

# Task Switching: Interplay of Reconfiguration and Interference Control

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The task-switching paradigm is being increasingly used as a tool for studying cognitive control and task coordination. Different procedural variations have been developed. They have in common that a comparison is made between transitions in which the previous task is repeated and transitions that involve a change toward another task. In general, a performance switch cost is observed such that switching to a new task results in a slower and more error-prone execution of the task. The present article reviews the theoretical explanations of the switch cost and the findings collected in support of those explanations. Resolution and protection from interference by previous events explain part of the switching cost, but processes related to task setting and task preparation also play a prominent role, as testified by faster execution and lower switch costs when the preparation time is longer. The authors discuss the evidence in favor of each of these sets of accounts and raise a number of questions that situate task switching in a broader context of cognitive control processes. The role of several aspects of the task set, including task variations, task-set overlap, and task-set structure, is addressed, as is the role of knowledge about probability of task changes and about the structure of task sequences.

**Keywords:** task switching, cognitive control, task-set reconfiguration, interference

Switching back and forth between different tasks is common in daily life. At first sight, people seem to cope quite well in situations involving several tasks. Switching from reading a newspaper to answering a phone, for example, is not experienced as being difficult. However, subjective experiences are slightly different when at least one of the tasks involved is highly demanding (e.g., interrupting a calculation to answer a phone or continuously switching between different languages in a conversation). As will become clear in the present article, research in the laboratory suggests that there are certain limits to mental flexibility and that switching between tasks comes with a certain cost.

The task-switching paradigm provides a laboratory tool for studying mental flexibility and control of goal-directed behavior in situations involving several tasks. This paradigm requires participants to switch frequently between two or more tasks. Switching from one task to another is slower and more error prone than repeating the same task (Jersild, 1927; Spector & Biederman, 1976), and this persists even over massive practice (Stoet & Snyder, 2007). The strength of the paradigm is that it enables

investigators to test hypotheses about the factors responsible for the cost associated with switching and, more generally, to test hypotheses about the processes that enable switching between different tasks and support flexible behavior. Some variants of the task-switching method have been around for a long time (see, e.g., Jersild, 1927), but they were used only sporadically until papers by Allport, Styles, and Hsieh (1994) and Rogers and Monsell (1995) spurred the interest in this methodology.

Task-switching research is driven by the question of which processes are responsible for the switch cost or, in more general terms, which processes enable people to switch flexibly from one task or action plan to another. One group of accounts attributes the switch cost and, in particular, the reaction time (RT) switch cost to the involvement of endogenous control processes that are needed to reconfigure the cognitive system to perform a new task (reconfiguration view). A *task set* is needed in order to perform a task. The task set is a specific configuration of the cognitive system. Following Logan and Gordon (2001), we define a task set as a collection of control settings or task parameters that program the system to perform processes such as stimulus identification, response selection, and response execution. Within this reconfiguration view, the switch cost reflects the time needed to reconfigure the task set (e.g., Mayr & Kliegl, 2000; Rogers & Monsell, 1995). Another group of accounts attributes the switch cost to interference between a previous and the present task execution, regardless of whether task-set reconfiguration takes place or not. In other words, this interference view sees the switch cost as the consequence of exogenously triggered processes to resolve interference in task execution (see, e.g., Allport et al., 1994; Meiran, Kessler, & Adi-Japha, 2008; Waszak, Hommel, & Allport, 2003; Wylie & Allport, 2000) and does not consider reconfiguration as an origin of the switch cost.

The reconfiguration view and the interference view are prominently present in the task-switching literature. As will become

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clear in the present article, both views have their merits. We review the evidence relevant to both views, and we demonstrate that both views account for overlapping as well as complementary parts of the findings. On the basis of these findings, we argue that there may be a common ground in these two classes of views, namely, the resolution of interference that arises at different levels and stages of processing during reconfiguration and task execution. In the end, a better understanding of the processes that contribute to switch cost and switch performance will also contribute to a better understanding of cognitive functioning and its underlying architecture in task planning and in changing plans.

The present article is meant to provide an integrative overview of the field. First, we address the methodological aspects; this involves an overview of the task-switching procedures and the utility of the key measures they provide. Second, we describe the most important theoretical views. Third, we focus on the empirical tests that have been inspired by these views; this includes an overview of the main findings. Finally, we focus on questions that have more or less been neglected so far. We do not include an overview of the brain imaging and event-related potential (ERP) data in the present review (for such a review, see Sakai, 2008), although some references to such studies are included when relevant to the issues discussed.

### Measuring Switch Cost: Methodological Issues

In this section, we briefly describe the most important task-switching procedures, and we discuss some of their main advantages and disadvantages.

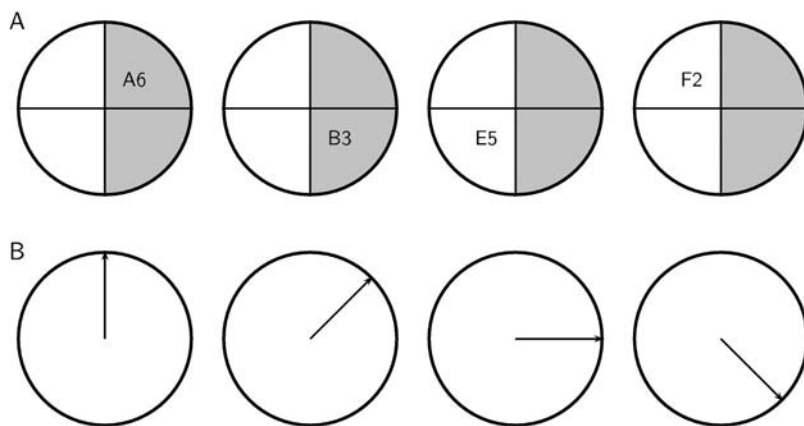
### List Procedure

Task switching was initially studied by means of the list procedure (e.g., Allport et al., 1994; Jersild, 1927; Spector & Biederman, 1976), which compares the time needed to complete two different kinds of lists: In the “pure lists,” a single task (A) is applied to all stimuli or targets in the list (AAAA . . . ; e.g., add 3 to each number), whereas in the “mixed or alternating lists,” two

tasks (A and B) are applied in alternation to the items (ABAB . . . ; e.g., alternate between +3 and -3). Performance differences between the two conditions have been interpreted as a measure of the cost associated with switching between tasks. However, there are several concerns: Apart from the possibility of previewing the next stimulus while responding to the present one (Spector & Biederman, 1976), the difference between the two types of lists may depend on factors other than task switching, such as working memory load for keeping track of the sequence of tasks (Rogers & Monsell, 1995) or increased likelihood of interference between the tasks involved in the mixed list condition (Rubin & Meiran, 2005). These additional processes may explain the observation of a *mixed-list cost*, which refers to the finding that task-repetition RTs are shorter in a pure list condition than in a mixed list condition (Braver, Reynolds, & Donaldson, 2003; Koch, Prinz, & Allport, 2005; Rubin & Meiran, 2005). On the basis of these considerations, researchers nowadays generally refer to the cost observed in the list procedure as *alternating-list cost* (sometimes also called global switch cost; cf. Kray & Lindenberger, 2000).

### Alternating Runs

To eliminate the confounds in the list procedure, Rogers and Monsell (1995) proposed the *alternating-runs* procedure, in which the participants execute a task a number of times before they switch to the other task. Hence, each task is repeated one or more times before a switch to the other task is required. For example, an alternation to the other task occurs every two trials when run length = 2 (AABBAA . . .). The load associated with keeping track of which task to perform is decreased by presenting the targets in segments of a square or a circle in such a way that the next target is shown at the next clockwise-located segment (see Figure 1A). Each time a reference line is crossed, a task switch is required. Task-switch costs can be calculated by comparing the performance in AB and BA transitions (task switches) with the performance in AA and BB transitions (repetitions). Both task repetitions and task switches occur within the same sequence of



**Figure 1.** Example of spatial cuing in the alternating runs procedure. Panel A shows predictable sequences: When the vertical midline is crossed, a task switch occurs. The gray area corresponds to one task (e.g., decide whether the digit is odd or even); the white area corresponds to the other task (e.g., decide whether the letter is a consonant or a vowel). Panel B shows unpredictable sequences: Each time the dial jumps to indicate 12 o'clock, a task switch is required.

events; therefore, the switch cost is not inflated by the differences between pure and mixed lists. In the standard variant of the alternating-runs procedure, the sequences are completely predictable as run length is constant. However, it is also possible to use variable runs. In such cases, a dial indicates the position in the sequence (see Figure 1B), and when the dial jumps to the starting position, the other task must be performed (e.g., Monsell, Sumner, & Waters, 2003; Sumner & Ahmed, 2006). Usage of unexpected jumps makes the task sequence unpredictable.

Even though the alternating-runs procedure has been used in several studies converging on a coherent set of findings, it has been the subject of criticism as well. Altmann (2007a) argued that there is a confound between switching and trial sequence because the switch trial always comes at the first position in the run, whereas repeat trials always come at the later positions in the run. He showed that there is a first-trial or restart cost in addition to the switch cost. Therefore, the switch cost in the alternating-runs procedure may be overestimated because it reflects the duration of both processes related to restarting and processes related to switching. Another shortcoming concerns an explanation of why the switch cost is reduced in blocks with a longer response–stimulus interval (RSI). As discussed below, this can be attributed to better or longer preparation for the upcoming task (e.g., Rogers & Monsell, 1995) or to dissipation of the previous task set (e.g., Meiran, Chorev, & Sapir, 2000). As both processes may occur in the RSI, it is impossible to dissociate their effects in the alternating-runs procedure, the more so because there is no means of knowing when participants will start preparation.

### Cuing Procedure

Like the alternating-runs procedure, the *cuing procedure* (Meiran, 1996; Sudevan & Taylor, 1987) presents a series of targets to which one of the tasks has to be applied. On each trial, a task cue indicates which task must be executed. The switch cost is measured by comparing transitions involving a task switch with transitions involving a task repetition in a single sequence of events (e.g., AABABBA . . .). The better control of the time parameters is a major advantage of the cuing procedure. Due to the occurrence of a cue, the RSI is subdivided into a response–cue interval (RCI) and a cue–stimulus interval (CSI), that is,  $RSI = RCI + CSI$  (see

Figure 2). Consequently, RCI and CSI can be manipulated independently. With a longer RCI, the activation of the previous task set may decay (also known as *task-set dissipation*). With a longer CSI, time available for preparation of the next task before stimulus onset increases. Meiran showed that the switch cost decreased when CSI increased (Meiran, 1996) and that variations in the RCI affected the switch cost mainly in the range between 0 and 500 ms (Meiran et al., 2000). Apart from the timing of the cue onset, another variable feature of this procedure is the amount of task-related information the cue provides. The task cues (also called explicit cues) can be transparent (e.g., *parity* or *P* to indicate a number parity judgment task; i.e., decide whether a number is odd or even), or they can be arbitrary (e.g., *X* to indicate the parity task). Switch costs are typically smaller for more transparent cues (e.g., Logan & Schneider, 2006; Miyake, Emerson, Padilla, & Ahn, 2004).

Notwithstanding its advantages, the cuing procedure suffers from one important confound: Every task switch is a cue switch, and every task repetition is a cue repetition. A partial deconfounding is possible when two different cues are used per task (Logan & Bundesen, 2003, 2004; Mayr & Kliegl, 2003). For example, the parity judgment task can be cued by *parity* or by *odd–even*; similarly, a magnitude judgment task (i.e., deciding whether a number is lower or higher than 5) can be cued by *magnitude* or by *low–high*. Three types of transitions are now possible, namely, cue repetitions (same cue, same task; e.g., *parity* – *parity*), task repetitions (different cue, same task; e.g., *parity* – *odd–even*), and task switches (different cue, different task; e.g., *parity* – *magnitude*). The performance difference between cue repetitions and task repetitions yields a *cue-switch cost*, and the performance difference between task repetitions and task switches yields a *corrected task-switch cost*. Some studies reported a quite large cue switch cost and only a small corrected task-switch cost (e.g., Logan & Bundesen, 2003, 2004; Monsell & Mizon, 2006). Thus, cue-related processes accounted for most of the uncorrected task-switch cost in these studies. However, other studies reported a larger corrected task-switch cost, showing that in some situations, cue-related processes account for only part of the uncorrected task-switch cost (e.g., Mayr & Kliegl, 2003; Monsell & Mizon, 2006). Nevertheless, the findings obtained by Logan and Bundesen (2003, 2004),

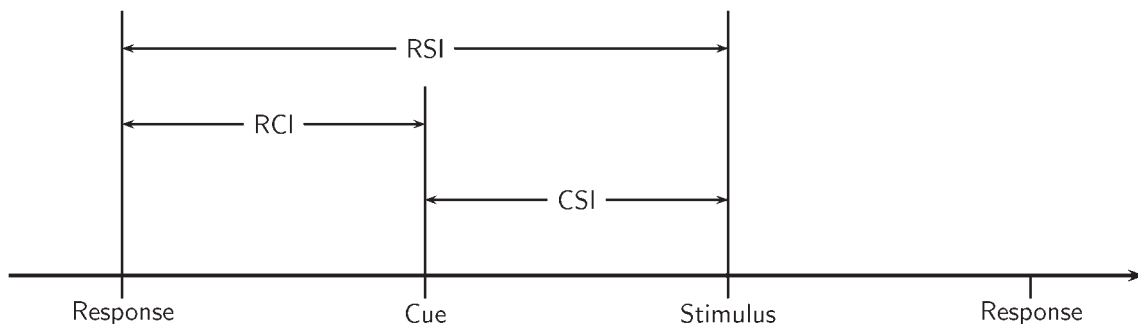


Figure 2. Relationship between response–stimulus interval (RSI), response–cue interval (RCI), and cue–stimulus interval (CSI). The role of task-set decay is fixed by keeping RSI constant; at the same time, the role of preparatory processing (CSI) can be varied. Likewise, the role of preparatory processing is fixed by keeping CSI constant; at the same time, the duration of decay (RSI) can be varied (see text and Meiran, 1996).

which show a large cue-switch cost and only a very small corrected task-switch cost, cast serious doubts on the utility of using one cue per task for the study of endogenously controlled switching. We come back to this important debate in a later section.

There are several variants of the cuing paradigm. A first variant is the *transition-cuing procedure*, in which the cues specify only whether to continue with the same task (cue *same*) or to move over to another task (cue *other*; Forstmann, Brass, & Koch, 2007; Forstmann, Brass, Koch, & von Cramon, 2005; Rushworth, Hadland, Paus, & Sipila, 2002; Schneider & Logan, 2007a; Van Loy, Liefoghe, & Vandierendonck, in press). Whereas this procedural variant has the advantage that both cues can co-occur with both tasks, it has the drawback that (so far) it is not clear which processes are responsible for the larger switch costs. Another variant of cuing is the *intermittent instruction procedure*, in which a task cue instructs participants to perform a task a number of times until the next cue is presented (Allport & Wylie, 2000; Altmann, 2002; Gopher, Armony, & Greenshpan, 2000). The intermittent-instruction procedure has the advantage that task repetitions are not necessarily cue repetitions. It also allows one to measure effects of task changes and task repetitions one or more trials after a cue instructs participants what to do, so that postponed effects of repeating or switching tasks can be tested.

### Voluntary Task Switching

The procedures considered so far can be considered to lack ecological validity, because in daily life, people usually have some freedom to select a task appropriate for the circumstances. Arrington and Logan (2004a) proposed the *voluntary task-switching procedure* to cope with this issue. They let the participants themselves decide which task to perform on each trial to diminish the role of environmental processes. The only constraints are that each task must be performed about equally often and that the sequence of selected tasks is random. Currently, there are three variants of this procedure. In the standard procedure, participants express their task choice by responding to the task stimuli by using one hand for one task and the other hand for the other task (Arrington & Logan, 2004a, 2005; Liefoghe, Demanet, & Vandierendonck, 2009). It is also possible to start each trial with a probe, prior to stimulus onset, to which the participants respond by

indicating the task they will perform (Arrington & Logan, 2005). This allows a distinction between a task-indication response and a task-execution response corresponding to task selection and task execution, respectively. A third variant is similar to the previous one, but the task must be indicated after completion of the task execution (Forstmann, Brass, Koch, & von Cramon, 2006; Forstmann, Ridderinkhof, Kaiser, & Bledowski, 2007).

In all its variants, this procedure results in task-switch costs, but it also provides information about task selection. Research has shown that the tendency to repeat the same task (perseveration) is large especially for short RSIs, in contrast with the typically observed alternation tendency in randomization tasks (e.g., Rapoport & Budescu, 1997). Based on these and other similar findings, Arrington and Logan (2005) argued that task choices are made in a top-down fashion. In subsequent studies, it became clear, however, that voluntary switching is vulnerable to exogenous influences as well (Arrington, 2008; Arrington & Rhodes, 2009; Demanet, Verbruggen, Liefoghe, & Vandierendonck, in press; Liefoghe, Demanet, & Vandierendonck, in press; Mayr & Bell, 2006; Yeung, 2010).

### Interim Conclusion

In order to help the reader to keep track of the large number of task-switching procedures, we present an overview in Table 1. It should be clear that task-switching performance is measured differently in the various procedures. Task-switch costs measured with different procedures also are not necessarily comparable. Differences in estimated switch costs may be due to the presence or absence of particular processes that contribute to the switch cost (e.g., processing of a task cue). For that reason, procedure-related differences in the switch cost are not necessarily informative, and one should refrain from drawing strong conclusions on the basis of such a comparison (see also Altmann, 2007a). In addition, it is important to keep in mind that apart from the differences between the procedures, many other variations (e.g., in the tasks used) do occur. As a consequence, even within a particular procedure, the switch cost observed in one experiment may be more influenced by situational or accidental factors than the switch cost in another experiment.

Table 1  
*Overview of the Task Switching Procedures: Name, Optional Variants, How Timing of Events Is Controlled, and How Switch Cost Is Defined*

| Procedure                | Variant            | Time control  | Measure of switch cost   |
|--------------------------|--------------------|---------------|--|
| List                     | Standard           | No            | Difference total time alternating list and pure lists  |
| List                     | Timed stimuli      | ITI           | Difference RT to stimuli in alternating and pure lists                                       |
| Alternating runs         | Fixed              | RSI           | Difference between RT of alternations and repetitions  |
| Alternating runs         | Variable           | RSI           | Difference between RT of alternations and repetitions  |
| Cuing                    | Explicit           | RSI, RCI, CSI | Difference between switch and repetition RTs   |
| Cuing                    | Transition         | RSI, RCI, CSI | Difference between switch and repetition RTs   |
| Intermittent instruction |                    | RSI, RCI, CSI | Difference between switch and repetition RTs as defined by instructional cue at start of run |
| Voluntary switching      | Standard           | RSI           | Difference between switch and repetition RTs   |
| Voluntary switching      | Task indication    | RSI, ITI      | Difference between switch and repetition RTs   |
| Voluntary switching      | After-task probing | RSI, ITI      | Difference between switch and repetition RTs   |

Note. ITI = intertrial interval; RT = reaction time; RSI = response-stimulus interval; RCI = response-cue interval; CSI = cue-stimulus interval.



## Theories of Task Switching

In the present section, we elaborate the two main views on the processes responsible for task-switching costs. The reconfiguration view and the interference view share the assumption that the correct execution of a task requires a task set that specifies the task-execution parameters. Preparation or configuration of a task set may consist of activating or chaining together a number of components or task-set parameters (Logan & Gordon, 2001; Monsell, 1996; Monsell & Mizon, 2006; Rogers & Monsell, 1995), or it may depend on direct retrieval of the task set from long-term memory (Mayr & Kliegl, 2000).

In general, both classes of theories assume that task-set configuration processes take place. However, the theories differ with respect to the role attributed to these processes in the causation of the switch cost. The reconfiguration view assumes that the switch cost reflects the duration of the configuration process; in contrast, the interference view assumes that the switch cost reflects overcoming of interference resulting from a previous execution of another task.

### The Interference View

In their seminal paper, Allport et al. (1994) proposed that the switch cost is due to *task-set inertia*. Task-set inertia refers to a persisting activation of previously activated task-set features, which interferes with responding to a stimulus that has been processed before in the context of another task. In addition, it is also possible that stimulus–task associations are acquired during the execution of a task, which become irrelevant when the task changes (e.g., Wylie & Allport, 2000). In other words, a task switch does require a new task set to become active, but the task-switch cost would be due to the requirement to overcome activation of the previous task set and activation triggered by stimulus–task associations that are no longer relevant. As will become clear when we discuss the main findings, several other sources of interference have also been identified. Regardless of the source of interference, all interference accounts have in common that they assume that the switch cost reflects the time needed to resolve the interference.

### The Reconfiguration View

The task-set reconfiguration view assumes that the switch cost reflects the time needed to reconfigure a task set (i.e., activate or chain task-set parameters; Logan & Gordon, 2001; Monsell & Mizon, 2006; Rogers & Monsell, 1995) or to retrieve the task set from long-term memory (Mayr & Kliegl, 2000; Rubinstein, Meyer, & Evans, 2001; Sohn & Anderson, 2001). When the task is repeated, reconfiguration will normally not be needed because the task set from the previous trial is still active; in contrast, when the task switches, reconfiguration is needed because the appropriate task set is not yet active. Therefore, the switch cost would reflect the time needed to reconfigure the task set. In the reconfiguration view, it is commonly assumed that once a task set has been activated, its activation may decrease (dissipation) but it remains active to some extent until another task set becomes activated. Strictly speaking, this strong assumption is not necessary. If a reconfiguration would be necessary on a repetition trial,

it would go faster due to priming of the task-set representation on the previous trial. The switch cost, then, is simply the consequence of this difference in reconfiguration processes in repetition and switch trials.

The reconfiguration view further assumes an operational distinction in task-reconfiguration processes and task-execution processes. In particular, manipulations that directly affect task execution do so independently from effects that occur at the level of the preparatory processes. In other words, variations in preparatory processing and in task processing should have additive results. Consistent with this idea, a few studies have shown that task-switch costs were additive with factors affecting task-execution speed, such as stimulus discriminability and task difficulty (Rubinstein et al., 2001), spatial stimulus–response compatibility (Liefoghe & Verbruggen, 2009; Meiran, 2005), distance priming (Liefoghe, Verbruggen, Vandierendonck, Fias, & Gevers, 2007), and variations in task expectancy and task recency (Ruthruff, Remington, & Johnston, 2001).

## Theory-Related Findings

In this section, we present an overview of the findings obtained with task-switching procedures and the theoretical accounts of these findings. We start the overview with a discussion of a range of findings that clarify the role of interference and inhibition in task switching.

### Response Interference, Carryover, Priming, and the Role of Inhibition

**Response-interference effects.** A first response-interference effect that is typically observed in task switching is the task-rule congruency effect. Most task-switching studies that involve switching between two tasks use bivalent stimuli, to which each task can be applied. For some stimuli, the response to the stimulus may be the same for both tasks; in this case, the response is task-rule congruent. For other stimuli, the response to the stimulus may be different for both tasks; in that case, the response is task-rule incongruent. Task-rule congruent responses are typically faster than task-rule incongruent responses (e.g., Goschke, 2000; Sudevan & Taylor, 1987), probably because incongruent response codes suffer from interference due to activated long-term memory representations of the irrelevant response codes (Meiran & Kessler, 2008).

A second response-interference effect is due to the repetition of the same response in a different task. In the context of single-task experiments, repetition of the same response to a repeating stimulus or stimulus category has been observed to result in a faster response (e.g., Pashler & Baylis, 1991). In the context of task switching, response repetitions are faster on task-repetition trials but slower on task-switch trials (Rogers & Monsell, 1995). Mayr and Bryck (2005) argued that the stimulus and response become associated with the task. This association is retrieved on the following trial; when the task has changed, this information is inconsistent with the currently relevant information. Consequently, the response-repetition benefit disappears and turns into a cost. Druey and Hübner (2008) showed that this interaction of task transition and response transition may also be the result of response inhibition applied immediately after execution of the re-

sponse to prevent accidental reexecution of the response (in line with some proposed models; e.g., J. W. Brown, Reynolds, & Braver, 2007; Gilbert & Shallice, 2002).

**Asymmetric switch costs.** Allport et al. (1994) observed larger costs when switching toward the dominant than toward the nondominant task set in Stroop tasks. In the most commonly used version of the Stroop task (Stroop, 1935), the color-word task, color names are printed in color. When the color word and the ink color differ, the stimuli are incongruent; when the word and the ink color are the same, the stimuli are congruent. In the color-word Stroop task, the word-reading task is said to be automatic and therefore dominant, whereas the color-naming task is less automatic and therefore nondominant. This difference in automaticity is reflected in the difference between congruent and incongruent stimuli. When participants name the ink color (nondominant task), performance is impaired for incongruent stimuli compared with congruent stimuli. However, when participants read the word (dominant task), there is most often no difference between incongruent and congruent stimuli (MacLeod, 1991). Given the relative difficulty of the word-reading task and the color-naming task and the asymmetry in congruency effects, it would seem easier to reconfigure the dominant (automated) word reading task than the nondominant color-naming task. Following this line of reasoning, switching from word reading to color naming would be slow whereas switching from color naming to word reading would be fast.

In fact, the opposite was observed. Allport et al. (1994) found an asymmetric switch cost (i.e., a large switch cost when switching from the color-naming to the word-reading task but no switch cost when switching from the word-reading to the color-naming task). This occurred irrespective of RSI duration. Allport et al. (1994) proposed the task-set inertia account to explain these findings: Each time a task switch occurs, processes associated with the previous task set persist and interfere with the new task set. The previous task set must be inhibited in order to overcome this (transient) proactive interference.<sup>1</sup> The amount of inhibition applied depends on the strength of the task set. In the color-word Stroop task, shifting toward the nondominant color task set requires a very strong inhibition of the previous (dominant) word task set, whereas shifting toward the dominant task set demands less inhibition of the nondominant task set. Consequently, when the dominant task set becomes relevant again, it must recover from this stronger inhibition. In other words, there is an asymmetry in the amount of inhibition applied, and this goes hand in hand with the time needed to recover from inhibition.

The asymmetric switch cost phenomenon was replicated in other studies (e.g., Allport & Wylie, 2000; Yeung & Monsell, 2003a, 2003b), including a study with children (Ellefson, Shapiro, & Chater, 2006) and a few studies of switching between languages (Meuter & Allport, 1999; Philipp, Gade, & Koch, 2007). The asymmetric switch cost was also replicated when switching between prosaccades and antisaccades (e.g., Barton et al., 2002; Barton, Greenzang, Hefter, Edelman, & Manoach, 2006; Cherkasova, Manoach, Intriligator, & Barton, 2002; Manoach et al., 2007), although these asymmetric switch costs could be due to inhibition of the oculomotor system in the execution of antisaccades (Barton et al., 2006).

However, some studies failed to find asymmetric switch costs. This was the case in conflict- and choice-RT tasks, (M. Hübner, Kluwe, Luna-Rodriguez, & Peters, 2004; Monsell, Yeung, &

Azuma, 2000), in language switching (Costa & Santesteban, 2004; Hernandez & Kohnert, 1999), and in saccadic tasks, (Reuter, Philipp, Koch, & Kathmann, 2006). Moreover, Yeung and Monsell (2003b) were able to reverse the asymmetry. They used manipulations to reduce the amount of Stroop interference either by delaying the processing of the dominant task or by varying the amount of response overlap between the two tasks. In all these experiments, the reduced Stroop interference did not result in a reduced degree of asymmetry but in a reversal of the asymmetric switch cost. Furthermore, Bryck and Mayr (2008) demonstrated that an asymmetry may even occur when no switch is required. They used an alternating-runs paradigm with runs of four. An RSI of 50 ms was used throughout, except after the second trial in the run and between runs. There they used a longer but variable RSI (500 or 5,000 ms), obtaining sequences like AA-AA-BB-BB. . . . When they used a longer RSI, selection costs were induced at the point of a task switch, and there was also a smaller asymmetric cost in the middle of the run of task repetitions. Bryck and Mayr assumed that after a longer RSI, there is a larger probability that the task set will be lost from working memory, so that within a run of repetitions a reretrieval of the task set from long-term memory may be required. As with the retrieval of a new task set on a switch trial, the reretrieval of the task set on a repetition trial suffers from long-term memory interference between the tasks, and this leads to an asymmetric cost. These findings also suggest that the asymmetry can be caused by factors other than inhibition. An alternative interpretation of these findings is that participants prepare for pairs of tasks so that there is a preparation cost for each group of tasks (cf. *infra*, Structures of task sequences).

All these deviant observations cast some doubt on the generality of the phenomenon of asymmetric switch costs and task-set inhibition as a driving factor. In all likelihood, the asymmetric switch cost is not a purely inhibitory phenomenon (Arbuthnott, 2008); instead, it may be based on a combination of factors related to endogenous control on the one hand and task strength and task priming on the other hand (see Gilbert & Shallice, 2002; Yeung & Monsell, 2003a).

**Carryover from previous trials.** Wylie and Allport (2000) used color-word Stroop tasks in which they varied the congruency of the Stroop stimuli over the trials. In their Experiment 2, participants applied the tasks to incongruent color-word stimuli for 24 trials and then continued to apply the same tasks to a mixture of neutral color stimuli (colored rectangles) and incongruent color-word stimuli. Participants were slower in word reading in the mixed block when they started with a block of only incongruent trials compared to when they immediately started with a mixed block. These interference effects due to previous task execution were strong, and although the effect diminished over trials, the slowing continued over the complete block of trials. These findings led Wylie and Allport to propose that interference was caused by stimulus-triggered retrieval of competing stimulus-response

<sup>1</sup> At this point, for completeness, it should be mentioned that over time, in different publications of Allport and colleagues, the proposed mechanism responsible for such effects has changed. As the proactive interference view proved untenable, Wylie & Allport (2000) suggested negative priming as the active mechanism.

associations. These associations were acquired over practice and were sometimes strengthened by repetition on previous trials.

This associative account was further elaborated by Waszak and colleagues (Waszak et al., 2003, 2004, 2005). They used picture-word Stroop stimuli, with picture naming and word reading as the two tasks. On the word-reading trials, the items could be old items encountered in the context of picture naming or they could be novel within the experiment. Switch costs were larger for old than for novel items. The effect was robust and occurred even when more than one hundred trials intervened between the two stimulus occurrences. Waszak et al. (2004) extended this finding by using probe stimuli that were semantically related to prime stimuli presented earlier in the context of picture naming. These findings are consistent with the proposal of Wylie and Allport (2000), if it is assumed that associations are formed among the stimulus compound, the response, the task goal, and/or the task set. In these experiments, all trials were incongruent; it follows that when the compound (picture and word) is repeated in a different task context, the association is triggered, leading to the activation of a response that is not appropriate in the current task. In a follow-up study, Waszak et al. (2005) tested whether their results were due to activation of the competing response or to negative priming; the latter refers to the observation that the response to a particular stimulus is slowed when the stimulus was previously irrelevant and therefore suppressed (e.g., Tipper, 1985; Tipper & Driver, 1988). Waszak et al. distinguished between two conditions: In the negative priming condition, the to-be-read word had been a distractor in an earlier picture-naming trial, whereas in the competitor-priming condition, the picture had been named in an earlier trial but the to-be-read word was never a distractor. The interference effects were due to competitor interference when there were many different stimuli, but negative priming also played a role when there were only a few reoccurring stimulus components.

Over practice, participants may learn other kinds of associations as well. Mayr and Bryck (2007) distinguished between a high-overlap condition in which the location of the stimulus was constant over tasks and a no-overlap condition in which the stimulus appeared on the left or on the right depending on the task. They found that the error switch cost, the Task Switch  $\times$  Repetition Priming interaction, and the task-rule congruency effect were eliminated in the no-overlap condition, consistent with an associative connection involving stimulus location. Apart from stimulus-response and stimulus-task associations, associations between task cue and tasks in the cuing procedure may be learned (Gade & Koch, 2007). Combined, these findings suggest that lower level information, such as stimulus-response variations, may become linked to higher level information, such as task sets and task goals (for other demonstrations of stimulus-induced conflicts, see Steinhäuser & Hübner, 2007, 2008; Wendt & Kiesel, 2008).

In sum, these studies yield a robust and consistent pattern. Binding of task goal, task set, stimulus, and response is probably at the basis of long-term (positive) priming effects in single-task situations but may play an adverse role in situations involving more than one task.<sup>2</sup> When a stimulus is repeated, previously associated information, such as a task goal, task set, and response, is retrieved, and this retrieval will interfere with performance when the information is incongruent with the currently relevant information (Allport & Wylie, 2000). This interference will slow responding.

**Task-set inhibition.** Some authors proposed that when a task set is no longer relevant, a new task set becomes active and the no longer relevant task set is inhibited. Task-set inhibition could be part of the reconfiguration process, or it could be used to resolve interference. Mayr and Keele (2000) reasoned that if a task set is inhibited, the task-set activation will decrease below the habitual activation level of that task set. Over time, the habitual activation level of the task set may be restored. Hence, a task set that was inhibited some time ago should be more easily reactivated than a task set that was inhibited more recently. As there are only two tasks in standard task-switching procedures, it is difficult to disentangle inhibition of the no longer relevant task set and activation of the upcoming task set. Therefore, Mayr and Keele developed a procedure with three tasks (A, B, C) to test the task-inhibition idea. By comparing CBA sequences with ABA sequences, they showed a lag-2 repetition cost (also known as backward inhibition effect) for the A task in the ABA sequence, consistent with the inhibition hypothesis.

Although task switching is involved in this procedure, most trials are switch trials; consequently, it is difficult to obtain a reliable measure of the switch cost and to find out to which extent the lag-2 repetition cost contributes to the task-switch cost. Nevertheless, some studies found both a switch cost and a lag-2 repetition cost (Mayr, 2001, 2002; Mayr & Keele, 2000), whereas others found only one of these effects consistently (Arbuthnott & Frank, 2000; Arbuthnott & Woodward, 2002). Furthermore, Philipp and Koch (2006) observed that the size of the lag-2 repetition cost was almost abolished when task-repetition trials were included, which suggests that the lag-2 repetition cost may be vulnerable to procedural variations.

It is still debated whether the lag-2 repetition cost is indeed due to task-set inhibition. Gade and Koch (2005) showed that the amount of inhibition applied to the B task in ABA and CBA sequences depends on the amount of activation of the preceding task (but see Altmann, 2007b, who studied the lag-2 repetition cost in an intermittent-instruction procedure where the run length simulated variation of the RCI). This suggests that the lag-2 repetition cost may not be entirely due to recovery from inhibition. Lien, Ruthruff, and Kuhns (2006) claimed that the role of task-set inhibition is rather limited. They varied the transitions between stimuli that afford only one task (univalent stimuli) and stimuli that afford both tasks (bivalent stimuli) and argued that bivalent stimuli require inhibition of the irrelevant task set but that univalent stimuli need no such inhibition. The expected larger difficulty of switching from a univalent to a bivalent stimulus was not confirmed. Lien et al. (2006) concluded that task-set inhibition does not play an important role. They argued that task-set activation and competition drive the switch costs; inhibition may occur but either is not adaptive or can be easily removed before the next task becomes relevant. Other studies also demonstrated that task-set

<sup>2</sup> The notions of binding and association are related. In the present article, we use the notion of binding to indicate a momentary or short-term coupling of elements in the service of a task. We use the term *association* to refer to a long-term coupling of elements. It is fair to say that a binding is a short-term association that may be kept in long-term memory if the elements involved in the binding are not needed in other couplings that could interfere with the already existing association.



inhibition is not always involved. For example, the lag-2 repetition cost disappears with spatial-location cues, but verbalization of these spatial cues reinstates the cost (Arbuthnott, 2005). This is consistent with the hypothesis that the discriminability of spatial cues elicits less lateral inhibition of the competing task sets; verbalization of the same cues reduces this discriminability, and more lateral inhibition therefore occurs. The role of cues in task-set inhibition was also demonstrated by Druey and Hübner (2007), who showed that task-set inhibition depends on cue–target overlaps.

In sum, task-set inhibition occurs under some circumstances, although several studies showed that it depends on factors such as the proportion of task repetitions and the cues that are used.

**Role of response selection.** Schuch and Koch (2003) focused on the role of response selection in task switching and examined whether a switch cost would occur if the task on the preceding trial is not executed (see also Kleinsorge & Gajewski, 2004). They used an adaptation of the go/no-go paradigm in which each stimulus was accompanied with a high or a low tone that indicated whether execution of the task was (go) or was not required (no-go). Schuch and Koch combined this variant of the go/no-go paradigm with cued switching and showed that switch costs and lag-2 repetition costs did not occur after a no-go trial, suggesting a critical role for response selection (see also Sdoia & Ferlazzo, 2008; Verbruggen, Liefoghe, Szmalec, & Vandierendonck, 2005). Further experiments showed that response selection but not response execution was the critical factor. Verbruggen, Liefoghe and Vandierendonck (2006) showed that switch costs were observed if participants had to select a response before they knew whether or not response execution was required. These results provide direct evidence for the distinct role of response selection in cued task switching and suggest that response execution is not a necessary factor for obtaining a switch cost. However, switch costs are larger when the response is actually executed, which suggests that response execution does contribute to the size of the switch cost (Philipp, Jolicoeur, Falkenstein, & Koch, 2007).

The role of response selection is consistent with the two-stage reconfiguration views (see below) that propose that reconfiguration finishes only with a task execution (cf. Rogers & Monsell, 1995; Rubinstein et al., 2001). The findings concerning the role of response selection may also be used to argue that the inhibition observed in the lag-2 repetition procedure may occur at the level of stimulus categorization/response selection (e.g., Schneider & Verbruggen, 2008) or at the level of attentional bias (Houghton, Pritchard, & Grange, 2009) and does not necessarily encompass the complete task set.

### Preparation, Cue Encoding, and the Role of Working Memory in Reconfiguration

In this section, we review findings that are related to reconfiguration processes. In particular, we address the role of preparation duration in reducing the switch cost and the factors that may modulate this effect. We also address the role of cue-related processes and working memory.

**Reduction in switch cost.** One important and straightforward prediction of the reconfiguration view is that the switch cost should disappear with sufficient preparation time. When preparation time increases, people can reconfigure the task set in advance.

Hence the switch cost should become smaller and even disappear completely when preparation time on task-switch trials increases. The resulting preparation effect consists of an interaction of preparation time (RSI in alternating runs, CSI in cuing) with transition (repetition vs. switch), such that the RT decrease with preparation time would be present for both repetitions and switches but would be larger for the switches than for the repetitions (e.g., Monsell & Mizon, 2006). By and large, numerous task-switching studies have reported such preparation effects, even though the switch cost did not disappear. This was the case for studies based on the alternating-runs procedure (Altmann, 2002; Koch, 2003; Mayr & Kliegl, 2000; Rogers & Monsell, 1995), on the explicit cuing procedure (Altmann, 2004a, 2004b; Logan & Bundesen, 2003, 2004; Mayr & Kliegl, 2000, 2003; Meiran, 1996, 2000b; Monsell & Mizon, 2006; Schneider & Logan, 2007b; Sohn & Anderson, 2003), on the transition cuing procedure (Forstmann, Brass, & Koch, 2007; Forstmann et al., 2005; Schneider & Logan, 2007b), or on the voluntary task-switching procedure (Arrington & Logan, 2004a, 2005).

The interference theory also predicts a preparation effect on the assumption that the correct task set must be activated on both repetition and switch trials and that this activation may be slowed due to persisting residual activation of the previous task set (task-set inertia) and to stimulus-based priming of the irrelevant task set. These adverse effects influence performance mostly on task-switch trials. Several studies showed that longer cue-based preparation largely overcomes task-set inertia (see, e.g., Koch & Allport, 2006; Yeung & Monsell, 2003a). However, cue-based preparation does not seem to overcome stimulus-based priming (see, e.g., Yeung & Monsell, 2003a), probably because these effects are triggered by the stimulus that comes at the end of the preparation interval. A functional magnetic resonance imaging (fMRI) study of Yeung, Nystrom, Aronson, and Cohen (2006) also indicates the presence of interference control during the preparation interval. Two tasks with a different brain signature were used, and residual activation of the previous task was shown on task-switch trials. In addition, Yeung et al. reported that on each trial, task-insensitive regions in the prefrontal cortex, parietal cortex, and presupplementary motor area were active. Thus, the study dissociated between task-selective and general-purpose mechanisms. These observations suggest the engagement of interference-control processes in task preparation and the operation of a control hierarchy responsible for maintaining task-specific information about rules or goals and for the coordination of these goals. In sum, the reconfiguration theory predicts smaller switch costs with longer preparation time on the basis of a task-set reconfiguration process, and the interference view makes a similar prediction on the basis of residual task-set activation. Empirical evidence thus tends to support both views.

**Residual switch cost.** Although reduction of the switch cost with preparation time seems to be in good agreement with the reconfiguration hypothesis, the switch cost almost never disappears completely after a long preparation interval (Allport et al., 1994; Logan & Bundesen, 2004; Mayr & Kliegl, 2000; Meiran, 1996; Rogers & Monsell, 1995). The switch cost after a long preparation interval is called the residual switch cost. The interference view completely accounts for this finding of a residual switch cost, because this account assumes that the switch cost is due to interfering events irrespective of the duration of preparation



(Allport & Wylie, 2000; Allport et al., 1994; Meiran, 2000b; Waszak et al., 2003; Wylie & Allport, 2000). However, it challenges the reconfiguration view.

A two-stage reconfiguration account was proposed in order to explain residual switch costs without rejecting the reconfiguration view (Mayr & Kliegl, 2000; Rogers & Monsell, 1995; Rubinstein et al., 2001). A first reconfiguration stage involves endogenous preparation for the upcoming task and can finish before stimulus presentation; the second reconfiguration stage involves exogenously triggered activation of task rules in working memory and occurs in response to the stimulus. However, a direct test of this hypothesis is difficult, as it involves an empirical dissociation between these two stages (for an attempt, see Hunt, Ishigami, & Klein, 2006; Hunt & Klein, 2002).

De Jong (2000) introduced the notion of *failure to engage* in task-set preparation to account for the residual switch cost. According to this all-or-none view, participants either may take the opportunity to fully prepare for the upcoming task or may fail to do so. On trials on which the preparation is started, there is no residual switch cost because reconfiguration has finished before stimulus onset. However, if the opportunity to prepare is not taken, reconfiguration starts only when the stimulus arrives. The residual switch cost is then simply the average of the trials with and the trials without preparation. De Jong presented RT and switch cost distributions that were consistent with the failure-to-engage hypothesis (see also De Jong, Berendsen, & Cools, 1999).

Assuming that residual switch costs are due to occasional failures to prepare, several researchers have attempted to find ways to reduce the residual cost. Stressing speed (Nieuwenhuis & Monsell, 2002) and usage of warning stimuli in the CSI or even before the cue (Meiran & Chorev, 2005) resulted in a decrease but not in a complete disappearance of the residual switch cost. Lien, Ruthruff, and Remington (2005) showed that the residual switch cost disappeared for some of the stimulus–response mappings. Moreover, Verbruggen, Liefvooghe, Vandierendonck, and Demanet (2007) found strongly reduced (and statistically no longer reliable) residual switch costs when the task cue was presented only briefly (64–128 ms) during CSI (see also Mayr, 2001). This suggests that the residual switch cost tends to disappear when participants are sufficiently encouraged to start advance task preparation. These findings are in line with those of S. Brown, Lehmann, & Poboka (2006), who proposed a variant of the failure-to-engage account. They argued that participants fail to engage in advance task preparation, but the preparation can start at any time between the presentation of the cue and the task stimulus. Consequently, the residual switch cost is due to a mixture of trials on which reconfiguration has finished before stimulus onset, trials on which reconfiguration has started but is not yet finished, and trials on which reconfiguration starts after stimulus onset. The important difference with De Jong's (2000) account is that S. Brown et al. did not assume that task preparation is all or none. Note that showing partial or complete success in reducing the residual switch cost obviates the need for introducing a two-stage conception of reconfiguration.

**Preparation modulated by design.** Several studies have shown that the preparation effect depends on design-specific features. In the alternating-runs procedure, Rogers and Monsell (1995) found that increasing RSI resulted in a switch cost decrease when RSI was blocked but not when it was randomized within

blocks. They argued that the unpredictability of RSI in the randomized condition could have discouraged advance preparation. Although these findings were replicated (Kramer, Hahn, & Gopher, 1999; Kray & Lindenberger, 2000; Monsell et al., 2003; Nieuwenhuis & Monsell, 2002), De Jong did find a switch cost reduction even with randomized RSIs in an alternating-runs design (De Jong, 2000, 2001; De Jong et al., 1999).

In the cuing procedure, preparation also depends on the design, although the effects are in the direction opposite that of the effects observed in the alternating-runs procedure. Many cuing studies have found the reduction in switch cost with increasing CSI (Garavan, 1998; Hahn, Andersen, & Kramer, 2003; Koch, 2001; Logan & Bundesen, 2003, 2004; Mayr, 2002; Mayr & Kliegl, 2003; Meiran, 1996, 2000a, 2000b; Meiran et al., 2000; Meiran & Marciano, 2002; Schuch & Koch, 2003; Tornay & Milan, 2001), although some others have failed (e.g., Koch, 2001). However, Altmann (2004a, 2004b) showed that in the cuing procedure, the reduction in switch cost is reliable only with a within-subjects variation of the preparation intervals (for similar results in the intermittent instruction procedure, see Poljac, de Haan, & van Galen, 2006).

Taken together, there is evidence that design features modulate the preparation effect in alternating runs and cuing, and this evidence limits the generalizability of the effect (Altmann, 2004a, 2004b). This variability in findings could be due to choices made by the participants within these procedures. If such (possibly strategically based) choices are possible, it may be argued that this does not refute the reconfiguration view and merely points toward the possibility that reconfiguration can be adapted to the situational constraints. Similarly, modulation by design could be due to a strategic decision to control interference in advance when the CSI is variable.

**Cue-switch cost.** Neither the reconfiguration view nor the interference view assumes that cue processing would contribute much to the task-switch cost. However, the large cue-switch cost and the small corrected task-switch cost in the double-cuing procedure (cf. supra) led Logan and Bundesen (2003) to claim that people combine the cue and the stimulus into a compound representation to which they respond. For example, a stimulus 7 can be responded to with the right button for “large” (i.e., when participants perform the magnitude task) or with the left button for “odd” (i.e., when participants perform the parity task). In combination with the task cue, a compound such as *magnitude-7* (where “magnitude” is the result of a cue encoding process, which starts when the cue is presented) can be unequivocally linked to the right response. In other words, no task-set reconfiguration would be needed because the task remains the same across all trials. A fit of three mathematical models of cued task switching (one based on task reconfiguration, one based on responding to a cue-stimulus compound, and one based on a combination) revealed that the cue-stimulus compound model explained the results more parsimoniously than the other models, which assumed an endogenous act of control (Logan & Bundesen, 2003).

Arrington and Logan (2004b) extended this view by showing that semantic associations mediate cue–target compound responding. Furthermore, in response to deviating findings reported by Mayr and Kliegl (2003); Logan and Bundesen (2004) replicated their previous findings and showed that with sufficient practice, arbitrary letter cues (such as *G* and *S* for the magnitude task) are

processed in the same way as meaningful word cues. They explained this by assuming that the task name acts as a mediator when arbitrary letter cues are used and that after training an association is established between an arbitrary cue and the mediator (see also Logan & Schneider, 2006; Logan, Schneider, & Bundesen, 2007; Schneider & Logan, 2005).

Several studies challenged the findings obtained by Logan and colleagues. Using the double cuing procedure, other authors reported substantial corrected switch costs (e.g., Mayr & Kliegl, 2003; Monsell & Mizon, 2006) and suggested that factors such as cue transparency and switch probability may play a role (Mayr, 2006; Monsell & Mizon, 2006; Schneider & Logan, 2006b). Furthermore, Jost, Mayr, and Rösler (2008) reported ERP data that contradict the cue-stimulus compounding account. The comparison between task-repetition and cue-repetition trials showed a frontocentral negativity about 300 ms after cue onset, probably related to cue-encoding processes. The comparison between task-switch and task-repetition trials showed a negativity with a different topography about 400 ms after stimulus onset, which is probably related to task-reconfiguration processes. Together, these findings suggest that both cue-encoding and task-reconfiguration processes contribute to the switch cost.

Arrington, Logan, and Schneider (2007) dissociated empirically between cue and target processing. Participants were instructed to respond to the cue before target onset. In some experiments, the response to the cue indicated which cue was presented; in this case, cue encoding still influenced target processing. In other experiments, the response to the cue indicated which task was to be performed. In the latter case only, cue encoding resulted in the activation of a semantic representation of the cued task rather than in the activation of verbal or phonological representation of the task cues. Moreover, Arrington et al. also observed substantial and reliable differences between task repetitions and task alternations in target responding. This pattern of findings falsifies the earlier interpretation (Logan & Schneider, 2006; Schneider & Logan, 2005) holding that no task-reconfiguration related processes were going on in the cuing procedure.<sup>3</sup> Thus, the idea that the switch cost can be attributed only to cue-related processes seems to be limited. Nevertheless, even though limitations of Logan's model are echoed by other authors (e.g., Altmann, 2006, 2007b), doubts about the validity of the standard (single) cuing procedure remain valid.

**Role of working memory.** For many authors, "adopting a task set" implies that working memory is required to keep task-set-related information active as long as it is considered relevant (see, e.g., Meiran & Kessler, 2008). The notion of working memory is also tightly linked with executive control (as shown in the volume by Miyake & Shah, 1999), with "set shifting" as one of the basic executive functions (e.g., Friedman et al., 2008; Miyake et al., 2000).

Baddeley, Chincotta, and Adlam (2001) focused on the role of executive control and verbalization in task switching. They compared performance in pure and alternating lists under concurrent tasks: articulatory suppression, which taxes verbalization, and random generation, and the Trails task (Lezak, 1983), which taxes executive control. Concurrent executive tasks impaired switching more than articulatory suppression, which in turn resulted in poorer performance compared to baseline. The latter finding suggests that verbalization is required to control maintenance of the

relevant task set. The contribution of verbalization to task switching was confirmed in other studies (Emerson & Miyake, 2003; Liefvooghe, Vandierendonck, Muyliaert, Verbruggen, & Vanneste, 2005; Miyake et al., 2004; Saeki & Saito, 2004a, 2004b, 2009; Saeki, Saito, & Kawaguchi, 2006). Furthermore, Bryck and Mayr (2005) showed that the role of verbalization is critical in endogenous maintenance and updating of a sequential plan. Combined, these studies show that task-set switching calls on (verbal) working memory. They do not clarify, however, whether task-set reconfiguration or interference control is the mediating mechanism. Articulatory suppression may interfere with the maintenance of the task name but may also lower protection against interference from the now-irrelevant task set.

Whereas verbalization is one aspect of working memory, executive or cognitive control is the most central function according to most theories of working memory (Baddeley & Hitch, 1974; Cowan, 2005; Engle, Kane, & Tuholski, 1999; Oberauer, 2009). Executive processes would control thought and action by activating goals and manipulating their activation (e.g., Logan & Gordon, 2001; Meyer & Kieras, 1997; E. K. Miller & Cohen, 2001; Unsworth & Engle, 2007). Because the goals trigger the task set, it can be expected that executive control sustains maintenance and updating of task sets in task switching. Only a few studies directly address this topic. Logan (2004) introduced the task-span method, which involves memorizing a list of task names such as "hi-low" and "odd-even." This list is then applied to a series of targets such as 1, 2, 3, . . . and one, two, three, . . . As in complex span procedures (e.g., Case, Kurland, & Goldberg, 1982; Daneman & Carpenter, 1980; Turner & Engle, 1989), this requires maintenance of information (the task names) concurrently with execution of the tasks. On the basis of the limited capacity of working memory, a trade-off between the two tasks is expected. Logan failed to find a trade-off between storage and task-switching (see also Logan, 2006). Similarly, Kane, Conway, Hambrick, and Engle (2007) compared task-switching performance of persons with high and low working memory span and did not find any evidence for a difference of the task-switch cost in relation to complex working memory span.

A number of other studies also failed to find an effect of a memory load on task-switching performance (e.g., Kiesel, Wendt, & Peters, 2007; Liefvooghe, Barrouillet, Vandierendonck, & Camos, 2008). However, Liefvooghe et al. (2008) found an effect of task switching on maintenance of the memory load in a strictly timed procedure. Hsieh (2002), on the contrary, also using a dual-task approach, reported an increase in switch cost due to the presence of an effortful secondary task. Furthermore, Demanet et al. (in press) showed that the role of exogenous influences in voluntary task switching increased under working memory load. In all, the evidence in favor of a storage/control trade-off is rather limited, although some studies support the hypothesis that executive control processes are shared between working memory and

<sup>3</sup> One possible concern with the double registration procedure is that the requirement to make a decision as to which task is being executed may interfere with ongoing processing. In particular, execution of a task-identification response may create an additional conflict with processing and categorization of the task stimulus, especially when cue identification and task execution overlap.

task switching (see also Friedman et al., 2008; Miyake et al., 2000).

The findings reviewed in this section support the reconfiguration as well as the interference view. The task-span studies of Logan (2004, 2006) were designed to test the role of working memory in maintaining and updating a plan of action, but the observations may also depend on interference between the task in the memorized list and the presently needed task set. Similarly, in the study of Liefoghe et al. (2008), the cost of few or many switches on maintenance may be caused by few or many reconfigurations or by few or many occurrences of a need for controlling interference between the previous and the present task set.

## Conclusion and Remarks

This overview of the most fundamental findings with respect to task-switching performance has shown that there is support for both main views. The findings regarding asymmetric switch costs, the observations with respect to aftereffects of previous task executions, and those regarding backward inhibition are in agreement with the interference view. Moreover, the interference view can also account, at least to some extent, for findings concerning the preparation effect, the residual switch cost, or the role of working memory in task switching.

The preparation effect predicted by the reconfiguration view is strongly supported by the findings. A series of unexpected observations has created challenges for the reconfiguration view. The residual switch cost is one such observation. However, with additional assumptions, this observation can be reconciled with the reconfiguration view. The modulation by design of the preparation effect is waiting for an appropriate account within the reconfiguration view but also within the interference view. Finally, in some situations, cue-encoding processes will modulate task-set configuration (see Arrington et al., 2007; Logan & Bundesen, 2003; Mayr & Kliegl, 2003; Monsell & Mizon, 2006). The available data do not seem to completely corroborate the reconfiguration view. However, the current evidence provided against this view cannot be considered sufficient for a rejection of the hypothesis.

It seems that the two main views show important overlaps in their predictive capabilities but are also complementary (see also Mayr & Bryck, 2007). The reconfiguration theory makes clear and detailed predictions about preparation for upcoming tasks, whereas the strength of the interference theory resides in predictions of task-set inertia and stimulus-based interference. Several studies have shown that both kinds of processes indeed play a role (apart from those already mentioned; see, e.g., Goschke, 2000). Nevertheless, it is also fair to say that both views are incomplete and that even the testing of these views has been incomplete thus far. A new theoretical effort integrating these two views or a formulation encompassing both views would be more valuable to the field. Before elaborating an integration of these views, we address a number of critical issues that are important for further advancing the field of task-switching research.

## Considerations About Task-Switching Processes

In the current section, we first address questions related to the assumptions that are left implicit in the present accounts of task switching and discuss the evidence, if any, in favor of these

assumptions. All these questions are directly or indirectly related to the task set. We also consider task switching in a broader context that includes the role of expectations and planning. This section should be of help in focusing on questions that have been left unanswered or that have not been brought to closure.

## Task Set

**Task-set notion.** The task set is a hypothetical construct introduced to explain goal-directed behavior. A definition of the task-set notion is at the same time a description of its components (control or parameter settings) and a hypothesis about goal-directed processing. For this reason, it is important to formulate the content, structure, and function of this construct as precisely as possible. Nevertheless, the concept of task set is often left undefined or is defined in such a way that it involves a wide range of components (e.g., Monsell & Mizon, 2006). A succinct definition of the task set should be preferred for reasons of parsimony, and the definition should build on a clear distinction between the task goal (the representation of what is to be achieved), the task set that provides a way to achieve that goal, and the task itself. First, we propose that the activated task goal plays a role in the configuration of the task set. This is similar to the way in which an activated goal constrains the rules that subsequently can become active in the ACT-R model (Anderson & Lebiere, 1998). Second, we propose that the task set consists of a number of task parameters that are necessary for achieving the task goal (e.g., Logan & Gordon, 2001) and protecting task processing against potential interference, as will become clear below.

The question of which task parameters are part of the task set is both theoretical and empirical. The executive control theory of visual attention (ECTVA; Logan & Gordon, 2001) provides an example of a theoretical elaboration that defines the task set as a number of task parameters. These parameters involve orientation of attention to the relevant stimulus aspects (see also Meiran, 2000b; Meiran & Marciano, 2002), setting of the response threshold, and a response bias. The response bias can be conceived as biasing toward the relevant stimulus-category rule (the task-based rule to categorize the stimulus) and the category-response mapping rule (see, e.g., Dreisbach, Goschke, & Haider, 2007).

The empirical question can be answered by performing empirical tests aimed to answer the question of whether a particular task parameter indeed belongs to the task set. Each proposal of a particular task parameter is involved in task-set configuration is a hypothesis that needs to be tested. For example, in the ECTVA theory, response threshold is one of the control parameters that regulates the speed/accuracy trade-off (e.g., Ratcliff, Van Zandt, & McKoon, 1999): When this threshold is low, it will be reached faster, but the probability of an error is higher because small incorrect activations based on "noise" can reach the threshold; in contrast, when the threshold is high, response is slow but the probability of an error is lower because small incorrect activations based on noise will less often reach the threshold. That the response threshold is indeed part of the task set was demonstrated in a study by Gopher et al. (2000). They showed preparation costs due to alternation between speeded and accurate responding. It seems, however, that even when this task parameter has been set during task preparation, its value can be changed over time (e.g., Strayer & Kramer, 1994; Verbruggen & Logan, 2009). For exam-



ple, a general control mechanism may raise the threshold after an error and lower it after a series of correct responses (e.g., Botvinick, Braver, Barch, Carter, & Cohen, 2001).

A study by Philipp and Koch (2005) tested another potential task parameter by examining whether lag-2 repetition costs occurred among the same task when executed in different response modalities. Lag-2 repetition costs among oral, manual, and foot responses were observed, suggesting that the task modality can be part of the task set (see also Koch, Gade, & Philipp, 2004). Other studies suggested that stimulus modality may play a role (Hunt & Kingstone, 2004; Murray, De Santis, Thut, & Wylie, 2009). The outcomes of such empirical tests serve to validate the theory of goal-directed behavior. Such testing is very relevant for understanding task switching, but it has implications for all situations in which goal-directed behavior can occur.

It is important to stress that, in general, researchers should clarify their view on the task set by explaining which task parameters need reconfiguration (see, e.g., Schneider & Logan, 2007a). On the basis of the evidence summarized here, a useful definition of the task-set construct would include the following task parameters: stimulus-category rules, category-response rules, orientation of attention (attentional bias), response threshold, and response modality. This list summarizes current knowledge but may be changed by future research.

**Task variations.** Which task parameters must be set largely depends on the specific tasks used. Although all tasks require setting of some of the task parameters, not all parameters are relevant for all possible tasks. A taxonomy of tasks is beyond the scope of this review. However, the variety of tasks used in task-switching studies raises the question about the role of the task properties in task switching.<sup>4</sup> In particular, the question should be to what extent properties of task-switching performance—such as switch cost, reduction of switch cost by preparation time, task-set inertia, and task-set interference—depend on task properties.

Knowledge about the processes involved in performing particular tasks requires development and testing of task models. The Stroop color-word naming task provides an example of a well-studied task (MacLeod, 1991). Process models have been developed for this task, and one of these (Cohen, Dunbar, & McClelland, 1990) was extended to a task-switching model (Gilbert & Shallice, 2002). Similarly, many studies have used parity and magnitude judgments on digits, backed by an extensive literature in the domain of numerical cognition (e.g., Campbell, 2005). The availability of validated knowledge about tasks provides an advantage to researchers who are in the process of selecting an appropriate task for testing their research question because the relevant task parameters are known. Unfortunately, for many tasks, the task properties have been less well studied, and better understanding of what each task involves is badly needed.

Some studies have reported effects of task properties on task-switching performance (Arrington, Altmann, & Carr, 2003; Ravizza & Carter, 2008; Rubinstein et al., 2001; Rushworth, Passingham, & Nobre, 2002, 2005; Wylie, Javitt, & Foxe, 2006). Rubinstein et al. (2001), for example, varied task properties such as familiarity, stimulus discriminability, and rule complexity (e.g., one-dimension vs. two-dimension categorization) and found that only rule complexity resulted in larger switch costs. In two ERP studies, Rushworth, Passingham, and Nobre (2002, 2005) showed distinct roles for changes of attention and changes of intention.

They studied cue-locked and stimulus-locked ERP waves with tasks that required switching of the category-response rule (triangle-left, triangle-right; first study) and tasks that required switches of visual attention (attention to color or to shape by selecting the correct element in a pair of shape/color stimuli; second study). They observed similarities in the activation patterns in cue-locked waves of both studies; this indicates that cue-related processing did not show differences across the conditions. In contrast, the stimulus-locked waves revealed early visual potentials in attentional switching and rather late response-related potentials in response-rule switching. All these studies show that variations in task features that are related to task parameters, such as stimulus-category rule (complexity), category-response rule (or mapping), and attentional bias, affect properties of task execution and task switching.

A more direct comparison of different tasks was performed by Yehene and Meiran (2007). They compared task switching in a cuing procedure with a “where” task (spatial categorization of a stimulus as left–right or up–down) and a “what” task (color or shape categorization). A preparation effect was observed in both tasks. However, this effect was much larger in the what task than in the where task. After a long CSI (1,000 ms), the RTs did not differ across tasks. After a short CSI (100 ms), the RTs of the mixed-task blocks were much larger in the what task than in the where task. These results show that preparation for the upcoming task and hence task-set reconfiguration are much more difficult in the what task than in the where task. This could be due to the involvement of different processing pathways (where and what) or to other factors that differ across the two tasks, such as the fact that the where task has nonarbitrary category-response rules whereas the what task is based on arbitrary category-response rules. Further studies comparing tasks with different properties that elucidate the task-specific contributions to task switching would be most welcome.

Apart from differences between pairs of tasks, the relationship between the two tasks within a pair may also play a role. For example, Wylie et al. (2006) reported an fMRI study in which colored rotating rectangles as were used as stimuli. The two tasks, classification of motion speed (slow, fast) and color (red, blue), relied on separable low-level neural circuits. Preparatory activity for the color task resulted in equally fast switch and repetition trials, whereas switching toward the motion task was accompanied with considerable behavioral costs and absence of activation in the motion circuits during preparation.

These examples show that task-related differences are underestimated and that it is worthwhile to clarify which processes are involved in performing a particular task and whether they are shared across the tasks. What we stress here is the importance of a more systematic approach to the role of task properties in view of a better knowledge of the task parameters. There is a need for knowledge about which task parameters are conducive to preparation and hence can play a role in task-set reconfiguration and which parameters affect task execution and thus may be at the basis of interference effects. It seems that fMRI, but also electroencephalography and magnetic electroencephalography, may

<sup>4</sup> We are indebted to Marcel Brass for bringing the important role of tasks to our attention.



prove a useful tool, because some aspects of task processing are more difficult to assess in behavioral studies. More specific information is needed for better understanding both the time course of task-set configuration and the way in which different tasks may interfere with each other.

**Task-set overlap.** Preparation for an upcoming task depends on task-set reconfiguration according to the reconfiguration view and on changing the activation of the task according to the interference view (e.g., Gilbert & Shallice, 2002). These processes take time and are at the basis of the reduction in switch cost with preparation time. The questions addressed here are how the two views specify the time course underlying preparation and how they differ from each other.

In studies using univalent stimuli, mixing costs but no switch costs have typically been observed (Jersild, 1927; Spector & Biederman, 1976). For example, when one task requires adding 3 to a number and the other task requires naming antonyms, switch costs are small or absent. This observation can be explained by assuming that the two task sets are completely different from each other, so that there is no risk that stimulus processing will be influenced by the irrelevant task set. As a consequence, the two task sets can be maintained active at the same time and performance control can be stimulus-based, because the stimuli do not overlap: Each stimulus is uniquely associated with one task. In contrast, there are conditions with univalent stimuli in which this is not the case. Rogers and Monsell (1995), for example, used stimuli with two features; one feature was task relevant, and the other either could be relevant for the alternative task (cross-talk condition) or did not correspond to any task in the experiment (no cross-talk condition). With the latter type of stimuli, these studies reported a smaller but still substantial switch cost (for similar results, see, e.g., Ruthruff et al., 2001). The fact that no response is defined for these stimulus aspects makes it unlikely that stimulus categorization processes would play a role. However, such functionally univalent stimuli require attentional selection of the relevant stimulus aspects, which is not the case in “truly” univalent stimuli. As soon as interference between relevant and irrelevant processing can occur, clearly, either more time is needed for setting the appropriate task parameters or more time is needed for making one of the task sets more active than the other. Because the amount of potential interference is still limited in the conditions discussed, the amount of readjustment is also limited.

When stimuli are bivalent, the task sets do overlap and conflicts may occur in different processing stages (e.g., Meiran, 2000a). In particular, when stimuli are bivalent, changes of the category-response rule as well as changes in stimulus-task binding may contribute to the switch cost. Meiran (2008) disentangled these two factors, which are normally confounded. He showed that these factors affect different aspects of processing. The switch cost was larger with bivalent than with univalent stimuli, but only the bivalence switch cost was sensitive to preparation duration. Variation in stimulus-task binding, on the contrary, affected only repetition RTs, especially with short preparation time. This pattern of results shows that task-set reconfiguration plays an important role in managing bivalence, whereas the potential for interference is rather limited (see also Meier, Woodward, Rey-Mermet, & Graf, 2009).

This discussion about task-set overlaps shows not only that the larger switch costs observed with functionally univalent and biva-

lent stimuli are due to task-set overlap but also that preparatory activity plays an important role. The interference view sees this preparatory processing as increasing the activation of the relevant task set, and a concomitant decrease in the activation of the irrelevant task set and the difference in level of activation between both should be large enough to prevent the occurrence of too many errors and to maintain an acceptable speed of execution (Steinhauser, Hübner, & Druey, 2009). In contrast, the reconfiguration view characterizes this preparatory activity as a process of task-set reconfiguration (i.e., of setting the task parameters), so that with more overlap between the relevant and irrelevant task set, more processing is needed to complete the setting of all the task parameters. When this is done, potential sources of interference are eliminated during reconfiguration, which results in a shielding of the task set from such interference (Goschke, 2000). It thus seems that the two views attempt to explain the same observations with regard to the difference between univalent and bivalent stimuli in different ways. A basis for attempting an integration of these main views seems to be available. We come back to this in the General Discussion.

**Task-set structure.** As task-set reconfiguration involves setting several task parameters, questions about the structure of the task set have also been raised. It is important to know whether these parameters form a unitary structure or whether they exist as a loose set. In the latter case, only task parameters that change have to be replaced: Task parameters that are no longer needed must be replaced by the task parameters needed for the new trial. Occasionally, interference control may be required to handle conflicting situations. In contrast, if the task parameters form a structure, the structure will determine which parameters need reconfiguration and the order of reconfiguration.

Kleinsorge and Heuer (1999) proposed a hierarchical organization of task parameters. They argued that on logical grounds there is a hierarchical structure between the task parameters. The stimulus is categorized on the basis of the stimulus-category rule (e.g., 3, small; 8, large); once the stimulus is categorized, the response is selected on the basis of the category-response rule (e.g., small-left, large-right). This logical structure determines the execution order of control processes involved in task-set configuration: First the task has to be selected, next the appropriate categorization rule must be applied to the stimulus, and finally the correct category-response rule is activated. Consequently, the amount of preparatory activity depends on the level in the hierarchy at which the change is required. If the task (top of hierarchy) changes, all levels have to be reconfigured; if the category-response rule (lowest level) changes, only that level is involved in reconfiguration. On this view, the size of the switch cost would depend on the number of changes required. It was predicted that a switch of task and its subordinate stimulus categorization would be faster than a change of task without a change in the subordinate stimulus categorization, because this partial switch (i.e., task but not response categorization) involves a complete switch at all levels plus an additional “reswitch” of the stimulus-category rule. The findings of Kleinsorge and Heuer (1999) confirmed these predictions (see also Kleinsorge, Heuer, & Schmidtke, 2001, 2002). The exact pattern of findings, however, depends on the presence of all task-mapping combinations in a sequence of events (Kleinsorge, Heuer, & Schmidtke, 2004).

The findings of Kleinsorge and colleagues contrast with the pattern originally obtained by Allport et al. (1994), who observed that switching between two task parameters (task rule; i.e., stimulus-categorization rule and stimulus dimension of Stroop stimuli) did not result in a larger cost than switching only the task or only the stimulus dimension. The results of Allport et al. contradict a hierarchical task-set structure, and they were replicated in several studies (R. Hübner, Futterer, & Steinhauser, 2001; Liefoghe, Christiaens, & Vandierendonck, 2010; Vandierendonck, Christiaens, & Liefoghe, 2008). Note, however, that R. Hübner et al. (2001) found a third pattern of results, namely, larger costs for two-parameter switches than for single-parameter switches. None of the studies cited in this paragraph confirmed the predictions based on a hierarchical account (but see Kleinsorge, 2004). It remains unclear, though, what is causing the discrepancy in the results.

The investigations on the task-set structure reveal three different patterns of findings, each suggesting a different way of structuring the task set. It is possible that the evidence for a hierarchically structured task set depends on the presence of a hierarchical priority relation among the task parameters, which would suggest that the way a task set is structured depends on the relationship among the task parameters. This issue has not been settled, and further tests are clearly necessary.

**Stability of task-set activation.** Many researchers assume that the task set of the previous trial can be maintained without the necessity for a reactivation or a reconfiguration. This assumption implies that task-set activation is relatively stable. Even though dissipation of the task set is expected to occur, it is also expected that the activation of the most recent task set will not drop below the activation of any other competing task set. In other words, task-set decay should not be so large that some other task set becomes more active and gains control over behavior.

The finding that longer preparation time also benefits repetition trials (although to a smaller extent than switch trials) suggests that the repeated task set may lose strength after task execution. This loss in activation may be due to several factors: passive task-set decay, interference, or active task-set inhibition. Altmann and Gray (2002) argued that decay plays a functional role in memory. Using the intermittent instruction procedure, they observed that response latencies over runs of the same task tended to become slower. Such *within-run slowing* suggests task-set decay. In a subsequent study, Altmann (2002) ruled out a number of alternative explanations and showed that within-run slowing was also observed in the alternating runs procedure, although it went unnoticed in the original study of Rogers and Monsell (1995).

The question may be raised, however, whether task-set dissipation is a passive process. Altmann (2005), for example, showed that the amount of task-set dissipation depends on whether inter-trial intervals are varied between or within subjects. These findings suggest that task-set activation depends on expectations of whether the task set will remain relevant or not, and they imply that the conceptualizations of task set reconfiguration as developed so far are incomplete in that expectancy processes are also playing a role in the control of task-set activations (see below).

An important implication of this discussion is that maintenance of the activation levels of the goal and the task set is an important factor in goal-directed behavior. In the extreme, loss of activation of task goal and task set may lead to goal neglect, as observed

under some pathological conditions (see, e.g., Duncan et al., 2008). The assumption of stability thus again shows that our knowledge about the task set requires improvement.

**Concluding remarks.** The issues addressed here are all related to the characteristics of the task set, which is an important construct in cognitive psychology with respect to the account of goal-directed behavior in general. This notion has been in use for a long time, but task-switching research has shown that more conceptual and empirical elaboration is needed for it to become an explanatory concept rather than a standard scheme that allows one to avoid a scientific analysis. Although the results of task-switching research have brought us this insight, the attempts to improve our conceptions of the task set will have to come not only from research on task switching but also from the other areas of research where the notion has been useful (see, e.g., Corbetta & Shulman, 2002, in the domain of selective attention).

## The Broader Context of Switching

Most of the research and theoretical development in task switching focuses on trial-to-trial transitions, as discussed in the previous section. However, human cognition is multilayered. Once tasks have to be performed in sequence, habituation and (implicit or explicit) learning lead to changes in the way the tasks are performed, and there is also active exploration of possibilities for making task execution less effortful and more efficient. In particular, predictability of the sequence of events, awareness and knowledge of this predictability and the resulting expectations, and also grouping and even planning may affect task-switching processes and performance. In the present section, we review relevant findings and their implication for the more general question raised here.

**Predictability and probability.** One important difference among the current task-switching procedures concerns predictability of the task sequence (e.g., list and alternating runs vs. cuing). Tornay and Milan (2001) used cuing with zero RCI in unpredictable and predictable sequences. In the unpredictable sequence, the switch cost was large for a short CSI and decreased when CSI increased. In contrast, in predictable sequences, the switch cost was relatively small for short CSI but did not further decrease when CSI increased. Moreover, in predictable sequences, RT did not decrease beyond the first repetition trial, whereas in the unpredictable condition, there was a gradual RT decrease over successive repetition trials (for similar results, see Altmann, 2007a; Milan, Sanabria, Tornay, & Gonzalez, 2005).

Monsell et al. (2003) replicated the pattern of findings reported by Tornay and Milan (2001) and argued that it is possible to modulate the readiness or bias toward the relevant task. As a consequence, in conditions with unpredictable sequences, repetition of the same task increases the bias toward this task, and this increase continues as the run goes on. These and similar findings suggest that predictability mainly affects the repetition RTs (see also Koch, 2008) and that predictability supports preparation for the upcoming task (Nicholson, Karayanidis, Davies, & Michie, 2006).

Other sequence regularities may also contribute to predictability. One aspect is the stimulus sequence (see, e.g., Gotler, Meiran, & Tzelgov, 2003). As stimulus sequences are normally composed randomly (with some restrictions, such as exclusion of stimulus

repetitions), there is no reason to suspect that this plays a role in the experiments discussed above. However, a predictable sequence of stimuli or responses offers additional opportunities for preparation or even for learning. Awareness may also play a role, as participants may be aware of regularities in the sequence and explicitly use this knowledge to guide their behavior. The role of this important aspect of predictability, knowledge about predictability, does not seem to be completely captured in the studies reviewed in this section (but see Sohn & Anderson, 2001, 2003). So it is not at all clear whether these studies really tapped similar aspects of predictability. Investigation of effects of implicit learning about the regularities in the sequence and effects of knowledge about such regularities on task-switching performance may help to better understand how predictability of tasks, stimuli, and responses can modulate control processes.

The probability of task switches is another aspect of the predictability of sequences. Several studies have varied the probability of the occurrence of a switch (Mayr, 2006; Mayr & Kliegl, 2003; Monsell & Mizon, 2006; Schneider & Logan, 2006b). Dreisbach, Haider, and Kluwe (2002) reasoned that task repetitions benefit from an activation advantage due to persisting activation from the previous task execution but also from an expectation advantage because participants tend to expect a repetition. Using four tasks, they manipulated the expectancy of a switch by using cues that signaled the probability of a switch to a particular task while keeping task frequency constant. They found that the execution latency decreased linearly with the expectation of a repetition, but the switch cost remained the same at each probability level. When the probability cues did not specify the upcoming task, latency still depended on probability but the switch cost also varied with probability, which led Dreisbach et al. to conclude that information about the identity of the upcoming task is used to inhibit the other task sets. Other studies showed that preparation effects are stronger in blocks with frequent switches than in blocks with frequent repetitions (Dreisbach & Haider, 2006). Together with the previous findings, these results converge on the hypothesis that preparation is dynamically modulated by the expected task requirements.

Combined, these studies show that predictability of sequential parameters (cues, tasks, stimuli, responses) and knowledge about the probability of particular sequences (e.g., task repetitions) affect performance in task switching. This finding has important theoretical implications. First, sequential regularities may support implicit learning about the structure of the sequences, and such learning may form a basis for exogenously triggered effects (Gotler et al., 2003). Second, knowledge about what is likely to happen next (expectancy, metacognition) may lend support to the reconfiguration process (e.g., Kleinsorge & Gajewski, 2008) and may also form a basis for strategic choices that underlie task switching efficiency. However, expectancy about upcoming situations may also facilitate control of interference. Third, it is also possible to consider the design-specific effects of task switching (Altmann, 2004a, 2004b) in this context, because these effects also seem to be related to predictability and expectation. It is fair to say that not so much is known about the interaction of these processes with cognitive control and whether or not they lead to particular decisions or even to the adoption of particular strategies, possibly by mediation of higher level executive control processes such as task planning.

**Structures of task sequences.** Factors such as predictability and expectation may lead to planning of a sequence of tasks instead of a single task at a time, as was demonstrated by Lien and Ruthruff (2004). They used two types of alternating runs sequences. In AB-AB-AB-... sequences, a task switch occurs at the ensemble boundary (indicated by the dash) while the ensembles repeat. In contrast, sequences of the form AB-BA-AB-... show the reversed pattern, in which task repetitions occur at the boundary but the ensembles switch. When intervals were fixed between the individual trials, they observed a relative switch cost for the first task in the ensemble (i.e., a task-switch cost but no ensemble-switch cost). Lien and Ruthruff varied the within-ensemble intertrial interval and stressed the underlying grouping in the series. This way, the relative switch cost of the first task of the ensemble was reversed into a benefit, and an ensemble-switch cost appeared. Findings such as these show that regularities (and, concomitantly, predictability; see also above) in a series of simple events are sufficient to elicit a structural representation that is reminiscent of sequences or series of events in skilled and planned behavior.

A related approach is based on the task-span procedure developed by Logan (2004). Starting from an unstructured sequence (in the sense of Lien & Ruthruff, 2004), Schneider and Logan (2006a) used sequences of four tasks, such as AABB and ABBA, which had to be applied over and again to a series of stimuli. Even though the ABBA sequence contains more task switches than the AABB sequence, Schneider and Logan observed no difference in terms of within-sequence switch cost, but they found a slower RT on the first task of each sequence. This sequence-initiation cost was also present in longer sequences (6 tasks) and was larger in more complex sequences (e.g., more switches). Further on, they combined these sequences into "super sequences," and they observed that the super-sequence initiation time was longer for super-sequence switches than for super-sequence repetitions. Overall, these findings suggest that preparation for an upcoming task and for an upcoming sequence of tasks are similar and that such preparation corresponds to the implementation of a plan (cf. G. A. Miller, Galanter, & Pribram, 1960).

In a follow-up study, Logan (2007) compared performance in three conditions: a task-span condition (tasks are memorized and then applied to a series of targets), a cued condition (same, but each target is preceded by a cue), and a memory-load condition (same as cued condition, but the memorized task names are irrelevant to the cued task switching because they could not be applied to the targets). RTs and switch costs were substantially larger in the task-span condition than in the cued condition and in turn in the loaded condition. However, a mere memory load during cued task switching did not affect the switch cost. In order to clarify the reason for the performance difference between the task-span condition and the cued-condition, further experiments varied the difficulty of the cued condition. When the task names were presented and memorized in the same order as the targets, the switch costs were smaller than when the order did not correspond. When the memorized task names were similar to the ones used as cues, the switch cost was larger than when the names were dissimilar. These findings are consistent with the hypothesis that both plan control (execution of each task in order and keeping track of the position in the sequence) and protection of interference from other tasks play a role.

Together with the sequence structuring approach of Lien and Ruthruff (2004), research with the task-span procedure shows that it is possible to distinguish between two hierarchically related levels of control (i.e., the level of the task and the level of the sequence of tasks or ensemble) and to examine how these levels interact. All these studies set the scene for an interesting line of investigation in which different hierarchical levels of control can be studied (see also Mayr, 2009). Such research presents a first step toward the study of planning and the switching of plans. Planning also involves hierarchical levels of control, but in addition, planning concerns sequences that are meaningful entities, as they were constructed as a means or a path toward achieving a goal. Thus far, only arbitrary sequences have been used. The necessary next step is to work with existing sequences of activities that lead up to a goal.

The extension of simple tasks to plans of task sequences is interesting because it is also at the heart of the executive function labeled as planning. Within the present context, the advantage is that characteristics of planning can be studied in a context of task—or rather plan—switching. This extension of the task-switching paradigm to plan switching also requires answers to a number of questions related to planning. Theoretical knowledge is rather scarce and has to be developed further on the basis of work already done (Burgess, Simons, Coates, & Cannon, 2005). Further

work along these lines not only will improve our knowledge of task and plan switching but will also advance knowledge about planning and the executive control of planning.

## General Discussion and Conclusion

The present overview of recent research on task switching has touched on a range of issues. Notwithstanding the different viewpoints and the difficulties of translating the subtle processing differences postulated in these views into appropriate experimental designs, progress has been made in several respects. In what follows, we first present a list of robust findings that can be used as benchmarks for theoretical development and formal modeling. Next, we discuss how an integration of the two main views can be achieved. Finally, we discuss developments that may profit from theory and methods of the task-switching paradigm.

## Summary of Findings

We present here an overview of what we consider to be basic and robust findings about task switching. The list is schematized in Table 2. This list is a collection of benchmarks that must be accounted for in any comprehensive view of task switching.

Table 2

*Robust Findings That Can Serve as Benchmarks for Further Theory Development*

| Finding  | Example reference               |
|--|---------------------------------|
| Procedure-related effects  |                                 |
| Alternating list cost (global switch cost)   | Jersild (1927)                  |
| Mixed list cost  | Los (1996)                      |
| Long RT and large switch cost in transition cuing  | Forstmann, Brass, & Koch (2007) |
| Repetition bias in selecting tasks in voluntary task switching   | Arrington & Logan (2004a)       |
| Switch cost smaller in voluntary task switching than in cuing  | Arrington & Logan (2005)        |
| Stimulus-related effects on task selection in voluntary task switching   | Mayr & Bell (2006)              |
| Theory-related effects   |                                 |
| Interaction of between-task congruency and switch cost   | Goschke (2000)                  |
| RT faster for response repetition than for response alternation in task repetition trial; reversed in switch trial                         | Kleinsorge & Heuer (1999)       |
| Lack of interaction of within-task congruency and compatibility factors with the switch cost   | Meiran (2005)                   |
| Interference from previous task execution  | Allport et al. (1994)           |
| Associative carryover from previous trials   | Waszak et al. (2005)            |
| Task-set dissipation effect (effect of trial delay)  | Meiran et al. (2000)            |
| Reduction in switch cost with preparation time   | Meiran (1996)                   |
| Larger preparation effect for switch than for repetition trials  | Monsell & Mizon (2006)          |
| Residual switch cost except when the cue disappears  | Verbruggen et al. (2007)        |
| Cue-stimulus compounding and absorption of the switch cost by the cues   | Logan & Bundesen (2003)         |
| Cue-target compatibility interaction with cue versus corrected task switch cost  | Schneider & Logan (2005)        |
| Role of switch frequency in size of cue switch cost  | Monsell & Mizon (2006)          |
| Design-specific switch cost reductions   | Altmann (2004a, 2004b)          |
| Switch cost depends on verbalization and inner speech  | Baddeley et al. (2001)          |
| Task span not different from memory span for task names  | Logan (2004)                    |
| Task switching interferes with maintenance of irrelevant information   | Liefooghe et al. (2008)         |
| Lag-2 repetition cost (backward inhibition)  | Mayr & Keele (2000)             |
| No switch cost when previous task response has not been selected   | Schuch & Koch (2003)            |
| Within-run slowing   | Altmann (2002)                  |
| No further RT decrease on consecutive repetitions in a predictable sequence, but continuing RT decreases on repetitions in random sequence | Tornay & Milan (2001)           |
| Switch cost is modulated by probability of task change   | Dreisbach & Haider (2006)       |
| Hierarchical versus linear organization of the task set  | Kleinsorge & Heuer (1999)       |
| Task-level versus ensemble-level switch costs  | Lien & Ruthruff (2004)          |
| Longer switch cost in switching away than switching toward a task independent from preparation interval                                    | Nicholson et al. (2006)         |

*Note.* The references listed in the second column of this table are not exhaustive but serve as exemplary references. RT = reaction time.



The switch cost is the ubiquitous finding in task switching. More important is how this cost behaves under different procedural variations. In the list paradigm, two kinds of switch cost have been documented, namely, the global switch cost (e.g., Kray & Lindenberger, 2000) and the mixed list cost (e.g., Los, 1996). In transition cuing, the RTs are longer and the switch costs are typically larger than in explicit cuing (e.g., Forstmann, Brass, & Koch, 2007). In voluntary task switching, the cost is smaller than in cuing (Arrington & Logan, 2004a) and there is a task-repetition bias in task selection (Arrington & Logan, 2005). The strong endogenous components notwithstanding, stimulus-related factors affect the selection of tasks (Mayr & Bell, 2006).

Independent of the procedures used, rule-congruent responses are faster than incongruent ones, and this effect interacts with switching (e.g., Goschke, 2000). Within-task congruency and compatibility, in contrast, does not interact with the switch cost (e.g., Meiran, 2005). Response repetitions are faster than response alternations in repetition trials, but the relationship is reversed in switch trials (e.g., Kleinsorge & Heuer, 1999). Furthermore, associative carryover effects from previous trials have been reported several times (Waszak et al., 2003, 2004, 2005). In a similar vein, absorption of the switch cost by the cues in cue-stimulus compounding (e.g., Logan & Bundesen, 2003) and interaction of cue-target compatibility with cue-switch versus task-switch costs (Schneider & Logan, 2005) have been reported.

A number of effects are related to changes in the task set. With longer delays since the last response, RTs become longer (task-set dissipation; e.g., Altmann, 2005; Meiran, 2000b). A longer preparation time results in a reduction of the switch cost (Meiran, 1996) in such a way that the preparation effect is larger for switch trials than for repetition trials (e.g., Monsell & Mizon, 2006). In general, even after a very long preparation interval, a residual switch cost remains (e.g., Rogers & Monsell, 1995), except when advance task preparation is strongly encouraged (Verbruggen et al., 2007). In situations with alternation among three tasks, a lag-2 repetition cost occurs (Mayr & Keele, 2000), and this cost depends on processing of the previous task up to a response selection (Schuch & Koch, 2003). Switching toward a particular task is faster than switching away from the current task because the latter option requires a choice between two tasks (Nicholson et al., 2006). Switch-cost reductions are, moreover, design specific: Effects that occur in a within-subjects design are not necessarily replicated in a between-subjects design (e.g., Altmann, 2004a, 2004b).

A number of switch-cost modulations depend on sequential parameters. For example, the relative sizes of the cue-switch cost and the task-switch cost depend on the frequency of switches (e.g., Mayr, 2006), and the switch cost is modulated by the probability of task changes (e.g., Dreisbach & Haider, 2006). In predictable sequences, there is no additional decrease of RT over successive repetitions of the same task, whereas in random sequences, each new repetition becomes faster (e.g., Tornay & Milan, 2001). Generally, there is even some within-run slowing over successive repetitions (Altmann, 2002).

Some working memory variables are also known to play a role in task switching. Several studies have shown that inner speech and its modulation by means of relevant or irrelevant verbalization affects the size of the switch cost (e.g., Baddeley et al., 2001). In contrast, task switching is not affected by irrelevant memory loads, as shown in the task-span procedure (Logan, 2004), although in the

reverse direction; the number of task switches performed during maintenance of an irrelevant memory load results in poorer recall of memorized information (Liefoghe et al., 2008).

Finally, task sets seem to be organized hierarchically. Different amounts of reconfiguration result, depending on the hierarchical level at which the switch occurs (Kleinsorge & Heuer, 1999), although this finding is not universal (e.g., Allport et al., 1994). Depending on factors that encourage sequence structuring, the relative size of task-level and ensemble-level switch costs can be modulated (Lien & Ruthruff, 2004; Logan, 2007).

## Toward Theoretical Integration

The present review shows that both main views—the reconfiguration view and the interference view—assume that control processes play an important role in task switching. They differ, however, in their hypotheses regarding the specific control processes involved in task switching. As a consequence, the two views are different but not mutually exclusive, and we see possibilities for integrating these views. In the present section, we further explore the possibilities for such an integration (see also Vandierendonck, in press). We focus on the two processing stages that contribute to the switch cost, namely, the task-preparation stage, which is at the basis of the reduction in switch cost with preparation time, and the stimulus-based processing stage, which is relevant for explaining the residual switch cost and some stimulus-based sources of interference.

**Task preparation stage.** Both views predict a preparation effect, namely, a reduction in switch cost with more preparation time. The interference view attributes this effect to the time needed to make the relevant task set more active than the irrelevant one. The duration of this process depends on the difference in activation between the two tasks and the extent to which one task interferes with the other. In contrast, the reconfiguration view assumes that preparation duration depends on the time needed to set all task parameters.

The section on task-set preparation showed that there is evidence in favor of task-set reconfiguration as well as interference control. The study by Yeung et al. (2006) suggested engagement of interference-control processes in the task preparation interval as well as control processes that regulate maintenance of task-specific information about rules or goals. Yeung et al. proposed that during preparation not only interference control but also task-set reconfiguration is taking place. In the section on task-set overlap, we point out that the differences in switch cost observed with different types of univalent and bivalent stimuli seem to depend on the presence of interference between the two tasks and their task sets (for support from neuroimaging, see Mueller, Swainson, & Jackson, 2007; Woodward, Metzack, Meier, & Holroyd, 2008). We noted that the presence of potential interference determines the extent by which the relevant task needs to be activated more than the irrelevant task in order to overcome this interference. However, evidence also shows that bivalent stimuli affect the time needed to set task parameters (Meiran, 2008).

Although both views tend to stress one kind of control and ignore the other, the evidence collected thus far indicates that both kinds of control, namely, interference control and control of task parameters, are involved in task preparation. Therefore, an integration of these views seems fairly straightforward, in that the time

needed to prepare for an upcoming task depends on two kinds of control processes. The first kind of control processes is best characterized as *reactive control*, and these processes control interference due to persisting activation of the previously relevant task set (task-set inertia) and to overlaps with the previously relevant task set (e.g., task-rule congruence). The second kind of control processes can be characterized as *proactive control*, which is achieved in task-set reconfiguration. This process usually is not described in terms of interference control. However, because task-set reconfiguration involves setting of task parameters such as attentional bias, stimulus-category rules, and category-response rules, we propose that a completely reconfigured task set achieves shielding of the goal from interference due to irrelevant tasks and processes. Because these parameters are set before task execution, the cognitive system is prepared for executing the task and interference becomes less likely. For example, when the attentional-bias parameter is adjusted during the preparation interval, participants are ready to focus on the relevant part of the stimulus and to ignore the irrelevant part of the stimulus. This corresponds with accounts of interference control in the Stroop task (e.g., Egner & Hirsch, 2005). Such proactive control reduces interference when the stimulus is presented. In other words, we propose, in line with the proposal made by Goschke (2000), that reducing sources of conflict is a natural part of task-set reconfiguration.

Several observations in the literature can be considered as precursors toward the integrative view we propose. It was noted, for example, that both types of control seem to occur in the same setting (Yeung et al., 2006) and that cue-triggered processing during the preparation interval is sensitive to interference provoked by the number of potential stimulus–response associations (Wylie, Murray, Javitt, & Foxe, 2009). Elaborating on these findings, we propose that goal achievement requires a stable task set as well as control of interference that is present in the preparatory interval. In particular, control processes are required that (a) set the task parameters, (b) dissolve existing binding among task parameters, and (c) realize new bindings overcoming interference due to carryover from the previous task execution (e.g., Kleinsorge & Gajewski, 2007; Stoet & Hommel, 1999). In other words, task-set preparation must be both reconfiguration and interference control if it is to explain the extant evidence regarding preparation-related switch costs. The model proposed by J. W. Brown et al. (2007) provides an important step toward such integration. This model has a task-set representation system and integrates all major sources of interference in a single model, namely, incongruence between responses; incongruence between successive task sets, which represents not only task-set inertia but also general response slowing after a change; and output priming. It does not yet include a mechanism to set task parameters but provides a framework that could enable an implementation of these control processes.

**Stimulus-based processing.** The present review shows that even when sufficient time is available for preparation, a residual switch cost is usually observed. The interference view easily explains such a finding by referring to the possibility that stimuli become associated with responses (e.g., Wylie & Allport, 2000) or with tasks (e.g., Mayr & Bryck, 2005; Waszak et al., 2005). These associations are retrieved when the stimulus is repeated, causing interference when the retrieved information is inconsistent with the currently relevant information. The reconfiguration view, on the contrary, has often struggled with the observation of a residual

switch cost. Within this view, the hypothesis of failure to engage in reconfiguration (De Jong, 2000) provides an elegant explanation that has received some support (e.g., S. Brown et al., 2006; Verbruggen et al., 2007). The residual switch cost could also be due to postponement of the reconfiguration of the category–response rule until the stimulus appears (i.e., the two-stage reconfiguration account; e.g., Rubinstein et al., 2001). Such postponement would have the advantage that not all the relevant category–response rules (e.g., small–left and large–right) have to be activated and kept active in working memory until the next stimulus is presented. It thus avoids unnecessary conflicts between the rules. Thus, the major part of reconfiguration can be completed during task preparation, and, hence, the postponed completion of reconfiguration may occur independently from an engagement to reconfigure.

There is no reason to doubt that activation of the category–response rule is part of task-set reconfiguration (see, e.g., Schneider & Verbruggen, 2008). However, complete activation of the relevant category–response mapping (Rubinstein et al., 2001) and inhibition of the irrelevant category–response mapping seem to be postponed until the stimulus has appeared (see Schuch & Koch, 2003; Verbruggen et al., 2006). This inhibition process is probably based on lateral inhibition taking some time to complete, which again shows that the residual switch cost must not necessarily be attributed to interference control and that part of the reconfiguration (i.e., activation and inhibition of category–response mappings) is completed after stimulus presentation. It can even be argued that this is biologically adaptive, because advance preparation for a particular task is advantageous. Postponing the completion until the environment really requires it may be useful in case a return to the previous task is still needed and would allow a rapid return to the previous task without the need for implementing a completely new reconfiguration.

The review has shown that stimulus processing can be affected by positive or negative priming from previous stimulus occurrences. These priming effects are independent of the task preparation effects (e.g., Koch & Allport, 2006). Although several investigators (e.g., Meiran et al., 2008; Monsell & Mizon, 2006; Rogers & Monsell, 1995) have recognized this type of interference, it was not incorporated into the reconfiguration view (but see Goschke, 2000, for an exception). Nevertheless, the two-stage reconfiguration account can easily be extended by assuming that the second stage of reconfiguration not only comprises delayed reconfiguration, as discussed in the previous paragraph, but also involves stimulus-based processing with the purpose of overcoming interference caused by the retrieval of inconsistent stimulus–response or stimulus–task associations.

**Summary and conclusion.** The proposed theoretical integration of the two main views seems natural and plausible. It combines the assets of both views. The reconfiguration view's account of task-set configuration, including the setting of task parameters, not only specifies how the task set is being prepared but can also specify how achieving a task goal can be protected against interference (although interference may not be fully eliminated). It is also recognized that reconfiguration is not always completed during the preparation interval. This may happen because there are motivational or strategic reasons for a later start of reconfiguration or because a delay of reconfiguration is useful for incorporating stimulus information in the reconfiguration process. Such late

processing may also be involved in stimulus-based interference control. This interpretation combines the interference view's claim that residual switch cost is basically due to recovery from interference with the reconfiguration view's claim that the residual switch cost is due to delayed reconfiguration. Such an integrated view can account for all the findings presented in the main part of this review. Yet, it leaves room for further development because it is a theoretical framework rather than a precise theory. Within this framework, specific models can be developed to generate more precise predictions. Several interesting and useful models have been developed so far; however, an integration of both views has not yet been achieved. Except for Meiran's CARIS model (Meiran et al., 2008), which is actually a family of descriptive models calling on a range of processes that may give rise to a switch cost, and the ECTVA theory (Logan & Gordon, 2001), all existing models of task switching are based on the interference view. This is clearly the case for the model of Gilbert and Shallice (2002). Also, the model proposed by Altmann and Gray (2008) is a new version of a model incorporating proactive interference, which accounts for preparation effects on the basis of repetition priming. As we have indicated, the model of J. W. Brown et al. (2007) offers a framework in which both interference and task-set reconfiguration could be implemented. Implementation of the proposed integration into a formal model, whether by extending an existing model or by developing a new one, is in our view a target for further research.

## Open Questions

There are various issues that need further investigation and clarification and that are not necessarily in the core of the research on task switching. Such research should be beneficial to further theoretical development in task switching and related fields. First, task switching may call on the same kind of control processes as do other multitasking procedures, such as the stop-signal procedure (Logan & Cowan, 1984; Verbruggen & Logan, 2008) and the PRP paradigm (e.g., Pashler, 1994; Telford, 1931; Welford, 1952). Studies have been reported on the interaction of response inhibition and task switching (Aron, Monsell, Sahakian, & Robbins, 2004; Aron, Robbins, & Poldrack, 2004; Verbruggen, Liefoghe, & Vandierendonck, 2005; Verbruggen, Schneider, & Logan, 2008) as well as on possible overlaps between task switching and PRP (Band & van Nes, 2006; Gilbert, 2005; Ivry & Hazeltine, 2000; Lien, Schweickert, & Proctor, 2003; Luria & Meiran, 2003; Oriet & Jolicoeur, 2003; Sigman & Dehaene, 2006). We did not elaborate on the relation with stopping and inhibition, because it remains unclear which task components may overlap; we did not include an extensive discussion of the relation between task switching and PRP, because there are some doubts as to whether active monitoring processes are involved in executing overlapping tasks (Jiang, Saxe, & Kanwisher, 2004).

We did not include an overview of findings based on neuroscientific methodologies such as ERP and fMRI in the present review because the rather large number of studies did not easily lead to a coherent set of findings. In fact, our knowledge of the brain areas and pathways involved in task switching is still rather meager, but there are hopeful new developments. It is clear that the prefrontal cortex is involved, but we are still waiting for more precise knowledge of which pathways and control loops in the brain are

crucial and how they relate to other task settings that are studied in cognitive control. In the same vein, it remains unclear how these processes develop with age and how they contribute to psychopathology and other deficits in brain functioning.

New developments are also coming along involving application of task-switching procedures in other contexts. We mention two of these. A first application concerns the role of task-switching methods in attempts to better understand psychopathological behavior. A promising study in this respect showed that executive control performance of a group of patients with closed-head injury improved after some sessions of task-switching practice (Stablum, Umiltà, Mazoldi, Pastore, & Magon, 2007). A similar study with dual-task practice did not produce such effects (Stablum, Umiltà, Mogentale, Carlan, & Guerrini, 2000). Apparently more so than dual tasking, task switching calls on executive control, which is consistent with other findings regarding dual-task performance (Jiang et al., 2004; Miyake et al., 2000). Such research also suggests implications for mental rehabilitation and for training more generally (see, e.g., Karbach & Kray, 2009). The second application concerns the problem of switching between solution methods (usually called "strategies") in problem solving involving sequences of simple problems (Lemaire & Lecacheur, 2010; Luwel, Schillemans, Onghena, & Verschaffel, 2009). Is the choice of a solution method in any way similar to the choice of a task, or is the relation a subordinate one in that a solution method is only a means to achieve a goal, so that the control processes involved are of a different kind? In fact, selection of solution methods, as described, for example, by Siegler and Lemaire (1997), is a highly controlled activity taking into account knowledge about the difficulty of the method and the limits and constraints of the processing system. If such a view on method selection is correct, control processes play a central role. Consequently, switching between methods or between different plans not only would require a reconfiguration of task parameters but also a mechanism for deciding between alternative possibilities for goal achievement.

In short, task-switching procedures have already propagated much research, but a lot more will be needed to alleviate our scientific hunger. No doubt, more is to be expected from the newer procedures such as transition cuing and voluntary task switching and from studies that look at the interactions at different levels in the processing hierarchy, in particular the interplay between plan-level and task-level processes.

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