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Two Decades of Research on Task Switching: What More Can We Ask?

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A key aspect of higher cognitive control is the ability to switch efficiently between alternative tasks in a manner that is appropriate to the situation. For instance, a bilingual speaker needs to control which language she/he uses depending upon who is being spoken to and to switch between languages when necessary. Since in any given context there is a range of tasks that could be performed, the question arises of how we control our use of different tasks over time. Much of the research into dynamic cognitive control for the past two decades has employed the “task switching” procedure which requires participants to respond to stimuli according to one of two alternative task-rules and switch the appropriate task-rule from trial to trial. Researchers have consistently found in such procedure that participants require more time in switching between two tasks than in merely repeating one task. In this article, I will review studies that have been conducted for the past two decades with various forms of task-switching paradigms and by use of behavioral and neuroimaging approaches. The review focuses on preparatory control mechanisms (switch-specific and/or generic) and theoretical accounts in task switching. The review also focuses on various interference phenomena in task switching, including switch response-repetition cost, proactive interference of tasks, backward inhibition, task rule congruency effect, and competitor rule suppression. Finally, I will provide perspectives on future research for the next decade.

Keywords: *cognitive control, inhibition, interference, preparatory, task switching*

Why Study Task Switching?

Why has task switching attracted the attention of many psychologists over the past two decades? It is a highly ecological problem. Daily scenarios often require that people switch among different activities such as reading a book, writing a paper, talking on the phone, browsing the Internet, watching television and so on. The ability to adapt our behavioral repertoire to different situations and tasks is crucial in daily life. How are we able to succeed when dealing with so many different activities? How do we organize our mind and body in a particular way? Specifically, how do we adopt appropriate

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"task sets" and flexibly shift from one to another? When people switch tasks, are there control processes that reconfigure the task set before or as the imperative stimulus is processed? Are there control processes that monitor our performance and adjust the task sets during or after an action? Although there are proven top-down control processes, are we susceptible to interference evoked by external information? The exploration of these issues has become a major research field in cognitive psychology over the past two decades. In addition, task switching is an experimental paradigm that explores the mechanisms of cognitive control to enable human behavioral flexibility not only in the field of cognitive neuroscience (Allport, Styles, & Hsieh, 1994; Meiran, 1996; Rogers & Monsell, 1995) but also in aging, clinical science, and educational research.

Because of its influential impact, a review on the development of task-switching research is timely. Moreover, because this research has been developed over the past two decades, identifying what issues have been addressed and what issues have not is important. To my knowledge, Monsell (2003) published the first review article on task switching; since then, five reviews have been published in the last two years, including three articles that reviewed only behavioral studies (i.e., Kiesel et al., 2010; Meiran, 2010; Vandierendonck, Liefooghe, & Verbruggen, 2010) and two articles that focused only on neuroimaging studies (i.e., Karayanidis et al., 2010; Schneider & Logan, 2009). Despite the availability of these reviews, this article differs from those already published by reviewing both behavioral and neuroimaging studies and discussing these findings and theories in chronological order. This article aims to provide readers with both a solid historical foundation and perspectives on future task-switching research.

Before reviewing the literature (Section 3), I describe a number of task-switching paradigms (including their basic taxonomies) and comment on their strengths and weaknesses (Section 2). This discussion is important because many paradigm variants have been developed and each measures task-switching performance differently; thus, these studies may tap into separate subcomponent processes. Therefore, a brief review of these paradigms should help readers follow the literature review.

Basic Task-Switching Paradigms and Taxonomies

Experimental psychologists have developed various task-switching paradigms to mimic real-world situations, especially during 1990s. To do so, they defined "task set" in a restricted way; that is, a task set consists of transient couplings of elementary stimulus features and immediate behavioral responses. For instance, a participant in a psychological experiment might be instructed to respond to odd or even numbers (e.g., press the left key for "7"). Alternatively, a participant might be instructed to respond to digits higher or lower than 5 (e.g., press the right key for "7"). Although seemingly trivial, researchers consistently find that shifting between these simple task sets incurs significant switch costs, i.e., longer reaction time (RT) for switched than repeat trials. There are variants of paradigms that have been developed to measure switch costs (see Figure 1).

The List Procedure

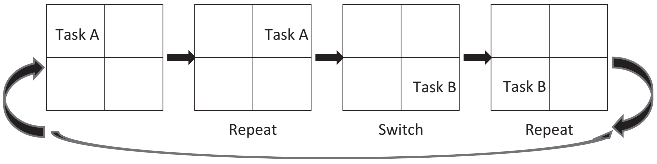
Jersild (1927) developed one of the earliest task-switching paradigms. This paradigm is also known as the "list procedure" in which the reaction times (RTs) needed to complete different lists are compared (see also Biederman, 1972; Spector & Biederman, 1976; but see Allport et al.'s (1994) Experiment 5, in which individual item RTs in different lists were compared). Jersild (1927) asked participants to read a list of items and either repeat one task (single-task list; e.g., Task A - Task A - Task A - Task A…; Task B - Task B - Task B - Task B…) or alternate between two tasks (mixed-task lists; e.g., Task A - Task B - Task A - Task B…; Task B - Task A - Task B - Task A…). For example, in one experiment Jersild either presented participants with a list of 2-digit numbers or a list of adjectives. In the control condition (single-task list), they either had to add three to a number or name the antonym of an adjective. In the alternating condition (mixed-task list), participants added three to the first number, named the antonym of an adjective, and so on (Figure 1a). Jersild measured participants' switch cost by subtracting their average RT on the single-task lists from their RT on the mixed-task lists.

a. The list procedure

＋3	Antonym	＋3/Antonym
15	Good	15
32	Thin	Happy
47	Happy	28
28	Hard	Fast
61	Fast	72
29	After	Cold
53	Down	43

single-task list mixed-task list

b. The alternating-runs procedure



c. The task-cuing paradigm

Cue A – Task A – **Cue A** – Task A – **Cue B** – Task B – **Cue A** – Task A …

→ Random task sequence

c2. The intermittently-cued procedure

Cue A – Task A – Task A – Task A – … – **Cue B** – Task B – Task B – Task B

Cue A – Task A – Task A – Task A – … – **Cue A** – Task A – Task A – Task A

d. Pair-wise task sequence paradigm

Condition	**Type of block**	**Stimulus 1**	**Stimulus 2**
Foreknowledge	Repetition	Task A	Task A
		Task B	Task B
	Switch	Task A	Task B
		Task B	Task A
Non-foreknowledge	Mixed	Task A	Task A
		Task A	Task B
		Task B	Task B
		Task B	Task A

e. The voluntary task-switching paradigm

Task A – Task B – Task A – Task A – Task B – Task B …

→ Voluntary choice whether to perform Task A or Task B

Figure 1. **Basic task-switching paradigms. See text for details.**

A major pitfall of the list procedure is that the comparison between single-task and mixed-task lists confounds actual ***switch costs*** and ***mixing costs***, because when compared to the single-task list, the mixed-task list may impose a greater working memory load, thus demanding greater effort and arousal (i.e., essence of mixing costs). These effects should be distinguished from actual switch operation costs. The actual ***switch costs*** should refer to the RT differences between switch and non-switch (repeat) trials within the same mixed-task list, rather in two separate lists, whereas ***mixing costs*** should refer to the RT differences between trials in the pure-task list and repeat trials in the mixed-task list (explained in more details in the following section). Unfortunately, with Jersild's original alternating procedure, it is impossible to tease apart the above two types of costs because there were no switch and repeat trials co-existed within the same mixed-task list.

The Alternating-Runs Procedure

Rogers and Monsell (1995) avoided confounding switch costs with mixing costs by introducing a paradigm in which switch and repeat conditions were mixed within the same block: the alternating-runs procedure. For each task, participants alternated between runs of two or more trials presented in one of four quadrants (for the spatial version, see Rogers & Monsell, 1995). For example, stimuli that appear in the upper two positions indicate Task A, where in the lower two positions indicate Task B (Figure 1b). Rogers and Monsell computed switch costs by subtracting the average RT of the repeat trials (the second trial on the sequence of Task A-<u>Task A</u> and Task B-<u>Task B</u>) from those of the corresponding switch trials (the second trial on the sequence of Task A-<u>Task B</u> and Task B-<u>Task A</u>). In this way, switch costs (also known as ***local switch costs***) can be measured accurately without contamination from unwanted differences in memory load, effort, arousal, and so on (i.e., mixing costs).

One major problem with the alternating-runs procedure is that the experimenter has little control over when the endogenous act of control begins. For example, a problem occurs when researchers try to disentangle the effects of active preparation from those of passive dissipation with the previous active task set during the stimulus-to-response interval.

The Task-Cuing Paradigm

To prevent an undetermined preparation period, the task-cuing paradigm was developed to independently manipulate the cue-stimulus interval ([CSI] allowing active preparation) and the response-cue interval ([RCI] allowing passive dissipation; Meiran, 1996; Meiran, Chorev, & Sapir, 2000). Before each target appears, a cue indicates which task to perform (see Figure 1c). For example, if a cue is blue, the task is to judge whether a digit is odd/even, whereas if a cue is red, the task is to judge whether it is more or less than 5. In this paradigm, the tasks occur randomly in a block. Because the experimenter has little control over when control begins in the alternating-runs paradigm (Meiran, 1996), researchers who emphasize examining the preparatory component process in task-switching paradigms suggest using a task-cuing paradigm that can accomplish this goal.

Another variant of the cuing procedure, the intermittently-cued (intermitted instruction) procedure, instructs participants to repeatedly perform a task until the next cue is presented (Allport & Wylie, 2000; Altmann, 2002; Gopher, Armony, & Greenshpan, 2000). For example, a series of targets are presented that are occasionally interrupted by cues signaling participants to repeat the task rule or switch to another task rule (see Figure 1c-2).

The problem with the task-cuing paradigm is that the cue itself may precede stimulus processing, thereby contaminating switch cost analyses (see Sohn & Carlson, 2000). Furthermore, the cuing paradigm is seriously confounded in that a task switch is a cue switch, and a task repeat is a cue repeat (for more on the cue-repetition effect, see Logan & Bundesen, 2003, 2004; Mayr & Kliegl, 2003). To overcome this problem, researchers modified this paradigm with either the double-cue procedure (Logan & Bundesen, 2003, 2004; Mayr & Kliegl, 2003) or the transition-cuing procedure (Forstmann, Brass, & Koch, 2007; Forstmann, Brass, Koch, & von Cramon, 2005). The double-cuing procedure arranges two cues to map to a single task (2:1 cue-to-task mapping), instead of using one cue per task (1:1 cue-to-task mapping) as in a conventional cuing paradigm. The transition-cuing procedure uses a pair of transition-cues (“stay,” “switch”), instead of direct task-name cues, such as “odd/even,” “more/less,” that typically used in a conventional cuing paradigm. For example, if the word “stay” appeared in advance of the stimulus, it indicated a task repetition; if the word “switch” appeared, it indicated a task switch.

The Pair-Wise Task Sequence Paradigm

To minimize the pitfalls of the task-cuing procedure, Sohn and Carlson developed a paradigm to address the relationship between task preparation and task switching (Sohn & Anderson, 2001; Sohn & Carlson, 2000). Their paradigm used a pair-wise task sequence rather than a long sequence of trials. Each trial sequence contained only two tasks. They manipulated the preparation effect so that participants performed: (1) only repeat trials in some blocks and only switch trials in other blocks (foreknowledge condition) or (2) both repeat and switch trials mixed randomly within each block (non-foreknowledge condition). In the *foreknowledge-repetition* block, Stimulus 1 and Stimulus 2 of the pair-wise trial sequence were the same task. In the *foreknowledge-switch* block, Stimulus 1 and Stimulus 2 were different tasks. In the *non-foreknowledge* blocks, task repetitions and task switches were randomly mixed within blocks (Figure 1d).

Although this paradigm received less attention compared to those previously mentioned, the pair-wise task sequence paradigm has one major advantage: Because each trial sequence contains only two stimuli, this paradigm minimizes the possible carry-over potential shift that cumulates in consecutive trials. As a result, this is the preferred paradigm for researchers who study the electrophysiological correlates of task switching. Previous task-switching studies have adopted a long sequence of steps with predictable task switches but have confronted a baseline problem.

Nevertheless, this pair-wise paradigm also has pitfalls. It has been often found that RT to the first stimulus in the foreknowledge conditions was affected by whether the second stimulus required a switch or repeat in task (see Hsieh & Chen, 2006, 2007). These results suggest that participants anticipate the second task while performing the first task in foreknowledge conditions (parallel processing of the two tasks).

The Voluntary Task-Switching Paradigm

In retrospect, all task-switching paradigms developed before 2004 inevitably confront the problem of a lack of ecological validity. The paradigms discussed in this paper thus far can be considered instructed task-switching paradigms; in reality, however, people often select tasks without instruction. In addition, although the task-cuing procedure was developed to separate active and passive processes, as previously mentioned, it confounds cue repetition with task repetition. Thus, whether switch costs reflect the active process of task switching or the passive encoding benefit of repeated cues is not clear (Logan & Bundensen, 2003; Mayr & Kliegl, 2003). Although researchers have modified the cuing paradigm by using double-cue or transition-cue procedures, Logan and his student developed an ecological task-switching paradigm in 2004. In this voluntary task-switching procedure, participants choose the task themselves; their only constraint is that they perform the two tasks with equal probability across a random sequence, yielding an average switch rate of 50% (Figure 1e). Arrington and Logan (2004b) claimed that their voluntary task-switching procedure necessarily involves active control processes (unlike procedures that require participants to respond to externally-provided task-switching cues; see also Arrington & Logan, 2005).

Despite the seemingly strong validity of the voluntary-task switching procedure (which is assumed to involve top-down control), voluntary task choice is susceptible to bottom-up biases, such as task-repetition (Mayr & Bell, 2006) or stimulus availability (Arrington, 2008). Nevertheless, using this paradigm to explore the interplay between top-down and bottom-up processes is a promising line of research.

Summary

Each of these paradigms has merits and pitfalls; although they all measure switch costs, different subcomponent processes might be derived from each paradigm. In the following sections, I describe the findings and theories associated with task switching in chronological order.

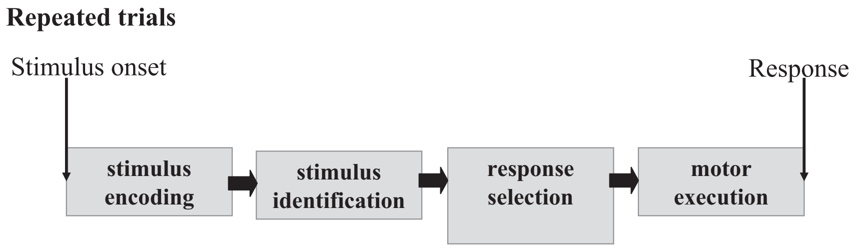
The First Decade (1990-2000)

Between 1990 and 2000, researchers who studied task-switching behavior primarily sought to explain ***switch costs***. Two major theories have been elaborated: ***passive decay of interference*** (*e.g., task set inertia and priming*) and *the* ***active top-down process*** *of task set reconfiguration (TSR)*. Passive decay of interference theory assumes that performance costs reflect a form of carry-over effect from a previous trial that is independent of a preparatory process. On the other hand, active process of TSR theory assumes that performance costs reflect the additional control reconfiguration needed to reconfigure the system for the switch to a new task. Their differences regarding the nature of switch costs can be illuminated in terms of information processing stream (see Figure 2 for some examples).

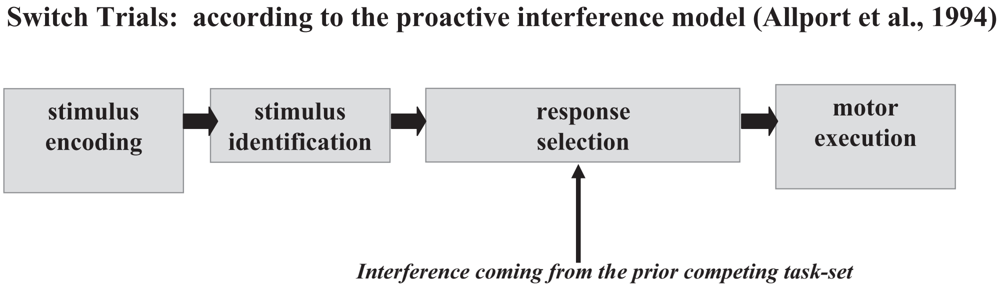
Passive Interference Decay

Allport et al. (1994) published a pioneering paper suggesting that switch costs are due to proactive interference using the list procedure. Google Scholar estimates that this paper has been cited approximately 902 times to date. In Experiment 5, Allport et al. (1994) used Stroop color-word stimuli (in which word meaning and word ink color are incongruent) and neutral stimuli (color words in black ink and a string of five Xs in one of five colors). One reason to use Stroop stimuli was to explore the relative asymmetrical strength of the two word-reading tasks. In other words, Allport et al. (1994) investigated whether task set shifting efficiency interacts with task strength. Based on what is known regarding executive control, one hypothesis asserted that the time cost to shift to the nondominant (i.e., more controlled) task should be greater compared to that of the dominant (i.e., less controlled) task. However, Allport and colleagues (1994) observed larger switch costs for the dominant word-reading task than for the nondominant color-naming task (***asymmetric switch costs***). Based on this unexpected observation, they hypothesized ***"task set inertia:"*** That observed switch costs are a form of ***proactive interference*** from the task set elicited by or for the preceding tasks. The imperative stimulus must trigger active disengagement from a preceding trial to the following trial. Thus, ***asymmetric switch costs*** exist because one must apply more cognitive resources to inhibit the dominant task set. This action allows participants to perform the nondominant task set in the preceding trial. This inhibition transfers to the next trial, overcoming the inhibition that prolongs response selection (Figure 2a).

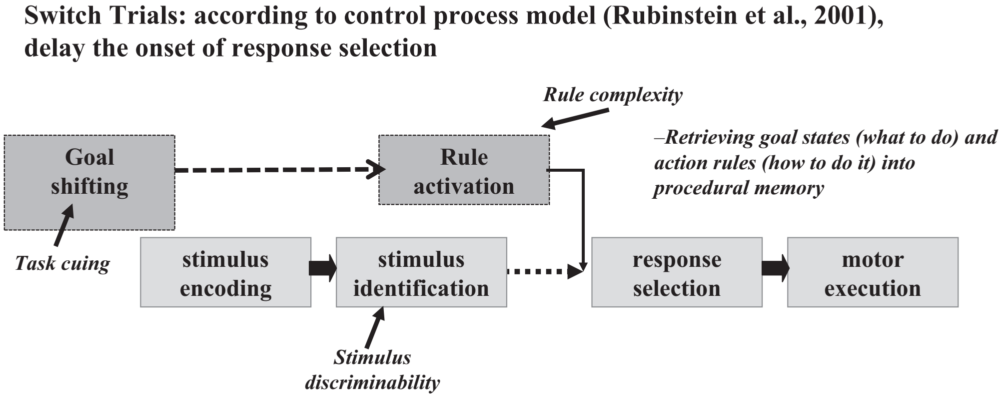
Allport and Wylie (1999) modified task set inertia theory to elaborate upon proactive interference as a ***task set priming*** effect. Long-term priming is attributed to the retrieval of task sets associated with the current stimulus (i.e., the involuntary stimulus-task binding effect; see also Wylie & Allport, 2000). Allport and Wylie (1999) developed a "before-and-after" paradigm to address the issue. They arranged a critical set of 30 trials of Stroop color naming task (phase 2) intervened between an initial baseline phase (phase 1) and a post-color phase (phase 3) of both Stroop- and neutral-word reading tasks. All word-reading were performed under pure task conditions. In critical phase 2, after practice of 10 trials, participants were told that they would perform 20 more trials of color-naming task, and after a pause of 2 seconds, participants were instructed to return to pure word-reading task (phase 3), and were assured, there would be no further color-naming task. Nevertheless, the authors observed a very large interference effect (including RTs and errors) on post-color word-reading (phase 3), compared to the baseline first-trial performance in phase 1. Based on the findings, the authors suggested that the "intentional shift to a competing (divergent) S-R task reveals task-switching costs, in the form of continued priming of the previous task (competitor priming) and suppression (negative priming) of the currently intended task" (Allport



a. Passive interference decay theory



b. A variant of task set reconfiguration (TSR) model



c. Intermediate theory

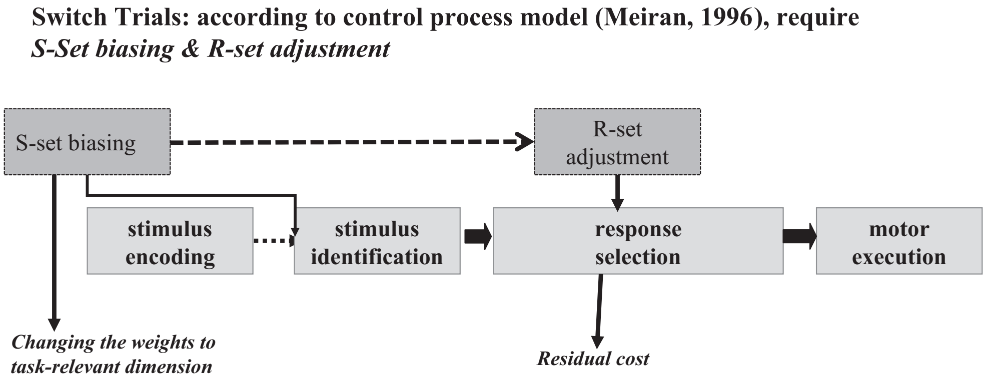


Figure 2. **Top panel denotes the sequence of processing performed on repeated trials; Panels a, b, c denote the three representative task-switching models. See text for details.**

& Wylie, 1999, p. 293). According to this version of the theory, switch costs arise because (1) the preceding trial (Trial n-1) ***suppresses*** the relevant task set of the current trial (Trial n), (2) Trial n-1 activates the irrelevant task set of Trial n, or (3) both 1 and 2. In other words, switch costs are due to the target stimulus triggering a bottom-up episodic retrieval or priming S-R mappings that interfere with the current switch trial (a passive mechanism).

Active TSR

Monsell studied task switching simultaneously with Allport's research. Unlike Allport et al.'s (1994) interference theory, however, Monsell's research group supported TSR theory based on the notion of executive control (Rogers & Monsell, 1995). TSR theory assumes that switch costs reflect the time needed to reconfigure a task set or to retrieve it from long-term memory. In addition, several other processes have also been included as part of the TSR function such as "shifting attention between stimulus attributes or elements, or between conceptual criteria, retrieving goal states (what to do) and condition-action rules (how to do) into procedural working memory (or deleting them), enabling a different response set and adjusting response criteria. TSR may well involve inhibition of elements of the prior task-set as well as activation of the required task-set" (Monsell, 2003, p. 135). Rogers and Monsell (1995) used an alternating-runs paradigm to manipulate the length of response-stimulus intervals (RSIs). They observed significant switch costs at all RSIs; however, switch costs were larger for short RSIs (i.e., 150 ms) and partially reduced as RSI increased. This result suggests that the time-consuming, stage-like process of reconfiguration that can be carried out in anticipating stimuli. This pioneer paper has been cited more than 1,238 times to date.

A Variant of the TSR Model

Rubinstein proposed a variant of the TSR model in his dissertation (published as Rubinstein, Meyer, & Evans, 2001). This model divided control processes required for switch, but not repeated, trials (i.e., switch-specific preparation effects) into two distinct component stages: goal shifting and rule activation. These component stages are separate from task-implementation processes (Figure 2b). Goal shifting can occur before stimulus onset if time permits and a task switch is expected (e.g., advanced reconfiguration); however, rule activation cannot start prior to stimulus onset (i.e., the post-stimulus control process), resulting in residual switch costs. Stimulus discriminability, which is relevant to stimulus identification, reliably affected mean RTs for both switch and repeated trials but had no effect on mean switch cost (e.g., additive; cf. Sternberg, 1969). Conversely, rule-complexity, which is relevant to rule-activation and response-selection affected mean RTs on repeated trials but more so on switch trials, affecting mean switch costs (e.g., over-additive; cf. Sternberg, 1969). The findings that ***stimulus discriminability*** affected on both repeated and switch trials, whereas ***rule-complexity*** affected more on switch trials appear to support Rubinstein et al.'s (2001) hypotheses of separate control and task-implementation processes. Another parameter, such as ***task-cuing*** (thought to be relevant to goal-shifting) was also found to affect more on switch trials as rule-complexity. However, both parameters, i.e., task-cuing and rule-complexity although affected more on switch than repeated trials, their effects together are shown to be additive rather than interactive on the amount of switch costs. The result thus supports the view that goal shift and rule activation are the two distinctive control component processes (cf. Sternberg, 1969).

Intermediate Theory

In addition to passive decay and active control, a third well-known and highly cited (approximately 559 times) theory took an intermediate view on switch costs. Meiran (1996) developed a cuing paradigm to disentangle passive decay processes from active preparatory processes by independently manipulating cue-stimulus and RCIs. Increasing the interval between the response to the previous trial (Trial n-1) and the cue onset of Trial n (i.e., the RCI) reduces switch costs. This finding is attributed to the passive dissipation of the task adopted in the previous trial because during this period, participants do not prepare for unknown forthcoming tasks. On the other hand, increasing the interval between the cue onset and the stimulus onset (i.e., the CSI) reduces switch costs, which reflects a preparatory component because an instructional cue has been provided (Meiran, 1996; Meiran et al., 2000).

By suggesting that switch costs contain both reconfiguration and task set persistence, Meiran et al. (2000) attempted to reconcile theories of active control and passive decay. Meiran used an information-processing model to suggest that an additional control process is required before the stimulus-identification stage on switch trials. This control process involves weighting task-relevant stimuli dimensions (referred to as stimulus-set, ***S-Set***, biasing). According to this model, S-Set biasing can be adjusted during the CSI and must be completed before stimulus identification. Consequently, if the CSI is too short, S-Set biasing proceeds after target presentation; if the CSI is sufficiently long, S-Set biasing can be completed during this interval and does not increase participant RT. Meiran et al. (2000) also postulated that another component, response-set (***R-Set***) adjustment, explains residual switch costs. Unlike the S-Set, the R-Set (biased in favor of the previous task dimension) cannot be adjusted during the pre-trial interval; however, it can be configured after a response selection resulting in the prolongation of switch-trial response (Figure 2c).

Theories to Account for Residual Switch Cost

Although these three theories delineate switch costs, they are challenged by the accompanying robust phenomenon of residual switch costs. The previously mentioned pioneering empirical studies were the first to find residual switch costs. For example, residual switch costs remain after increasing the CSI to more than 1,000 ms (Allport et al., 1994; Meiran, 1996; Rogers & Monsell, 1995). Furthermore, Meiran (1996) observed a significant switch-cost reduction when the CSI was extended from 132 ms to 1,632 ms in a task-cuing paradigm. Because switch costs are significantly reduced with longer preparatory intervals, it is surprising that many researchers report that residual switch costs remain after providing participants with ample preparatory time (e.g., Meiran & Chorev, 2005). This finding suggests that some of the reconfiguration processes needed to prepare for a task set cannot be completed before the onset of the stimulus.

As previously mentioned, researchers' theories needed to explain why residual switch costs happen. Allport et al.'s (1994) ***interference theory*** assumes that switch costs are due to interference regardless of the duration of preparatory period. To accommodate for residual switch costs in their ***TSR*** theory, Rogers and Monsell (1995) added an additional process to the model (also known as "AP" theory). Rogers and Monsell's (1995) theory also distinguishes between two components: An ***endogenous*** preparation process that operates from the point the task is known and an ***exogenous*** component process involved at the end of task processing. Residual switch costs arise because the "completion of the reconfiguration is triggered only by, and must wait upon, the presentation of a task-associated stimulus" (Rogers & Monsell, 1995, p. 224).

The Failure-to-Engage (FTE) Hypothesis: Is Switch-Specific Preparation All or None?

Contrary to the two-stage reconfiguration model (AP theory), de Jong (2000) proposed that the single-process FTE model explains residual costs. According to FTE theory, residual costs are attributable to intermittent failures during advance preparation and not an inability to completely reconfigure a task switch during the preparatory interval. Given an ample amount of time to prepare, participants succeed in only a portion of the trials before stimulus onset. Furthermore, they do not prepare before stimulus onset for other trials. As such, performance on switch trials with advance preparation should be similar to that of repeat trials, whereas performance on switch trials without advance preparation should resemble that of switch trials with a short preparatory interval.

However, instead of disputing the AP theory, de Jong (2000) reconciled the two views by developing a mixture model for evaluating the proportional contributions of both FTE and AP accounts to the residual switch cost. de Jong (2000) computed cumulative distribution functions (CDFs) by dividing the rank-ordered RTs for each participant, for each condition into deciles and then computing the mean RTs for each deciles. de Jong used the following equations to formalize the FTE hypothesis: $F_{\text{switch, long PI}}(t) = \alpha F_{\text{prepared}}(t) + (1 - \alpha)F_{\text{unprepared}}(t)$, where $_{\text{switch, long PI}}$ is the CDF for switch trials with a long preparation interval (PI), F_{prepared} (i.e., repeat trials at long PI) and $F_{\text{unprepared}}$ (i.e., switch trials at short PI) are the theoretical CDFs for the prepared and unprepared state, and α is the mixing probability that preparation is carried out and completed during the long preparation interval; whereas $(1 - \alpha)$ is the probability that preparation fails to be initiated even during the long preparation interval.

de Jong (2000) further suggested that the mixture model can be generalized to allow for the possible contribution of an additional exogenous component of task-set reconfiguration proposed by the AP hypothesis to residual switch costs. To estimate the contribution of this AP factor, de Jong (2000) added a parameter, δ, to represent the duration of this hypothetical exogenous component. The formula can be modified as: $F_{\text{switch, long PI}}(t) = \alpha F_{\text{prepared}}(t - \delta) + (1 - \alpha)F_{\text{unprepared}}(t)$. According to de Jong (2000), with $\alpha = 1$, the generalized mixture model reduces to the pure AP hypothesis; with $\delta = 0$, the model reduces to the pure FTE hypothesis; and with intermediate cases, i.e., $0 < \alpha < 1$ and $\delta > 0$, the model comprises a range of models in which various proportions of residual costs are attributed to failure to engage in advance preparation (i.e., FTE) and to an additional exogenous component (i.e., AP). Thus, the distribution of RTs in switch trials with a long preparatory interval should be well fitted by a mixture of RTs from repeat trials and switch trials with a short preparatory interval. The fitting technique yielded two free parameters in order to optimize the fit: The first parameter (α: a value between 0 and 1) representing the probability of FTE trials, and the second parameter representing the average duration (δ: in ms) of the exogenous component of the AP theory. Accordingly, fitting RTs to the generalized mixture model proposed by de Jong (2000) allows us to examine whether residual switch costs could be attributed solely to intermittent failures to take advantage of opportunities for advance preparation, or could be also attributed to the presence of fundamental preparatory limitations, as proposed by the AP hypothesis.

However, de Jong's mixture model of the FTE with a binary-state (or discrete-state: "prepared" vs. "unprepared" trials) assumption has been subjective to some criticisms. One major criticism lies in the strict assumption of a pure binary mixture of "prepared" and "unprepared" trials in the original FTE model. Brown, Lehmann, and Poboka (2006) provided a critical test on this strict binary assumption by examining if the six RT distributions -- collected from switch and repeat trials, each for three different RSIs -- would share a common crossing point (Brown et al., 2006). Their rationale was derived from Falmagnes's (1968) proof that all binary mixture models should predict the same crossing point across all mixtures of the paired-distributions (i.e., changes in mixture probabilities). However, their RT distributions did not hold a fixed-point property. Nevertheless, instead of abandoning the FTE model, Brown et al. (2006) rescued it from a strict fixed-point prediction by relaxing the stringent assumption of binary all-or-none prepared states. For example, they amended the mixture model by allowing the prepared and unprepared mixing distributions to shift with RSI to fit the data. Another criticism suggested that a partial-mapping preparation hypothesis could equally account for de Jong's (2000) findings (see Lien, Ruthruff, Remington, & Johnston, 2005). According to the partial-mapping preparation hypothesis, participants may always engage in preparation for a task switch if ample preparation time is given. However, this preparation is limited because participants can prepare for only a subset of S-R pairs on a trial; some S-R pairs may show little switch costs, while others show large switch costs. In other words, in contrast to de Jong's (2000) suggestion that people do not prepare for all of the tasks some of the time, the partial-mapping preparation hypothesis suggests that people prepare for some of the tasks (some S-R pairs) all of the time.

Switch Response Repetition Costs

Apart from the aforementioned theories, switch response-repetition costs have also received attention in the literature. In a typical RT choice paradigm, participants classify multidimensional, bivalent stimuli according to particular rules. These rules typically map a set of dimension values (e.g., red and green) to response keys (e.g., right and left). As such, any two consecutive trials may involve similar or different responses. Response repetition benefits (i.e., the reduction in RT and error rate) in RT choice tasks are often reported in the literature (e.g., Bertelson, 1965; Campbell & Proctor, 1993; Pashler & Baylis, 1991). In a task-switching paradigm, however, Rogers and Monsell (1995) obtained the opposite result: Repetition incurred additional costs on switch trials. This phenomenon has been well established in the task-switching literature (Hübner & Druey, 2006; Kleinsorge & Heuer, 1999; Mayr & Bryck, 2005; Rogers & Monsell, 1995; Schuch & Koch, 2004).

Rogers and Monsell (1995) offered three hypotheses to explain switch response repetition cost. The first hypothesis regards the relationship between the response and the stimulus category. This hypothesis suggests that "the strengths of associations between the categorical attributes of a stimulus (i.e., consonant, vowel, even, odd) and motor responses (e.g., left or right index finger flexions) are continuously modified by experience. We may suppose that every response to a stimulus results in an increment in the associative strength of the link between the response and the stimulus category responsible and a corresponding decrement in the associative strength of the link between the other stimulus attributes and the response. These increments then decay. Production of a response triggered by the same attribute will be temporarily facilitated, whereas production of a response triggered by a different attribute should exhibit interference (Rogers & Monsell, 1995, pp. 226-227)." The second hypothesis concerns the transient suppression of all active responses. This hypothesis suggests that "the effect reflects the operation of a control mechanism by which shifts of task-set are accompanied by the transient suppression of all active responses. That is, when a task-switch is called for, all ongoing response activity is inhibited as belonging to the previous task, and this inhibition takes some time to wear off. If a particular finger movement subject to this inhibition happens to be called for in executing the new task, a greater increment of response activation is required to overcome the inhibition than would otherwise be needed (Rogers & Monsell, 1995, pp. 226-227)." The third hypothesis regards a possible mechanism that prevents the perseverative re-execution of a response. In addition, Kleinsorge and Heuer (1999) explained this phenomenon in relation to a hierarchical task-space structure in working memory. Specifically, the relevant dimension is at the top level of the hierarchy, whereas responses occupy lower levels of the hierarchy. According to this theory, the switch signal (which pertains to the dimension level) spreads uncontrollably to subordinate levels in the hierarchy. Thus, a task switch would generate a tendency to switch responses, whereas a task repeat does not. Despite all these hypotheses that have been posed during the 1990s, there is no conclusive evidence to support one theory over another.

Summary of Task-Switch Research in the 1990s

To summarize, several paradigms and well-known theories delineate switch costs and residual switch costs. The focus of research in the 1990s relied heavily on the debate between passive decay interference and active reconfiguration theories. In retrospect, the dispute between passive decay and active control influenced research over the next decade and even today. Many researchers knew that this disagreement was not mutually exclusive (see de Jong, 2000). During this decade, the switch-specific phenomenon, response-repetition costs, also received much attention; however, its underlying mechanism has not been discovered.

The Second Decade (2000-2010)

Backward Inhibition

Before 2000, almost all task-switching studies used two tasks to investigate task shifting. However, not only do two-task scenarios lack ecological validity (i.e., people often switch between more than two tasks in the real world), but they also make disentangling the activation and suppression that contribute to ***asymmetric switch costs*** impossible (Allport et al., 1994). Therefore, Mayr and Keele (2000) developed a three-task switching paradigm to disentangle these two processes. They compared two triplex sequences (Task A-Task B-Task A versus Task C-Task B-Task A) and found that RTs on the third task (Task A) were slower in the former compared to the latter condition. This effect is known as "backward inhibition" or the "n-2 task-repetition cost." Mayr and Keele reasoned that the n-2 task-repetition cost occurs because a recently performed task is inhibited to facilitate a task switch. Therefore, Mayr and Keele (2000) demonstrated the importance of deactivating previously relevant task sets (Mayr & Keele, 2000; see also Hübner, Dreisbach, Haider, & Kluwe, 2003).

Following Mayr and Keele (2000), additional studies have provided empirical evidence that suggests a link between ***inhibition*** and ***task switching*** (for a review see Koch, Gade, Schuch, & Phillip, 2010). Friedman and Miyake (2004) used structural equation modeling to suggest that task-switching ability is related to response-distracter inhibition. Derrfuss et al. (2005) employed a quantitative meta-analytic approach to show that Stroop and task-switching paradigms activate the inferior frontal junction, which is related to inhibitory cognitive control (Derrfuss, Brass, Neumann, & von Cramon, 2005; for different views regarding affected brain areas that subserve the inhibitory process [e.g., the right prefrontal cortex] see Aron, Robbins, & Poldrack, 2004; Mayr, Diedrichsen, Ivry, & Keele, 2006). These studies provide convergent evidence that task switching involves an inhibitory process. This line of research is still promising.

The Cue-switch Versus the Task-switch

Task Switching Is Cue Switching

In addition to backward inhibition, two papers by Logan and Bundesen as well as Mayr and Kliegl had large impacts on the field in this decade. Before these seminal works, Meiran's (1996) cuing paradigm was widely used in task switching studies because it allowed researchers to explore preparatory processes. However, Logan and Bundesen (2003) changed the field when they argued that the cuing paradigm confounded task switches with a cue switches (see Mayr & Kliegl, 2003 for a more attenuated viewpoint in the next section). The traditional cuing paradigms used a 1:1 cue-to-task mapping method, which caused task switches to occur concurrently with cue switches from previous trials. Cues associated with similar tasks might prime each other; thus, task switching is a shift between cue-stimulus compounds. To disentangle cue switches from task switches, Logan and Bundesen suggested using a 2:1 cue-to-task mapping (double-cue) method, that is, arranging two cues per task (e.g., Logan & Bundesen, 2003). For example, Logan and Bundesen (2003) used two cue words "odd-even" and "parity" to indicate the odd/even task, and another two cue words "high-low" and "magnitude" to indicate the more or less than 5 task. Other researchers have suggested using the transition-cue method (Forstmann et al., 2007). The transition-cuing procedure uses a pair of transition-cues ("stay," "switch") so that if the word "stay" appeared in advance of the stimulus, it indicated a task repetition, whereas if the word "switch" appeared, it indicated a task switch. The double-cue method allows researchers to examine three types of task switching: no switches, cue switches without task switches, and both cue and task switches. Using the modified cuing method, Logan and Bundesen contrasted the performance costs that arise from a "pure" cue-switch (i.e., the performance difference between cue switches without a task-switch and no-switch conditions) with the costs measured for both cue and task switches. Logan and Bundesen (2003) observed that there were surprisingly few pure task-switch costs (i.e., the difference between the cue switches without a task-switch condition and both cue- and task-switch conditions) but significant cue-switch costs. Based on this finding, they suggested that participants learn a ‘‘stimulus-compound strategy’’ that entails cue encoding, stimulus encoding, and response to both. They also argued that task-switch performance in the explicitly cued procedure is simply a cue switch that does not assume a task switch (also known as the "compound-cue" model). This argument has significantly affected the field of task-switch research (see Arrington & Logan, 2004a; Arrington, Logan, & Schneider, 2007; Logan & Schneider, 2006; Schneider & Logan, 2005). Today, almost all studies with a cuing paradigm must control cue switching by using either a double-cue or transition-cue method.

Task Switching ***<u>Is Not Only</u>*** *Cue Switching*

As opposed to Logan and Bundesen (2003), Mayr and Kliegl (2003) concurrently found substantial task-switch costs and cue-switch costs also using the double-cue method. For example, Mayr and Kliegl (2003) arranged two capital letters "G" and "S" to indicate the color task, and the other two capital letters "B" and "W" to indicate the form task. They found that there were substantial cue-switch costs even if the associated task remained unchanged. However, differing from Logan and Bundesen, Mayr and Kliegl (2003) also observed significant task-switch costs when contrasted RTs between cue switches without task switches and both cue and task switches conditions. Based on these findings, Mayr and Kliegl (2003) disagreed with Logan and Bundesen's (2003) suggestion that task switching is simply cue switching. Furthermore, instead of claiming that switch costs measured using the traditional cuing paradigm reflect the retrieval of cue-stimulus compounds (i.e., switching between compound-cues rather than tasks) as suggested by Logan and Bundesen (2003), Mayr and Kliegl (2003) argued that "the cue-switch cost represent the extra time cost associated with a change of the retrieval path in long-term memory that needs to be used to activate the associated task set (Fortsmann et al., 2007, p. 394)."

Why did these two studies, Logan and Bundesen (2003) and Mayr and Kliegl (2003), although using the same double-cue method, obtain different results? These two experiments had numerous differences between them including the types of tasks and cues used, whether the CSI was held constant or varied within a block of trials, and the probability of a task switch; thus, determining whether a task-change effect occurred is difficult. The difference in switch probability is noteworthy. Logan and Bundesen (2003) used no-switch and cue switch probabilities of $p = .25$ and a task switch probability of $p = .5$. In contrast, Mayr and Kliegl (2003) used a task switch probability of $p = .33$ (see Experiment 3 in Monsell & Mizon, 2006). Why should switch probability matter? Mayr reasoned, "a critical decision subjects may have to make on each trial of the cued task switching paradigm is whether or not to abandon the current task set. It is possible that this decision is at least partly based on the switch probability in a given situation (Mayr, 2006, p. 794)." Monsell and Mizon (2006) also speculated the discrepancy may be due to the fact that "participants may be encouraged to engage in TSR *prior* to the cue if they think there is a good chance that the task will change anyway…. If a cue change is associated with a high probability of a task change, it may be a tempting strategy to begin to reconfigure as soon as a changed cue is detected, reversing the process if the cue, when interpreted, turns out to signal the same task as before (Monsell & Mizon, 2006, p. 500)."

Task Switching ***<u>Is Not</u>*** *Cue Switching*

Altmann (2006) published the article "Task switching is not cue switching" to argue against Logan and Bundensen's (2003) idea that task-switch costs can be reduced solely to cue-switch costs. Altmann (2006) organized trials into pairs, with a Trial 1 followed by a Trial 2 in a pair. A task cue was presented only prior to Trial 1 to indicate which task to be performed, but not prior to Trial 2, so that participants could only reapply the same cue from Trial 1 in order to respond to Trial 2 in a pair. The double-cue method was also applied on a task cue, in which cues were mapped 2:1 to tasks (e.g., the capital letters "H" and "U" indicated the up/down judgment task, and "W" and "L" indicated the thick/thin judgment task). Altmann's (2006) inference logic is that if the compound-cue model proposed by Logan and Bundesen (2003) was correct, then one should not expect to observe a task-switch cost on Trial 2, since there was no physical cue presented prior to Trial 2, thus no perceptual encoding was needed. However, the result turned out to be that the uncued Trial 2 of a pair showed a robust task-switch cost, which appeared to disagree with the compound-cue model. Altmann (2006) further addressed two other theoretical questions regarding the compound-cue model in the paper, and found that the model could not perfectly fit the empirical data. Based on these findings, Altmann clearly stated his position as follows: "The present study addresses three questions concerning this reduction hypothesis. First, does switching cues account for all relevant variance associated with switching tasks? Second, how well does this hypothesis generalize beyond the experimental procedure from which it was developed? Third, how well does this new procedure preserve relevant measures such as task-switch cost? The answers (no; not very; not very) suggest that task switching does not reduce to cue switching (Altmann, 2006, p. 1016).”

Voluntary Task Switch

Given the drawbacks of using conventional task-cuing paradigms to investigate the real top-down control process in task switching, Arrington and Logan (2004b, 2005) developed a new task-switching procedure, voluntary task switch (VTS), to pursuit the “***real***” task switch cost as a result from top-down control process. Unlike the conventional task-switching paradigm where an external cue or instruction to switch is given, in the VTS procedure, participants are asked to switch at their own will, but with the constraint that they should mimic flipping a coin scenario to choose the two tasks randomly and equally often. Arrington and Logan (2004b, 2005) compared three critical conditions throughout a series of experiments, such as VTS condition with a meaningless black warning box presented prior to the stimulus onset (i.e., VTS-B), VTS condition with a colored warning box (without association with either task) presented prior to the stimulus onset (i.e., VTS-C), and a conventional task-cuing condition where a colored warning box was also randomly selective presented, but differing from VTS-C condition, in this CUE condition the colored warning box is now associated with a particular task indicating which task should be performed. In one of Arrington and Logan’s (2005) serial experiments, i.e., Experiment 3, where the cue- and task-switch confounding was removed by incorporating the double-cue method for the CUE paradigm, switch costs in the CUE paradigm was found to be independent of the length of preparatory intervals. Conversely, switch costs in VTS paradigms showed a significant reduction with the increasing preparatory intervals. The results thus appear to support the idea that VTS is a more valid paradigm than the conventional CUE paradigm to explore the nature of switch costs.

Following Arrington and Logan (2004b, 2005), researchers began to reinvestigate many issues that had been explored using traditional task-switching paradigms because they believed that traditional task-switching paradigms might not tap active-control processes. Although Arrington and Logan (2004b, 2005) proposed this VTS procedure to examine switch costs via top-down control processes, years of research have consistently found that imperative stimuli influence task choice even in voluntary task settings. For example, Mayr and Bell (2006) found stimulus repetition effects on task choice using voluntary task switching (VTS; see also Arrington, 2008; Arrington, Weaver, & Pauker, 2010; Demanet, Verbruggen, Liefooghe, & Vandierendonck, 2010). Specifically, previous trial stimulus repetition increases the likelihood of task repetition. One explanation for this task-repetition bias is that the presentation of a previously encountered stimulus would result in the retrieval of stimulus-task binding that then biases task choice as well as task readiness (Arrington et al., 2010).

Another phenomenon of note is that switch costs decrease as RSIs increase; however, they do so to a much smaller degree in VTS than that observed in the cuing paradigm (Arrington & Logan, 2005). In one of Arrington and Logan’s (2005) experiments, switch cost (177 ms) was smaller in the voluntary task-switching paradigm compared to the cuing paradigm (279 ms). This effect was due to slower RTs in repetition trials of the former design compared to the latter design. Participants may treat trials as discrete events to reach full randomization, possibly by inhibiting the preceding task set (Mayr & Bell, 2006). Using this strategy, RTs on repetition trials are slower compared to those typically found in cuing paradigms. Lien and Ruthruff (2008) sought evidence of task-set inhibition in VTS by examining whether participants in a VTS setting would avoid performing a task from which they had recently switched (reminiscent of the backward inhibition observed in the traditional cuing paradigm). They found that participants were less likely to generate Task A-Task B-Task A sequences compared to Task C-Task B-Task A sequences, suggesting inhibition took place in VTS.

Electrophysiological Research (2000-2010): Event-Related Potentials (ERPs)

Electrophysiological studies of task switching have emerged over the past decade. There are several reasons for this research movement. First, behavioral measurements cannot indicate the length of information processing. Second, behavioral measurements do not indicate the order in which processing stages occur. Conversely, event-related potentials (ERPs) measure processing (in milliseconds) between a stimulus and a response, which allows researchers to infer the processes that precede a response.

Electrophysiological Correlates of Task-Switch Implementation: Stimulus-Locked ERP

Most ERP studies in this field have identified smaller positivities (e.g., P3b-like components) for task switches relative to repeat trials following stimulus onset (e.g., Barceló, Periáñez, & Knight, 2002; Gehring, Bryck, Jonides, Albin, & Badre, 2003; Hsieh & Chen, 2006; Hsieh & Liu, 2008, 2009; Karayanidis, Coltheart, Michie, & Murphy, 2003; Kieffaber & Hetrick, 2005; Poulsen, Luu, Davey, & Tucker, 2005; Swainson et al., 2003; Wylie, Javitt, & Foxe, 2003). For example, Barceló et al. (2002) reported a smaller positivity in parietal P3b on switch trials after stimulus onset, which suggests ***working memory task-rule rehearsal***. Similarly, Gehring et al. (2003) observed a reduced P3b under task-switching conditions and hypothesized that this result might indicate ***the deterioration of working memory regulation processes*** on switch trials. Likewise, Karayanidis and colleagues (2003) observed a smaller stimulus-locked positivity (P3b range) for task switches relative to repeat trials. Additionally, Hsieh and Chen (2006) employed a pair-wise task-switching paradigm that involved manipulating different RSIs and the foreknowledge of task conditions. These authors also observed a post-stimulus P3b attenuation for task switches relative to repeat trials. Moreover, the differential ERP modulations for switch trials appeared to be larger under foreknowledge compared to non-foreknowledge conditions. In summary, these electrophysiological studies provide convergent evidence of switch-related P3b modulations following switch trial stimulus onset.

Electrophysiological Correlates of Task-Switch Preparatory Processes: Cue-locked ERP

Compared to stimulus-locked ERP, cue-locked ERP provides more information regarding the preparatory processes of task switching because it allows researchers to observe brain activity before stimulus onset. Many task-switch ERP studies have been published in recent years. Of these studies, several focus on task preparation.

Switch-specific vs. generic advance preparatory processes: Cue-locked ERP

Behavioral studies have investigated whether there is a switch-specific or generic advance preparatory process. Despite the controversy regarding residual switch costs, almost all task-switching theories acknowledged the existence of preparatory processes during the cue period before stimulus onset (see the review in the previous section). The active TSR theory assumes a switch-specific preparation where switch trials require at least one more process compared to repeat trials. The interference theory does not assume extra processes in switch trials but assumes the same preparatory processes in task-switch and repetition trials (i.e., general preparatory processes; see Kiesel et al., 2010 for review). However, using a behavioral approach, it is difficult to separate preparatory processes from task-implementation processes; thus, cue-locked ERPs have been used to address this question. Unfortunately, the results are still inconclusive even with an ERP approach.

Many ERP studies have identified at least one large positivity for task-switch trials compared to repeat trials at a posterior (e.g., centro-parietal) site on the scalp. This positivity occurs approximately 400 ms after cue onset, suggesting a switch-specific preparatory process (i.e., differential switch positivity) correlated with advance preparation processes (e.g., Goffaux, Phillips, Sinai, & Pushkar, 2006; Karayanidis et al., 2003; Kieffaber & Hetrick, 2005; Lavric, Mizon, & Monsell, 2008; Miniussi, Marzi, & Nobre, 2005; Nicholson, Karayanidis, Poboka, Heathcote, & Michie, 2005; Rushworth, Passignham, & Nobre, 2002; Swainson et al., 2003).

Alternatively, mixed-block repeat and switch trials elicit a P3-like component of differing magnitudes. Research suggests that this component reflects a general preparatory process (e.g., Jost, Mayr, & Rösler, 2008). Wylie et al. (2003) did not observe switch-related frontopolar activity; however, they found differential activity associated with the task switch at ***posterior and parietal areas approximately 220 ms after onset***. Given that there was no evidence of an additional ERP component for switch trials, these authors argued against a reconfiguration process but interpreted the effect in terms of a competition model. That is, preparing to switch tasks is understood as the beginning of the competition between potentially relevant tasks that is resolved during the switch trial. We added a non-foreknowledge control condition in which participants did not know in advance which task would be switched (Hsieh & Chen, 2006). Likewise, we observed that task-switch trials evoked a larger differential positivity (D-Pos) during the RSI under foreknowledge conditions compared to repeat trials. This observation supports the idea that task preparation occurs prior to the onset of stimulus. However, we observed that the preparation process was not specific to switch trials. This result suggests that a generic preparatory process is involved in repeat and switch trials.

Nevertheless, Poulsen et al. (2005) reconciled these views when they suggested that two preparatory processes co-exist: a general preparatory component of the right-lateralized frontopolar medial negativity (which occurs in both task-repeat and task-switch trials) and a switch-specific preparatory component of the centro-parietal positivity (which occurs only in task-switch trials). In conclusion, it is unknown whether there is a switch-specific process, a general preparatory process, or both.

Stage at Which Information Processing Is Engaged by a Switch Operation: Lateralized Readiness Potential (LRP)

Unlike other researchers, we adopted another ERP component, the LRP, to investigate whether there is a switch-specific preparatory process (Hsieh, 2006; Hsieh & Chen, 2006, 2007; Hsieh & Liu, 2005; Hsieh & Yu, 2003a, 2003b). The LRP is the most relevant component to indicate the stage at which an information processing effect occurs.

The LRP is derived from the readiness potential that precedes voluntary hand movements. The readiness potential (RP) is a slow, negative potential that develops approximately 1 second before a voluntary hand movement. Approximately 0.5 seconds before a hand moves, the RP becomes lateralized. Larger amplitudes can be seen over the hemisphere contralateral to the response at sites over the motor cortex (C3 & C4; C3’ & C4’). The LRP is a correlate of hand-response preparedness and measures selective central response activation. Two types of LRP intervals can be derived; the first is time-locked to the onset of the stimulus (i.e., stimulus-locked LRPs), and the second is time-locked to the onset of the response (i.e., response-locked LRPs; Coles, 1989; Gratton, Coles, Sirevaag, Eriksen, & Donchin, 1988; Leuthold, Sommer, & Ulrich, 1996). Stimulus-locked LRPs are sensitive to stimulus identification and response-selection. Response-locked LRPs are sensitive to motor execution. In addition to these intervals, Hsieh and Yu (2003a, 2003b) analyzed P300 peak latency, which is related to the time course of stimulus encoding and identification (Kutas, McCarthy, & Donchin, 1977; Luck, 1998; McCarthy & Donchin, 1981). Using all three latencies allows researchers to examine when the switch effect occurred in the information-processing stream in order to disentangle different theoretical models (see Figure 3).

The logic behind the research by Hsieh and colleagues is as follows: If task switching, task preparation, or both affect late processes in the task processing stream, we should observe identical stimulus-locked LRP intervals under different conditions. Conversely, if task switching, task preparation, or both affect earlier premotor processes, such as stimulus identification and response selection, we should observe different stimulus-locked LRP intervals. If the P300 peak latency is also affected, we can determine whether changes in the stimulus-locked LRP intervals are attributable to stimulus identification or response selection. Finally, by observing whether these factors have additive or interactive effects on the changes in ERP

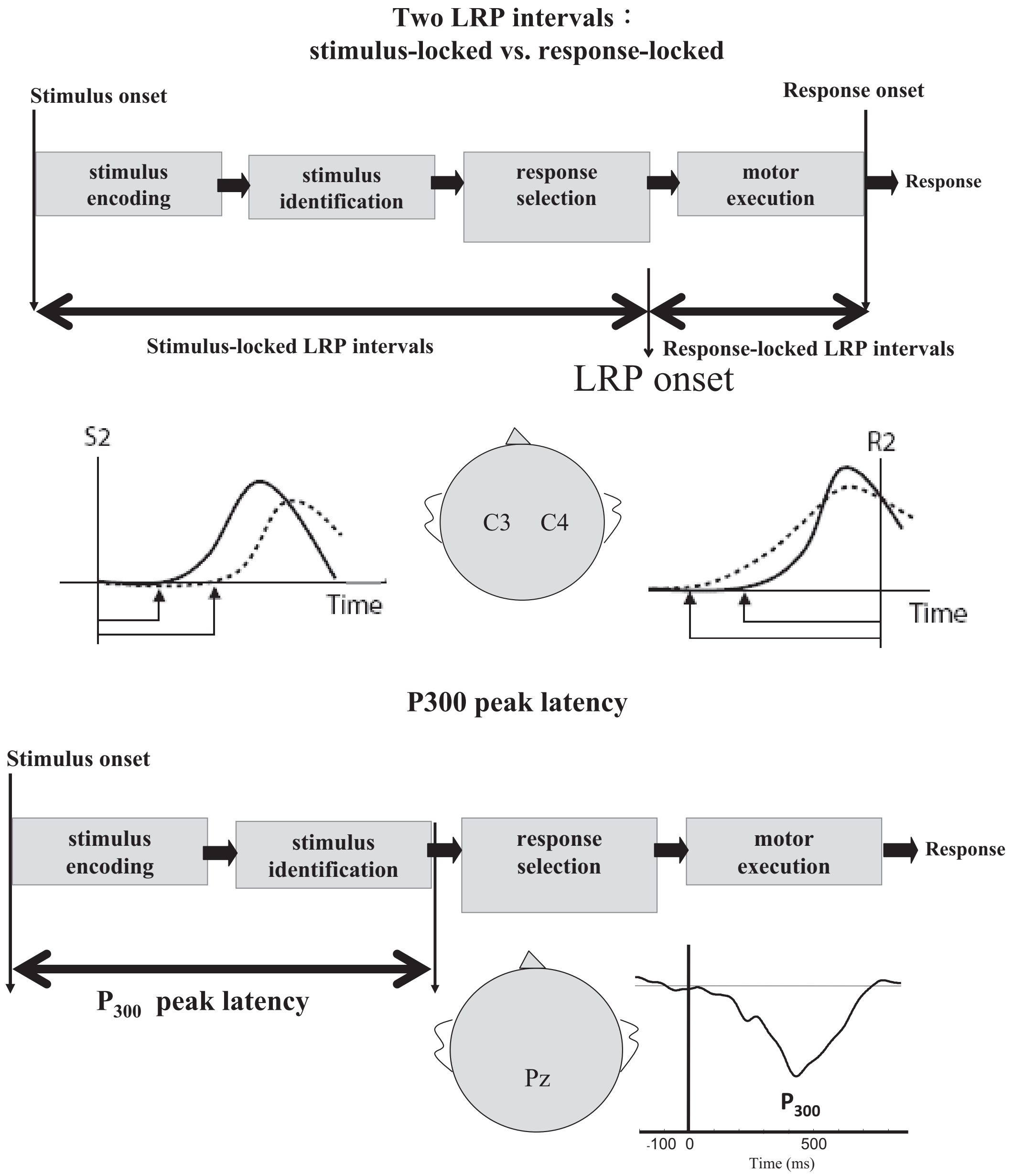


Figure 3. **Diagrams of task processing chain. Upper panel: The S-LRP (stimulus-locked LRP) interval is related to the duration of pre-motor processes (e.g., stimulus encoding, stimulus identification, and response selection). The R-LRP (response-locked LRP) interval is related to the duration of motor execution. Lower panel: The P300 latency is thought to be a relative measure of stimulus encoding and identification.**

latencies, we can infer whether they affect the same or different stages of processing.

Our results show that stimulus-locked LRP intervals were significantly different between switch and repeat trials, whereas response-locked LRP intervals and P300 peak latencies were nearly identical between switch and repeat trials (Hsieh, 2006; Hsieh & Chen, 2007; Hsieh & Liu, 2005; Hsieh & Yu, 2003a, 2003b). These results suggest that task switching occurred after stimulus identification but before motor execution. Furthermore, task switch and foreknowledge are likely additive effects because stimulus-locked LRP intervals suggest that these factors are independent. This finding implies that there is a generic, rather than a switch-specific, preparatory process.

Distinct vs. Non-separable Control Brain Regions Related to Task Implementation: Evidence from Neuroimaging Research (2000-2010): Functional Magnetic Resonance Imaging (fMRI)

Researchers have also used fMRI techniques to address whether there is an independent brain region responsible for preparatory control processes or if there are no differences in brain regions involved in switch preparation/task implementation. This line of research aims to isolate the brain activity associated with task-switch preparation. By stretching out the preparation interval to several seconds, researchers can attempt to separate modulations of the blood-oxygen-level-dependent (BOLD) signal modulations linked to preparatory activity from changes associated with stimuli processing on switch trials. Some researchers have reported that switch-task preparation activates different brain regions compared to those activated by switch-trial stimuli (Sohn, Ursu, Anderson, Stenger, & Carter, 2000). Specifically, Sohn et al. (2000) showed that during preparation, trials with foreknowledge had higher activation increases in the right lateral prefrontal cortex and the left superior posterior parietal cortex compared to trials with no foreknowledge. Meanwhile, MacDonald et al. (2000) found that the left dorsal lateral prefrontal cortex (DLPFC) was selectively engaged during the preparatory period but more so for color naming than for word reading (MacDonald, Cohen, Stenger, & Carter, 2000). This finding is consistent with the DLPFC's role in control implementation. Conversely, the anterior cingulated cortex (ACC) was selectively activated during the response period but more for incongruent than for congruent color-naming trials. This finding is consistent with the ACC's role in conflict monitoring.

However, evidence from other fMRI studies does not support the idea of an independent brain region involved in task-switch preparation because they did not find that preparation activates regions that are different from those that activate basic task processes. For example, Dove, Pollmann, Schubert, Wiggins, and von Cramon (2000) observed that several brain areas are involved in task switching, including the lateral prefrontal and lateral premotor cortices, the bilateral anterior insula, the left intraparietal sulcus, the supplementary motor area (SMA and pre-SMA), the cuneus and precuneus, the posterior cingulate, and the bilateral thalamus. However, task repetition also activated these regions. The only difference between conditions was the activation level. Hence, they found no distinct task control areas separately from task implementation areas.

In summary, fMRI results were also inconclusive as ERPs regarding whether there is a switch-specific or generic preparatory process.

Summary of the Second Decade of Research

Research between 2000 and 2010 focused on the relationship between inhibition and task switching (e.g., backward inhibition). Much of this research used electrophysiological and neuroimaging approaches, such as ERPs and fMRIs, to investigate issues left unresolved using behavioral approaches: Specifically, the issue of whether there is a switch-specific or generic preparatory process. The significant finding of this decade was the discovery that cue switches and task switches are confounded. Finally, researchers developed a more ecologically valid task-switching paradigm, VTS, which received much attention.

The Third Decade (2010-): Perspectives on the Future Research

Many researchers have explored switch costs. After two decades, these scientists have reached at least one consensus: switch costs reflect active, top-down control processes as well as passive, bottom-up interactions between successively activated task sets. Moreover, there might be switch-specific and generic preparatory processes in task switching. What more can future research examine? Where is this field headed? I propose three possible directions: First, research should examine the relationship between ***conflict*** and ***task switching***; second, it should examine the relationship between ***task type*** and ***task switching***; and third, it should examine the ***neural correlates*** of task switching and their relationship with ***individual variability*** (i.e., differences in performance). Other issues mentioned in the earlier sections of this paper are also worth pursuing; however, for the sake of brevity I will not elaborate on them again in this section.

Conflict and Task Switching

The Task Rule Congruency Effect (TRCE)

The first promising line of research is the relationship between task conflict and task switching. In typical task switching experiments, participants classify multidimensional objects according to a particular rule. These rules typically map dimensional values, such as red or green, onto response keys, such as *right* or *left*. In task switching experiments, a relevant rule dictates the correct response that should be chosen for each trial; however, there are also irrelevant rules related to tasks that were required in the past or will be required in the future. Therefore, irrelevant task rules might activate either a *congruent* response or an *incongruent* response.

Given the scenario described above, the ***TRCE*** is an important behavioral marker for the costs associated with maintaining task readiness (see Sudevan & Taylor, 1987, for the first demonstration of this marker and Meiran & Kessler, 2008, for a review). The TRCE is the relatively poor performance of a participant on incongruent trials in which irrelevant rules activate competing responses. Incongruent trials are compared with congruent trials without such a response conflict. The TRCE indicates that irrelevant rules are not completely ignored. As Goschke (2000) noted, cognitive control often involves maintaining a balance between conflicting demands. In task switching, this conflict arises because participants need to maintain high task readiness while remaining focused on relevant task rules and ignoring irrelevant task rules. Therefore, studying the TRCE is pertinent to task-switching research. We used an ERP approach to investigate the relationship between task conflict and task switching (Hsieh & Liu, 2008, 2009)

The New Inhibitory Phenomenon: Competitor Rule Suppression (CRS)

In a recent behavioral study, Meiran and colleagues demonstrated a new inhibitory phenomenon, which we labeled, ***CRS*** (Meiran, Hsieh, & Dimov, 2010). In this study, we showed evidence for a finely targeted mechanism that operates only on the task rule (the relatively abstract level of the ***task rule***), which generated the response conflict. To demonstrate CRS, Meiran et al. (2010) used a four-task paradigm in which each trial had a relevant task rule and three irrelevant task rules, some of which activated a competing response. CRS is a sequential effect that refers to the relationship between the incongruence in Trial n-1 and performance in Trial n. For example, Trial n-1 involves Dimension A as the relevant dimension and Dimension B as the irrelevant dimension, and Trial n involves Dimension B as the relevant dimension. In the scenario that Dimension B generated incongruence in Trial n-1, we call it "CRS+." We hypothesized that CRS+ is associated with slow responses in Trial n. The comparison condition in which Dimension B did not generate incongruence in Trial n-1 is called "CRS-." In addition, we calculated two other conditions, Similar+ and Other+ (see Meiran et al., 2010, for details), to compare with CRS+ because CRS+/CRS- differences can be explained in terms of conflict monitoring (i.e., CRS+ trials are characterized by a greater conflict in Trial n-1; Botvinick, Braver, Barch, Carter, & Cohen, 2001). According to the conflict monitoring theory, conditions characterized by a high degree of conflict result in a subsequent increase in control.

The critical finding in Meiran et al. (2010) concerns the fate of task rules that generated a response conflicts. We orthogonally compared three conditions: CRS (CRS+ vs. CRS-), Similar (Similar+ vs. Similar-) and Other (Other+ vs. Other-). The results showed that the main effect of CRS, but not Similar or Other, was significant. These results suggest that CRS inhibits task rules that generate incongruence during the preceding trial. Moreover, this inhibition is not merely a reaction to the incongruence of Trial n-1 because Similar and Other conditions did not produce significant effects. This study provides evidence that there are various forms of inhibition in task switching (for a review, see Koch et al., 2010). Among these inhibitions, CRS is the most finely tuned. Because the CRS phenomenon was only recently discovered, there are many more factors that need to be explored.

Task Type and Task Switching

Another promising line of research is the relationship between task type and task switching. Researchers have indicated that different types of switch tasks are involved in different control strategies (e.g., Meiran & Marciano, 2002). Meiran and Marciano (2002) demonstrated that while advance preparation to redirect selective attention is effective in classification tasks, it is compromised in same/different judgment tasks. That is, while in a classification task, such as classifying a digit as an odd or even number, switch costs were found to be reduced as the preparatory interval increased; whereas in a same/different judgment task, such as judging if a pair of digits are the same or different in terms of their color, switch costs did not vary as a function of preparatory intervals (Meiran & Marciano, 2002). Although researchers often refer to "task switching," there are many different types of switch tasks; thus, future research should test whether these tasks tap into the same control processes. As Prinz (1997) elaborated, even the simplest cognitive task (e.g., RT) requires a task set. Various task-switching studies have used many different types of switch tasks, such as shifting between relevant object dimensions (e.g., Owen, Roberts, Polkey, Sahakian, & Robbins, 1991; Rogers, Andrews, Grasby, Brooks, & Robbins, 2000; Rushworth, Passingham, & Nobre, 2005), objects stored in working memory (e.g., Garavan, 1998), stimulus-response rules (e.g., Cools, Clark, Owen, & Robbins, 2002; Rubinstein et al., 2001; Rushworth et al., 2002), task sets (both stimulus and response sets, e.g., Rogers & Monsell, 1995; Sohn & Anderson, 2001), target-levels (global vs. local; e.g., Wilkinson, Halligan, Marshall, Buchel, & Dolan, 2001), semantic classifications (odd/even vs. vowel/consonant judgments, e.g., Rogers & Monsell, 1995), response modes (e.g., simple vs. choice response; e.g., Koch, Gade, & Philipp, 2004), and response modalities (vocal vs. finger vs. foot response; e.g., Philipp & Koch, 2005). Differences inherent to these tasks might explain the variability in the findings of the task switching literature. Unfortunately, few studies have formally addressed this issue. Moreover, these task procedures and experimental settings often vary; thus, making direct comparisons between these studies is difficult. Therefore, research that systematically compares different types of switch tasks is warranted and may help to resolve conflicts among task-switching models.

The question of whether different types of switch tasks activate disparate cognitive processes or just one cognitive process is worth investigation. Indeed, I am currently investigating this issue.

The Neural Correlates of Task Switching and Their Relationship to Individual Variability

The cognitive neuroscience of task switching is less than 10 years old. Although much progress has been made toward identifying the neural correlates of task switching, as described in the previous section, more research is needed to determine if there is more than one brain region that controls task switching. More importantly, more and more research has indicated there are individual differences in performance (e.g., fast vs. slow RTs) related to task-switch efficacy (for a review, see Karayanidis et al., 2010). This line of research has focused on the correlations between neuroscience and behavioral data. For example, by partitioning ERP data into fast vs.

slow RT trials, Lavric et al. (2008) found a large late frontal negativity and a parietal positivity on fast RT trials. Karayanidis et al. (2009) correlated the amplitude of an early cue-locked positivity with behavioral data and found that a larger early cue-locked positivity was associated with greater advanced preparation. Likewise, fMRI research has found a positive correlation between the activation of the left inferior frontal junction and the magnitude of a behavioral cuing effect, which suggests the presence of cue-elicited task preparation (for a review, see Schneider & Logan, 2009). Because high-tech methodologies are increasingly common, neuroimaging approaches are moving the task-switch field in the right direction; however, researchers should still remember to account for individual variability.

Summary of the Third Decade of Research

Because this decade is just beginning, perspectives on future research are warranted. I proposed three lines of research to investigate the relationships between: task conflict and task switching; task type and task switching; and the neural correlates of task switching and its relationship to individual differences in performance.

Final Remarks

This review article provided a chronological review of the publications that have substantially influenced the field of task switching. For the sake of brevity, this article focused on studies that are research milestones. I hope that readers, especially those who are new to the field, grasp these developments, avoid historical mistakes (confounds), and ask research questions that continue to move task-switching investigations forward.

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作業轉換研究的二十年回顧：還有什麼議題可繼續追問？

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高等認知控制的重要面向之一是能夠因應環境而有效率的在不同作業之間做轉換。例如，一位雙語者必須能夠依據她／他所談話的對象來決定使用哪一種語言做溝通，並且要能夠隨時在必要時去轉換使用不同的語言。既然在任何一個情境脈絡下都存在許多的不同作業可以執行，那麼究竟我們是如何去控制使用這些與時俱變的不同作業已成為一個重要的研究課題。在過去的二十年，許多為理解動力性認知控制的研究者已普遍使用「作業轉換」的程序：要求實驗參與者要對兩種不同的作業規則做嘗試次之間的快速轉換。透過這個作業程序，研究者發現實驗參與者轉換作業時所須花費的時間要比重複作業來得長。本篇回顧性文章將總覽過去二十年來使用各種不同類型的作業轉換派典之相關研究，包括行為的以及神經影像為取向的研究。本文將著重於作業轉換的準備控制機制（轉換特定性及／或一般性）及其相關理論。同時文中將評述作業轉換的各種干擾現象，包括作業轉換的反應重覆虧損、作業前向干擾、後向抑制、作業規則相容性、競爭規則抑制等等。最後，文中將展望作業轉換之研究未來十年的可行性研究議題。

關鍵詞：干擾、作業轉換、抑制、準備、認知控制