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Control and Interference in Task Switching—A Review

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The task-switching paradigm offers enormous possibilities to study cognitive control as well as task interference. The current review provides an overview of recent research on both topics. First, we review different experimental approaches to task switching, such as comparing mixed-task blocks with single-task blocks, predictable task-switching and task-cuing paradigms, intermittent instructions, and voluntary task selection. In the 2nd part, we discuss findings on preparatory control mechanisms in task switching and theoretical accounts of task preparation. We consider preparation processes in two-stage models, consider preparation as an all-or-none process, address the question of whether preparation is switch-specific, reflect on preparation as interaction of cue encoding and memory retrieval, and discuss the impact of verbal mediation on preparation. In the 3rd part, we turn to interference phenomena in task switching. We consider proactive interference of tasks and inhibition of recently performed tasks indicated by asymmetrical switch costs and n-2 task-repetition costs. We discuss stimulus-based interference as a result of stimulus-based response activation and stimulus-based task activation, and response-based interference because of applying bivalent rather than univalent responses, response repetition effects, and carryover of response selection and execution. In the 4th and final part, we mention possible future research fields.

Keywords: task switching, cognitive control, interference

Human behavior is highly adaptive and flexible in response to changing environmental demands. This flexibility requires complex cognitive control processes, which allow humans to not only respond reactively but also to behave in a more proactive way to achieve goals and to perform tasks. The exploration of the processes underlying flexible task performance has become a major research topic in cognitive psychology, and task switching has been developed as an experimental paradigm to explore the mechanisms of cognitive control (e.g., Allport, Styles, & Hsieh, 1994; Jersild, 1927; Rogers & Monsell, 1995).

In task-switching experiments, participants perform a discrete task on each trial. On some trials the task changes (switch trials), and on others it does not (repeat trials). We review below several ways of arranging the task sequence to obtain switch and repeat conditions. Performance in task switches is compared with that in repetitions. The basic phenomenon is that there is a highly robust "switch cost" in both reaction time (RT) and error rates. To explain the nature of switch costs has been the major goal in studies of task switching.

The study of task switching has become an extremely active research field in experimental psychology and cognitive neuroscience. For example, a review article of Monsell (2003) published only 7 years ago has been cited 314 times (Social Science Citation Index; date of search: 1/2/2010). Moreover searching for the terms "task* switch*" or "task* shift*" resulted in 2,513 hits in Medline and PsycINFO (date of search: 1/2/2010; duplicates are removed), whereby 2,308 articles were published in 2002 or later, and 1,857 were published between 2005 and 2010. This research activity has led to a better understanding of many variables affecting the

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cognitive and neural mechanisms underlying task switching and has fostered important recent theoretical developments and discussions. Because this research field is growing so quickly, it is increasingly more important to have review articles that organize the knowledge already attained in this field in a comprehensive framework. Previous review articles on task switching (Allport & Wylie, 1999; Logan, 2003; Monsell, 2003) have proved highly useful to this purpose. However, since then, there has been a tremendous growth of the number of published studies and, correspondingly, of important new methods, phenomena, and theoretical ideas. Therefore, we felt that it was important to provide a review that incorporates these new developments and that discusses new directions in the study of task switching.

The aim of this article is to review the recent empirical evidence and theoretical development in task switching. We primarily review the behavioral literature and the issues that behavioral research has risen, whereas we do not provide a comprehensive review on neuroscientific and neuropsychological data. Further, the review does not provide detailed in-depth discussion of computational modeling of task switching but instead provides descriptions of a large number of phenomena that need to be addressed by computational theories. We structure this article as follows. First, we describe basic paradigms and phenomena. Then, we review evidence on the cognitive and neural mechanisms underlying task preparation in task switching. In a third section, we discuss mechanisms underlying interference phenomena in task switching. In a final section, we highlight two issues that we believe may be important in future studies.

Task Switching

In task-switching experiments, participants are instructed to switch (at least occasionally) between different tasks. As for what constitutes a "task," a general definition is problematic, as Rogers and Monsell (1995) already noted, "it is difficult to define with precision ... what constitutes a 'task'" (p. 208). However, in practice the requirement for a classifiable and measurable response to a punctuate stimulus means that task-switching experiments typically use tasks such as word reading, color and object naming, categorizing digits regarding magnitude or parity, categorizing letters as vowel or consonant, categorizing words as living/nonliving, or responding according to the location of a stimulus. Thus, tasks entail performing some specified mental operation or action in response to stimulus input. In task-switching experiments, well-defined stimulus-response (S-R) tasks are usually used (so-called "single step tasks"; Monsell, 1996, p. 95). Quite often stimuli are *bivalent*, which means that they fit to several tasks (e.g., number stimuli fit both to magnitude and parity categorization tasks). Further, quite often the same responses are used for both tasks, such as a left key press to indicate that a number is smaller than a given reference value or even, and a right key press to indicate that a number is larger or odd. When using bivalent stimuli and overlapping responses, a stimulus can either be congruent (i.e., it affords the same response in both tasks) or incongruent, affording different responses in both tasks. We refer to the issue of stimulus bivalence and congruency in later sections.

In theory, if a person intends to do a task, he/she adopts a corresponding mental task set (e.g., Allport et al., 1994; Jersild, 1927; Rogers & Monsell, 1995; Spector & Biederman, 1976; see also Ach, 1910/2006). The term *task set* refers to the organization of cognitive processes and mental representations that enable the person to act in accordance to task requirements. Thus, a task set must include the representation of task-relevant stimuli and task-relevant responses and the corresponding S-R mappings. For some tasks, the S-R mappings are relatively easy because they are highly overlearned (such as in word reading or object naming), whereas for other tasks, the S-R mappings are more difficult to establish because they are arbitrary (e.g., blue → left response key, red → right response key) or because they overlap for different possible tasks (e.g., naming the ink color of a color word or reading the word itself; e.g., Stroop, 1935).

Over the years, task-switching research has advanced with regard to the experimental methods. In the following, we review five different basic paradigms (for an overview, see Figure 1).

Mixed-Task Blocks Versus Single-Task Blocks

The first studies on task switching applied fixed task sequences, in which the task switched every trial (ABAB sequences; Allport et al., 1994; Fagot, 1994; Jersild, 1927; Spector & Biedermann, 1976). Performance in these mixed-task blocks was compared with performance in single-task blocks, which require only one task (AAA or BBB). For example, Jersild (1927) instructed his participants to perform just one arithmetic task in a block of trials (single-task lists: adding 6 to each number or subtracting 3 from each number) or to switch every trial between two arithmetic tasks in a block (mixed-task lists: adding 6 to the first number, subtracting 3 from the second, again adding 6 ...).

Later studies often applied mixed-task blocks including both switch and repetition trials (e.g., AABBAA sequences). Across a considerable variety of different task combinations, it was found that participants took longer to complete mixed-task blocks than single-task blocks, indicating *alternation costs* or *mixing costs* (see, e.g., R. Hübner, Futterer, & Steinhauser, 2001; Koch, Prinz, & Allport, 2005; Los, 1996; Rubin & Meiran, 2005; Steinhauser & Hübner, 2005). Mixing costs reflect the "global" costs associated with task switching compared with performance in single-task situations (cf. Mayr, 2001).

However, Rogers and Monsell (1995; see also Fagot, 1994) argued that delayed responses in mixed-task blocks do not necessarily reflect a switching process but can alternatively be interpreted in terms of higher working memory load in mixed-task blocks. Although in single-task blocks just one S-R-mapping (one task set) needs to be maintained, mixed-task blocks require maintaining two different task sets (for empirical support, see Logan, 2007). Because of this criticism, this experimental paradigm is seldom used nowadays. Nevertheless, the origin of mixing costs remains an important issue (e.g., Braver, Reynolds, & Donaldson, 2003; Rubin & Meiran, 2005). Regarding the experimental procedure, paradigms were developed that allowed researchers to examine "local" switch costs within mixed-task situations. We describe these paradigms next.

Predictable Task Switching

Rogers and Monsell (1995) introduced the usage of predictable task sequences (termed the *alternating-runs paradigm*). In the

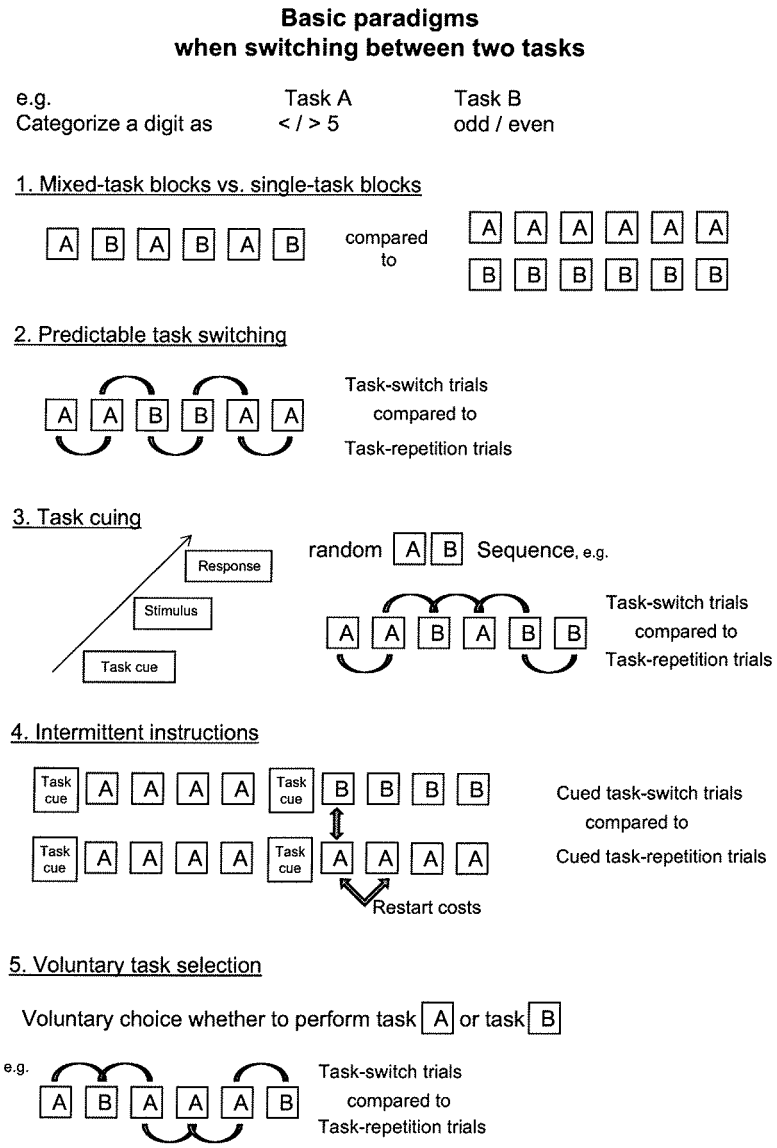

Figure 1. Basic paradigms when switching between two tasks. 1. Performance in mixed ABABAB task blocks is compared with performance in single-task blocks AAAA and BBBB. 2. In predictable task-switching paradigms, such as the alternating-runs paradigm, tasks switch after a predictable run length (e.g., run length of 2 establishes AABBAABB sequences). Performance in task-switch trials is compared with performance in task-repetition trials. 3. In the task-cuing paradigm, a cue is presented in each trial to indicate the currently required task. Performance in task-switch trials is compared with performance in task-repetition trials. 4. In the intermittent-instruction paradigm, the same task is required until a new task cue is presented. Performance in cued task-switch trials is compared with performance in cued task-repetition trials. In addition, in task-repetition trials, the presentation of a task cue induces restart costs. 5. In the voluntary task-selection procedure, participants voluntarily decide whether they perform Task A or B upon a presented stimulus.

alternating-runs paradigm, tasks switch in a regular manner after a constant number of trials, referred to as *run*, involving the same task (often tasks switch every second trial; AABBAABB sequences). For instance, Rogers and Monsell presented on each trial a pair of a letter and a digit in one of four quadrants on the computer screen. If the stimuli were presented in one of the upper quadrants, participants categorized the digit as being odd or even, and if the stimuli were presented in one of the lower quadrants, participants categorized the letter as a vowel or consonant. Stimulus location changed in a clockwise manner from trial to trial so that participants always performed two digit categorizations in a row followed by two letter categorizations.

Using this paradigm, Rogers and Monsell (1995) compared performance in task-switch trials (i.e., Task A performed after Task B or vice versa) with performance in repetition trials under identical overall working memory demands. The major finding of the alternating-runs paradigm is impaired performance (i.e., increased RTs and error rates) in switch trials compared with repetition trials. This finding has been termed *switch costs*. Note that (a) switch costs were substantial even though the tasks were rather simple, (b) the task sequence was entirely predictable, and (c) there was an external spatial location cue indicating the serial position in the run (cf. Koch, 2003).

Variants of alternating runs can be produced by varying run length (e.g., run length of 4: "AAAABBBB"; see, e.g., Monsell, Sumner, & Waters, 2003). Interestingly, in the alternating-runs paradigm, responding is usually slower only in the first trial of a run, that is, in the switch trial (Monsell et al., 2003; Rogers & Monsell, 1995, Experiment 6).

Other variants of predictable switching include either short sequences of just two tasks that were specified in advance (e.g., Goschke, 2000; Sohn & Anderson, 2001) or situations in which participants perform longer, more complex task sequences in a predictable manner (e.g., Gotler, Meiran, & Tzelgov, 2003; Koch, 2001, 2005, 2008; Logan, 2007; Schneider & Logan, 2006). Notwithstanding the differences between the various predictable task-switching paradigms, they all have in common that they allow the measurement of "local" switch costs, which have been shown as a highly robust empirical finding.

Task-Cuing Paradigm

As an alternative to predictable sequences, a task-cuing paradigm with unpredictable sequences has been developed (e.g., Meiran, 1996; Sudevan & Taylor, 1987; see also Shaffer, 1965, 1966). In this paradigm, the order of the tasks and thus the order of task switches and repetitions are random. To specify the currently required task, an explicit task cue precedes or accompanies the stimulus. For example, in Sudevan and Taylor's (1987) study, participants switched between categorizing a digit as odd/even or as smaller/larger than 5. The tasks were cued by the letters OD/EV and LO/HI for odd/even and low/high, respectively. Other studies used the task names (e.g., magnitude or parity) or symbols (e.g., a square or a diamond) as task cues. We address the impact of the nature of task cues in later sections.

As in predictable task-switching paradigms, performance in switch trials is compared with performance in repetition trials. Again, performance is typically worse in switch trials than in repetition trials, revealing robust switch costs also in the task-cuing paradigm (see, e.g., Altmann, 2004; Dreisbach, Haider, & Kluwe, 2002; Hoffmann, Kiesel, & Sebald, 2003; Koch, 2001; Meiran, 1996; Meiran, Chorev, & Sapir, 2000). In contrast to predictable runs paradigms, response times usually decline further if the same task repeats for several trials (e.g., Meiran et al., 2000, Experiment 1; Monsell et al., 2003). Importantly, the task-cuing paradigm allows to vary the interval between the task cue and the target stimulus (cue-stimulus interval [CSI]), an issue that we revisit in later sections.

Intermittent Instructions

Intermittent-instruction paradigms require that participants perform a sequence of trials with the same task. The sequence of trials is occasionally interrupted by a cue that informs participants what to do on the following trial sequence until the next interruption by a cue. The order of the interrupting task cues is random so that the tasks either repeat or switch in consecutive runs.

For example, Gopher, Armony, and Greenshpan (2000) administered short blocks of 15 trials during which only a single-task switch would or would not occur (see also Allport & Wylie, 2000; Gopher, 1996). Task cues indicating the to-be-performed task on the following trials were presented prior to the first trial and (randomly chosen) prior to one of Trials 4–11. Comparing performance in cued-switch trials and performance in cued-repetition trials revealed robust switch costs. In addition, this paradigm showed *restart costs*, that is, a slowdown of responding in explicitly cued-repetition trials relative to repetition trials that were not immediately preceded by a task cue.

Similar findings were obtained by Altmann and Gray (2008) using longer blocks that included several intermittent instructions. In addition to switch costs and restart costs, Altmann and Gray observed that within a run, response times and error rates increased with run length, revealing so-called within-run slowing (see also Altmann, 2002; Altmann & Gray, 2002; Poljac, de Haan, & van Galen, 2006; Poljac, Koch, & Bekkering, 2009). Currently, it is unclear whether within-run slowing effects depend on intermittent instructions or do likewise occur in predictable task-switching settings with longer runs. For example, Waszak, Hommel, and Allport (2003) observed within-run slowing for run length of 3, whereas Rogers and Monsell (1995) or Monsell et al. (2003) did not find within-run slowing when using alternating runs of run length of 4 or 8.

Voluntary Task Selection

Recently, Arrington and Logan (2004a, 2005) investigated internally generated task switches in contrast to switches that are required according to external cues or regular sequences (see also Arrington, 2008; Arrington, Logan, & Schneider, 2007; Arrington & Yates, 2009; Forstmann, Brass, Koch, & von Cramon, 2006; Liefooghe, Demanet, & Vandierendonck, 2009; Mayr & Bell, 2006). In voluntary task selection, participants decide themselves on each trial which of two tasks to perform. To enable this free choice, stimuli are, like in most task-switching procedures, bivalent (i.e., afford both tasks). In contrast to most procedures, responses for the two tasks are given on separate, nonoverlapping sets of keys, so that the experimenter can infer which task was chosen. Even though participants voluntarily decide for a task switch, robust switch costs emerge in this paradigm.

Summary

The different paradigms are similar regarding the fact that they measure the costs of switching tasks. Note that costs that are assessed as mixing costs in the comparison between mixed-task blocks and single-task blocks represent more "global costs," whereas the costs assessed as switch costs in the comparison between task-switch trials and task-repetition trials

represent "local" switch costs (e.g., Kray & Lindenberger, 2000; Mayr, 2001).

Although all paradigms revealed the general effect of switch costs, the different paradigms reveal specific results and functional dependencies, which are considered in detail later. Most importantly, two major research topics can be distinguished: first, preparation for an upcoming task, and second, interference due to recent performance of the alternative task(s). In the following, we describe the empirical findings and corresponding theories of task preparation and task interference.

Preparation in Task Switching

In task switching, the term *task preparation* is used to refer to processes that improve performance when participants know which task is required prior to onset of the target stimulus. In this part, we first present empirical evidence for task preparation. Then we discuss temporal preparation (i.e., generic preparation to process a stimulus and/or to emit a response at a specific point in time) and decay as alternative explanations for the observed preparation effects.

In the following sections, we consider two-stage models of switch-specific preparation processes and models that conceive of switch-specific preparation as an all-or-none process. Finally, we review empirical evidence questioning that preparation is switch-specific, and we present models conceptualizing preparation as interaction of cue encoding and memory retrieval. These models assume that task preparation is not switch-specific but occurs in both switch trials and repetition trials.

Empirical Evidence for Task Preparation

Task preparation has been mainly examined in studies that manipulated the time intervals prior to stimulus onset. In predictable-switching paradigms (e.g., alternating runs), the interval between the response in the preceding trial and the onset of the next task stimulus (i.e., response-stimulus interval [RSI]) is varied. In the task-cuing paradigm, the interval between cue and stimulus (i.e., CSI) as well as the interval between response in the preceding trial and onset of the cue (i.e., response-cue interval [RCI]) is varied.

Using the alternating-runs paradigm, Rogers and Monsell (1995) instructed their participants to either categorize a digit as odd or even or a letter as a vowel or consonant (see Figure 2). As described in the previous section, the task sequence varied predictably in runs of two (e.g., AABBAABB). Critically, Rogers and Monsell varied the RSI between and within blocks to provide participants with extra time to prepare for the upcoming task. These authors found that task-switch trials benefited more from longer RSIs than task-repetition trials, resulting in reduced switch costs. They proposed that this reduction of switch costs with long RSIs suggests preparation—or *advance reconfiguration*—for the upcoming task. Interestingly, Rogers and Monsell observed the reduction of switch costs only when they varied the RSI between blocks and not when they varied the RSI within blocks. We revisit this issue later.

Supporting evidence for the proposal of advance reconfiguration comes from the task-cuing paradigm. For example, in a study by Meiran (1996), a spatial stimulus appeared in one

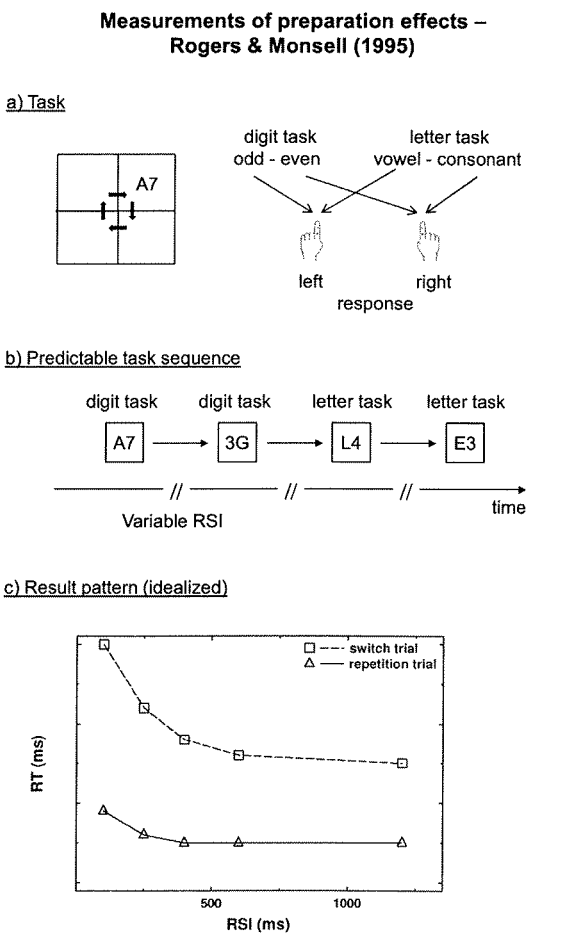

Figure 2. Measurement of preparation effects in Rogers and Monsell's (1995) study. (a) Stimulus presentation rotates clockwise in a 2 × 2 matrix to instruct an AABB task order. Participants switch between classifying a digit as odd or even and classifying a letter as a vowel or consonant. (b) Tasks alternate in a predictable AABB task sequence. The response-stimulus interval (RSI) is variable. (c) Switch costs (i.e., reaction time [RT] difference between switch and repetition trials) are reduced with long RSIs.

location of a 2 × 2 grid, and arrow cues indicated whether participants had to make a spatial judgment with respect to the vertical or horizontal stimulus position (i.e., up-down vs. left-right judgment; see Figure 3). Prolonging the CSI resulted in decreased switch costs.

These two studies exemplified the frequently observed reduction of switch costs on the basis of prolonging the time interval prior to stimulus onset. In other studies, tasks—such as parity and magnitude judgments on digit stimuli (e.g., Koch, 2003; Logan & Bundesen, 2004), size categorization and living/nonliving decision on words (e.g., Arrington & Logan, 2004b), or form and color judgments (e.g., M. Hübner, Kluwe, Luna-Rodriguez, & Peters, 2004a; Monsell & Mizon, 2006)—have been used. Notwithstanding the specifics of the required tasks, preparatory reductions of switch costs have been demonstrated in many studies (e.g., Hoff-

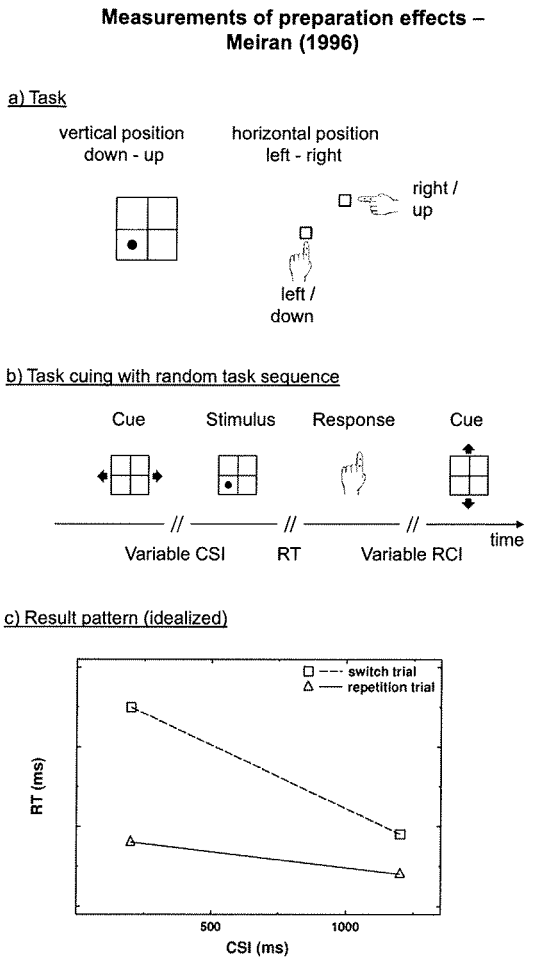

Figure 3. Measurement of preparation effects in Meiran's (1996) study. (a) Participants switch between responding according to the vertical and horizontal location of a stimulus. (b) The currently relevant task is cued by left/right or up/down pointing arrows; task sequence is random. The cue-stimulus interval (CSI) is variable. (c) Switch costs (i.e., reaction time [RT] difference between switch and repetition trials) are reduced with long CSIs. RCI = response-cue interval.

mann et al., 2003; Kiesel & Hoffmann, 2004; Koch, 2001; Meiran et al., 2000; Monsell et al., 2003).

Temporal Preparation or Decay of Task Set as Alternative Explanation?

Before we continue with discussing theoretical models of task preparation, we consider two possible alternative explanations for the observed effects of the intervals prior to stimulus onset in task switching: temporal preparation and decay.

When preparation time is varied randomly, this introduces temporal variability. Thus, it seems reasonable to consider whether some of the observed preparation effects in task switching are actually due to temporal preparation rather than task-specific preparation. Temporal preparation is typically studied using manipulations of the interval between an uninformative warning signal and a target stimulus (*foreperiod*; see, e.g., Lohmann, Herbort, Wagener, & Kiesel, 2009; Los, Knol, & Boers, 2001; Niemi & Näätänen, 1981; Woodrow, 1914). The majority of earlier research on foreperiod effects used simple RT tasks (for a review, see, e.g., Niemi & Näätänen, 1981); but, there is some evidence from choice tasks too (e.g., Bausenhart, Rolke, Hackley, & Ulrich, 2006; Fischer, Schubert, & Liepelt, 2007; Los & van den Heuvel, 2001), suggesting that temporal preparation can indeed affect performance in single-task settings. However, in the present context, the critical question is whether nonspecific temporal preparation contributes to, or is even essential for, the preparation effects observed in task switching.

The existing data suggest that temporal preparation plays a minor role at best in task switching. For example, inserting warning signals prior to stimulus onset in predictable task sequences (Rogers & Monsell, 1995) had only very small effects, which were the same for switches and repetitions. Likewise, inserting a warning signal prior to cue onset in random task sequences had only very weak effects, and these effects were not switch-specific (Meiran et al., 2000; see also Meiran & Chorev, 2005). Meiran et al. (2000) attributed these effects to stimulus-induced shifts in phasic alertness. Irrespective of the underlying mechanisms of warning-signal effects (see, e.g., Hackley & Valle-Inclán, 2003; Kiesel & Miller, 2007), the important result of these studies was clearly that effects of nonspecific temporal preparation (as opposed to task-specific preparation) were numerically very small (i.e., almost by an order of magnitude smaller than task-specific preparation effects) and did not differ for task switches and repetitions. Thus, even though nonspecific temporal preparation occurs, temporal preparation plays only a minor role in switch-specific preparation.

Another alternative explanation for preparation effects in task switching is passive decay. Specifically, prolonging the intertrial interval (e.g., RSI in alternating runs or RCI + CSI in task cuing) provides time not only for active preparation of the upcoming task but also for changes relating to the *preceding* task, such as passive "decay" of activation of the preceding task set (Allport et al., 1994; Altmann, 2005; Meiran, 1996). If switching between tasks is more difficult when the preceding task set is more active, decay of the preceding task set should reduce switch costs. Hence, preparation as well as decay could in principle affect the size of switch costs.

The task-cuing paradigm allows examining the potential effects of decay time on switch costs, independent of active preparation. To do so, the CSI, which represents the time available for cue encoding and task preparation, is held constant, whereas the interval between response in trial n-1 and cue onset in trial n (RCI) is varied. In fact, it has been found that switch costs decrease with increasing RCI (e.g., Altmann, 2005; Koch, 2001; Meiran et al., 2000), consistent with the idea that task activation passively and rapidly decays over time following execution of a response (however, for an account relating RCI effects to changes in temporal distinctiveness of prior processing episodes, see Horoufchin, Philipp, & Koch, in press). That is, the idea of passive task-set decay suggests that when a new task set needs to be activated on a switch trial, there is reduced competition from the preceding task for longer RCIs (this topic is discussed in more detail in the Proactive Interference of Tasks section), resulting in reduced switch costs.

Importantly though, at least two lines of evidence rule out decay as the primary explanation for reduced switch costs with prolonged intertrial intervals. First, Rogers and Monsell (1995) varied RSI in the alternating-runs paradigm in separate blocks (Experiment 3) as well as randomly from trial to trial within blocks (Experiment 2). They observed reduced switch costs only with blocked RSIs but not with random RSIs. Rogers and Monsell argued that a passive process of decay is expected to occur independently of such manipulations. Instead, they assumed that the switch-cost reduction for blocked RSI reflects active preparation processes that were somehow disturbed by random RSIs.

Second, the task-cuing paradigm can be used to demonstrate effects of preparation of the upcoming task, independent of decay-time effects. For this purpose, either the CSI is varied while holding RSI constant (i.e., by varying RCI inversely to CSI) or CSI and RCI are varied independently. A multitude of studies using these manipulations have found that performance generally improves with increasing CSI and that in many cases switch costs also decrease with increasing CSI (e.g., Arrington & Logan, 2004b; Koch, 2001; Logan & Bundesen, 2003; Logan & Schneider, 2006; Meiran, 1996; Meiran et al., 2000; for a review, see Monsell, 2003).

Taken together, the effects of manipulating the intertrial intervals can be considered as evidence for task preparation in task switching. Different classes of theories on task preparation are discussed in the next subsections.

Switch-Specific Preparation Processes in Two-Stage Models

Decreasing switch costs with increasing CSI (or RSI) have been taken as an indicator for task preparation. However, even with ample time for preparation, often so-called "residual" switch costs remain (e.g., Fagot, 1994; Meiran, 2000a; Rogers & Monsell, 1995; Rubinstein, Meyer, & Evans, 2001; but see Verbruggen, Liefooghe, Vandierendonck, & Demanet, 2007). To account for these findings, two-stage models of task reconfiguration have been proposed by Rogers and Monsell (1995), Mayr and Kliegl (2000, 2003), Rubinstein et al. (2001), and Meiran (2000a). Generally, these models entail a first stage that can occur prior to stimulus onset and a second stage that has to wait until stimulus presentation. Thus, they assume a structural inability to fully prepare for a task switch.

Rogers and Monsell (1995) assumed processes of "reconfiguration" that are required in switch trials but not in repetition trials. These reconfiguration processes entail "retrieval or reinstatement of the relevant task-set" (Monsell, Yeung, & Azuma, 2000, p. 253) and take place in two different stages: A first task-set-reconfiguration process starts as soon as participants finished performance of the previous trial and are informed about the upcoming task (either due to fixed task order or due to presentation of a cue). The authors took their finding of reduced switch costs with increasing RSI as suggesting that reconfiguration takes place prior to stimulus onset (advance reconfiguration), which they termed the *endogenous component* of task-set reconfiguration (Rogers & Monsell, 1995). The observation of residual switch costs is considered to reflect a second task-set-reconfiguration process that can occur only after stimulus presentation. Consequently, this has been termed the *exogenous component* of task-set-reconfiguration (see also Monsell et al., 2000).

Rubinstein et al. (2001) implemented endogenous and exogenous reconfiguration processes in the framework of the production system EPIC (executive production/interactive control; Meyer & Kieras, 1997a, 1997b). Endogenous preparation for the upcoming task consists of *goal-shifting*, that is, the current goal is inserted in declarative working memory, and the previous goal is deleted. The exogenous reconfiguration process is *rule-activation*, which loads S-R translation rules for the current task into procedural working memory.

Meiran (2000a) specified the processes involved in advance reconfiguration as a change of the attentional weighting of stimuli to favor the currently relevant stimulus features. This *stimulus set biasing* (Meiran, 2000a) can refer to any relevant stimulus attributes, that is, perceptual categories—such as red/green, spatial categories such as left/right, or semantic categories such as odd/even—become preactivated on the basis of the cue or knowledge about task order (see, e.g., Desimone & Duncan, 1995; Koch & Allport, 2006; Logan & Gordon, 2001; Meiran, 2000a; E. K. Miller & Cohen, 2001). To account for residual switch costs, Meiran (2000a) assumed a change of the associative weighting in the response set. The *response set* is defined as the associative links between nominal responses (e.g., left key press) and task-specific stimulus categories (e.g., "odd" vs. "smaller than 5"). However, this "response recoding" occurs only after task performance and thus always refers to the response set of the previous trial. Thus, in contrast to Rogers and Monsell (1995) and Rubinstein et al. (2001), according to Meiran (2000a), residual switch costs do not reflect an exogenous component of task reconfiguration required for task performance because response set biasing occurs simply as a by-product of task execution rather than as an additional control process (see also Meiran, Kessler, & Adi-Japha, 2008).

Taken together, there are several models that assume two stages of task-set reconfiguration to account for the observations that (a) switch costs decrease with increasing CSIs (or RSIs) and (b) despite long CSIs (or RSIs), residual switch costs remain. Thereby, the term *reconfiguration of task sets* originally introduced by Rogers and Monsell (1995) implies that there are processes (be they endogenous or exogenous processes) that occur just in switch trials but are not required in repetition trials. However, there is also another two-stage model proposed by Mayr and Kliegl (2000, 2003) that does not share this assumption. This model is described in later sections.

Whereas these two-stage models were introduced to explain residual switch costs within a preparation framework, other accounts assume that residual switch costs are not related to preparation at all. Such "hybrid" accounts also assume an active reconfiguration process. This process can be carried out before the stimulus (if there is sufficient time and if participants are sufficiently motivated), thus accounting for the reduction in switch cost with preparation. However, these accounts take residual switch costs as primary evidence for task interference, as proposed, for example, more recently by Monsell (2003). We discuss task interference in detail in the second part of our review.

In the next sections, we first present models that explain the two components of switch costs by assuming a single process of reconfiguration, which sometimes occurs as task preparation (i.e.,

prior to the onset of the target stimulus) but sometimes fails to occur prior to target onset. Then, we present empirical data and models that question whether preparation processes are unique for switch trials.

Switch-Specific Preparation as All-or-None Process

Instead of assuming incomplete task reconfiguration in all trials, De Jong (2000) proposed the *failure-to-engage hypothesis*, which postulates that complete task preparation (or *intention activation*) occurs on some trials, whereas participants fail to engage in advance reconfiguration processes on other trials. In the latter trials, reconfiguration has to occur after presentation of the imperative stimulus, which explains why residual switch costs remain even when complete reconfiguration in advance is possible. Consequently, performance in task-switch trials (under conditions of ample time for preparation) reflects a mixture of trials with complete preparation and trials that lack any preparation (and still require full task-set reconfiguration after stimulus presentation).

As evidence for this assumption, De Jong (2000) put forward a formal mixture model. Using this model, he could show that RT distributions for switch trials with ample preparation time can be fit as a mixture of RTs from fully prepared trials (estimated from repetition trials obtained in conditions with long preparation time) and completely unprepared trials (estimated from switch trials obtained in conditions with short preparation time).

Nieuwenhuis and Monsell (2002) applied De Jong's (2000) mixture model to the data reported by Rogers and Monsell (1995, Experiment 3) and found good fits of the model to the data. Further, they had participants perform the same tasks as Rogers and Monsell but introduced a payoff system combined with extensive feedback to motivate participants to minimize RT. Interestingly, the proportion of fully prepared trials increased only marginally, revealing that strong incentives to prepare do not increase the proportion of fully prepared trials substantially. Recently, however, Verbruggen et al. (2007) observed that the duration of task-cue presentation affected task preparation. Restricting the cue presentation to very brief durations (e.g., 64 ms) by removing the cue during the preparation interval decreased the residual switch costs substantially and in some cases even completely (see, however, Steinhauser, Maier, & Hübner, 2007, who obtained substantial residual switch costs despite of using brief cue durations). Verbruggen et al. assumed that immediate cue removal encouraged participants to complete task reconfiguration in advance. Thus, if Verbruggen et al.'s findings turn out to be robust, one might assume that functional constraints in cue processing can influence task preparation more strongly than monetary incentives, suggesting that failures to engage in task preparation are not purely motivational (see also Nieuwenhuis & Monsell, 2002).

The basic idea of De Jong's (2000) mixture model is that participants are able to fully prepare the upcoming task in a task switch, but that they fail to do so on a substantial number of trials. This all-or-none idea is also incorporated in a model proposed by Sohn and Anderson (2001), who likewise assumed an all-or-none-preparation. Sohn and Anderson used the adaptive control of thought-rational (ACT-R) model (Anderson & Lebiere, 1998) to implement a two-component ACT-R model of task switching. This model assumes a "prepare-switch" procedure that either changes the task or fails to change the task during the preparation time for the upcoming task. Likewise, Mayr and Kliegl (2000), who suggested that task preparation is based on retrieval of the S-R rules of the upcoming task, pointed out that all-or-none preparation is consistent with the assumption of probabilistic failures of such rule retrieval. Similarly, in Logan and Bundesen's (2003) model, cue encoding is implemented as an all-or-none process. We explain the accounts of Mayr and Kliegl and of Logan and Bundesen in more detail in the Preparation as Interaction of Cue Encoding and Memory Retrieval section.

However, the assumptions of the mixture model have been discussed controversially. Whereas it seems straightforward to assume that switch trials in conditions with short preparation time represent trials without any preparation, it is questionable whether repetition trials obtained in conditions with long preparation time indeed represent trials with complete preparation. For example, Allport and Wylie (1999; see also Wylie & Allport, 2000) disputed the idea that performance in task-repetition trials provides a good estimate of fully prepared processing because they observed substantial variations in task-repetition performance. Furthermore, the observation of mixing costs, which represent poorer performance in task-repetition trials in mixed-task blocks relative to performance in single-task blocks, casts serious doubts on the idea of taking task-repetition trials as a fully prepared baseline.

Also, Lien, Ruthruff, Remington, and Johnston (2005) examined in more detail why participants seem to prepare the task in some trials but fail to do so in other trials. In their study, participants switched between performing a color task or a shape task upon colored shape stimuli. Each task consisted of three S-R rules. For example, participants pressed a left key for triangles, a middle key for diamond, and a right key for shapes. Lien et al. found that residual switch costs varied depending on the single S-R rule. For each participant, there was a "preferred" S-R rule for each task that did not induce switch costs, whereas the other two S-R rules induced large switch costs despite that participants could prepare for the upcoming task for more than 2 s. Consequently, Lien et al. assumed that participants always partially prepared a task by preparing one S-R link completely and that they failed to prepare the other two S-R links of the task. Hence, Lien et al. explained residual switch costs by assuming an all-or-none preparation process that refers only to a part of the S-R mapping of the upcoming task, whereas De Jong (2000) assumed (failure of) preparation of the entire "task." However, the critical issue is clearly whether preparation is all-or-none or whether it is more gradual, which seems to be a difficult empirical question. Furthermore, all-or-none preparation models assume that preparation is switch-specific, that is, it occurs on switch trials only. Because of this assumption, any evidence for preparation effects in task repetitions would be problematic for this class of models. We discuss the question of whether preparation is indeed switch-specific in the next section.

Is Preparation Switch-Specific? Empirical Data

Switch costs as well as the preparatory reduction of switch costs play an important role in theoretical accounts of task switching. The accounts reviewed in the previous sections assume switch-specific preparation, that is, switch trials compared with repetition trials require at least one additional process of task "reconfiguration." Alternatively, there are also accounts that do not assume

extra processes in switch trials compared with repetition trials. Instead, these latter accounts assume that the same processes take place in switch and repetition trials but that these processes require more time in switch trials.

Before discussing these accounts in detail, we first present empirical evidence suggesting that task preparation is not necessarily switch-specific. First, most studies that varied preparation time observed that RTs also decrease in task-repetition trials as preparation time increases. This finding is a clear hint for preparation in task-repetition trials. In the following, we discuss in more detail findings revealing that task preparation is not switch-specific. For this purpose, we discuss two lines of evidence that have been considered as evidence that preparation is not restricted to switch trials but may also be observed (to a lesser extent) in repetition trials. Then, we discuss whether and how results of recent studies using functional magnetic resonance imaging (fMRI) and event-related potentials (ERPs) can contribute to clarifying whether there is an extra process of switch-specific preparation.

First, some studies manipulated preparation time in a between-subjects design. For example, Altmann (2004) used the task-cuing paradigm and presented the task cues either short (100 ms) or long (900 ms) before the stimulus. Long CSIs compared with short CSIs resulted in generally reduced RTs in switch trials as well as repetition trials, but there was no significant reduction of switch costs (see also Koch, 2001, 2005; Koch & Allport, 2006). This finding seems clear evidence that not only switch-specific preparation but some kind of generic preparation occurs in switch and repetition trials. More specifically, there are two studies that directly contrasted the effects of CSI variation in a between-subjects design and a within-subject design. Whereas the preparatory reduction of switch costs was observed only when preparation time was varied within-subject, prolonging the preparation time generally reduced RTs in both settings in switch trials as well as repetition trials (Altmann, 2004; Koch, 2001). Altmann therefore concluded "that generic preparation is more basic than switch preparation, raising the question of whether a switching mechanism is really needed to explain switch cost" (p. 161). To account for these results, Altmann and Gray (2008) assumed that participants try to prepare (i.e., to encode the task cue) as efficiently as possible in the available preparation time but that they avoid to maintain a state of high preparedness for durations longer than necessary. To this end, preparation efficiency is adjusted according to predicted preparation time and results in a similar state of preparation (and thus in similar switch costs) for each CSI level when participants are confronted with one level only. However, when preparation time varies within-subject block by block (or trial by trial), preparation efficiency is biased by exposure to the other CSI level. As a consequence, the maximum state of preparation is timed somewhat later for short CSIs and somewhat earlier for long CSIs, leading to less than optimal preparation for the short CSIs and therewith to the observed reduction of switch costs for long CSIs. Note, however, that an implication of this reasoning would be that within-block and between-blocks manipulations of CSI should lead to different preparation effects, but this prediction was not supported by data observed by Monsell and Mizon (2006, Experiments 4 and 5).

Taken together, Altmann and Gray (2008) assumed that the reduction of switch costs with a long CSI does not reflect the duration of switch-specific preparation but rather the inability to optimally adjust preparation efficiency to a given CSI when being confronted with multiple CSIs. However, although the functional mechanisms underlying this particular set of findings probably needs more research (see also Steinhauser et al., 2007, who proposed that participants favor a generic-preparation strategy over a switch-specific strategy under high stress compared with low stress), a major finding of these studies is clearly that preparation effects in task repetitions can be similar in size to preparation effect in task switches. This finding has been supported by other studies, which we discuss next.

The second line of evidence for the idea that preparation is not restricted to task switches comes from studies that manipulated task predictability while keeping preparation time constant. For example, Dreisbach et al. (2002) had participants switch between four different tasks. In each trial, they presented probability cues indicating the probability that the currently performed task would be repeated (100%, 75%, 50%, 25%, or 0%) and the probability that a specific alternative task would be required (0%, 25%, 50%, 75%, or 100%). Interestingly, switch costs did not differ for the varying probabilities. In contrast, if the cue indicated the next task with high probability compared with low probability, participants responded faster in switch trials as well as in repetition trials, indicating that participants prepare for the required task in both trial types depending on the task probability.

Likewise, Koch (2005) varied task predictability by using the cuing paradigm combined with alternating-runs sequences (AABB etc.). Participants first performed the predictable AABB sequence, in which performance could rely on both the task cues and the predictability of the sequence. Then, participants performed an unpredictable task sequence, in which performance cannot rely on predictability but only on task cues. Performance in unpredictable sequences was much worse than in predictable sequences in both switch trials and repetition trials, but switch costs were not affected by the removal of task predictability. This finding suggested that the preparation benefit due to task predictability was not switch-specific, even though the benefit of task predictability was numerically very substantial. Similar findings have been reported in a number of other studies using variants of this method (Gotler et al., 2003; Heuer, Schmidtke, & Kleinsorge, 2001; M. Hübner, Kluwe, Luna-Rodriguez, & Peters, 2004b; Koch, 2001, 2008; Ruthruff, Remington, & Johnston, 2001; Sohn & Carlson, 2000).

The absence of a switch-specific preparation effect on the basis of task predictability seems to suggest that a kind of task-updating process is equally needed in switches and repetitions (see, e.g., Gotler et al., 2003; Koch, 2003, 2005). Consistent with this suggestion, it has been found that patients with Parkinson's disease, who are known for being impaired at using internally generated information for motor control, are also impaired at using this internal predictability information for task preparation relative to an age-matched healthy control group (Werheid, Koch, Reichert, & Brass, 2007).

Taken together, the manipulation of preparation time in the cuing paradigm and the manipulation of predictability of task sequences in "hybrid" cuing-plus-predictability paradigms reveal robust preparation effects in switch trials as well as in repetition trials. These findings question whether task preparation is switch-specific. In addition, the preparatory reduction of switch costs can be explained by assuming that preparation is often more effective

in switch trials than in repetition trials because there is more interference in task-switch trials because of having performed the alternative task just recently (e.g., Gilbert & Shallice, 2002; Koch & Allport, 2006; Yeung & Monsell, 2003b; for further discussion of this topic, also see the Proactive Interference of Tasks section).

Consistent with the assumption that there are similar preparation processes with varying intensities in switch and repetition trials, a number of fMRI studies did not find switch-specific activations in the preparation phase (e.g., Brass & von Cramon, 2002, 2004; Braver et al., 2003; Dove, Pollmann, Schubert, Wiggins, & von Cramon, 2000; Luks, Simpson, Feiwell, & Miller, 2002; but see Wylie, Javitt, & Foxe, 2006). For example, Brass and colleagues consistently reported that an area in the frontal cortex, at the junction of the inferior frontal sulcus and the precentral sulcus (*inferior frontal junction*), was active during task preparation (Brass & von Cramon, 2002, 2004; see also Brass, Derrfuss, Forstmann, & von Cramon, 2005; Derrfuss, Brass, Neumann, & von Cramon, 2005). Activation in this area was found for both switch and repetition trials, suggesting that preparatory processes are not switch-specific (Brass & von Cramon, 2004). However, because of the relatively low temporal resolution of fMRI, these studies require specific experimental set-ups to distinguish task preparation and task execution. Brass and von Cramon (2002), for example, explored task preparation in trials in which only a task cue but no stimulus was presented. It is conceivable that inclusion of such trials discourages task preparation and that the observed activation was at least partly driven by task-cue identification processes.

Because of their high temporal resolution, ERPs might be more suitable than fMRI to address the question of preparation. For example, a recent ERP study, which allowed an online measurement of cue-triggered processes, revealed that both switch and repetition trials elicit a P3b component (Jost, Mayr, & Rösler, 2008). These authors assumed that the P3b in the preparatory interval reflects endogenous or cognitive aspects of "context updating" (see Donchin & Coles, 1988) because the P3b amplitude was related to response speed. In contrast to the random task-switch conditions, cues in single-task blocks, in which trial-by-trial updating is not necessary, did not elicit a P3b. This large difference between single-task blocks and mixed-task blocks, along with rather small differences between switch trials and repetition trials, is in line with the above described findings from behavioral and fMRI studies and seems to indicate that updating processes are initiated whenever a task-indicating cue is presented.

However, a number of ERP studies reported switch-related differences during the preparation interval and interpreted them as reflecting functional differences in switch and repetition trials. For example, Nicholson, Karayanidis, Bumak, Poboka, and Michie (2006) observed an increased parietal positivity in switch trials compared with repetition trials 400 ms after cue onset (see also Steinhauser, Hübner, & Druey, 2009; for similar results in the alternating-runs paradigm, see Karayanidis, Coltheart, Michie, & Murphy, 2003). Interestingly, Lavric, Mizon, and Monsell (2008) observed similar P3 components in switch and repetition trials. However, in this study, a switch-related posterior positivity and anterior negativity emerged approximately 500 ms after the task cue. The amplitude of this "posterior positivity–anterior negativity" complex correlated with the behavioral reduction of switch costs and was larger for fast than for slow responses. This relationship with behavioral measures was taken as evidence that the switch-sensitive ERP modulation during the CSI reflects anticipatory task-set reconfiguration.

To conclude, fMRI and ERP studies are inconclusive regarding differences or similarities of preparatory processes in switch and repetition trials. One reason is the relatively low temporal resolution that limits the usefulness of fMRI to study preparatory processes. Another reason, however, is that the mere observation of an increased ERP amplitude in switch trials compared with repetition trials is well in line with the assumption that preparation occurs in both trial types but to a stronger degree in switch trials. Furthermore, there are hardly any ERP studies that explicitly tested for *functional differences* between switch and repetition trials—that is, objective criteria such as topographical differences between switch and repetition trials or source localization were seldom used to investigate whether switch and repetition trials entail qualitatively different processes. In the next section, we present models that predict similar processes of cue encoding and memory retrieval in switch trials as well as repetition trials. To account for switch costs, these models assume that cue encoding and task-related memory processes take longer in task switches than in repetitions.

Preparation as Interaction of Cue Encoding and Memory Retrieval

Logan and Bundesen (2003) and Mayr and Kliegl (2003) pointed out one important feature in the task-cuing paradigm. Hitherto a task repetition was always associated with a cue repetition, whereas a task switch was associated with a cue switch. To dissociate task switching from "cue switching," these authors used a 2:1 mapping of cue-to-task, so that a cue change could still result in a task repetition. For example, in Mayr and Kliegl's study, participants switched between categorizing a colored form regarding color or form. The cues "G" and "S" indicated the color task, and the cues "B" and "W" indicated the form task. Using this 2:1 mapping of cue-to-task, it was found that there are indeed substantial costs of cue switching even if the associated task remains unchanged (see also Logan & Bundesen, 2003). This finding suggests that traditionally measured switch costs (i.e., the performance difference between task switches and task repetitions) in the task-cuing paradigm have a component that is attributable to processes associated with cue switching.

To account for their findings, Mayr and Kliegl (2003) suggested that preparation is not task-specific but reflects the interaction of cue encoding and memory retrieval. Mayr and Kliegl (2000, 2003) assumed that participants activate the currently relevant S-R rules, conceptualized as a long-term memory retrieval process, during the preparation interval. According to this assumption, the cue-switch costs represent the extra time costs associated with a change of the retrieval path in long-term memory that needs to be used to activate the associated task set (see also Gade & Koch, 2007a; Koch & Allport, 2006). That is, these authors basically have maintained a two-process view of task switching and have argued that cue encoding relates to a process of task-set activation, which is more difficult when the retrieval path changes. In addition, there is a second process associated with task implementation that has to wait until the target stimulus is presented. Thus this task-implementation process is reflected by residual switch costs.

Altmann and Gray (2008) put forward a rather similar but more formalized model. Based within Anderson and Lebiere's (1998) ACT-R production rule system, Altmann and Gray conceptualized preparation as retrieval of task codes in working memory. Retrieval of task codes occurs in switch and repetition trials but requires more time in switch trials because of stronger proactive interference from previously retrieved task codes. As retrieval of task codes occurs during the preparation interval (CSI), switch costs decrease with longer CSIs. To account for residual switch costs, Altmann and Gray did not assume a second process that has to wait until the target stimulus is presented, like Mayr and Kliegl (2000, 2003), but instead assumed failures to engage in task-code retrieval in line with De Jong's (2000) failure-to-engage hypothesis.

Using the 2:1 cue-to-task mapping, both Mayr and Kliegl (2003) and Logan and Bundesen (2003) observed substantial costs of cue encoding in task-repetition trials when the cue changed. Yet, their findings differed regarding the comparison of performance in switch and repetition trials with cue changes. Mayr and Kliegl observed switch costs, whereas Logan and Bundesen did not always observe substantial performance differences. In line with their finding, Logan and Bundesen brought forward a formal model that can account for differences in task + cue switch trials and task + cue repetition trials (i.e., switch costs in previous task cuing studies) without assuming an endogenous process of task reconfiguration. More specifically, Logan and Bundesen suggested that participants adopt a *stimulus-compound strategy* that entails encoding of the cue, encoding of the stimulus, and responding to the compound of both. The cue-stimulus compounds serve to retrieve the correct response from long-term memory. In this model, performance differences in switch and repetition trials occur in cue-repetition trials because cue encoding is primed because of residual activation of an identical cue in short-term memory. These performance differences decrease with longer CSIs as the likelihood increases that cue encoding is completed during the CSI. To account for residual switch costs, Logan and Bundesen suggested that either cue encoding fails in some trials (as De Jong, 2000, similarly suggested that task preparation fails in some trials) or that the preparation time is underestimated and that the preparatory interval is shorter than the maximum time required to complete cue encoding. In a study by Schneider and Logan (2005), for example, the longest preparation interval was 800 ms and revealed residual switch costs of 58 ms. The formal model of cue encoding predicted rather similar costs of 46 ms for a preparation interval of 800 ms. Thereby, cue encoding is modeled by an exponential distribution that is characterized by a long upper tail so that even when the mean cue encoding time is short, the probability that cue encoding is not yet complete after long preparation time (e.g., 800 ms) is still substantial.

In a number of articles, Logan and colleagues further developed the compound-retrieval account by specifying the representation of cue and target. Arrington and Logan (2004b) proposed semantic representations of cues and targets (e.g., via associative links to highly overlearnt categories, such as "odd" in the context of numbers) and consequently semantic cue-target compounds instead of perceptual, gestalt-like cue-target compounds. Schneider and Logan (2005; see also Logan & Schneider, 2006) implemented the semantic representation of cues in the formal model by assuming that encoding of one specific cue either leads to partial associative activation of the other cue that instructs the same task or leads to activation of a "mediator" (that can be thought of as a common task representation) related to the task. Consequently, RTs in task-repetition trials with cue switches are shorter than RTs in switch trials with cue switches because in the former trials cue encoding is faster because of residual activation in short-term memory. Recently, Arrington et al. (2007) obtained substantial task-switch costs when separating the cue-encoding phase from the stimulus-processing phase by asking participants to respond to the cue to indicate the currently required task before responding to the target (*double registration*). To account for these findings, Arrington et al. assumed that cue encoding results in a general task representation. Thereby, the task representation might include a goal representation (like suggested by Sohn & Anderson, 2001, 2003), S-R rules (like suggested by Mayr & Kliegl, 2003), stimulus-set biasing (like suggested by Meiran, 2000a), or task-set reconfiguration (like suggested by Rogers & Monsell, 1995). Importantly, Schneider and Logan's model that just assumes cue encoding processes cannot account for this finding because an additional task representation is required.

During the recent years, there have been several experimental investigations of cue switching versus task switching (e.g., Altmann, 2006, 2007; Forstmann, Brass, & Koch, 2007; Gade & Koch, 2008; Mayr, 2006; Monsell & Mizon, 2006; Schneider & Logan, 2005). This research has inspired many studies showing that task switching in the task-cuing paradigm indeed entails more than just cue switching. In addition to the just mentioned study by Arrington et al. (2007) showing "true" switch costs, Monsell and Mizon (2006) observed large switch costs that declined with CSI in settings in which the probability of a task-switch was low and cue repetitions never occurred (for similar results, see also Lavric et al., 2008; Schneider & Logan, 2006).

Likewise, Gade and Koch (2007a) found that a reversal of the cue-task mapping produces strong performance disruption and increased switch costs even on congruent trials in which the response to the cue-stimulus compound does not change. In this study, tasks were indicated by shape cues (e.g., square vs. diamond). Participants switched between categorizing a letter as a vowel or consonant and categorizing a digit as odd or even. In each trial, a letter and a number were presented, and the same response keys were used for both tasks, which led to congruent and incongruent trials. In a training phase, participants could acquire cue-stimulus compounds, but in a test phase, the cue-task mapping was reversed. In the reversal phase, responding to congruent stimuli was impaired despite the fact that the compound of cue and stimulus required the same response in training and reversal phase.

Similarly, Altmann (2007) has found that task-inhibition effects using the method of n-2 task-repetition costs (e.g., Mayr & Keele, 2000; for a review, see Koch, Gade, Schuch, & Philipp, 2010) are independent of the issue of whether the cue repeats from trial n-2 to trial n or whether the cue switches (see also Gade & Koch, 2008). We return to this issue in the Task Inhibition and N-2 Task-Repetition Costs section.

Consistent with the claim that the task-cuing paradigm entails task switching in addition to cue switching, a number of recent ERP studies using the 2:1 cue-to-task mapping procedure (e.g., Jost et al., 2008; Lavric et al., 2008; Nicholson et al., 2006) showed that the larger parietal positivity that is usually observed for switch trials compared with repetition trials during the prepa-

ratory interval (e.g., Karayanidis et al., 2003; Miniussi, Marzi, & Nobre, 2005; Nicholson, Karayanidis, Poboka, Heathcote, & Michie, 2005; Wylie, Javitt, & Foxe, 2003) primarily refers to task switches rather than cue switches. Nicholson et al. (2006) used two different cues per task, a color cue and a form cue, to indicate the required task (magnitude or parity judgment). They demonstrated that the switch-related positivity occurred regardless of whether cue category repeated or switched. Jost et al. (2008) directly compared ERPs in task-switch trials and cue-switch trials and found a relative negativity starting 400 ms after presentation of the target stimulus. This effect differed regarding timing and topography from the effect between cue-switch trials and cue-repetition trials, providing evidence for distinct task processing in task-switch trials compared with cue-switch trials.

Likewise, Brass and von Cramon (2004) reported an fMRI study using the 2:1 cue-to-task mapping. They presented two task cues per trial, whereby the two cues were either identical (cue repetition), similar regarding the task meaning (cue switch), or they differed regarding task meaning (meaning switch). Contrasting the meaning-switch and the cue-switch conditions revealed strong activation in the left inferior frontal junction. Because both conditions involve a cue-switch, this contrast is supposed to indicate cortical regions that are related to the updating of the relevant task set rather than to a mere cue-encoding process. Note that previous studies that contrasted task-switch trials and task-repetition trials found inferior frontal junction activation in both trial types, suggesting that preparatory processes are not switch-specific.

Taken together, the general result of these studies can be summarized as showing that the 2:1 cue-to-task mapping procedure has indeed served to isolate yet another important component process of task switching (i.e., cue-encoding repetition priming). Such priming effects need to be considered in theories of task switching. However, the studies also demonstrate that there are usually substantial "true" task-switch costs that decrease if participants prepare the task.

Task Switching and Verbal Mediation

Performance in the task-cuing paradigm differs depending on the type of the applied cues, that is, whether the cues are transparent or nontransparent. Transparent cues are, for example, word cues that directly indicate the relevant task (e.g., magnitude) or S-R mapping (e.g., even-odd). For nontransparent cues, the mapping between cue and task is arbitrary and has to be learned by the participants (e.g., when the magnitude task is indicated by a diamond). A number of studies demonstrated that switch costs are smaller with transparent cues than with nontransparent cues (see Arbuthnott & Woodward, 2002; Logan & Bundesen, 2004; Logan & Schneider, 2006; Mayr & Kliegl, 2000; Miyake, Emerson, Padilla, & Ahn, 2004). This result has been taken as evidence for verbal mediation in task switching. Transparent cues allow a direct task-relevant verbalization, whereas for nontransparent cues, the meaning of the cue has to be retrieved first (cf. Logan & Schneider, 2006).

Goschke (2000) noted that such an interpretation is in line with a claim of Luria (1969), who suggested that language—or more precisely, inner speech—facilitates action control (see also Vygotsky, 1934/1962; Zelazo, 1999). There are a number of task-switching studies that further support this claim by showing that task-irrelevant verbalization decreases task-switching performance (e.g., Baddeley, Chincotta, & Adlam, 2001; Bryck & Mayr, 2005; Emerson & Miyake, 2003; Goschke, 2000; Miyake et al., 2004; Saeki & Saito, 2004).

For example, in Goschke's (2000) study, participants performed a letter and a color classification task either in single-task blocks or in mixed-task blocks with alternating task order. Target stimuli were colored letters, and letter and color identity were mapped onto the same response keys. Consequently, some target stimuli were associated with the same responses or with different responses in the two tasks, that is, the targets were congruent or incongruent regarding the response requirements of both tasks. One group of participants named the to-be-performed task by saying "color" or "letter" during the RSI. Another group of participants pronounced the task-irrelevant words "Monday" or "Tuesday." Performance in this latter group was impaired relative to the other group. In particular, participants responded more slowly in mixed-blocks, and they showed larger congruency effects, that is, impaired performance, when responding to incongruent targets compared with congruent targets (for a detailed description of congruency effects, see the Stimulus-Based Response Activation section). Goschke assumed that participants covertly name the task and that this inner speech facilitates task-switching performance. Consequently, articulatory suppression of inner speech by task-irrelevant verbalization impairs performance while switching tasks.

Kray, Eber, and Karbach (2008) found that facilitation effects due to task-relevant verbalization were especially large in younger children and older adults, that is, age groups that are assumed to have difficulties to maintain task sets and to switch between them (e.g., Cepeda, Kramer, & Gonzalez de Sather, 2001; Karbach & Kray, 2007; Kray & Lindenberger, 2000; Mayr, 2001). Thus, verbal labeling of a task seems to facilitate switching to this task. This effect is potentially very important and suggests interesting future research questions, such as whether verbal mediation improves task preparation or reduces interference. Further research will be required to integrate the observed effects of verbal mediation in functional theories of task switching.

Summary

Preparation effects are measured with different methods, either by varying the preparation time (i.e., the RSI in predictable sequences or the CSI in the cuing procedure) or by varying task predictability (i.e., comparing performance in predictable vs. unpredictable sequences). Preparation is not just switch-specific but also improves performance in task repetitions. For current research, it is a challenge to decide whether the observed performance improvements indeed reflect preparation or whether the alternatively suggested accounts of decay and stimulus-compound strategies are also viable explanations. Nevertheless, a wide range of experiments suggests that preparation effects can be measured. In addition, there is some agreement when comparing theoretical accounts that preparation includes a strengthening of task-relevant stimulus features/categories and retrieval of S-R rules. In contrast, the nature of residual switch costs is controversially discussed as either representing response-related configuration processes that have to wait upon stimulus presentation or as reflecting interfer-

ence by the other task. This latter topic is now addressed in more detail.

Interference in Task Switching

In task switching, processes that impair performance and that occur because of having previously performed a different task and/or expecting to perform a different task subsequently interfere with current performance. Interference varies with certain characteristics of the tasks, and it occurs not just in switches but also in repetitions (*mixing costs*; see, e.g., Allport et al., 1994; Koch et al., 2005; Los, 1996; Poljac et al., 2009; Rubin & Meiran, 2005; Steinhauser & Hübner, 2005). In this part of the review, we first discuss proactive interference of tasks. Then, we refer to stimulus-based interference, and, finally, we review evidence for response-based interference.

Proactive Interference of Tasks

Two-stage models of task-set reconfiguration assume that switch costs primarily reflect the duration of active task-set reconfiguration processes that occur as an "inserted" processing stage either prior to stimulus onset or that are triggered by stimulus onset. In contrast, Allport and colleagues proposed a rather different account (e.g., Allport et al., 1994; Allport & Wylie, 1999; Wylie & Allport, 2000).

Allport and colleagues originally assumed that switch costs arise from "a kind of proactive interference (PI) from competing S-R mappings with the same stimuli" (Allport et al., 1994, p. 436), and they termed this interference *task-set inertia*. Allport and Wylie (1999) specified the nature of this proactive interference as follows: "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" (p. 293). According to this proposal, performance is assumed to suffer—and more so on switches than on repetitions—because the currently relevant task set was suppressed when it was previously irrelevant and/or because the currently irrelevant task set received extra activation when it was previously relevant.

Note that whereas reconfiguration accounts suggest that switch costs reflect directly, at least partly, the duration of active control processes (*task-set reconfiguration*; cf. Rogers & Monsell, 1995), Allport and Wylie's (1999) proposal suggests that switch costs primarily reflect the more passive *after-effects* of previous active control processes (i.e., *task-set inertia*), which result in both positive and negative priming of task sets. In this situation of task interference (i.e., heightened competition between task sets), switch costs represent mainly the "additional time needed for the system to settle to a unique response decision" (Allport et al., 1994, p. 437). Thus, whereas early proponents of task-set reconfiguration (like Rogers & Monsell, 1995) attempted to explain all of the switch costs in terms of task-set reconfiguration, Allport et al. (1994) explained all of the switch costs in terms of task-set inertia. Meanwhile, hybrid accounts assume that switch costs reflect both reconfiguration and interference processes (e.g., Monsell, 2003; Ruthruff et al., 2001; Sohn & Carlson, 2000).

Evidence for the contribution of proactive task interference to switch costs has been obtained by a number of findings. In the following, asymmetrical switch costs and n-2 repetition costs are discussed in more detail, as these two findings probably represent the most convincing evidence for proactive interference in task switching.

Switch-cost asymmetries. Empirical support for the notion of proactive interference of tasks comes from the observation that switch costs are often markedly asymmetrical for a pair of tasks (e.g., Allport et al., 1994; Meuter & Allport, 1999; Monsell et al., 2000; Yeung & Monsell, 2003a, 2003b). Specifically, when participants switch between two tasks of unequal strength (or "difficulty"), switch costs are usually higher for the easier, more dominant task. For example, participants in Allport et al.'s (1994) study switched between reading a color word and naming the ink color in which the word was printed. Although naming the ink color was generally slower than word reading, switch costs were higher for word reading than for color naming. If switch costs represented primarily the duration of a switch-specific reconfiguration process, one would certainly assume that switch costs should be smaller when switching to the easy, dominant task, but the empirical data show the opposite result.

A similar switch-cost asymmetry was observed in studies on language switching. For example, Meuter and Allport (1999) used a cuing paradigm in which participants named visually presented digits either in their first language (L1) or in their second language (L2). These authors found larger switch costs for the dominant L1 relative to the costs when switching to L2 (for similar results, see, e.g., Costa & Santesteban, 2004; Finkbeiner, Almeida, Janssen, & Caramazza, 2006; Philipp, Gade, & Koch, 2007).

To explain this surprising finding, Meuter and Allport (1999) assumed that the dominant L1 needed to be suppressed when performing in L2. Because the baseline activation of L1 is usually much higher than that of L2, this L1-suppression has very strong after-effects, in the form of negative priming, on performing in L1 again. However, because L2 is generally weaker, it does not need to be suppressed so strongly when performing in L1, and therefore the after-effects of this suppression are relatively smaller when switching back to L2. Put differently, Meuter and Allport assumed that in bilingual switching, mental lexicons are controlled by inhibition of competing lexicons (see also Green, 1986), and this inhibition persists over time, resulting in stronger effects on L1 than on L2. The observation of asymmetrical switch costs in other pairs of tasks, such as with Stroop word reading and color naming (Allport et al., 1994), can be explained in a similar way by assuming proactive interference on the basis of differential persistence of task-set inhibition, with more inhibition of the stronger task (i.e., word reading, in the example).

Yeung and Monsell (2003b) replicated the switch-cost asymmetry in Stroop word-reading and color-naming tasks, but they also showed that this asymmetry occurs less consistently than previous studies seemed to suggest. In their Experiment 1, they showed that the switch-cost asymmetry reversed when the onset of the word relative to the color was delayed, effectively reducing the temporal overlap in stimulus processing, despite that there was still substantial Stroop interference for delayed onsets. In their Experiment 3, they had participants perform a digit naming task and a color task, and in the color task they manipulated both the response category (i.e., the abstract meaning of the response, like "up," "down," "one," "two") and the response modality (vocal vs. manual) to produce conditions of varying response-set overlap between the

two tasks. Their results replicated the switch-cost asymmetry with full overlap (i.e., when the color task stimuli were also mapped to vocal digit naming responses), but the asymmetry reversed when the tasks did not fully overlap in both response categories and response modalities. Yeung and Monsell summarized their findings as suggesting that the "asymmetry of switch costs will consistently be observed only in conditions that maximize the degree of interference between tasks" (p. 464).

To account for asymmetrical switch costs, Yeung and Monsell (2003b) developed a formal model that assumes task priming. The authors propose that task priming, which represents the after-effects of previous task performance, and current control processes interact with task strength, which is represented as the baseline level of activation of a particular task. Notably, active control processes serve to increase the activation of the currently relevant task set, whereas priming is modeled as a persisting but temporally transient increase of activation of the previously performed task. Moreover, task priming is asymmetrical in pairs of tasks with different strength, with priming being larger following performance of the weak task because this task has a lower baseline activation, so that any given extra activation based on priming has an influence that is proportionally stronger relative to that for a task that has already a high degree of baseline activation.

In addition, Yeung and Monsell (2003b) assumed that control is dynamically adjusted to the level of interference (see also Brown, Reynolds, & Braver, 2007; Gilbert & Shallice, 2002; Goschke, 2000). Specifically, they assumed that more control is needed in a situation in which interference is high. Interference is highest when switching to the weak task, but this interference is greatly reduced in a task repetition, calling for less control input, which in turn reduces the repetition benefit of the weak task relative to that of the stronger task.

Importantly, Yeung and Monsell's (2003b) task-priming model has two noteworthy features. First, it models the switch-cost asymmetry in pairs of tasks with different strength such that carry over of task-set activation benefits repetition trials and hinders switch trials. Consequently, switch costs not just reflect the cost of switching but also include the benefit of repetition. The idea that switch costs represent actually a repetition benefit has been suggested by a variety of other authors too (e.g., Dreisbach et al., 2002; Koch & Philipp, 2005; Logan & Bundesen, 2003). In the present context, referring to repetition benefits in addition to switch costs nicely exemplifies the idea that the performance difference between switch trials and repetition trials is due to the influence of the previous task—proactive task interference, or task set inertia.

Second, Yeung and Monsell (2003b) modeled switch-cost asymmetries in terms of positive priming, that is, persistence of increased activation, rather than by assuming negative priming in the form of persisting inhibition of the stronger task. In principle, though, it seems conceivable to cast this model also in terms of persisting inhibition or by assuming both kinds of processes, but it is not possible to decide between these alternative models when using only two tasks.

The question of whether proactive task interference, and switch-cost asymmetries in particular, require the assumption of persisting task-set inhibition (i.e., negative task priming) is a difficult theoretical and empirical question (for a discussion, see Koch, Gade, et al., 2010). As we have discussed earlier, Allport and Wylie (1999) assumed both positive and negative task priming. The idea of negative priming is particularly pertinent in the literature on bilingual switching, in which switch-cost asymmetries have been taken as a hallmark of inhibitory control of the mental lexicon (for discussion, see, e.g., Costa & Santesteban, 2004; Meuter & Allport, 1999; Philipp, Gade, & Koch, 2007; Philipp & Koch, 2009). Correspondingly, Yeung and Monsell (2003b) conceded that "it is likely that a complete model of task switching will need to incorporate inhibitory effects" (p. 468). As our current discussion should have made clear, though, switch-cost asymmetries do not require the assumption of inhibitory control. We discuss solid empirical evidence for a contribution of inhibitory control in task switching later in the Task Inhibition and N-2 Task-Repetition Costs section. Before we do so, we discuss two further studies that demonstrate proactive interference.

In a study using fMRI, Yeung, Nystrom, Aronson, and Cohen (2006) presented evidence suggesting that activation persists in neural processing pathways, which leads to increased interference in task switches (see Wylie et al., 2006). Specifically, these authors used a pair of tasks that are known to activate highly distinguishable brain regions, namely face categorization and word categorization. They found that neural activation in brain regions relevant for the competing task predicted the size of the behavioral switch costs. Accordingly, these data suggest that proactive interference of task sets, and of activation in the neural correlates corresponding to task processing, strongly contribute to task switching.

Masson, Bub, Woodward, and Chan (2003) used a slightly different approach to examine proactive interference in task switching. In their study, participants switched between word reading and color naming. Word reading was more difficult when the stimuli in the previous color-naming trials were words (i.e., bivalent stimuli) compared with asterisks (univalent stimuli). Because the words produced more interference with color naming than the asterisks, color naming needed to be more strongly implemented (see Yeung & Monsell, 2003b) or word naming needed to be more strongly inhibited. Masson et al. favored an inhibitory account and suggested that inhibition of the otherwise dominant word-reading pathway occurred in the word condition, in which the stimuli afforded word reading in addition to color naming but not in the asterisk condition (for discussion, see Masson, Bub, & Ishigami, 2007). However, as we have already discussed, although the assumption of inhibitory processes as contributing to switch costs is certainly plausible (see, e.g., Allport & Wylie, 1999; Brown et al., 2007; Goschke, 2000; Philipp, Kalinich, Koch, & Schubotz, 2008; Yeung & Monsell, 2003b), it is important to obtain solid empirical evidence for task inhibition also in experimental procedures for which noninhibitory accounts are not feasible. This empirical evidence has been reported in the form of n-2 task-repetition costs.

Task inhibition and n-2 task-repetition costs. Objections against accounts in terms of inhibitory control processes in task switching that were based on asymmetrical switch costs can be overcome when using a method that involves switching among three tasks. To this end, Mayr and Keele (2000) devised a paradigm in which participants had to detect a deviant in a multistimuli display. Stimuli were rectangles that varied according to the stimulus dimensions of color, orientation, and movement direction. The task of the participants was to localize the deviant on a specified stimulus dimension. Mayr and Keele found that partici-

pants' performance was impaired in n-2 repetitions of the relevant dimension (e.g., ABA) compared with n-2 switches (CBA), giving rise to what the authors termed *backward inhibition*. This term refers to the idea that tasks (or task-relevant stimulus dimensions) become the target of an inhibitory process once these tasks are actively abandoned (for a review, see Koch, Gade, et al., 2010).

Similar task-inhibition effects on the level of stimulus categorizations have been observed in other studies (e.g., Arbuthnott, 2005; Arbuthnott & Frank, 2000; Arbuthnott & Woodward, 2002; M. Hübner, Dreisbach, Haider, & Kluwe, 2003; Koch, Philipp, & Gade, 2006; Schuch & Koch, 2003; Sdoia & Ferlazzo, 2008). Moreover, n-2 repetition costs were observed using even simpler spatial response rules (horizontal, vertical, and diagonal) in a display in which the stimulus was presented at one of the four corners (Mayr, 2001, 2009). In addition, n-2 task-repetition costs were also observed with respect to output-related aspects of processing, such as response mode (choice response vs. simple response; see Koch, Gade, & Philipp, 2004) or response modality (e.g., vocal vs. manual responses; see Philipp & Koch, 2005). Taken together, these studies suggest that inhibition can occur at many different levels of task processing (see also Houghton, Pritchard, & Grange, 2009).

N-2 repetition costs are typically explained by assuming that the persistence of inhibition is stronger when the previously inhibited task was performed just two trials ago relative to having performed that task with a longer lag. This assumption gained some support from studies showing that n-2 repetition costs diminished with increasing RCI (e.g., Koch et al., 2004; Mayr, 2001; Mayr & Keele, 2000), suggesting that inhibition, once exerted, decays over time (for a discussion, see Gade & Koch, 2005).

As we have described, the common interpretation of n-2 repetition costs in three-task settings is that it refers to "tasks" (or their respective representation). However, with respect to (n-1) switch costs with two tasks, Logan and colleagues (e.g., Logan & Bundesen, 2003; Schneider & Logan, 2005) proposed that these costs might be mainly due to repetition-priming processes at the level of cue encoding (see the earlier Preparation as Interaction of Cue Encoding and Memory Retrieval section). Thus, the question arises whether n-2 repetition costs similarly reflect priming of cue encoding. In that case, a cue representation that has been the target of an inhibitory process would be more difficult to encode in an n-2 cue repetition relative to an n-2 cue switch. Several studies examined this issue by using two cues for each of the three tasks to dissociate n-2 cue repetitions from n-2 task repetitions. To this end, performance in these two sequence conditions was compared with that in n-2 task switches (which are by definition also n-2 cue switches). Importantly, these studies generally found significant n-2 repetition costs even for n-2 cue switches that signaled n-2 task repetitions, suggesting that the inhibition effect is not targeted at cue-encoding processes or cue representations (e.g., Altmann, 2007; Gade & Koch, 2008; Mayr & Kliegl, 2003).

The observation of n-2 repetition costs indicates that inhibitory processes play an important role in task switching, suggesting that task inhibition also plays a role in (n-1) switch costs (e.g., Mayr & Keele, 2000; Schuch & Koch, 2003). However, note that switch costs and n-2 repetition costs are empirically dissociable (see Philipp, Jolicoeur, Falkenstein, & Koch, 2007; Philipp & Koch, 2006). For example, the strength of the cue-task association influences switch costs but not n-2 repetition costs (Arbuthnott & Woodward, 2002). Additionally, it has been frequently reported that switch costs decrease with preparation time (e.g., Meiran et al., 2000; Rogers & Monsell, 1995), but manipulations of preparation time had no significant impact on n-2 repetition costs under most conditions (Gade & Koch, 2008; Mayr & Keele, 2000; Schuch & Koch, 2003). Preparatory reductions of n-2 task-repetition costs have been observed only in conditions that entail the opportunity of response preparation in addition to task preparation (e.g., for a simple-response task; Koch et al., 2004) or when the task was a naming task with a relatively small stimulus set (Philipp, Gade, & Koch, 2007). More evidence for a dissociation of switch costs and n-2 task-repetition costs comes from fMRI and neuropsychological studies.

Dreher and Berman (2002) used fMRI to examine neural correlates of the processes involved in inhibitory control of task sets. To this end, they used letters as stimuli and had participants switch among three tasks. The tasks were to decide whether the letter was a vowel or consonant, whether it was presented in upper case or lower case, or whether it appeared before or after "m" in the alphabet. The trials were organized in triplets, with the critical contrast being whether there is n-2 task repetition within a triplet (i.e., ABA) or not (i.e., CBA). The authors found significant behavioral n-2 task-repetition costs, and the fMRI data revealed neural activity primarily in the right ventrolateral prefrontal cortex as a correlate of n-2 task-repetition costs. Dreher and Berman accounted for this finding by assuming that activity in this brain region may reflect the consequences of processing a task that has been inhibited recently rather than the online triggering of inhibition of competing tasks. Thus, right prefrontal cortex may be involved in *overcoming* residual task-set inhibition. However, which brain regions are causally involved in triggering task-set inhibition remains unclear. Also, there is discussion as to when exactly inhibition of competing tasks is triggered. Inhibition might occur while preparing for a task switch prior to the onset of the new task-stimulus or after stimulus onset when resolving response conflicts in the new task (e.g., Mayr & Keele, 2000; for a discussion, see Philipp, Jolicoeur, et al., 2007). However, the temporal resolution of fMRI data is probably too low to distinguish between these alternatives; therefore, Dreher and Berman's fMRI data are perhaps not fully conclusive regarding the issue of whether the increased right ventrolateral brain activation reflects triggering or overcoming task-set inhibition.

More recent neuropsychological data from studies testing frontal patients seem to suggest that right frontal cortex is also causally involved in task-set inhibition. Mayr, Diedrichsen, Ivry, and Keele (2006) tested patients with left and right prefrontal brain lesions. Using procedure paradigm in which participants switched among several spatial response rules, these authors examined n-2 repetition costs. They found that right prefrontal patients had reduced n-2 repetition costs, whereas left prefrontal patients showed n-2 repetition costs that were in the range of that of the healthy control group. In contrast, left prefrontal patients showed increased switch costs relative to the other groups. This neuropsychological dissociation suggests that n-2 repetition costs and (n-1) switch costs depend on proper function in different brain regions. It is tempting to suggest that right prefrontal brain regions are involved more strongly in inhibiting task sets, whereas left prefrontal regions are perhaps more involved in selection and activation of task sets (see also Brass et al., 2005). Some caution is nevertheless warranted

because the group of right prefrontal lesion patients was very small ($n = 4$), and two of the patients showed small n-2 repetition costs.

However, there is converging evidence from a study by Aron, Monsell, Sahakian, and Robbins (2004), who used a predictable switching paradigm with run length of 3. They found that right frontal lesion patients showed a stronger congruency effect, suggesting that the effect of conflict at the response level is higher in these patients than in left frontal patients and controls. The authors interpreted the increased congruency effect as suggesting that right frontal patients had difficulties in inhibiting the responses that were activated by the competing task set, and this effect was particularly pronounced at short preparation intervals, when the relevant task set should be less strongly activated than at long preparation intervals. It should be noted, though, that a recent study by Shallice, Stuss, Picton, Alexander, and Gillingham (2008), using a large sample of frontal patients, could not confirm the findings of the studies of Mayr et al. (2006) and Aron, Monsell, et al. These authors found performance impairments primarily in a group of patients with lesion in superior medial cortex but not in patients with left or right frontal lesions. However, this study used a pair of cued spatial judgment tasks (Meiran, 1996); therefore, these results may point to the role of methodological differences that make a direct comparison difficult (as discussed by Shallice et al., 2008), and it is probably fair to claim that the procedure used by Shallice et al. did not allow to derive a clear measure of task-set inhibition. In light of these recent results, it is interesting that a close relation between inhibitory processes and right frontal brain regions (particularly the middle frontal gyrus) has been shown also with other experimental paradigms, such as the go/no-go paradigm and the stop-signal paradigm (for a review, see Aron, Robbins, & Poldrack, 2004). For example, Aron, Robbins, and Poldrack (2004) observed a correlation of switch costs with right frontal damage and a correlation of stopping performance with right frontal damage suggesting that right "frontal damage appeared most consistent with impaired ability to suppress irrelevant responses or irrelevant task-sets on the switch trial relative to non-switch trials" (p. 171).

In sum, studies on n-2 repetition costs indicate that inhibitory processes play an important role in task control (see Koch, Gade, et al., 2010). Yet, at present it is ambiguous whether and to which amount inhibitory processes contribute to switch costs. Therefore, it seems to be appropriate to assume that activation of the relevant task set is clearly a major mechanism that enables to switch between tasks, but inhibition of irrelevant task sets may also contribute to task switching. Hence, we can conclude that both persisting activation and inhibition of tasks can cause interference when switching between tasks.

Stimulus-Based Interference

Performance in task switching, and switch costs in particular, is strongly affected by whether the target stimulus of a current trial does or does not afford application of the competing task (i.e., univalent vs. bivalent target stimuli), and, if it does, by whether the stimulus is associated with the same response or with different responses in the two tasks (bivalent target stimuli are either "congruent" vs. "incongruent"; see Figure 4).

In the following, we first discuss stimulus-based interference at the response level and then stimulus-based interference at the task level. Here, we focus on effects of stimulus bivalence and congruency. Effects of response bivalence, that is, whether the same responses are required for both tasks, are considered in the next subsection on response-based interference.

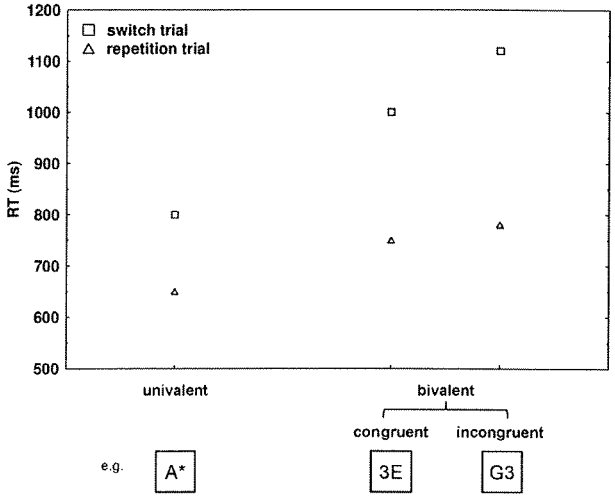

Figure 4. Stimulus-based interference, for example, in Rogers and Monsell's (1995) study. Participants switch between a letter and a digit task; they press a left key for "odd" and "vowel" and a right key for "even" and "consonant." Responding is slower, and switch costs are increased for bivalent compared with univalent stimuli, especially for incongruent stimuli. RT = reaction time.

Stimulus-based response activation. Switch costs are smaller when the stimuli are univalent (i.e., afford only one task) than when they are bivalent (e.g., Allport et al., 1994; Jersild, 1927; Rogers & Monsell, 1995; Spector & Biedermann, 1976). It has been argued that bivalent stimuli cause competition because they are potentially associated with the competing task, but they also afford a response in the context of the competing task (e.g., Rogers & Monsell, 1995; Rubin & Koch, 2006). The *congruency effect* refers to the finding that participants respond faster to stimuli that afford the same responses for both tasks (congruent stimuli) compared with stimuli that afford different responses for both tasks (incongruent stimuli). For example, if one task maps odd digits onto the left response and even digits onto the right response, and the other task maps high digits onto the left response and low digits onto the right response, then a high odd digit is congruent and a high even digit is incongruent. The congruency effect suggests that stimuli activate responses not just according to the currently relevant task rules (i.e., S-R mappings) but also according to the currently irrelevant task rules of the competing task.

Typically, the congruency effect is higher in switch trials than in repetition trials, which may reflect higher proactive interference in a task switch (e.g., Wendt & Kiesel, 2008). However, unlike switch costs, the congruency effect is often not affected by manipulations of preparation time (Allport et al., 1994; Fagot, 1994; Meiran, 1996; Rogers & Monsell, 1995). This finding has been referred to as one "of the more surprising observations in the task-switching literature" (Monsell et al., 2003, p. 338). If task preparation strengthens the relevant stimulus dimension, response activation according to the irrelevant S-R rules should be dimin-

ished because of reduced processing of the irrelevant stimulus dimension. However, the empirical data pattern appears to be somewhat mixed. For example, Meiran et al. (2000) found that the congruency effect was reduced by preparation, particularly in task-switch trials. However, other studies did not confirm this preparation effect on congruency effects (e.g., Fagot, 1994; Monsell et al., 2003; Rogers & Monsell, 1995; M. Hübner et al., 2004b). More recently, it has been observed that preparation reduces the congruency effect mainly if the probability of a task switch was small ($p = .25$) but not when switches and repetition were equiprobable (Monsell & Mizon, 2006), suggesting that the effectiveness of task preparation depends on switch probabilities. In any case, more research is needed to clarify the relation of congruency effects, switch costs, and task preparation (see also Kiesel, Wendt, & Peters, 2007; Meiran & Kessler, 2008).

Yet, even if task preparation does not necessarily reduce the size of the congruency effect in the current trial, there may be nevertheless important effects of having responded to an incongruent stimulus on a task switch. Specifically, it has been observed that switch costs are higher *after* a trial with an incongruent stimulus (Goschke, 2000; see also Brown et al., 2007; Monsell et al., 2003). Goschke (2000) suggested that incongruent stimuli produce a response conflict that triggers online additional strengthening of the current task set and inhibition of the competing task set. This pattern of increased activation and inhibition carries over to the next trial (proactive interference) and increases switch costs. Such sequential effects of congruency have inspired Brown et al. (2007) to postulate an incongruency "detector" that reacts to response conflicts, which plays an important part in their model. The incongruency detector is also accompanied by a change detector, which monitors for task switches (see also Monsell & Mizon, 2006, who also assumed a process that detects the occurrence of a task switch; however, for empirical evidence against a change detector as proposed by Monsell & Mizon, 2006, see Logan, Schneider, & Bundesen, 2007). Note that a rather similar mechanism was proposed by Botvinick, Braver, Barch, Carter, and Cohen (2001) to account for the reduction of the congruency effect (using a flanker paradigm) after an incongruent trial (e.g., Gratton, Coles, & Donchin, 1992). We refer back to this point in the Conclusions section.

Importantly, much of the theorizing on congruency effects has focused on response conflicts, yet bivalent stimuli afford not only two responses but also two tasks. There is evidence for conflict because of the stimulus reactivating a competing task set, not just a response (e.g., Rogers & Monsell, 1995). In the next section, we review the empirical support for this claim.

Stimulus-based task activation. As mentioned earlier, switch costs are often massively reduced with univalent stimuli, that is, when stimuli are processed just for one of the instructed tasks (Allport et al., 1994; Jersild, 1927; Spector & Biederman, 1976), whereas substantial switch costs usually emerge for bivalent stimuli. For instance, Rogers and Monsell (1995) used a digit classification task and a letter classification task and presented bivalent stimuli (e.g., G7) or univalent stimuli (e.g., G#). RTs were highest on incongruent trials, but RTs on congruent trials were still higher than on univalent trials, even though on congruent trials both tasks would activate the same response, which should be beneficial (see Figure 4; for similar results, see also Fagot, 1994). Although these effects usually occur on both task-repetition trials and task-switch trials, they tend to be more marked for the latter, thereby affecting switch costs. The finding that switch costs were smaller for univalent stimuli than for congruent stimuli led Rogers and Monsell to conclude that a stimulus (or irrelevant stimulus attribute) associated with a competitor task may interfere with current task processing not only by yielding "crosstalk" at the level of responses (because of being processed according to the S-R mapping of the competitor task) but also by reevoking the competitor task's abstract set (*exogenous cuing of task set*; see also Monsell, Taylor, & Murphy, 2001; Rubin & Koch, 2006).

Further evidence for such an exogenous cuing of task set was brought forward by Koch and Allport (2006). In their study, participants switched between magnitude and parity classifications of stimulus digits, with each digit occurring uniquely in one of the tasks. After some practice, the stimulus-to-task assignment was reversed. This reversal resulted in a substantial increase in switch costs, suggesting that switch costs can result in part also because divergent stimulus-to-task mappings produce item-specific associations between stimuli and tasks.

Recently, Steinhauser and Hübner (2009) proposed a method how to distinguish between stimulus-based task conflicts and stimulus-based response conflicts. They had participants switch between categorizing the color and the meaning of a colored word (Stroop, 1935) in a task-cuing paradigm. The stimuli were univalent or bivalent, and bivalent stimuli were either congruent or incongruent. By fitting an ex-Gaussian function to the empirical RT distributions, parameters for the exponential and the Gaussian portion of the distributions were estimated. It turned out that the Gaussian parameters reflected mainly response conflict, that is, congruent stimuli produced smaller values than incongruent stimuli, whereas values for univalent stimuli were in between. In contrast, the exponential parameter reflected mainly task conflict, that is, univalent stimuli led to much smaller values than congruent and incongruent stimuli. These findings suggest that stimulus-based task conflict and stimulus-based response conflicts are indeed dissociable phenomena and that they can be distinguished by considering their differential effects on RT distributions (however, for criticism on ex-Gaussian modeling, see Matzke & Wagenmakers, 2009).

The finding that specific stimulus exemplars activate task sets exogenously is further supported by Waszak et al.'s (2003) study. When participants switch between word reading and object naming on picture-word Stroop stimuli, switch costs observed in the dominant word reading task increased with the frequency of occurrence of the specific relevant stimulus component as a distractor in the object naming task (see also Allport & Wylie, 2000, Experiment 5; but see Steinhauser & Hübner, 2007).

Note, however, that item-specific task-set priming does not always appear to contribute very strongly to switch costs. For example, Koch et al. (2005) used alphabet arithmetic tasks but did not find item-specific priming effects in switch costs, even though they found such effects on mixing costs. Moreover, Arrington and Logan (2004b) varied the size of the stimulus set, so that one group of participants had a small number of stimuli that repeated very often (and occurred in both tasks), whereas another group were presented with a new stimulus on every trial, so that no item-specific stimulus-task associations could have been formed. This variation did not affect switch costs, so that item-specific task-set priming apparently played no role. However, it is difficult to

interpret this null-effect because Arrington and Logan's study differed in many methodological aspects from the studies referred to above. Therefore, it appears cautious to conclude that item-specific stimulus-to-task priming can contribute to switch costs substantially, but the boundary conditions for this contribution still need more research.

Taken together, there is stimulus-based interference in task switching because stimuli can activate those responses as well as those task sets they are associated with—irrespective of whether this response or task set is currently relevant or irrelevant. In addition to such stimulus-based response and task activation, there is ample evidence for response-based interference, which is reviewed in the next subsection.

Response-Based Interference

In many task-switching studies, the responses are bivalent, that is, the same responses are required for both tasks (e.g., Meiran, 1996; Rogers & Monsell, 1995). In this section, we first discuss the finding that bivalent responses compared with univalent responses increase switch costs. Then we discuss the impact of response repetitions on switch costs, and finally we refer to specific carryover effects of response selection and execution.

Univalent versus bivalent responses (overlap of response sets). In tasks with bivalent responses, identical motor responses are used in each task. For example, when participants switch between a digit- and a letter-classification task, pressing a response key with the right index finger might indicate odd digits in the digit task and vowels in the letter task, whereas pressing a response key with the left index finger might indicate even digits or consonants. In comparison, univalent responses might require pressing a right or left response key in the digit task and pressing an upper or lower response key in the letter task. Similarly, naming the correct response feature ("odd" vs. "even" in the digit task, and "vowel" vs. "consonant" in the letter task) would be considered to be univalent responses. Switch costs are larger with bivalent rather than univalent responses (see, e.g., Brass et al., 2003; Meiran, 2000b).

Note that response bivalence need not be tied to using the exact same responses for the tasks. That is, the "sameness" of the response is not bound to the specific motor response but to the abstract response meaning. Hence, responding with a "left" and a "right" response in both tasks may be sufficient to consider the responses as bivalent, even though they could be given by key presses in one task and vocally in the other task (cf. Gade & Koch, 2007b; R. Hübner & Druey, 2006; Schuch & Koch, 2004). Thus, overlap in the response categories appears to be sufficient to increase switch costs in comparison with univalent responses.

It is an important question whether additional overlap in the response modality (e.g., manual vs. vocal) would lead to even more "similar" responses than overlap in the abstract response category alone. As described earlier, Yeung and Monsell (2003b) manipulated the overlap in both response category and response modality and found increased switch costs particularly if both response categories and modalities overlapped (see also Sohn & Anderson, 2003), suggesting that overlap of response modality contributes to effects of response bivalence.

Meiran (2000a; Meiran et al., 2008) proposed an account of effects of response valence. He suggested that the previously used task-specific response categories (which Meiran, 2000a, called *response set*) lead to interference in a task switch and, consequently, to switch costs. This response-based component of switch costs is related to a process called *response recoding* (cf. Meiran, 2000b; Schuch & Koch, 2003), which leads to a change in the "meaning" of a bivalent response. According to Meiran's (2000a) model, response recoding cannot occur prior to stimulus onset but must be triggered by the response itself, possibly as a function of strengthening task-specific response mappings *after* they have been applied (for discussion and an updated model, see Meiran et al., 2008).

The neural correlates of effects of response bivalence, and of the hypothesized process of response recoding, was examined by Brass et al. (2003) in a study using fMRI. The authors compared performance in blocks with univalent responses and blocks with bivalent responses and found more activation in right lateral prefrontal cortex with bivalent responses. Brass et al. suggested that this effect reflected response recoding. Interestingly, this brain region has also been implicated by other studies as being involved in inhibitory processes (e.g., for a review, see Aron, Robbins, & Poldrack, 2004). Hence, it is tempting to speculate that bivalent responses trigger a process of inhibition of competing task-specific response mappings, which would be consistent with recent work on n-2 task-repetition costs (Gade & Koch, 2007b; Philipp, Jolicoeur, et al., 2007; Schuch & Koch, 2003; see below).

Further evidence for the effect of response bivalence comes from the analysis of specific sequential effects. One set of findings refers to the interaction of response repetition and task switching, and another set refers to the after-effects of withholding a response (in a no-go or stop trial) on performance in the subsequent trial.

Response-repetition effects. It has long been known that repeating the response on two consecutive trials of a choice task leads to a reduction in response time (e.g., Bertelson, 1965; Campbell & Proctor, 1993; Pashler & Baylis, 1991). In the context of task switching, however, a more complex pattern was found. Rogers and Monsell (1995) showed that response repetitions are beneficial only when the task is repeated. In contrast, response repetitions produce costs when the task is switched. This interaction of task switching and response repetition was replicated for different types of tasks like symbolic classification tasks (e.g., Rogers & Monsell, 1995), spatial tasks (Meiran, 2005), and auditory tasks (Quinlan, 1999), as well as for all main variants of the task-switching paradigm (e.g., Kleinsorge, 1999; Meiran, 2005; Rogers & Monsell, 1995; Sohn & Carlson, 2000).

Meanwhile, a number of studies examined the interaction of response repetition and task switching (e.g., Druey & Hübner, 2008a, 2008b; R. Hübner & Druey, 2006, 2008; Koch, Schuch, Vu, & Proctor, 2010; Schuch & Koch, 2004; Steinhauser et al., 2009). Although these studies generally confirmed this interaction and showed response-repetition benefits in task repetitions, there are also studies that found a somewhat diverging result. Schneider and Logan (2005; see also Arrington & Logan, 2004b) used two cues per task and found response-repetition benefits only if the cue repeated, but a task repetition that was triggered by a changed cue did not result in response-repetition benefits (but see Mayr & Kliegl, 2003, Experiment 2). It is unclear whether this diverging finding might have resulted from methodological differences across studies, so that it is an interesting issue for further research

to examine how response-repetition benefits interact with cue-repetition benefits.

Given this complex pattern of results, the question emerges as to how the often observed interaction of task switching and response repetition could be explained. Rogers and Monsell (1995) proposed three possible explanations, which are not necessarily mutually exclusive: a reconfiguration account, an association account, and an inhibition account.

First, the *reconfiguration account* assumes that preparing for a task switch implies that also a response switch is prepared. As a consequence, the usually observed response-repetition benefit turns into a cost in case of a task switch. A specific version of this account has been proposed by Kleinsorge (1999; Kleinsorge & Heuer, 1999), who assumed that tasks are hierarchically represented and that switching a higher level (here: the task) automatically implies switching of lower levels (here: the response).

Second, the *association account* assumes that task execution implies that the association between the current response (or response category) and a stimulus category is strengthened, whereas the association between this response and alternative stimulus categories is weakened. As a consequence, response repetitions are beneficial in case of a task repetition because the previously strengthened category-response rule is reapplied. In contrast, response repetitions are costly in case of a task switch because the previously weakened category-response rule needs to be applied (e.g., Meiran, 2000a; Schuch & Koch, 2004). The associative mechanism has been interpreted in terms of response-set reconfiguration (Meiran, 2000b) or response recoding (Schuch & Koch, 2004), by which response categories (e.g., left hand) are automatically bound (i.e., associated) to their meaning (e.g., odd number).

Finally, the *inhibition account* assumes that a response is inhibited after execution to counteract perseverative tendencies (cf. Smith, 1968). This process alone would lead to a general response-repetition cost on both task-switch trials and task repetitions. However, a second process, namely priming of the stimulus category, compensates inhibition on trials on which the task as well as the response is repeated. A newer version of this account has been proposed by R. Hübner and Druey (2006), who suggested that the functional role of response inhibition is to reduce the risk of an accidental reexecution of the previously primed response (see also Steinhauser et al., 2009).

In sum, three accounts have been considered for the finding that response repetitions are only beneficial in task repetitions but are costly in task switches. The accounts of reconfiguration, association, and inhibition are not mutually exclusive; instead, all three mechanisms may contribute to the observed interaction. However, whereas the third account refers to specific inhibition of *one* response, the next section deals with general inhibition of a task set (measured as n-2 task-repetition costs), which is likewise influenced by response-related processes.

Carryover effects of response selection and execution. It has been argued that task inhibition, measured as n-2 task-repetition costs, occurs as a consequence of task competition at the response level (e.g., Gade & Koch, 2005, 2007b; Philipp, Jolicoeur, et al., 2007; Schuch & Koch, 2003). For example, Schuch and Koch (2003) demonstrated the role of response processes in n-2 repetition by introducing no-go trials in the task sequence. A go versus no-go signal was auditorily presented simultaneously with onset of the target stimulus, transforming 25% of all trials unpredictably into no-go trials (or "stop" trials, because the target stimulus itself did not indicate whether to respond, as it is the case in common no-go trials in single-task studies). The critical finding was that n-2 repetition costs were substantially smaller after no-go trials than after go trials, suggesting that competition during response selection or execution triggers n-2 repetition costs. These findings invite the conclusion that response requirements trigger n-2 repetition costs.

This conclusion is supported by data reported by Philipp, Jolicoeur, et al. (2007), who devised a *go-signal paradigm*. In this paradigm, participants are required to prepare the task-specific motor response but are not allowed to execute the prepared response until a go signal is presented (for motor precuing, see, e.g., J. O. Miller, 1982; Rosenbaum, 1980, 1983). In 25% of all trials, the go signal was replaced with a no-go signal, so that the already prepared response had to be withheld. Importantly, the authors manipulated the go-signal interval (GSI) to be randomly short or long. When the GSI was long in the current trial, substantial response-preparation effects occurred in go trials, and n-2 repetition costs were fully eliminated in such trials. Yet, with a short GSI in the current trial, the results mimicked the results of Schuch and Koch (2003), showing smaller n-2 repetition costs when the preceding trial (i.e., trial n-1) was a no-go trial. Critically, after *no-go trials with long GSI* (i.e., when the response ought to be fully prepared in trial n-1 but was not actually executed), n-2 repetition costs were significantly smaller relative to when the preceding trial was a *go trial* with long GSI (i.e., prepared *and* executed response). This finding suggests that not only selection but also execution of a prepared response plays a critical role in n-2 repetition costs.

Consistent with the idea that switch costs arise in part because category-response rules were strengthened in the preceding trial, it has been found that not just n-2 response repetition costs but also (n-1) switch costs depend on response execution in the previous trial (Koch & Philipp, 2005; Philipp, Jolicoeur, et al., 2007; Schuch & Koch, 2003; Verbruggen, Liefooghe, Szmalec, & Vandierendonck, 2005). Note that switch costs disappear following a no-go trial even if a go-signal procedure was used to ensure that response selection could occur in these trials (Philipp, Jolicoeur, et al., 2007; see also Verbruggen, Liefooghe, & Vandierendonck, 2006). This finding provides clear evidence that the costs occur not only as a result of response-selection processes but also, or even mainly, as a result of processes triggered by response initiation or execution (for a discussion, see Philipp, Jolicoeur, et al., 2007).

Such a conclusion was also derived by Steinhauser and Hübner (2006, 2008). These authors found that errors lead to switch benefits instead of switch costs on the following trial, provided that the error occurs as a result of to task confusion (see also Meiran & Daichman, 2005). To account for this finding, they assumed that if the wrong task is accidentally applied, then the wrong category-response rules are strengthened. Furthermore, Steinhauser and Hübner (2006) observed switch benefits only following consciously detected errors but not following immediately corrected errors. Thus, they suggested that strengthening of category-response rules is triggered by the execution of a task-relevant response.

Summary

Interference in task switching can occur as a result of different sources. In this section, we first dealt with interference effects as a result of persisting activation and inhibition of task sets. We have discussed asymmetrical switch costs with respect to the question of whether they can be taken as indicator for persisting activation of the nondominant task, persisting inhibition of the dominant task, or both. A more convincing indicator for persisting inhibition of a recently abandoned task set is the observation of n-2 repetitions costs.

Second, we have reviewed studies suggesting that interference occurs because stimuli activate responses and task sets they are associated with. Consequently, task performance can be impaired if stimuli are associated with competing responses and competing task sets.

Third, there is ample evidence for response-based interference. Switch costs are increased for bivalent responses relative to univalent responses because bivalent responses need to be automatically "recoded," which can create interference in a task switch. Furthermore, response repetitions are beneficial in task repetitions but costly in task switches, which supports the notion of strengthening of response categories (even though other explanations are feasible, too). Finally, the inhibition of recently performed tasks seems to be triggered by processes occurring during response selection and execution.

Conclusions

In this article, we reviewed the literature on task switching. We organized this review in two major research topics, namely task preparation and task interference. Task switching has been and still is an extremely active research field. Many important questions have been asked in the last 10–15 years (and some of them became at least partly answered), and challenging new research questions are still being developed. One of the most appealing features of studying task switching is the promise that it offers a window into the study of "executive" control processes. However, this review has revealed that it is not yet clear whether task switching can keep this promise and whether it is theoretically necessary to postulate executive control processes to explain switch costs, at least in the task-cuing paradigm (for a discussion, see, e.g., Monsell & Mizon, 2006; Schneider & Logan, 2005, 2009). At the same time, research on task switching has revealed ample evidence for task interference at different levels in processing the target stimuli and executing the required responses. We would like to end this review by highlighting two issues that we believe may be important in future studies.

One issue refers to task interference. It has been suggested that most (if not all) empirical phenomena in task switching can be explained by assuming interactive processes of associative biasing and memory retrieval (e.g., Altmann & Gray, 2008; Koch & Allport, 2006; Schneider & Logan, 2005). This suggestion relates current research on task switching to theories in diverse areas of cognitive psychology, such as memory and categorization (e.g., Logan & Gordon, 2001). However, it still seems neglected that the processes that were postulated to enable participants to switch tasks are ultimately those processes that enable biological organisms to respond flexibly in changing behavioral contexts. This more "ecological" and evolutionary perspective suggests that there may be a closer and heuristically fruitful relation to theories of conditioning as developed in the research area of animal learning and behavior (see also Prinz, Aschersleben, & Koch, 2009). Elaborating this relation would be beyond the scope of the present review of task switching, but we would like to encourage researchers to consider this relation in future theorizing.

A second issue that we would like to highlight as an important topic of future research refers to the role of monitoring processes in task switching. Monitoring processes have been the subject of rather extensive research in single-task contexts (for reviews, see, e.g., Botvinick, Cohen, & Carter, 2004; Holroyd & Coles, 2002; Yeung, Botvinick, & Cohen, 2004). Yet, there are so far only beginnings of systematic investigation of the role of monitoring in task switching. For example, preliminary evidence comes from studies showing that increased response conflict (e.g., with incongruent stimuli) increases switch costs on the subsequent trial, which may reflect a process of online monitoring and detection of conflict, recruiting control processes to overcome this conflict (see Brown et al., 2007; Goschke, 2000; Yeung & Monsell, 2003b). However, one problem with applying current models of action monitoring to task switching is that these models considered only simple choice tasks, whereas action-monitoring processes are confronted with more complex demands under task switching. There are already some studies that tried to bridge the gap between single-task studies of conflict processing (particular with respect to sequential effects) and task switching (e.g., Kiesel, Kunde, & Hoffmann, 2006; Philipp, Jolicoeur, et al., 2007; Steinhauser & Hübner, 2008; Verguts & Notebaert, 2008). Moreover, Monsell and Mizon (2006) argued that monitoring processes could also be involved in task-set reconfiguration, suggesting that endogenous reconfiguration has to be triggered by a process detecting the occurrence of a task switch (for a similar suggestion, see also Brown et al., 2007; however, for a critical view on Monsell & Mizon's, 2006, proposal, see Logan et al., 2007). However, a number of questions remain open. For example, is action monitoring under task switching sensitive for the source of conflict, and, if so, are processes like task strengthening or reconfiguration also guided by specific monitoring processes? Answers to these questions will contribute substantially to a better understanding of control processes in task switching.

Finally, this review mainly focused on cognitive research on the topic of task switching. Yet, when theorizing about the way executive control mechanisms are implemented—because of well-known associative learning and memory mechanisms or because of yet-to be specified higher order "executive" mechanisms—it is also important to learn more about the neural mechanisms that enable flexible behavior. Instead of sticking to the concept of a *homunculus* (see Logan, 2003) that does all the cognitive control work, it might be more promising to think about cognitive mechanisms that enable different brain modules to interact with each other and to coordinate the respective cognitive lower level processes (e.g., Monsell, 1996). Indeed, there is a large amount of data from fMRI, electroencephalography, and patient studies investigating neural correlates of executive control processes with the task-switching paradigm. Currently, cognitive psychology and the cognitive neurosciences need to start to work hand in hand on the topic of executive control, and we aim to achieve further cross-fertilization of these different research fields. This cross-fertilization will have

important implications for research in many areas of psychology, such as psychopathology, clinical psychology, neuropsychology, and developmental psychology.

References

Ach, N. (2006). *Über den Willen* [On volition]. Leipzig, Germany: Quelle & Meyer. Retrieved from http://www.psychologie.uni-konstanz.de/abteilungen/kognitive-psychologie/various/narziss-ach/ (Original work published 1910)

Allport, A., Styles, E. A., & Hsieh, S. (1994). Shifting intentional set: Exploring the dynamic control of tasks. In C. Umilta & M. Moscovitch (Eds.), *Conscious and nonconscious information processing: Attention and performance XV* (pp. 421–452). Cambridge, MA: MIT Press.

Allport, A., & Wylie, G. (1999). Task switching: Positive and negative priming of task-set. In G. W. Humphreys, J. Duncan, & A. M. Treisman (Eds.), *Attention, space and action: Studies in cognitive neuroscience* (pp. 273–296). Oxford, England: Oxford University Press.

Allport, A., & Wylie, G. (2000). Task switching, stimulus-response bindings, and negative priming. In S. Monsell & J. Driver (Eds.), *Control of cognitive processes: Attention and performance XVIII* (pp. 35–70). Cambridge, MA: MIT Press.

Altmann, E. M. (2002). Functional decay of memory for tasks. *Psychological Research, 66,* 287–297. doi:10.1007/s00426-002-0102-9

Altmann, E. M. (2004). The preparation effect in task switching: Carryover of SOA. *Memory & Cognition, 32,* 153–163.

Altmann, E. M. (2005). Repetition priming in task switching: Do the benefits dissipate? *Psychonomic Bulletin & Review, 12,* 535–540.

Altmann, E. M. (2006). Task switching is not cue switching. *Psychonomic Bulletin & Review, 13,* 1016–1022.

Altmann, E. M. (2007). Comparing switch costs: Alternating runs and explicit cuing. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 33,* 475–483. doi:10.1037/0278-7393.33.3.475

Altmann, E. M., & Gray, W. D. (2002). Forgetting to remember: The functional relationship of decay and interference. *Psychological Science, 13,* 27–33.

Altmann, E. M., & Gray, W. D. (2008). An integrated model of cognitive control in task switching. *Psychological Review, 115,* 602–639. doi: 10.1037/0033-295X.115.3.602

Anderson, J. R., & Lebiere, C. (1998). *The atomic components of thought.* Mahwah, NJ: Erlbaum.

Arbuthnott, K. (2005). The influence of cue type on backward inhibition. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 31,* 1030–1042. doi:10.1037/0278-7393.31.5.1030

Arbuthnott, K., & Frank, J. (2000). Executive control in set switching: Residual switch costs and task-set inhibition. *Canadian Journal of Experimental Psychology, 54,* 33–41.

Arbuthnott, K., & Woodward, T. S. (2002). The influence of cue-task association and location on switch cost and alternating-switch cost. *Canadian Journal of Experimental Psychology, 56,* 18–29.

Aron, A. R., Monsell, S., Sahakian, B. J., & Robbins, T. W. (2004). A componential analysis of task-switching deficits associated with lesions of left and right frontal cortex. *Brain, 127,* 1561–1573. doi:10.1093/brain/awh169

Aron, A. R., Robbins, T. W., & Poldrack, R. A. (2004). Inhibition and the right inferior frontal cortex. *Trends in Cognitive Sciences, 8,* 170–177. doi:10.1016/j.tics.2004.02.010

Arrington, C. M. (2008). The effect of stimulus availability on task choice in voluntary task switching. *Memory & Cognition, 36,* 991–997. doi: 10.3758/MC.36.5.991

Arrington, C. M., & Logan, G. D. (2004a). The cost of a voluntary task switch. *Psychological Science, 15,* 610–615.

Arrington, C. M., & Logan, G. D. (2004b). Episodic and semantic components of the compound-stimulus strategy in the explicit-task cuing procedure. *Memory & Cognition, 32,* 965–976.

Arrington, C. M., & Logan, G. D. (2005). Voluntary task switching: Chasing the elusive homunculus. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 31,* 683–702. doi:10.1037/0278-7393.31.4.683

Arrington, C. M., Logan, G. D., & Schneider, D. W. (2007). Separating cue encoding from target processing in the explicit task-cuing procedure: Are there "true" task switch effects? *Journal of Experimental Psychology: Learning, Memory, and Cognition, 33,* 484–502. doi:10.1037/0278-7393.33.3.484

Arrington, C. M., & Yates, M. M. (2009). The role of attentional networks in voluntary task switching. *Psychonomic Bulletin & Review, 16,* 660–665. doi:10.3758/PBR.16.4.660

Baddeley, A., Chincotta, D., & Adlam, A. (2001). Working memory and the control of action: Evidence from task switching. *Journal of Experimental Psychology: General, 130,* 641–657. doi:10.1037//0096-3445.130.4.641

Bausenhart, K., Rolke, B., Hackley, S., & Ulrich, R. (2006). The locus of temporal preparation effects: Evidence from the psychological refractory period paradigm. *Psychonomic Bulletin & Review, 13,* 536–542.

Bertelson, P. (1965, April 10). Serial choice reaction-time as a function of response versus signal-and-response repetition. *Nature, 206,* 217–218.

Botvinick, M. M., Braver, T. S., Barch, D. M., Carter, C. S., & Cohen, J. D. (2001). Conflict monitoring and cognitive control. *Psychological Review, 108,* 624–652. doi:10.1037/0033-295X.108.3.624

Botvinick, M. M., Cohen, J. D., & Carter, C. S. (2004). Conflict monitoring and anterior cingulate cortex: An update. *Trends in Cognitive Sciences, 8,* 539–546. doi:10.1016/j.tics.2004.10.003

Brass, M., Derrfuss, J., Forstmann, B., & von Cramon, D. Y. (2005). The role of the inferior frontal junction area in cognitive control. *Trends in Cognitive Sciences, 9,* 314–316. doi:10.1016/j.tics.2005.05.001

Brass, M., Ruge, H., Meiran, N., Rubin, O., Koch, I., Zysset, S., . . . von Cramon, D. Y. (2003). When the same response has different meanings: Response recoding in the fronto-lateral cortex. *NeuroImage, 20,* 1026–1031. doi:10.1016/S1053-8119(03)00357-4

Brass, M., & von Cramon, D. Y. (2002). The role of the frontal cortex in task preparation. *Cerebral Cortex, 12,* 908–914.

Brass, M., & von Cramon, D. Y. (2004). Decomposing components of task preparation with functional magnetic resonance imaging. *Journal of Cognitive Neuroscience, 16,* 609–620.

Braver, T. S., Reynolds, J. R., & Donaldson, D. I. (2003). Neural mechanisms of transient and sustained cognitive control during task switching. *Neuron, 39,* 713–726.

Brown, J. W., Reynolds, J. R., & Braver, T. S. (2007). A computational model of fractionated conflict–control mechanisms in task-switching. *Cognitive Psychology, 55,* 37–85. doi:10.1016/j.cogpsych.2006.09.005

Bryck, R. L., & Mayr, U. (2005). On the role of verbalization during task set selection: Switching or serial order control? *Memory & Cognition, 33,* 611–623.

Campbell, K. C., & Proctor, R. W. (1993). Repetition effects with categorizable stimulus and response sets. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 19,* 1345–1362. doi:10.1037/0278-7393.19.6.1345

Cepeda, N. J., Kramer, A. F., & Gonzalez de Sather, J. C. M. (2001). Changes in executive control across the life span: Examination of task-switching performance. *Developmental Psychology, 37,* 715–730. doi:10.1037/0012-1649.37.5.715

Costa, A., & Santesteban, M. (2004). Lexical access in bilingual speech production: Evidence from language switching in highly proficient bilinguals and L2 learners. *Journal of Memory and Language, 50,* 491–511. doi:10.1016/j.jml.2004.02.002

De Jong, R. (2000). An intention-activation account of residual switch costs. In S. Monsell & J. Driver (Eds.), *Control of cognitive processes: Attention and performance XVIII* (pp. 357–376). Cambridge, MA: MIT Press.

Derrfuss, J., Brass, M., Neumann, J., & von Cramon, D. Y. (2005). Involvement of the inferior frontal junction in cognitive control: Meta-analyses of switching and Stroop studies. *Human Brain Mapping, 25,* 22–34. doi:10.1002/hbm.20127

Desimone, R., & Duncan, J. (1995). Neural mechanisms of selective visual attention. *Annual Review of Neuroscience, 18,* 193–222.

Donchin, E., & Coles, M. G. (1988). Is the P300 component a manifestation of context updating? *Behavioral and Brain Sciences, 11,* 357–427.

Dove, A., Pollmann, S., Schubert, T., Wiggins, C. J., & von Cramon, D. Y. (2000). Prefrontal cortex activation in task switching: An event-related fMRI study. *Cognitive Brain Research, 9,* 103–109.

Dreher, J.-C., & Berman, K. F. (2002). Fractionating the neural substrate of cognitive control processes. *Proceedings of the National Academy of Sciences, USA, 99,* 14595–14600. doi:10.1073/pnas.222193299

Dreisbach, G., Haider, H., & Kluwe, R. H. (2002). Preparatory processes in the task-switching paradigm: Evidence from the use of probability cues. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 28,* 468–483. doi:10.1037/0278-7393.28.3.468

Druey, M., & Hübner, R. (2008a). Effects of stimulus features and instruction on response coding, selection, and inhibition: Evidence from repetition effects under task switching. *Quarterly Journal of Experimental Psychology, 61,* 1573–1600. doi:10.1080/17470210701643397

Druey, M., & Hübner, R. (2008b). Response inhibition under task switching: Its strength depends on the amount of task-irrelevant response activation. *Psychological Research, 72,* 515–527. doi:10.1007/s00426-007-0127-1

Emerson, M. J., & Miyake, A. (2003). The role of inner speech in task switching: A dual-task investigation. *Journal of Memory and Language, 48,* 148–168.

Fagot, C. (1994). *Chronometric investigation of task switching.* Unpublished doctoral dissertation, University of California, San Diego.

Finkbeiner, M., Almeida, J., Janssen, N., & Caramazza, A. (2006). Lexical selection in bilingual speech production does not involve language suppression. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 32,* 1075–1089. doi:10.1037/0278-7393.32.5.1075

Fischer, R., Schubert, T., & Liepelt, R. (2007). Accessory stimuli modulate effects of nonconscious priming. *Perception & Psychophysics, 69,* 9–22.

Forstmann, B. U., Brass, M., & Koch, I. (2007). Methodological and empirical issues when dissociating cue-related from task-related processes in the explicit task-cuing procedure. *Psychological Research, 71,* 393–400. doi:10.1007/s00426-005-0040-4

Forstmann, B. U., Brass, M., Koch, I., & von Cramon, D. Y. (2006). Voluntary selection of task sets revealed by functional magnetic resonance imaging (fMRI). *Journal of Cognitive Neuroscience, 18,* 388–398.

Gade, M., & Koch, I. (2005). Linking inhibition to activation in the control of task sequences. *Psychonomic Bulletin & Review, 12,* 530–534.

Gade, M., & Koch, I. (2007a). Cue-task associations in task switching. *Quarterly Journal of Experimental Psychology, 60*(A), 762–769. doi:10.1080/17470210701268005

Gade, M., & Koch, I. (2007b). The influence of overlapping response sets on task inhibition. *Memory & Cognition, 35,* 603–609.

Gade, M., & Koch, I. (2008). Dissociating cue-related and task-related processes in task inhibition: Evidence from using a 2:1 cue-to-task mapping. *Canadian Journal of Experimental Psychology, 62,* 51–55. doi:10.1037/1196-1961.62.1.51

Gilbert, S. J., & Shallice, T. (2002). Task switching: A PDP model. *Cognitive Psychology, 44,* 297–337. doi:10.1006/cogp.2001.0770

Gopher, D. (1996). Attention control: Explorations of the work of an executive controller. *Cognitive Brain Research, 5,* 23–38.

Gopher, D., Armony, L., & Greenshpan, Y. (2000). Switching tasks and attention policies. *Journal of Experimental Psychology: General, 129,* 308–339.

Goschke, T. (2000). Intentional reconfiguration and involuntary persistence in task set switching. In S. Monsell & J. Driver (Eds.), *Control of cognitive processes: Attention and performance XVIII* (pp. 331–355). Cambridge, MA: MIT Press.

Gotler, A., Meiran, N., & Tzelgov, J. (2003). Nonintentional task set activation: Evidence from implicit task sequence learning. *Psychonomic Bulletin & Review, 10,* 890–896.

Gratton, G., Coles, M. G. H., & Donchin, E. (1992). Optimizing the use of information: Strategic control of activation of responses. *Journal of Experimental Psychology: General, 4,* 480–506.

Green, D. W. (1986). Control, activation, and resource: A framework and a model for the control of speech in bilinguals. *Brain and Language, 27,* 210–223.

Hackley, S. A., & Valle-Inclán, F. (2003). Which stages of processing are speeded by a warning signal? *Biological Psychology, 64,* 27–54. doi:10.1016/S0301-0511(03)00101-7

Heuer, H., Schmidtke, V., & Kleinsorge, T. (2001). Implicit learning of sequences of tasks. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 27,* 967–983.

Hoffmann, J., Kiesel, A., & Sebald, A. (2003). Task switches under go/no go conditions and the decomposition of switch costs. *European Journal of Cognitive Psychology, 15,* 101–128. doi:10.1080/09541440244000003

Holroyd, C. B., & Coles, M. G. H. (2002). The neural basis of human error processing: Reinforcement learning, dopamine, and the error-related negativity. *Psychological Review, 109,* 679–709. doi:10.1037/0033-295X.109.4.679

Horoufchin, H., Philipp, A. M., & Koch, I. (in press). The dissipating task-repetition benefit in task switching: Task-set decay or temporal distinctiveness? *Journal of Experimental Psychology: Human Perception and Performance.*

Houghton, G., Pritchard, R., & Grange, J. (2009). The role of cue-target translation in backward inhibition of attentional set. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 35,* 466–476. doi:10.1037/a0014648

Hübner, M., Dreisbach, G., Haider, H., & Kluwe, R. H. (2003). Backward inhibition as a means of sequential task-set control: Evidence for reduction of task competition. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 29,* 289–297. doi:10.1037/0278-7393.29.2.289

Hübner, M., Kluwe, R., Luna-Rodriguez, A., & Peters, A. (2004a). Response selection difficulty and asymmetrical costs of switching between tasks and stimuli: No evidence for an exogenous component of task-set reconfiguration. *Journal of Experimental Psychology: Human Perception and Performance, 30,* 1043–1063. doi:10.1037/0096-1523.30.6.1043

Hübner, M., Kluwe, R. H., Luna-Rodriguez, A., & Peters, A. (2004b). Task preparation and stimulus-evoked competition. *Acta Psychologica, 115,* 211–234. doi:10.1016/j.actpsy.2003.12.007

Hübner, R., & Druey, M. D. (2006). Response execution, selection, or activation: What is sufficient for response-related repetition effects under task shifting? *Psychological Research, 70,* 245–261. doi:10.1007/s00426-005-0219-8

Hübner, R., & Druey, M. (2008). Multiple response codes play specific roles in response selection and inhibition under task switching. *Psychological Research, 72,* 415–424. doi:10.1007/s00426-007-0118-2

Hübner, R., Futterer, T., & Steinhauser, M. (2001). On attentional control as a source of residual shift costs: Evidence from two-component task shifts. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 27,* 640–653.

Jersild, A. T. (1927). Mental set and shift. *Archives of Psychology, Whole No. 89.*

Jost, K., Mayr, U., & Rösler, F. (2008). Is task switching nothing but cue priming? Evidence from ERPs. *Cognitive, Affective, & Behavioral Neuroscience, 8,* 74–84. doi:10.3758/CABN.8.1.74

Karayanidis, F., Coltheart, M., Michie, P. T., & Murphy, K. (2003). Electrophysiological correlates of anticipatory and poststimulus components of task switching. *Psychophysiology, 40,* 329–348.

Karbach, J., & Kray, J. (2007). Developmental changes in switching

between mental task sets: The influence of verbal labeling in childhood. *Journal of Cognition and Development, 8,* 1–32.

Kiesel, A., & Hoffmann, J. (2004). Variable action effects: Response control by context-specific effect anticipations. *Psychological Research, 68,* 155–162. doi:10.1007/s00426-003-0152-7

Kiesel, A., Kunde, W., & Hoffmann, J. (2006). Evidence for task-specific resolution of response conflict. *Psychonomic Bulletin & Review, 13,* 800–806.

Kiesel, A., & Miller, J. (2007). Impact of contingency manipulations on accessory stimulus effects. *Perception & Psychophysics, 69,* 1117–1125.

Kiesel, A., Wendt, M., & Peters, A. (2007). Task switching: On the origins of response congruency effects. *Psychological Research, 71,* 117–125. doi:10.1007/s00426-005-0004-8

Kleinsorge, T. (1999). Response repetition benefits and costs. *Acta Psychologica, 103,* 295–310.

Kleinsorge, T., & Heuer, H. (1999). Hierarchical switching in a multidimensional task space. *Psychological Research, 62,* 300–312.

Koch, I. (2001). Automatic and intentional activation of task sets. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 27,* 1474–1486.

Koch, I. (2003). The role of external cues for endogenous advance reconfiguration in task switching. *Psychonomic Bulletin & Review, 10,* 488–492.

Koch, I. (2005). Sequential task predictability in task switching. *Psychonomic Bulletin & Review, 12,* 107–112.

Koch, I. (2008). Instruction effects in task switching. *Psychonomic Bulletin & Review, 15,* 448–452. doi:10.3758/PBR.15.2.448

Koch, I., & Allport, A. (2006). Cue-based preparation and stimulus-based priming of tasks in task switching. *Memory & Cognition, 34,* 433–444.

Koch, I., Gade, M., & Philipp, A. M. (2004). Inhibition of response mode in task switching. *Experimental Psychology, 51,* 52–58. doi:10.1027//1618-3169.51.1.52

Koch, I., Gade, M., Schuch, S., & Philipp, A. M. (2010). The role of inhibition in task switching—A review. *Psychonomic Bulletin & Review, 17,* 1–14. doi:10.3758/PBR.17.1.1

Koch, I., & Philipp, A. M. (2005). Effects of response selection on the task-repetition benefit in task switching. *Memory & Cognition, 33,* 624–634.

Koch, I., Philipp, A. M., & Gade, M. (2006). Chunking in task sequences modulates task inhibition. *Psychological Science, 17,* 346–350.

Koch, I., Prinz, W., & Allport, A. (2005). Involuntary retrieval in alphabet-arithmetic tasks: Task-mixing and task-switching costs. *Psychological Research, 69,* 252–261. doi:10.1007/s00426-004-0180-y

Koch, I., Schuch, S., Vu, K.-P., & Proctor, R. W. (2010). *Response discriminability in task switching—Dissociating effects of anatomical and spatial response separation.* Manuscript submitted for publication.

Kray, J., Eber, J., & Karbach, J. (2008). Verbal self-instructions in task switching: A compensatory tool for action-control deficits in childhood and old age? *Developmental Science, 11,* 223–236. doi:10.1111/j.1467-7687.2008.00673.x

Kray, J., & Lindenberger, U. (2000). Adult age differences in task switching. *Psychology and Aging, 15,* 126–147. doi:10.1037//0882-7974.15.1.126

Lavric, A., Mizon, G. A., & Monsell, S. (2008). Neurophysiological signature of effective anticipatory task-set control: A task-switching investigation. *European Journal of Neuroscience, 28,* 1016–1029. doi:10.1111/j.1460-9568.2008.06372.x

Liefooghe, B., Demanet, J., & Vandierendonck, A. (2009). Is advance reconfiguration in voluntary task switching affected by the design employed? *Quarterly Journal of Experimental Psychology, 65,* 850–857. doi:10.1080/17470210802570994

Lien, M.-C., Ruthruff, E., Remington, R. W., & Johnston, J. C. (2005). On the limits of advance preparation for a task switch: Do people prepare all the task some of the time or some of the task all the time? *Journal of Experimental Psychology: Human Perception and Performance, 31,* 299–315. doi:10.1037/0096-1523.31.2.299

Logan, G. D. (2003). Executive control of thought and action: In search of the wild homunculus. *Current Directions in Psychological Science, 12,* 45–48.

Logan, G. D. (2007). What it costs to implement a plan: Plan-level and task-level contributions to switch costs. *Memory & Cognition, 35,* 591–602.

Logan, G. D., & Bundesen, C. (2003). Clever homunculus: Is there an endogenous act of control in the explicit task-cuing procedure? *Journal of Experimental Psychology: Human Perception and Performance, 29,* 575–599. doi:10.1037/0096-1523.29.3.575

Logan, G. D., & Bundesen, C. (2004). Very clever homunculus: Compound stimulus strategies for the explicit task-cuing procedure. *Psychonomic Bulletin & Review, 11,* 832–840.

Logan, G. D., & Gordon, R. D. (2001). Executive control of visual attention in dual-task situations. *Psychological Review, 108,* 393–434.

Logan, G. D., & Schneider, D. W. (2006). Priming or executive control? Associative priming of cue encoding increases "switch costs" in the explicit task-cuing procedure. *Memory & Cognition, 34,* 1250–1259.

Logan, G. D., Schneider, D. W., & Bundesen, C. (2007). Still clever after all these years: Searching for the homunculus in explicitly cued task switching. *Journal of Experimental Psychology: Human Perception and Performance, 33,* 978–994. doi:10.1037/0096-1523.33.4.978

Lohmann, J., Herbort, O., Wagener, A., & Kiesel, A. (2009). Anticipation of time spans: New data from the foreperiod paradigm and the adaptation of a computational model. In G. Pezzulo, M. V. Butz, O. Sigaud, & G. Baldassarre (Eds.), *ABiALS 2008* (pp. 170–187). Berlin, Germany: Springer.

Los, S. A. (1996). On the origin of mixing costs: Exploring information processing in pure and mixed blocks of trials. *Acta Psychologica, 94,* 145–188.

Los, S., Knol, D., & Boers, R. (2001). The foreperiod effect revisited: Conditioning as a basis for nonspecific preparation. *Acta Psychologica, 106,* 121–145.

Los, S., & van den Heuvel, C. (2001). Intentional and unintentional contributions of nonspecific preparation during reaction time foreperiods. *Journal of Experimental Psychology: Human Perception and Performance, 27,* 370–386.

Luks, T. L., Simpson, G. V., Feiwell, R. J., & Miller, W. J. (2002). Evidence for anterior cingulate cortex involvement in monitoring preparatory attentional set. *NeuroImage, 17,* 792–802. doi:10.1006/nimg.2002.1210

Luria, A. R. (1969). Speech development and the formation of mental processes. In M. Cole & I. Maltzman (Eds.), *A handbook of contemporary Soviet psychology* (pp. 121–162). New York, NY: Basic Books.

Masson, M. E. J., Bub, D. N., & Ishigami, Y. (2007). Task-set persistence modulates word reading following resolution of picture-word interference. *Memory & Cognition, 35,* 2012–2018.

Masson, M. E. J., Bub, D. N., Woodward, T. S., & Chan, J. C. K. (2003). Modulation of word-reading processes in task switching. *Journal of Experimental Psychology: General, 132,* 400–418. doi:10.1037/0096-344.132.3.400

Matzke, D., & Wagenmakers, E.-J. (2009). Psychological interpretation of ex-Gaussian and shifted Wald parameters: A diffusion model analysis. *Psychonomic Bulletin & Review, 16,* 798–817. doi:10.3758/PBR.16.5.798

Mayr, U. (2001). Age differences in the selection of mental sets: The role of inhibition, stimulus ambiguity, and response-set overlap. *Psychology and Aging, 16,* 96–109.

Mayr, U. (2006). What matters in the cued task-switching paradigm: Tasks or cues? *Psychonomic Bulletin & Review, 5,* 794–799.

Mayr, U. (2009). Sticky plans: Inhibition and binding during serial-task

control. *Cognitive Psychology, 59,* 123–153. doi:10.1016/j.cogpsych.2009.02.004

Mayr, U., & Bell, T. (2006). On how to be unpredictable: Evidence from the voluntary task-switching paradigm. *Psychological Science, 17,* 774–780.

Mayr, U., Diedrichsen, J., Ivry, R., & Keele, S. W. (2006). Dissociating task-set selection from task-set inhibition in the prefrontal cortex. *Journal of Cognitive Neuroscience, 18,* 14–21.

Mayr, U., & Keele, S. W. (2000). Changing internal constraints on action: The role of backward inhibition. *Journal of Experimental Psychology: General, 129,* 4–26. doi:10.1037//0096-3445.129.1.4

Mayr, U., & Kliegl, R. (2000). Task-set switching and long-term memory retrieval. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 26,* 1124–1140. doi:10.1037/0278-7393.26.5.1124

Mayr, U., & Kliegl, R. (2003). Differential effects of cue changes and task changes on task-set selection costs. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 29,* 362–372. doi:10.1037/0278-7393.29.36.362

Meiran, N. (1996). Reconfiguration of processing mode prior to task performance. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 22,* 1423–1442.

Meiran, N. (2000a). Modeling cognitive control in task-switching. *Psychological Research, 63,* 234–249.

Meiran, N. (2000b). Reconfiguration of stimulus task sets and response task sets during task switching. In S. Monsell & J. Driver (Eds.), *Control of cognitive processes: Attention and performance XVIII* (pp. 377–399). Cambridge, MA: MIT Press.

Meiran, N. (2005). Task rule-congruency and Simon-like effects in switching between spatial tasks. *Quarterly Journal of Experimental Psychology, 58*(A), 1023–1041. doi:10.1080/02724980443000421

Meiran, N., & Chorev, Z. (2005). Phasic alertness and the residual task-switching cost. *Experimental Psychology, 52,* 109–124. doi:10.1027/1618-3169.52.2.109

Meiran, N., Chorev, Z., & Sapir, A. (2000). Component processes in task switching. *Cognitive Psychology, 41,* 211–253. doi:10.1006/cogp.2000.0736

Meiran, N., & Daichman, A. (2005). Advance task preparation reduces task error rate in the cuing task-switching paradigm. *Memory & Cognition, 33,* 1272–1288.

Meiran, N., & Kessler, Y. (2008). The task rule congruency effect in task switching reflects activated long-term memory. *Journal of Experimental Psychology: Human Perception and Performance, 34,* 137–157. doi:10.1037/0096-1523.34.1.137

Meiran, N., Kessler, Y., & Adi-Japha, E. (2008). Control by action representation and input selection (CARIS): A theoretical framework for task switching. *Psychological Research, 72,* 473–500. doi:10.1007/s00426-008-0136-8

Meuter, R. F. I., & Allport, A. (1999). Bilingual language switching in naming: Asymmetrical costs of language selection. *Journal of Memory and Language, 40,* 25–40.

Meyer, D. E., & Kieras, D. E. (1997a). A computational theory of executive cognitive processes and multiple-task performance: Part 1. Basic mechanisms. *Psychological Review, 104,* 3–65.

Meyer, D. E., & Kieras, D. E. (1997b). A computational theory of executive cognitive processes and multiple-task performance: Part 2. Accounts of psychological refractory-period phenomena. *Psychological Review, 104,* 749–791.

Miller, E. K., & Cohen, J. D. (2001). An integrative theory of prefrontal cortex function. *Annual Review Neuroscience, 24,* 167–202.

Miller, J. O. (1982). Discrete versus continuous stage models of human information processing: In search of partial output. *Journal of Experimental Psychology: Human Perception and Performance, 8,* 273–296. doi:10.1037/0096-1523.8.2.273

Miniussi, C., Marzi, C. A., & Nobre, A. C. (2005). Modulation of brain activity by selective task sets observed using event-related potentials. *Neuropsychologia, 43,* 1514–1528. doi:10.1016/j.neuropsychologia.2004.12.014

Miyake, A., Emerson, M. J., Padilla, F., & Ahn, J. (2004). Inner speech as a retrieval aid for task goals: The effects of cue type and articulatory suppression in the random task cueing paradigm. *Acta Psychologica, 115,* 123–142. doi:10.1016/j.actpsy.2003.12.004

Monsell, S. (1996). Control of mental processes. In V. Bruce (Ed.), *Unsolved mysteries of the mind* (pp. 93–148). Hove, England: Erlbaum.

Monsell, S. (2003). Task switching. *Trends in Cognitive Sciences, 7,* 134–140. doi:10.1016/S1364(03)00028-7

Monsell, S., & Mizon, G. A. (2006). Can the task-cuing paradigm measure an endogenous task-set reconfiguration process? *Journal of Experimental Psychology: Human Perception and Performance, 32,* 493–516. doi:10.1037/0096-1523.32.3.493

Monsell, S., Sumner, P., & Waters, H. (2003). Task-set reconfiguration with predictable and unpredictable task switches. *Memory & Cognition, 31,* 327–342.

Monsell, S., Taylor, T. J., & Murphy, K. (2001). Naming the color of a word: Is it responses or task sets that compete? *Memory & Cognition, 29,* 137–151.

Monsell, S., Yeung, N., & Azuma, R. (2000). Reconfiguration of task-set: Is it easier to switch to the weaker task? *Psychological Research, 63,* 250–264.

Nicholson, R., Karayanidis, F., Bumak, E., Poboka, D., & Michie, P. T. (2006). ERPs dissociate the effects of switching task sets and task cues. *Brain Research, 1095,* 107–123. doi:10.1016/j.brainres.2006.04.016

Nicholson, R., Karayanidis, F., Poboka, D., Heathcote, A., & Michie, P. T. (2005). Electrophysiological correlates of anticipatory task-switching processes. *Psychophysiology, 42,* 540–554. doi:10.1111/j.1469-8986.2005.00350.x

Niemi, P., & Näätänen, R. (1981). Foreperiod and simple reaction time. *Psychological Bulletin, 89,* 133–162.

Nieuwenhuis, S., & Monsell, S. (2002). Residual costs in task switching: Testing the failure-to-engage hypothesis. *Psychonomic Bulletin & Review, 9,* 86–92.

Pashler, H., & Baylis, G. (1991). Procedural learning: 2. Intertrial repetition effects in speeded-choice tasks. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 17,* 33–48. doi:10.1037/0278-7393.17.1.33

Philipp, A. M., Gade, M., & Koch, I. (2007). Inhibitory processes in language switching? Evidence from switching language-defined response sets. *European Journal of Cognitive Psychology, 19,* 395–416. doi:10.1080/09541440600758812

Philipp, A. M., Jolicoeur, P., Falkenstein, M., & Koch, I. (2007). Response selection and response execution in task switching: Evidence from a go-signal paradigm. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 33,* 1062–1075. doi:10.1037/0278-7393.33.6.1062

Philipp, A. M., Kalinich, C., Koch, I., & Schubotz, R. I. (2008). Mixing costs and switch costs when switching stimulus dimensions in serial predictions. *Psychological Research, 72,* 405–414. doi:10.1007/s00426-008-0150-x

Philipp, A. M., & Koch, I. (2005). Switching of response modalities. *Quarterly Journal of Experimental Psychology, 58*(A), 1325–1338. doi:10.1080/02724980443000656

Philipp, A. M., & Koch, I. (2006). Task inhibition and task repetition in task switching. *European Journal of Cognitive Psychology, 18,* 624–639. doi:10.1080/09541440500423269

Philipp, A. M., & Koch, I. (2009). Inhibition in language switching: What is inhibited when switching among languages in naming tasks? *Journal of Experimental Psychology: Learning, Memory, and Cognition, 35,* 1187–1195. doi:10.1037/a0016376

Poljac, E., de Haan, A., & van Galen, F. P. (2006). Current task activation

predicts general effects of advance preparation in task switching. *Experimental Psychology, 53,* 260–267. doi:10.1027/1618-3169.53.4.260

Poljac, E., Koch, I., & Bekkering, H. (2009). Dissociating restart costs and mixing costs in task switching. *Psychological Research, 73,* 407–416. doi:10.1007/s00426-008-0151-9

Prinz, W., Aschersleben, G., & Koch, I. (2009). Cognition and action. In E. Morsella, J. Bargh, & P. M. Gollwitzer (Eds.), *The psychology of action, Volume 2: Mechanisms of human action* (pp. 35–71). Oxford, England: Oxford University Press.

Quinlan, P. T. (1999). Sequential effects in auditory choice reaction time tasks. *Psychonomic Bulletin & Review, 6,* 297–303.

Rogers, R. D., & Monsell, S. (1995). Costs of a predictable switch between simple cognitive tasks. *Journal of Experimental Psychology: General, 124,* 207–231.

Rosenbaum, D. A. (1980). Human movement initiation: Specification of arm, direction, and extent. *Journal of Experimental Psychology: General, 109,* 444–474. doi:10.1037/0096-3445.109.4.444

Rosenbaum, D. A. (1983). The movement precuing technique: Assumptions, applications, and extensions. In R. A. Magill (Ed.), *Memory and control of action* (pp. 231–274). Amsterdam, the Netherlands: North-Holland.

Rubin, O., & Koch, I. (2006). Exogenous influences on task-set activation in task switching. *Quarterly Journal of Experimental Psychology, 59,* 1033–1046. doi:10.1080/02724980543000105

Rubin, O., & Meiran, N. (2005). On the origins of the task mixing cost in the cuing task-switching paradigm. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 31,* 1477–1491. doi:10.1037/0278-7393.31.6.1477

Rubinstein, J. S., Meyer, D. E., & Evans, J. E. (2001). Executive control of cognitive processes in task switching. *Journal of Experimental Psychology: Human Perception and Performance, 27,* 763–797. doi:10.1037//0096-1523.27.4.763

Ruthruff, E., Remington, R. W., & Johnston, J. C. (2001). Switching between simple cognitive tasks: The interaction of top-down and bottom-up factors. *Journal of Experimental Psychology: Human Perception and Performance, 27,* 1404–1419. doi:10.1037//0096-1523.27.6.1404

Saeki, E., & Saito, S. (2004). Effect of articulatory suppression on task-switching performance: Implications for models of working memory. *Memory, 12,* 257–271. doi:10.1080/09658210244000649

Schneider, D. W., & Logan, G. D. (2005). Modeling task switching without switching tasks: A short-term priming account of explicitly cued performance. *Journal of Experimental Psychology: General, 134,* 343–367. doi:10.1037/0096-3445.134.3.343

Schneider, D. W., & Logan, G. D. (2006). Priming cue encoding by manipulating transition frequency in explicitly cued task switching. *Psychonomic Bulletin & Review, 13,* 145–151.

Schneider, D. W., & Logan, G. D. (2009). Selecting a response in task switching: Testing a model of compound cue retrieval. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 35,* 122–136. doi:10.1037/a0013744

Schuch, S., & Koch, I. (2003). The role of response selection for inhibition of task sets in task shifting. *Journal of Experimental Psychology: Human Perception and Performance, 29,* 92–105. doi:10.1037/0096-1523.29.1.92

Schuch, S., & Koch, I. (2004). The costs of changing the representation of action: Response repetition and response-response compatibility in dual tasks. *Journal of Experimental Psychology: Human Perception and Performance, 30,* 566–582.

Sdoia, S., & Ferlazzo, F. (2008). Stimulus-related inhibition of task set during task switching. *Experimental Psychology, 55,* 322–327. doi:10.1027/1618-3169.55.5.322

Shaffer, L. H. (1965). Choice reaction with variable S-R mapping. *Journal of Experimental Psychology, 70,* 284–288.

Shaffer, L. H. (1966). Some effects of partial advance information on choice reaction with fixed or variable S-R mapping. *Journal of Experimental Psychology, 72,* 541–545.

Shallice, T., Stuss, D. T., Picton, T. W., Alexander, M. P., & Gillingham, S. (2008). Multiple effects of prefrontal lesions on task-switching. *Frontiers in Human Neuroscience, 1,* 1–12. doi:10.3389/neuro.09.002.2007

Smith, M. C. (1968). Repetition effect and short-term memory. *Journal of Experimental Psychology, 77,* 435–439.

Sohn, M.-H., & Anderson, J. R. (2001). Task preparation and task repetition: Two-component model of task switching. *Journal of Experimental Psychology: General, 130,* 764–778.

Sohn, M.-H., & Anderson, J. R. (2003). Stimulus-related priming during task switching. *Memory & Cognition, 31,* 775–780.

Sohn, M.-H., & Carlson, R. A. (2000). Effects of repetition and foreknowledge in task-set reconfiguration. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 26,* 1445–1460.

Spector, A., & Biederman, I. (1976). Mental set and mental shift revisited. *American Journal of Psychology, 89,* 669–679.

Steinhauser, M., & Hübner, R. (2005). Mixing costs in task shifting reflect sequential processing stages in a multicomponent task. *Memory & Cognition, 33,* 1484–1494.

Steinhauser, M., & Hübner, R. (2006). Response-based strengthening in task shifting: Evidence from shift effects produced by errors. *Journal of Experimental Psychology: Human Perception and Performance, 32,* 517–534. doi:10.1037/0096-1523.32.3.517

Steinhauser, M., & Hübner, R. (2007). Automatic activation of task-related representations in task shifting. *Memory & Cognition, 35,* 138–155.

Steinhauser, M., & Hübner, R. (2008). How task errors affect subsequent behavior: Evidence from distributional analyses of task switching effects. *Memory & Cognition, 36,* 979–990. doi:10.3758/MC.36.5.979

Steinhauser, M., & Hübner, R. (2009). Distinguishing response conflict and task conflict in the Stroop task: Evidence from ex-Gaussian distribution analysis. *Journal of Experimental Psychology: Human Perception and Performance, 35,* 1398–1412. doi:10.1037/a0016467

Steinhauser, M., Hübner, R., & Druey, M. (2009). Adaptive control of response preparedness in task switching. *Neuropsychologia, 47,* 1826–1835. doi:10.1016/j.neuropsychologia.2009.02.022

Steinhauser, M., Maier, M., & Hübner, R. (2007). Cognitive control under stress: How stress affects strategies of task-set reconfiguration. *Psychological Science, 18,* 540–545.

Stroop, J. R. (1935). Studies of interference in serial verbal reactions. *Journal of Experimental Psychology, 18,* 643–662. doi:10.1037/h0054651

Sudevan, P., & Taylor, D. A. (1987). The cuing and priming of cognitive operations. *Journal of Experimental Psychology: Human Perception and Performance, 13,* 89–103. doi:10.1037/0096-1523.13.1.89

Verbruggen, F., Liefooghe, B., Szmalec, A., & Vandierendonck, A. (2005). Inhibiting responses when switching: Does it matter? *Experimental Psychology, 52,* 125–130. doi:10.1027/1618-3169.52.2.125

Verbruggen, F., Liefooghe, B., & Vandierendonck, A. (2006). Selective stopping in task switching: The role of response selection and response execution. *Experimental Psychology, 53,* 48–57. doi:10.1027/1618-3169.53.1.48

Verbruggen, F., Liefooghe, B., Vandierendonck, A., & Demanet, J. (2007). Short cue presentations encourage advance task preparation: A recipe to diminish the residual switch costs. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 33,* 342–356. doi:10.1037/0278-7393.33.2.342

Verguts, T., & Notebaert, W. (2008). Hebbian learning of cognitive control: Dealing with specific and nonspecific adaptation. *Psychological Review, 115,* 518–525. doi:10.1037/0033-295X.115.2.518

Vygotsky, L. S. (1962). *Thought and language.* Cambridge, MA: MIT Press. (Original work published 1934)

Waszak, F., Hommel, B., & Allport, A. (2003). Task-switching and long-term

priming: Role of episodic stimulus-task bindings in task-shift costs. *Cognitive Psychology, 46,* 361–413. doi:10.1016/S0010-0285(02)00520-0

Wendt, M., & Kiesel, A. (2008). The impact of stimulus-specific practice and task instructions on response congruency effects between tasks. *Psychological Research, 72,* 425–432. doi:10.1007/s00426-007-0117-3

Werheid, K., Koch, I., Reichert, K., & Brass, M. (2007). Impaired self-initiated task preparation during task switching in Parkinson's disease. *Neuropsychologia, 45,* 273–281. doi:10.1016/j.neuropsychologia.2006.07.007

Woodrow, H. (1914). The measurement of attention. *Psychological Monographs, 5,* 1–158.

Wylie, G., & Allport, A. (2000). Task switching and the measurement of "switch costs." *Psychological Research, 63,* 212–233.

Wylie, G. R., Javitt, D. C., & Foxe, J. J. (2003). Task switching: A high-density electrical mapping study. *NeuroImage, 20,* 2322–2342. doi:10.1016/j.neuroimage.2003.08.010

Wylie, G. R., Javitt, D. C., & Foxe, J. J. (2006). Jumping the gun: Is effective preparation contingent upon anticipatory activation in task-relevant neural circuitry? *Cerebral Cortex, 16,* 394–404. doi:10.1093/cercor/bhi118

Yeung, N., Botvinick, M. M., & Cohen, J. D. (2004). The neural basis of error detection: Conflict monitoring and the error-related negativity. *Psychological Review, 111,* 939–959. doi:10.1037/0033-295x.111.4.931

Yeung, N., & Monsell, S. (2003a). The effects of recent practice on task switching. *Journal of Experimental Psychology: Human Perception and Performance, 29,* 919–936. doi:10.1037/0096-1523.29.5.919

Yeung, N., & Monsell, S. (2003b). Switching between tasks of unequal familiarity: The role of stimulus-attribute and response-set selection. *Journal of Experimental Psychology: Human Perception and Performance, 29,* 455–469. doi:10.1037/0096-1523.29.2.455

Yeung, N., Nystrom, L. E., Aronson, J. A., & Cohen, J. D. (2006). Between-task competition and cognitive control in task switching. *The Journal of Neuroscience, 26,* 1429–1438. doi:10.1523/JNEUROSCI.3109-05.2006

Zelazo, P. D. (1999). Language, levels of consciousness, and the development of intentional action. In P. D. Zelazo, J. Astington, & D. Olson (Eds.), *Developing theories of intention: Social understanding and self-control* (pp. 95–117). Mahwah, NJ: Erlbaum.