials) were also included, totaling 740 trials presented across 4 blocks of 185 trials each. The entire experiment lasted approximately 60 minutes.

2.3 Procedure

Participants performed different semantic processing tasks on target stimuli according to cue instructions (Figure 1). For example, they might need to determine whether the current digit was odd. Each trial began with a 500 ms fixation cross at the center of the screen, followed by a random 500–800 ms blank interval, then a 1000 ms cue presentation, another 500–800 ms blank interval, and finally the digit stimulus, which remained until participants responded. Participants completed a practice block before the formal experiment, during which they received feedback. They were instructed to respond as quickly and accurately as possible throughout the experiment.

2.4 EEG Recording and Analysis

EEG data were recorded using a Brain Products system with a 64-channel electrode cap according to the extended 10-20 international system. The online reference was at FCz, ground at AFz, and vertical electrooculogram (EOG) recorded 1 cm below the right eye orbit. The sampling rate was 500 Hz with a bandpass filter of 0.05-100 Hz. All electrode impedances were maintained below 10 kΩ.

For offline analysis, bilateral mastoids (TP9 and TP10) were re-referenced, and independent component analysis (ICA) was used to remove artifacts related to blinks, eye movements, and muscle activity from all electrodes. Offline bandpass filtering was set to 0.1-24 Hz, with an artifact rejection criterion of $\pm$80 V. ERP epochs ranged from -200 to 1000 ms relative to stimulus onset, with a 200 ms pre-stimulus baseline. Only correct trials were averaged for each condition, and grand averages were computed across participants.

Based on previous task-switching and hierarchical control research (Han et al., 2018; Li et al., 2019; Lu et al., 2017; Rubinstein et al., 2001), 18 electrode sites were selected: F1, F2, F3, F4, F5, F6, C1, C2, C3, C4, C5, C6, P1, P2, P3, P4, P5, and P6. These were grouped into six brain regions: left frontal (F1, F3, F5), right frontal (F2, F4, F6), left central (C1, C3, C5), right central (C2, C4, C6), left parietal (P1, P3, P5), and right parietal (P2, P4, P6).

Based on previous research and visual inspection of ERP waveforms, the following time windows were selected for analysis. For the cue-locked phase, mean amplitudes of P2 (220-270 ms) and CNV (800-1000 ms) over left parietal regions were subjected to 2 (hierarchical level: high, low) × 2 (task type: repetition, switching) repeated-measures ANOVA. To visualize hierarchical effects on switch costs across ERP components, difference waves (switch minus repeat) were compared using paired-samples t-tests. For the target-locked phase, four time windows were analyzed: P2 (150-200 ms), N2 (200-250 ms), P3 (340-420 ms), and SP (600-1000 ms). Given that N2 differences were primarily observed over anterior and central regions, N2 amplitudes were analyzed using 2 (hierarchical level: high, low) × 2 (task type: repetition, switching) × 2 (anterior-posterior region: frontal, central) × 2 (hemisphere: left, right) repeated-measures ANOVA. P2, P3, and SP amplitudes were analyzed using 2 (hierarchical level: high, low) × 2 (task type: repetition, switching) × 3 (region: frontal, central, parietal) × 2 (hemisphere: left, right) repeated-measures ANOVA. Additionally, N2 difference waves were analyzed using 2 (hierarchical level: high, low) × 2 (region: frontal, central) × 2 (hemisphere: left, right) repeated-measures ANOVA, while P2, P3, and SP difference waves were analyzed using 2 (hierarchical level: high, low) × 3 (region: frontal, central, parietal)

× 2 (hemisphere: left, right) repeated-measures ANOVA. Greenhouse-Geisser correction was applied to p-values, and Bonferroni correction was used for multiple comparisons, with significance set at $\alpha = 0.05$.

Figure 1. Task hierarchical structure and experimental procedure.

3. Results

Both behavioral and ERP analyses were based on correct trials, excluding practice data, the first trial of each block, trials with RTs faster than 200 ms or exceeding 2.5 SDs of each participant' s mean, post-error trials, no-go trials and their subsequent go trials, and filler trials.

3.1 Behavioral Results

Mean accuracy and RTs for each condition are presented in Table 1. Accuracy analysis revealed a marginally significant main effect of task type, $F(1, 27) = 4.21$, $p = 0.050$, $\mathrm{p}^2 = 0.13$, with lower accuracy for task switching (94.9%) than repetition (96.3%). The main effect of hierarchical level was significant, $F(1, 27) = 43.06$, $p < 0.001$, $\mathrm{p}^2 = 0.61$, with lower accuracy for high-level (93.9%) than low-level tasks (97.3%). The interaction between task type and hierarchical level was not significant ($p = 0.341$). Paired-samples t-tests comparing switch costs between low-level (-0.8%) and high-level tasks (-2%) revealed no significant difference ($p > 0.050$).

RT analysis showed a significant main effect of task type, $F(1, 27) = 62.84$, $p < 0.001$, $\mathrm{p}^2 = 0.69$, with longer RTs for task switching (1030 ms) than repetition (869 ms). The main effect of hierarchical level was significant, $F(1, 27) = 115.87$, $p < 0.001$, $\mathrm{p}^2 = 0.81$, with longer RTs for high-level (1093 ms) than low-level tasks (806 ms). The interaction between task type and hierarchical level was significant, $F(1, 27) = 21.61$, $p < 0.001$, $\mathrm{p}^2 = 0.44$. Simple effects analysis revealed that RTs were longer for switching than repetition at both hierarchical levels, and longer for high-level than low-level tasks for both transition types. Paired-samples t-tests comparing switch costs showed significantly greater costs for high-level (236 ms) than low-level tasks (87 ms), $t(27) = 4.65$, $p < 0.001$, $d = 1.78$.

Table 1. Reaction times (ms) and accuracy (%) across conditions.

Condition	RT (M ± SD)	Accuracy (M ± SD)
Low-level repetition	763 ± 170	97.7 ± 2
Low-level switching	850 ± 206	96.9 ± 3
High-level repetition	975 ± 138	94.9 ± 4
High-level switching	1211 ± 202	92.9 ± 5

3.2 ERP Results

3.2.1 Cue-Locked ERPs P2. The main effect of hierarchical level was significant, $F(1, 27) = 8.71$, $p = 0.006$, p^2 = 0.244, with larger P2 amplitudes for high-level (5.65 V) than low-level tasks (4.75 V; see Figure 2). No other main effects or interactions were significant (all $ps > 0.050$). Paired-samples t-tests on difference waves revealed no significant difference between high-level (0.31 V) and low-level (0.30 V) task switching-repetition differences, $t(27) = -0.01$, $p = 0.989$, $d = -0.005$.

CNV. The main effect of hierarchical level was not significant ($p > 0.050$). The main effect of task type was significant, $F(1, 27) = 24.36$, $p < 0.001$, p^2 = 0.474, with more positive amplitudes for task switching (1.51 V) than repetition (0.23 V). The interaction between hierarchical level and task type was significant, $F(1, 27) = 5.17$, $p = 0.031$, p^2 = 0.161. Simple effects analysis revealed that task switching elicited more positive CNV amplitudes than repetition at both hierarchical levels ($p$low = 0.004, $p$high < 0.001). For task switching trials, high-level switching (1.92 V) elicited more positive amplitudes than low-level switching (1.09 V, $p = 0.018$), whereas no hierarchical difference emerged for repetition trials ($p = 0.995$). Paired-samples t-tests on difference waves showed that the switching-repetition amplitude difference was significantly larger for high-level (0.82 V) than low-level tasks (-0.01 V), $t(27) = 2.27$, $p = 0.031$, $d = 0.87$.

Figure 2. Cue-locked ERP waveforms across conditions.

3.2.2 Target-Locked ERPs P2. The main effect of task type was significant, $F(1, 27) = 5.47$, $p = 0.027$, p^2 = 0.169, with smaller P2 amplitudes for task switching (2.27 V) than repetition (2.76 V). The interaction between hierarchical level and task type was significant, $F(1, 27) = 8.41$, $p = 0.007$, p^2 = 0.238. Simple effects analysis revealed that at the high hierarchical level, task switching (2.14 V) elicited smaller P2 amplitudes than repetition (3.08 V, $p = 0.002$), whereas no difference emerged at the low hierarchical level ($p = 0.860$). Analysis of difference waves revealed a significant main effect of hierarchical level, $F(1, 27) = 8.41$, $p = 0.007$, p^2 = 0.238, with larger difference wave amplitudes for high-level (-0.93 V) than low-level tasks (-0.04 V). The main effect of brain region was significant, $F(1, 27) = 14.35$, $p < 0.001$, p^2 = 0.347, with smaller difference waves over parietal (0.04 V) than frontal (-0.81 V) and central (-0.68 V) regions. The main effect of hemisphere was marginally significant, $F(1, 27) = 3.66$, $p = 0.066$, p^2 = 0.119.

N2. The main effect of task type was significant, $F(1, 27) = 6.31$, $p = 0.018$, p^2 = 0.189, with more negative N2 amplitudes for task switching (2.31 V) than repetition (2.86 V; see Figure 3). The interaction between hierarchical level and task type was marginally significant, $F(1, 27) = 3.68$, $p = 0.066$, p^2 = 0.120. Analysis of difference waves revealed a significant main effect of hierarchical level, $F(1, 27) = 4.82$, $p = 0.037$, p^2 = 0.152, with larger difference wave amplitudes for high-level (-0.89 V) than low-level tasks (-0.20 V). The main effect of hemisphere was significant, $F(1, 27) = 6.10$, $p = 0.020$, $p^2 = 0.185$, with larger difference waves over left (-0.69 V) than right hemisphere (-0.40 V). No other main effects or interactions were significant (all $ps > 0.050$).

P3. The main effect of task type was significant, $F(1, 27) = 9.52$, $p = 0.005$, $p^2 = 0.261$, with smaller P3 amplitudes for task switching (2.71 V) than repetition (3.53 V). The three-way interaction between hierarchical level, anterior-posterior region, and hemisphere was significant, $F(2, 54) = 8.59$, $p = 0.002$, $p^2 = 0.241$, though simple effects analysis revealed no significant results (all $ps > 0.050$). The interaction between task type and hemisphere was significant, $F(1, 27) = 4.26$, $p = 0.049$, $p^2 = 0.136$, with simple effects showing smaller P3 amplitudes for switching than repetition in both hemispheres ($p$left $= 0.004$, $p$right $= 0.008$). No other main effects or interactions were significant (all $ps > 0.050$). Analysis of difference waves for high- and low-level tasks revealed no significant main effects or interactions (all $ps > 0.050$).

SP. The main effect of task type was significant, $F(1, 27) = 6.48$, $p = 0.017$, $p^2 = 0.194$, with smaller SP amplitudes for task switching (0.69 V) than repetition (1.27 V). The interaction between hierarchical level and task type was significant, $F(1, 27) = 4.99$, $p = 0.034$, $p^2 = 0.156$. Simple effects analysis revealed that at the high hierarchical level, task switching (0.45 V) elicited smaller SP amplitudes than repetition (1.51 V, $p = 0.004$), whereas no difference emerged at the low hierarchical level ($p = 0.693$). The interaction between task type and anterior-posterior region was marginally significant, $F(2, 54) = 3.35$, $p = 0.062$, $p^2 = 0.111$. The interaction between task type and hemisphere was significant, $F(1, 27) = 4.21$, $p = 0.050$, $p^2 = 0.135$, with simple effects showing smaller SP amplitudes for switching (0.32 V) than repetition (1.13 V) in the left hemisphere ($p = 0.003$) but not in the right ($p = 0.172$). The three-way interaction between hierarchical level, task type, and hemisphere was significant, $F(1, 27) = 5.83$, $p = 0.023$, $p^2 = 0.178$, with simple effects revealing that in the left hemisphere, high-level switching (-0.07 V) elicited smaller SP amplitudes than high-level repetition (1.36 V, $p = 0.001$), whereas no other significant effects emerged in the right hemisphere (all $ps > 0.050$). No other main effects or interactions were significant (all $ps > 0.050$). Analysis of difference waves revealed a significant main effect of hierarchical level, $F(1, 27) = 4.99$, $p = 0.034$, $p^2 = 0.156$, with larger difference wave amplitudes for high-level (-1.05 V) than low-level tasks (-0.11 V). The main effect of hemisphere was marginally significant, $F(1, 27) = 4.21$, $p = 0.050$, $p^2 = 0.135$, with larger difference waves over left (-0.80 V) than right hemisphere (-0.36 V). The interaction between hemisphere and hierarchical level was significant, $F(1, 27) = 5.83$, $p = 0.023$, $p^2 = 0.178$, with simple effects showing larger difference waves for high-level (-1.44 V) than low-level tasks (-0.16 V) in the left hemisphere ($p = 0.011$) but not in the right ($p = 0.166$). No other main effects or interactions were significant (all $ps > 0.050$).

Figure 3. Target-locked ERP waveforms across conditions.

Figure 4. Topographic maps of difference waves for different hierarchical levels in the target-locked phase.

4. Discussion

Using a cued task-switching paradigm, this study compared electrophysiological differences in cognitive control (proactive and reactive) between high- and low-level task switching. Behavioral results showed longer RTs and higher error rates for task switching than repetition, reflecting typical switch costs (Barceló & Cooper, 2018; Kiesel et al., 2010; Rogers & Monsell, 1995; Schneider, 2017; Swainson et al., 2017, 2019; Tarantino et al., 2016). High-level tasks showed longer RTs and higher error rates than low-level tasks, consistent with previous hierarchical task research and reflecting the greater complexity and abstraction of high-level tasks (Hirsch et al., 2020; Li et al., 2019; Lu et al., 2017).

The significant interaction between task type and hierarchical level revealed that switch costs were modulated by hierarchy, with significantly greater switch costs for high-level than low-level tasks. This aligns with previous findings (Kleinsorge & Heuer, 1999; Collins et al., 2014). In our study, high- and low-level tasks differed in processing complexity. During low-level task switching, participants only needed to shift attention between single semantic features (e.g., from parity to magnitude). In contrast, high-level task switching required switching both attribute identification and semantic judgment processes. According to interference theory (Allport et al., 1999; Meiran, 2008; Waszak et al., 2003; Wylie & Allport, 2000), low-level switching only requires inhibiting one attribute from the previous task, whereas high-level switching demands inhibition of two attributes (e.g., both digit identification and semantic processing). Task-set reconfiguration theory (Mayr & Kliegl, 2000; Rogers & Monsell, 1995) suggests that high-level tasks involve more complex elements requiring reconfiguration (e.g., digit identification, semantic judgment, response selection), making switching more difficult. Second, proactive control triggered by cues differs across hierarchical levels. Nicholson et al. (2006) manipulated cue informativeness to dissociate preparatory effects on proactive and reactive control, finding that increasing cue-target intervals (CSI) only affected proactive control. In our study, the 1600 ms CSI allowed proactive preparation to reduce switch costs in low-level tasks. However, for high-level tasks, whether the task requires a response can only be determined after target onset and completion of the first processing stage, suggesting that increased high-level switch costs may result from less adequate proactive control during the CSI.

Importantly, the larger RT switch costs for high-level tasks cannot be attributed to occasional no-go trials. Participants made no response on these trials, similar to no-go trials in response inhibition studies. Previous research has shown that introducing no-go trials in task switching can induce N-2 repetition costs in task-repeat trials, prolonging RTs and reducing or eliminating switch costs (Schoch & Koch, 2003). However, our study found larger switch costs in high-level tasks despite including no-go trials, indicating that the significant differences between high- and low-level tasks are not due to no-go trial presence.

4.1 Hierarchical Nature of Proactive Control

In cued task-switching research, the cue processing phase is typically defined as proactive control (Karayanidis et al., 2003), involving selective attention to task-relevant cue information, active representation and maintenance in working memory, and formation of corresponding response preparation. Our study found clear hierarchical effects in the cue-locked P2 time window, consistent with Han et al. (2018), suggesting that hierarchical differences are detected by the brain approximately 200 ms after cue presentation for both hierarchical rules and tasks. The parietal P2 is associated with early perceptual (Han et al., 2018) and attentional processes (Luck & Hillyard, 2010). For instance, P2 is observed when discriminating whether target stimuli contain task-relevant perceptual features (Han et al., 2018). In our experiment, high-level task cues elicited larger P2 amplitudes than low-level cues, indicating that participants allocated more attentional resources to encoding cue perceptual features when preparing for high-level tasks, enabling subsequent retrieval of more complex task rules.

In the CNV time window, task switching elicited more positive amplitudes than repetition at both hierarchical levels, with this switch positivity reflecting differential task preparation processes. Previous research indicates that task paradigms (Karayanidis et al., 2003, 2010; Kieffaber & Hetrick, 2005; Nicholson et al., 2005; Swainson et al., 2006), cue presentation methods (Kieffaber & Hetrick, 2005), cue explicitness (Rushworth et al., 2002), and practice (Karayanidis et al., 2003; Nicholson et al., 2005) do not eliminate switch positivity, suggesting differential involvement of proactive control when cues signal switching versus repetition. In our study, the cue-locked CNV switch positivity likely reflects this proactive control process.

Furthermore, the switching-repetition amplitude difference in the CNV window was significantly larger for high-level than low-level tasks, with this hierarchical difference in difference waves arising from more positive-going amplitudes for high-level versus low-level switching. Research shows that CNV, as an effective index of proactive control, is more engaged for difficult than simple tasks (Poljac & Yeung, 2014) and is modulated by the number of task-set dimensions (Kieffaber et al., 2013), with more dimensions requiring stronger proactive control and eliciting more positive CNV amplitudes. When encountering task switching with different dimensional parameters, the brain allocates more proactive control to multi-dimensional task switching (Kleinsorge & Heuer, 1999). We propose that cue-locked CNV amplitudes reflect preparation for different tasks: during task repetition, participants can simply reapply the previous task rule, eliciting more negative CNV amplitudes, whereas during task switching, the rule maintained in working memory is no longer applicable, requiring retrieval of a new rule matching the current cue and eliciting more positive CNV amplitudes. Compared with low-level switching, high-level switching requires retrieval of more complex cue information and longer task rule reconfiguration time, resulting in more positive-going CNV amplitudes.

4.2 Hierarchical Nature of Reactive Control

Reactive control refers to the flexible use of task-relevant information at the moment of response, resolving conflicts by retrieving and reactivating previous cue information when needed to guide current responses and correct erroneous response tendencies (Braver et al., 2007). In our low-level tasks, participants could effectively prepare during the post-cue interval and simply retrieve cue information to make a button press when the target appeared. In high-level tasks, however, participants still needed to retrieve and reactivate the rule represented by the previous cue after target onset to process the target' s first dimension (precondition) and determine whether a response was required. If so, they then retrieved the response mapping rule to execute the response. Thus, high-level tasks require more reactive control. ERP results showed that task switching elicited smaller P2 amplitudes than repetition. The P2 component is thought to be related to task activation (Kieffaber & Hetrick, 2005) and has been interpreted as an index of S-R association retrieval or evaluation of whether stimulus dimensional features are task-relevant (Rushworth et al., 2002). Our study further found that switching effects were modulated by hierarchical level: high-level switching elicited smaller P2 amplitudes than high-level repetition, whereas no such difference emerged between low-level switching and repetition. We infer that when target digits appeared, high-level tasks still required processing of dimensional features to determine whether the current trial required a response. For example, if the cue indicated a rule to judge the magnitude of odd numbers but the target digit was even, no response was required. Thus, the P2 component in our study may be related to evaluating whether stimulus dimensional features match the target category.

In the target-locked phase, a significant switching effect emerged in the N2 time window, with task switching eliciting more negative N2 amplitudes than repetition, replicating previous findings (Han et al., 2018; Gajewski et al., 2010; Nicholson et al., 2005; Swainson et al., 2006, 2003). The N2 component is most prominent over frontal and central regions, with source localization indicating primary generation in the anterior cingulate cortex. Larger N2 amplitudes under conflict conditions suggest its involvement in conflict monitoring (Van Veen & Carter, 2002; Yeung & Cohen, 2006) or response selection mechanisms (Gajewski et al., 2008, 2010, 2018; Yeung & Cohen, 2006). In our study, task switching required overcoming interference from irrelevant task sets to accomplish the target task (Allport & Wylie, 1999; Wylie & Allport, 2000). The larger amplitude difference between high-level task switching and repetition compared with low-level tasks likely reflects greater inhibition demands in high-level tasks. For example, when switching from "parity judgment for numbers greater than 5" to "magnitude judgment for even numbers," participants must inhibit both digit identification (i.e., whether >5) and semantic processing, whereas low-level switching only requires inhibiting one semantic attribute.

Previous research has shown that smaller target-locked P3 or SP amplitudes for task switching than repetition reflect task execution processes (Han et al., 2019) and response-set reconfiguration (Barceló et al., 2000; Waszak et al., 2003; Xie et al., 2020). Our study found a clear switching effect in the P3 window, with task switching eliciting smaller P3 amplitudes than repetition, consistent with previous target-locked P3 findings (Han et al., 2018; Karayanidis et al., 2003, 2010; Kieffaber & Hetrick, 2005; Nicholson et al., 2006; Swainson et al., 2003). Researchers have suggested that smaller P3 amplitudes (i.e., switch negativity) reflect reduced S-R association stability (Barceló et al., 2000). During task repetition, S-R associations remain identical to the previous trial, allowing simple rule application, whereas new S-R associations formed during switching are less stable, requiring longer response-set reconfiguration time (i.e., longer RTs). Some studies (Hsieh & Wu, 2011; Li et al., 2019) have combined target-locked P3 and late components into a late sustained slow wave associated with response preparation during execution. Our study observed significant switching effects in the SP window, with task switching eliciting smaller SP amplitudes than repetition, suggesting that this response-set reconfiguration process extends into the SP time window.

Most importantly, comparing SP amplitude differences between high-level task switching and repetition with those between low-level switching and repetition revealed significantly larger difference wave amplitudes for high-level tasks in left central-posterior regions. This indicates differential cognitive control processes during response-set reconfiguration across hierarchical levels: reconstructing task sets during high-level switching is more difficult than during low-level switching, and newly formed S-R associations are less stable. Notably, according to Kleinsorge and Heuer' s (1999) hierarchical task-switching model, task goals are higher-level than S-R mapping rules, requiring greater cognitive control and potentially exerting different hierarchical effects. Compared with Han et al. (2018), where hierarchical effects on rule reconfiguration appeared in the P3 window (350–450 ms), our task reconfiguration hierarchical effects emerged later in the SP window (600–1000 ms). This discrepancy may stem from different manipulated task-set elements: Han et al. (2018) investigated hierarchical levels of response rule switching by manipulating cue features, whereas our study manipulated task hierarchy. Within a task set, tasks are higher-level and more abstract than response rules (Kleinsorge & Heuer, 1999), making their reconfiguration more difficult and potentially causing hierarchical effects to appear later.

Thus, we infer that within a task set, hierarchical organization exists not only among tasks, associations, and responses, but also among stimuli, tasks, or rules themselves. Whether this hierarchical representation is implicit (Collins et al., 2014) or explicit (Han et al., 2018, 2019), switching across different hierarchical levels requires different amounts of cognitive control, resulting in different switch costs, with higher-level (task or rule) switches incurring greater costs than lower-level switches. Moreover, within a specific task set, cognitive control over high-level task goals may differ from control over response rules, with the former requiring greater control and more time.

Our study extends previous research by investigating hierarchical cognitive control using a cued task-switching paradigm, but has several limitations. First, hierarchical level changes were inevitably confounded with task complexity (i.e., higher levels were more complex). Future research should explore effective ways to dissociate hierarchy from complexity. Second, although no-go trials were included to ensure participants followed instructions, they were infrequent and treated as filler trials excluded from analysis. Future studies could incorporate no-go trials as an experimental variable to investigate how response selection, response inhibition, and backward inhibition influence hierarchical task switching.

5. Conclusion

Using a nested cue-task switching paradigm, this study investigated hierarchical control processes and their neural mechanisms in task switching. Results showed that high-level task switch costs were significantly greater than low-level task switch costs. Cue-locked ERP results demonstrated that the CNV amplitude difference between high-level task switching and repetition was significantly larger than for low-level tasks, reflecting enhanced proactive control allocated to high-level tasks during preparation for upcoming target tasks. Target-locked ERP results showed that amplitude differences between high-level task switching and repetition were significantly larger than for low-level tasks in both N2 and SP components, reflecting increased reactive control during inhibition of old task sets and reconfiguration of new response sets. These findings indicate that in task switching, both proactive control for task preparation and reactive control related to inhibiting old task sets and reconfiguring new task sets increase with higher task hierarchy (i.e., greater abstraction or complexity).

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Note: Figure translations are in progress. See original paper for figures.