CHAPTER 11

Task Switching: Mechanisms Underlying Rigid vs. Flexible Self-control

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ABSTRACT

This chapter reviews the historical and current literature on task switching, focusing primarily on cognitive-behavioral studies on healthy human subjects. It outlines what I see to be widely accepted conclusions. These include the notion that tasks have mental representations ("task sets") and that a change in this representation results in slowing (although the exact reasons for the slowing are debated). Following Ach (2006/1910), the chapter divides the processes that are currently mentioned in the literature into those making an inner obstacle against a task switch (thus causing rigidity) and those that enable a task switch (thus supporting flexibility). It also discusses some major controversies in the field and suggest that many of these controversies are more apparent than real by pointing out the many issues where a broad consensus exists.

Keywords: Task switching, flexibility, literature review

Typical examples of situations involving self-control are characterized by their "don't" feature, such as being offered a bowl of delicious ice cream although you are on a diet (e.g., Vohs & Heatherton, 2000). Nonetheless, "do" situations also involve self-control. An example is your boss entering your office asking you to do something although you are deeply immersed in working on your favorite project. Here, self-control is needed both to interrupt the ongoing activity and to initiate the alternative activity. Research shows that complying with "do" commands is more difficult (Logan & Burkel, 1986) and is developmentally delayed (Kochanska et al., 2001) as compared with "don't" commands. One reason for this may be that self-control (also termed "cognitive control" and "executive functioning," *see* Miller & Cohen, 2001; Wood & Grafman, 2003) comprises several abilities. This is evident in low interindividual correlations between various control functions (e.g., Miyake et al., 2000) and somewhat differential functional anatomy (e.g., Bunge, 2004; Collette & Van der Linden, 2002).

At least five relatively independent domains of executive functioning have been identified, including working memory (WM) updating (e.g., Kessler & Meiran, 2006; Morris & Jones, 1990), behavioral inhibition (Logan, 1994; Friedman & Miyake, 2004), online performance monitoring (e.g., Botvinick et al., 2001), multitask coordination (e.g., Logan & Gordon, 2001; Meyer & Kieras, 1997a, 1997b; Pashler, 1994), and mental set shifting. Emotion regulation (Ochsner & Gross, 2005) may represent a sixth dimension in this taxonomy. The present chapter addresses the most widely used approach to the study of mental set shifting (or cognitive flexibility), which is the task switching paradigm (Logan 2003; Monsell, 2003, for recent reviews). Given the recent explosion of knowledge on this topic, the present review is inherently limited and it focuses on cognitive behavioral studies performed on healthy young human adults.

It is now widely claimed that self-control has developed in the Homo Sapiens to match the cognitive challenges of the complex social interactions that characterize our species (e.g., Adolphs, 2003; Barkley, 2001; Baumeister, 2005). Although the role of inhibition in social interaction has been widely acknowledged (e.g., Barkley, 2001), the role of cognitive flexibility in the social domain has been less explored. Nonetheless, theoretical analysis suggests that cognitive flexibility features a key role in social interactions. First, Baumeister noted that a crucial feature of Homo Sapiens is collaborative interaction involving division of labor and collaborative problem solving. To negotiate the division of labor while working on the solution, individuals must understand the intentions of their collaborators as well as the collaborator's potential contribution to the solution. In addition, there is a need for flexible shifts of attention between perspectives (one's own perspective and the collaborator's perspective), between focusing on the problem and focusing on understanding the collaborator's approach, and so forth. Supporting evidence comes from a study by Bonino and Cattelino (1990). They showed that children who were characterized as flexible according to their performance on the Wisconsin Card Sorting Test (arguably, the predecessor of the modern task-switching paradigm) were better able to negotiate collaborative problem solving than their less flexible counterparts. Second, the complex division of labor that characterizes modern social structures further demands individuals to constantly change their perspective as they change their social roles and their relative position in the social hierarchy. Third, this complex structure of labor division puts individuals in a position in which multiple long-term tasks are carried out in parallel, such as parenting, earning an income, and working toward an academic degree. These ongoing tasks are broken down into manageable subtasks and these subtasks become constantly intertwined. As a result, everyday life is often characterized by frequent switches between the subtasks, such as switching between answering a phone call from your child to continuing work on your Ph.D. dissertation. Finally, collaborative interaction often involves emotion regulation to maintain the socially appropriate stance. Furthermore, some emotion regulation strategies, such as reappraising a situation, involve a shift in mental perspective, and as such are functionally analogous to task switching (Shepps & Meiran, 2007). It should be noted that generating collaboration often involves reappraising the situation and accepting the collaborator's perspective.

The Task Switching Paradigm

Most of the current chapter is devoted to a review of the cognitive literature on task switching. This research has focused almost exclusively on the physical domain. It has helped to reveal the cognitive and neural mechanisms supporting rigidity and flexibility. I hope that the present review will promote the much needed work of understanding the role of human cognitive rigidity and flexibility in the social domain.

Historic Foundations

This section mentions only four papers, which I view as cornerstones in this literature. Ach (2006/1910) noted that the will's duty is to overcome inner obstacles that prevent it from achieving its goals. According to him, these inner obstacles are mostly habits. He used a paradigm that is surprisingly similar to modern task-switching paradigms. His paradigm consisted of two phases. In Phase 1, subjects learned to perform a given task on a set of stimuli. In Phase 2, subjects were required to perform another task on the same stimuli, and reaction time (RT) was measured to the nearest millisecond (!). Ach showed that the task switch resulted in considerable slowing in Phase 2 reactions, a phenomenon that today we call "switch cost." He interpreted the switch cost as reflecting the effort of the will in overcoming the habit formed during Phase 1. Ach also measured the number of Phase 1 practice repetitions required to form a habit that was sufficiently strong to overcome the will during Phase 2. Overcoming the will was reflected in the erroneous execution of the task practiced in Phase 1 during Phase 2. This measure was taken as an index of what he called the "*associative equivalent* of the will," which is an indirect index of will power. Note that many current works view switch cost as an index for lack of control. In contrast, Ach's view of switch cost is of a measure of will *effort*, not of will *power*. Peculiarly, his measure of will power has not to my knowledge been applied in later studies.

Jersild (1927) is often cited as the inventor of the modern task-switching paradigm (although what is the first study to my knowledge was conducted by Jones, 1915, cited by Bernstein, 1924). He asked his subjects to alternate between two familiar tasks that were performed on the same set of stimuli, such as adding a digit and subtracting another digit. (e.g., switching between a "+3" operation and a "–1" operation.). Note that Ach's (2006/1910) and Jersid's paradigms have in common the feature that the execution of one task creates a tendency (or habit) to perform Task A that forms the "inner obstacle" while performing Task B. Jersild's experiments resulted in three important findings. First, switch costs were robust when the stimuli were *bivalent* (affording two tasks, e.g., a digit when the tasks are "+1" and "–1"). Second, there were no switch costs when the stimuli were *univalent* (uniquely affording one task, e.g., words requiring an "opposite" task, e.g., white → black, and digits requiring a numerical task such as "+3"). The first two findings show that the habit to perform a given task tends to bind with the stimuli (Waszak et al., 2003). Finally, the costs were markedly reduced when there was an external reminder regarding which task was required (the stimuli for one task were on the right and those for the other task were on the left). The last effect shows that switch costs are partly determined by task-goal (un)certainty. All these effects were replicated in later studies.

Biederman (1972) provided crucial evidence that subjects can (at least partially) ignore information that was deemed irrelevant by the current task instructions. For example, if instructions indicate that color is relevant and size is irrelevant, subjects can partly ignore the size information. Shaffer (1965) developed the task cuing paradigm in which the tasks change randomly and each trial begins with a task cue telling which task to execute. Shaffer was also the first researcher who compared three conditions in the same experiment. These include a condition with a single task, and two conditions from the blocks that involved task switching: task-switch trials, in which the task has just switched, and *task-repetition trials*, in which the current task was the same as the previously executed task. This design allows one to separate two costs associated with switching tasks, later discussed by Braver et al. (2003); Fagot (1994), Kray and Lindenberger (2000), Koch et al. (2005), Los (1996), Meiran et al. (2000) and Rubin and Meiran (2005), among others. The first is "switch cost" and it refers to the difference between task-switch and task-repetition trials. The second is "mixing cost" and it refers to the cost associated with being in a situation involving potential switching. Mixing cost is defined as the performance difference between task-repetition trials (taken from blocks in which the tasks switch) and single-task blocks.

Task Switching Paradigms

Although researchers often refer to *the* task switching paradigm, there are, in fact, many different paradigms, and it still remains to be shown whether these paradigms tap the exact same abilities. This issue is particularly important for researchers who wish to incorporate task-switching into their studies as measures of cognitive flexibility. Based on the following sections, my advice is to use, if possible, more than one task-switching paradigm to ensure that one measures flexibility as opposed to task-specific processes. The currently used task-switching paradigms differ from one another in at least four respects: *(a)* the tasks; *(b)* whether the tasks involve a single step or multiple steps; *(c)* how the tasks are instructed; and *(d)* when they are instructed.

Task Differences

Task switching paradigms involve two or more tasks. In terms of responses, the tasks may require manual responses (often key presses, e.g., Rogers & Monsell, 1995), vocal responses (e.g., Allport et al., 1994; Jersild, 1927), or eye movements (e.g., Hunt & Klein, 2002). In terms of memory access, the tasks may require perceptual classification (such as color decision, e.g., Fagot, 1994; Hartley et al., 1990), semantic retrieval, as in making an odd–even judgment on digits or vowel–consonant judgment on letters (Rogers & Monsell, 1995), spatial location judgments (de Jong, 1995; Meiran, 1996; Shaffer, 1965), or episodic memory retrieval (Mayr & Kliegl, 2000). In terms of decision type, the tasks may require classification (e.g., Rogers & Monsell, 1995), odd-item out decisions (Mayr & Keele, 2000), or same–different judgments (Meiran & Marciano, 2002). Only a few studies have tried to examine how the choice of tasks influences task-switching performance. The few studies that looked into this issue found a remarkable degree of task specificity. For example, Yehene and Meiran (2007) showed that most of the reliable individual differences variance in switch costs is task specific (.64 to .85) and in another switch-related effect (the congruency effect, explained below), the entire reliable variance is task specific. Meiran et al. (2002) and Meiran and Marciano (2002) used the same stimuli with manual responses but using classification and same-different judgments, respectively. The results of the two studies differed substantially. Specifically, although preparation drastically reduced switch costs in classification tasks, it did not reduce the costs at all with same-different judgments. Hunt and Klein (2002) showed that switch costs were eliminated for eye movement responses, whereas they are not eliminated for key-press and vocal responses. Mayr and Kliegl (2000) showed that semantic memory tasks and episodic memory tasks produce very different switch cost profiles.

Single Step vs. Multistep Tasks

Although nearly all the studies studied single-step tasks, in which each task constitutes a single stimulus and a single response and S-R sequence, some studies focused on multistep tasks. Luria et al., (2006), Luria and Meiran (2003, 2006) and Schneider and Logan (2006) studied the effects of changing the order of tasks when the tasks themselves remain the same. Hayes et al. (1998) studied the influence of changing response sequence. Both of these changes incurred switch cost in spite of the fact that the subtasks were kept constant across the order switch. Namely, every trial required both color classification and letter classification, only in different orders.

Methods for Task Instruction

There are three principled methods to instruct subjects about the task change: from memory, by means of an instructional cue, or by the subjects' choice. Instruction method appears to have an important influence on the processes contributing to the observed switch costs (e.g., Altmann, 2007).

Instructions from Memory

Instruction from memory was the method chosen by Jersild (1927). In his experiments, subjects either executed each of two tasks (Task A and Task B) in isolation or alternated between them (ABAB…). Such a method requires keeping in memory the task sequence and monitoring the progress along that sequence (*see* Rubinstein et al., 2001). The method has been criticized on the basis of lacking a proper baseline. To remedy this problem, Rogers and Monsell (1995) introduced the *alternating runs paradigm*, in which subjects alternated between runs of trials involving the same task. When the run length is 1, the method is equivalent to Jersild's. When it is 2, the sequence is AA-BB-…, and so forth.

There are now additional techniques to instruct the tasks from memory. For example, subjects may receive a cue indicating the task sequence in the next two (Sohn & Carlson, 2000) or more trials (Gopher et al., 2000).

Capitalizing on the advantage of this technique, Gopher et al. showed that the initial slowing in the beginning of the run is found also for task repetitions, indicating a "restart cost" (*see also* Allport & Wylie, 2000). A similar approach was developed by Logan (2004) to assess working memory (WM) capacity for task sequences. Logan found that when subjects are asked to memorize a long series of tasks, they form task chunks that are analogous in many respects to the item chunks in short-term memory tasks (Miller, 1956). Moreover, Logan reported that the beginning of a "task-chunk" is indicated by response slowing. Subjects can also be told to SWITCH tasks or STAY on a task (Forstmann et al., 2005), so that the next task is based on their memory of the preceding task, or receive a cue in the beginning of a run of trials, forcing them to maintain the task goal in memory throughout the run (Altmann & Gray, 2002). Additionally, subjects may learn a task sequence implicitly, so that their performance is assisted by the (implicit) memory of the task sequence (e.g., Gotler et al., 2003; Heuer et al., 2001; Koch, 2001).

Instructions in Each Trial

The first author to have used this method was Shaffer (1965), as described already. The advantage of this method is that it enables tight control over task preparation time. This advantage has been used by Hartley et al. (1990), Meiran (1996), Shaffer (1965), and Sudevan and Taylor (1987) to study task preparation effects by varying the interval between the task instructions and the target stimulus. A methodological issue is that the task set adopted in the preceding trial decays over time (Allport et al., 1994; Meiran et al., 2000). Thus, task preparation time and the time allowed for the previous task set to decay are potentially confounded. Solutions to this problem were offered by Meiran (1996) and Meiran et al. (2000). Another problem is that task repetitions are associated with a repetition of the task cue, and this may contribute to switch effects. Solutions to this problem were developed by Arrington et al. (2007), Logan and Bundesen (2003), Mayr and Kliegl (2003), and Monsel and Mizon (2006). It is still debated whether the cue repetition effect is a purely perceptual phenomenon unrelated to task control (Logan & Bundesen, 2003; Schneider & Logan, 2005) or representing a component control process (Arrington et al., 2007; Mayr & Kliegl, 2003, *see also* Gade & Koch, 2007).

There are numerous studies comparing the alternating runs paradigm in which task instructions come from memory with the cuing paradigm described here. Rogers and Monsell (1995) looked at position in run effects. Specifically, they had runs of four trials (AAAA-BBBB-…) so that performance in the 1st through 4th positions could be compared. Their results used longer runs to show that the first trial in the run (which is the switch trial) is associated with poorer performance than the remaining trials in the run (repeat trials), which show similar level of performance. This "position-in-run" effect depends on the paradigm. When the tasks are ordered randomly and instructed by means of an external cue, position in run leads to response facilitation even for repeat trials (Meiran et al., 2000). Monsell et al. (2003), who made a direct comparison between these two techniques, suggested that the trend for speeding observed in the cuing paradigm results from a gradual increase in task commitment. In the alternating runs paradigm, in which the task order is known in advance, full commitment is achieved immediately.

Self-Selected Tasks

There are three procedures in which subjects choose which task to execute. In one procedure (Arrington & Logan, 2004, 2005), subjects are told to switch between tasks under the constraint that the number of task switches will be roughly equal to that of task repetitions. This procedure yields switch effects of usual size and apparently the difference relative to the experimenter-instructed approaches described above does not lie there (Mayr & Bell, 2006). It lies in the frequency in which subjects switch, for which the common finding shows that subjects prefer to stay on the task, and switch on less than 50% of the trials, contrary to instructions. Although it is tempting to interpret this tendency to stay on a task as reflecting autonomous choice, it in fact is affected by stimulus factors such as stimulus repetition (Mayr & Bell, 2006). Another approach was used by Forstmann et al. (2006), who gave their subjects more than just two tasks and instructed them to either STAY or SWITCH. Because there were more than two optional tasks to switch to, the switch condition involved a task choice. A recently introduced third method involves letting subjects to choose freely the task to execute without any constraint. The surprising finding is that nearly all the subjects choose to switch tasks even when switching is from an easy task to a more difficult one (Kessler et al., 2009).

Mental Sets and Task Sets

The concept of mental set has a long and perhaps notorious history in psychology. Gibson's (1941) classical review of the early works was highly critical of the concept and argued that it is poorly defined. A much improved definition of mental set is afforded by indices taken from the task switching paradigm. It should be kept in mind, however, that the greater precision came at the cost of a potential loss of generality, because what the task switching paradigm presumably involves is a "task set" which may be a narrower term than "mental set."

The term "task set" refers to the active mental representations that afford the chosen cognitive activity. As elaborated beautifully by Prinz (1997), even the simple RT task, that arguably is the simplest cognitive task, requires a task set. The task requires making a predetermined response (e.g., press a key) to any stimulus that is presented without making any judgment concerning the stimulus. According to Prinz, even this incredibly simple task requires the intention (or "task set") to make the required response, without which no response would be made.

What does a task set include? It includes *(a)* the goal state; *(b)* the selection of task- relevant information by attentional mechanisms, including the relevant stimulus information and the relevant feedback information; *(c)* activated task-relevant semantic information (e.g., when the task requires odd-even judgment, the relevant numerical information needs to be active); *(d)* activated response information, such as the readiness to respond with the right and the left hand, and what each response means in the context of the given task (e.g., "a right key press means 'odd' "); *(e)* the activated response rules, such as "if ODD, press LEFT;" *(f)* the order of actions and action interrelatedness information if the task is one involving multiple actions (e.g., Luria & Meiran, 2003, 2006; Schneider & Logan, 2006), and so forth. All these could be described system parameters that change when the task changes (Logan & Gordon, 2001; Meiran, 2000a; Meiran et al., 2008).

As a rule, when any of these parameters changes, responding is slowed. This has been shown for changes involving the stimulus dimension (Meiran & Marciano, 2002; Ward, 1982), decision rule (Allport et al., 1994; Schneider & Logan, 2007), response modality (Philipp & Koch, 2005), subtask order in multistep tasks (Luria & Meiran, 2003; Luria et al., 2006), a change in the meaning associated with a given key press (Brass et al., 2003; Meiran, 2000b; 2005; Meiran & Marciano, 2002), and so forth.

Once we know that a parameter change results in slowing we can begin asking, how are task sets mentally represented? One possibility is that task sets are represented in a unified format, which is analogous to a computer file that contains all the parameters and is retrieved as a unit. Alternatively, task sets may be viewed as *ad hoc* assemblies of parameters (distributed representation) that change asynchronously. There is no definitive answer to this question. One approach to answer this question is to compare conditions involving multiple parameter changes to conditions with a single parameter change. Some studies report that changing multiple parameters results in greater slowing as compared with changing a single parameter (e.g., Arrington et al., 2003; Steinhauser & R. Hübner, 2005; R. Hübner et al., 2001). Such a result suggests that each parameter change is associated with independent slowing—that slowing is additive. It implies that task sets have distributed representations (supporting positions like those of Logan & Gordon, 2001 and Meiran, 2000a). Other studies find that a change in two parameters results in equal slowing as a change in one parameter (e.g., Allport et al., 1994), a result that supports the unified representation idea. Hahn et al. (2003) and R. Hübner et al. (2001) observed additive slowing in some conditions but in other conditions a double parameter switch incurred as much slowing as did a single parameter switch. What seems to explain this discrepancy between the two sets of conditions is subjects' strategic tendency to form a unified representation. This choice of strategy is apparently made when the parameters are coupled in the experiment (a certain relevant stimulus dimension always went together with a specific judgment). I (Meiran, 2000b) looked at the time course of preparation as a function of the parameter change. In this study, it was shown that a change in the direction of attention to the relevant stimulus features occurred in anticipation of the target, but a change in the meaning of the responses occurred after or during response. This finding supports the distributed representation notion.

Regardless of these not yet fully resolved issues, most researchers seem to regard switch-related slowing as a marker for a mental set change. (The only notable exceptions are the theories of Logan & Bunsesen, 2003, and Schneider & Logan, 2005, and related empirical works). They disagree on whether the set change reflects goal-related "top-down" processes (e.g., Rogers & Monsell, 1995; Rubinstein et al., 2001), more reflexive "bottom-up" processes (e.g., Allport et al., 1994; Allport & Wylie, 2000) or a combination of both (Koch & Allport, 2006; Meiran, 1996, 2000a, 2000b; Meiran et al., 2000; Sohn & Anderson, 2001; Yeung & Monsell 2003b).

This dispute had and still has an immense influence on the field. I believe that the disagreement is more apparent than real. For example, those who argue that the control operating in task switching is reflexive still acknowledge the fact that performance on this paradigm involves cognitive control. In fact, their idea is that task sets persist beyond the time in which they were relevant (Allport et al., 1994) or get automatically retrieved by the stimuli to which they applied beforehand (Allport & Wylie, 2000). Similarly, those researchers who argue that the task-set change is goal-directed (e.g., Rogers & Monsell, 1995; Rubinstein et al., 2001) currently acknowledge the fact that task sets have inertia (*see* especially Yeung & Monsell, 2003a, 2003b), which may be regarded as a more passive form of control.

What Makes a Cognitive Task?

Perhaps a more basic question to ask before characterizing task sets is, "What makes a cognitive task?" Recent studies have shown that the definition of a cognitive task depends, to a large extent, on what subjects subjectively perceive to be a task. This answer is very much in line with the conclusions above that it is a change in the mental representation (of the task parameters) that results in slowing.

Support comes from studies on multi-step tasks, showing switch effects when the task pair changes (from, say "respond to color → respond to letter" to "respond to letter → respond to color"), but the tasks remain the same. Note that the perceptual grouping of the letter and color tasks into a task pair dictates switch effects and, hence, how the tasks are represented mentally (Lien & Ruthruff, 2004; Luria & Meiran, 2003, 2006). Corroborating evidence comes also from studies on single-step tasks showing that the same transition incurs a task switch cost when the instructions refer to tasks but not when they refer to individual stimulus–response pairings (Dreisbach et al., 2006, 2007). Finally, Yehene et al. (2005) reported a neurological case, AF, who was asked to perform a standard task switching paradigm involving SHAPE and SIZE tasks. This patient showed task mixing costs in spite of the fact that she had stopped switching and performed only the SIZE task. Similar effects were found in that study among a group of control participants who were instructed to be ready for a task switch upon a given instruction, which never occurred.

It has long been acknowledged that goals and tasks are arranged in hierarchies (e.g., the seminal paper by Norman & Shallice, 1986). Recent works using task-switching paradigms provide support for this position. This evidence comes from two sources. One is from studies in which the tasks involve multiple steps (Luria &

Meiran, 2003, 2006; Luria et al., 2006; Schneider & Logan, 2006). The other comes from studies involving switching between multiple tasks that form a hierarchy (Kleisorge & Heuer, 1999). The signature for hierarchical control in multi step size is the sequence initiation time, seen in slower responding in the first trial of the sequence (*see also* Logan, 2004). The signature of hierarchical control within a multi-layered task array is the propagation of the switch-signal in the hierarchy. This propagation results in a somewhat paradoxical phenomenon of easier switching when multiple task elements are switched (for detail, *see* Kleisorge & Heuer, 1999).

Processes

Once we have some grasp concerning what makes a task and what is a task set, we can proceed in asking what processes are involved in switching tasks and task sets (and, by extension, which processes contribute to mental rigidity and flexibility). Based on Ach's (2006/1910) conception, I divide the processes into two broad classes. The first class includes those processes that create the inner obstacle (and contribute to cognitive rigidity). The second class includes processes that ensure successful goal achievement (and contribute to cognitive flexibility). A similar hybrid account for task switching performance appears in many recent theories (e.g., Gilbert & Shallice, 2002; Koch & Allport, 2006; Meiran, 2000; Meiran et al., 2000; Meiran & Daichman, 2005; Sohn & Anderson, 2001; Sumner & Ahmed, 2006; Yeung & Monsell, 2003a, 2003b).

Inner Obstacles and Contributions to Rigidity

Task-Set Inertia

One process that enhances the inner obstacle is the inertia of the mental sets (Allport et al., 1994; *see* Sumner & Ahmed, 2006, for a discussion of the various potential forms of the task-set inertia). Presumably, tasks that demand more intensive control efforts form more durable memory traces, a fact that makes switching *away* from these tasks more difficult. For example, when subjects switch between tasks of unequal familiarity, such as color naming and word reading of Stroop stimuli, the less habitual task (color naming) requires a greater degree of top-down control (e.g., MacDonald et al., 2000, for evidence). Consequently, switching away to the easier task results in a seemingly paradoxical increase in the switch cost observed in the *easier* task, a phenomenon called "switch asymmetry". This phenomenon is also observed when bilingual subjects switch between a dominant and a nondominant language (Meuter & Allport, 1999). However, there are studies reporting the opposite, more intuitively predicted trend whereby switch costs are larger for the more difficult task (e.g., Rubintein et al., 2001). This latter finding is referred to as "reversed asymmetry." Yeung and Monsell (2003a) found switch asymmetry when there was a high degree of response conflict and reversed asymmetry with lower response conflict.

When switching from Task A to Task B, two control operations are required. One is to inhibit Task set A, which has become irrelevant. The other is to activate Task set B, which has become relevant. The task-set inertia process discussed above is usually interpreted as a carryover of *activation*. Another form of inner obstacle is lingering inhibition. Lingering inhibition has been studied in two paradigms. Mayr and Keele (2000) introduced the backward inhibition paradigm. According to them, task transition involves the suppression of the abandoned task, which enables one to go on to the next task in the sequence. Moreover, this task suppression tends to persist. Accordingly, they designed a three-task paradigm, with Tasks A, B, and C. This enabled them to compare two kinds of task sequences, both involving an immediate task switch. In one sequence, Task A was performed after having just been abandoned. This was the A → B → A sequence. In the control condition, Task A was performed after having been abandoned a longer time before, a C → B → A sequence. The major finding was that performance was poorer when the task had just been abandoned as compared to when it had been abandoned a longer time before. The effect was labeled "backward inhibition" and it has been replicated in a variety of paradigms since then (e.g., Arbuthnott & Frank, 2000; Schuch & Koch, 2003).

In the experiments of Masson et al. (2003), subjects reacted to pairs of stimuli. The first stimulus required naming in which color was written either an incompatible color word or a row of Xs. The second stimulus was verbal and required word reading. The results show that word reading was slowed when preceded by incompatible color naming as compared to neutral (Xs) color naming. A similar effect was found for other reading tasks as well. This result shows that when subjects executed the color naming response, they needed to block the word reading processing pathway. It also shows that this inhibition persisted beyond the time when it was needed, indicating task-set inertia.

Stimulus-Set Binding

Yet another form of inner obstacle is *stimulus-set binding*, according to which task sets bind with the stimuli on which the task was executed. Note that unlike the task-set inertia idea, assuming that the task set persists in an active state, the stimulus-set binding idea is that the set gets automatically retrieved when the stimuli are re-encountered. Potentially, this is a useful process because in most cases, stimuli consistently require a given task. However, rarely, a given stimulus might require a new task, making it likely that the wrong task set will be retrieved. Accordingly, switch costs are increased for stimuli that have been previously associated with the alternative task set (Allport & Wylie, 2000; Gilbert & Shallice, 2002; Waszak et al. , 2003).

Retroactive Adjustments

The final form of inner obstacle concerns the fine tuning of the control parameters that presumably takes place in order to continuously optimize performance in a given task. This process creates an inner obstacle because when there is a task switch from Task A to Task B, the cognitive system has just become better tuned to execute Task A, and this fine tuning impairs performance on the following Task B (Meiran, 1996, 2000a, 2000b). Essentially, this form of inner obstacle resembles (or may even be identical with) negative transfer effects discussed in the learning literature. It is well-documented that subjects may switch to a more cautious strategy after making an error or after encountering an error-prone condition (e.g., Brown et al., 2007; Goschke, 2000). Similarly, subjects pay more attention to a given stimulus aspect after that stimulus was relevant in the preceding trial (M. Hubener et al., 2004). In task switching, it appears that the adjustment applies mostly to the meaning associated with each key press. Specifically, in many task switching experiments, a given key press is associated with two meanings, one for each task. For example, in switching between COLOR and SHAPE, pressing the left key may indicate both CIRCLE and RED, depending on the task. Results suggest that the association between the given meaning (e.g., CIRCLE) and the key press (left key) is strengthened after executing the SHAPE task. As a result, there is a performance cost when the task switches and the left key is used to indicate the other meaning (RED) (Brass et al., 2003; Meiran, 2000a; Schuch & Koch, 2004).

Based on this rationale, one would predict that switch costs would be lessened if there were less opportunity for retroactive adjustment. Indeed, switch costs are actually eliminated when the pre-switch response is inhibited (e.g., Philipp et al. 2007; Schuch & Koch, 2003). Similarly, when the preswitch trial involves the erroneous execution of the wrong task, switch costs turn into switch gains, because what is nominally a task switch is actually a task repetition (Steinhauser & R. Hübner, 2006). Finally, one would predict that a greater degree of retroactive adjustment would result in enlarged switch costs. This prediction was borne out by Sumner and Ahmed (2006).

Conclusions

When people engage in a cognitive activity such as task execution, they adopt mental sets. These sets involve the needed operations but also the inhibition of the no longer needed processes. The sets are memory representations, and as such, they persist in time beyond the point in which they were relevant. Moreover, the sets are automatically retrieved when the target stimuli associated with them are re-presented. Finally, mental sets dictate the type of online fine tuning of the system that is normally enacted to ensure continuous improvement in performance. This fine tuning becomes counterproductive when the activity changes. All these factors form inner obstacles and are therefore causes for behavioral and cognitive rigidity. The role of the intentional control processes described in the following section is to combat the inner obstacles in order to ensure flexible and intentional processing.

Control Processes and Contributions to Flexibility

According to the present definition, a control process is any process that helps to overcome the inner obstacles in the service of flexible goal directed behavior. No assumption is made that control processes need to reflect the action of an autonomous agent or that control processes need to be conscious (e.g., *see* Gotler et al., 2003; Meiran et al., 2002, showing evidence for nonconscious control). Finally, no assumption is made that control processes are more endogenous than the processes contributing to the inner obstacle. Here, I refer to Rogers and Monsell's (1995) influential division of processes into "endogenous" (which according to them means "intentional") and "exogenous." In fact, some of the inner obstacles just described stem from within (from subjects' memories) and are, in that sense, "endogenous." Concomitantly, some control processes are invoked by an external stimulus, such as a task cue, and should therefore be regarded as "exogenous."

Three control processes feature a major role in the current literature on task switching. These include *(a)* deciding which task to execute and maintaining goal representation in memory; *(b)* inhibiting the alternative tasks and filtering out task irrelevant information; and *(c)* performance monitoring. I will discuss these processes in turn.

Task Decision and Goal Maintenance

Before executing a task, subjects must know what the required task is. The information regarding task identity may either be retrieved from memory (Logan, 2004; Rubinstein et al., 2001) or become available via the processing of a task cue. These processes have been described as "goal setting" (Rubinstein et al., 2001) or "task decision" (Fagot, 1994). An additional process is holding the task identity in some form of WM. Below, I review some supporting evidence.

The first is Jersild's (1927) task-cuing effect described in Historical Foundations (smaller switch costs when the tasks are cued), which indicates that the retrieval of the next goal affects performance. Rubinstein et al. (2001) further showed that the task-cuing effect is additive with (and hence, independent from) the effect of task complexity. This result led the authors to suggest two serially ordered executive processes: goal setting and task-rule implementation. Support for the idea that task goals are held in some WM comes from studies showing that loading this system impairs task-switching performance at least in some cases (Baddeley et al., 2001; Bryck & Mayr, 2005; Emerson & Miyake, 2003).

The second piece of evidence comes from Jersild (1927), who showed that when each task is associated with a distinct stimulus set, switching costs are absent. One could interpret this finding as evidence that when the stimulus sets are disjoint (and clearly distinguishable, *see* Sumner & Ahmed, 2006) there is no need to make a top-down task decision. The role of unambiguous stimulus-task association has been elegantly demonstrated by Allport et al. (1994, Experiment 4). In this study, the authors used disjoint (univalent) stimuli: groups of digits (e.g., 333) and Stroop stimuli (e.g., the word "RED" written in blue ink), each affording only one task in the given context. As found by Jersild, there were no switch costs. However, when the task performed on each subset of the stimuli changed (from counting the digits to saying the digit value, for example) switch costs were found. Note that the stimuli remained univalent even after the task change because each stimulus category was uniquely associated with one task. Arguably, the switch costs were caused by the created need to recall which exact task to execute on the given stimulus type.

Following Braver et al. (2003), Fagot (1994), and Los (1996), among others, Rubin and Meiran

(2005) distinguished between switching cost and mixing cost (*see* the description of Shaffer, 1965, in Historical Foundations). They showed that stimulus bivalence (whether the stimulus affords the competing task) affected mixing costs and not switching costs and suggested that, when the tasks change unpredictably, mixing costs represent mostly task decision difficulty. Bryck and Mayr (2005) provided additional evidence supporting this assumption.

Further evidence for task decision comes from the increase in RT with an increasing number of tasks (Biederman, 1973; Dixon, 1981; Dixon & Just, 1986; Meiran et al., 2002). Interestingly, all these studies found the effect in conditions with little time to prepare and not when subjects were given time to prepare, suggesting that the choice among the potential tasks is made in anticipation of the task. Similarly, RT was affected by explicit blockwide task expectancy (Dreisbach et al., 2002; Ruthruff et al., 2001; Sohn & Carlson, 2000) and by implicit task expectancy. The last form of expectancy is created in experiments in which subjects are led to believe that the task sequence is random, whereas in fact it consists of a repetitive pattern. Replacing the repetitive pattern by a new pattern resulted in response slowing. This result indicates that the subjects have learned the repetitive task pattern and made use of it. The effects of expectancy are equivalent for switch trials and task repetition trials (Gotler et al., 2003; Heuer et al., 2001; Koch, 2001; *see also* Koch, 2005), presumably because of the need to make a task decision in both cases in the absence of an instructed task sequence.

Although the studies, reviewed above, point to the importance of having a vivid WM representation of the task goal, Altmann and Gray (2002; 2008) show evidence that forgetting this goal may also be functional. Specifically, they were interested in the effect of the position in run on RT. A run is defined as a series of trials in which the task is repeated in a context in which tasks may switch. Specifically, the first position in the run is a switch trial, because the previous trial involved another task. All the remaining positions in the run involve task repetition. Altmann and Gray showed that RT slightly but consistently increased over the run. Based on this evidence and a formal model they argued that the “within-run slowing” is evidence for the forgetting of the goal that, according to them, is functional because it allows for the smooth encoding of the next goal. It should be pointed out that although the within-run slowing was replicated in Altmann's lab under a variety of conditions (e.g., Altmann, 2002), and a similar (albeit nonsignificant) trend was found by Rogers and Monsell (1995) among others, many other studies consistently find within-run speeding, especially when the task order is random (Meiran et al., 2000; Meiran & Marciano, 2002; Monsell et al., 2003; Sumner & Ahmed, 2006; *see also* Tornay & Milàn, 2001, for the same, albeit nonsignificant trend). A potential difference between the two types of studies is the presentation of a task cue in the beginning of the run (Altmann's studies) or in every trial (the remaining studies; *see* Altmann, 2002).

Inhibition

Task switching requires the interruption of one task in favor of the alternative task. The interruption aspect is likely inhibitory. The fact that task switching involves inhibition is supported by two pieces of evidence that were already reviewed, including Mayr and Keele's (2000) backward inhibition effect and Masson et al.'s (2003) effects concerning pathway inhibition.

Additional evidence for the involvement of inhibition in task switching comes from Logan and Burkell (1986), who studied inhibition within the framework of the stop-signal paradigm (Logan, 1994, for review). In the stop-signal paradigm subjects are first pretrained on a task to create a strong tendency to execute this task. Afterward, they are required to withhold task execution on a certain (low) proportion of the trials, and their inhibitory abilities are measured. The Logan-Burkel paradigm requires that instead of withholding responses (as in the standard stop-signal paradigm), subjects execute another task. In that respect, this paradigm resembles the task-switching paradigm. Logan and Burkel's results indicate that inhibition was less effective (and more demanding) in this stop-switch paradigm as compared to the standard stop-signal paradigm in which no task switching was required. Nonetheless, the difference was not large: about 40 milliseconds.

Finally, the fact that task switching involves inhibition is supported by three additional facts. One is the fact that the Stroop task, commonly taken as a measure of inhibition, and task switching activate similar regions in the prefrontal cortex, including the posterior lateral prefrontal cortex (Derfusss et al., 2005) and the anterior cingulate gyrus (Dosenbach et al., 2006). Second, switch costs show a substantial individual differences correlation with the ability to suppress dominant responses and ignore interference (Friedman & Miyake, 2004). Finally, Yeung et al. (2006; *see also* Wylie et al., 2004) asked subjects to switch between a color task and a face task, capitalizing on the distinct brain topography of these two tasks. Importantly, they showed that individual differences in switch costs were positively correlated with individual differences in the degree to which the currently irrelevant brain region was active. Namely, when performing the FACE task, for example, brain regions associated with the COLOR task were active, and the degree to which they were active determined the size of the behavioral switch costs observed in the FACE task. This evidence clearly associated switch costs with the failure to inhibit the irrelevant task. It should be mentioned that the contribution of inhibition to switch effects remains somewhat controversial (e.g., Lien et al., 2006).

Information Filtering

Although the term "inhibition" usually refers to the entire task, filtering refers to the selection of specific task related information such as word information when performing color naming (Masson et al., 2003). Hübner et al. (2004) additionally showed that information that was relevant for the task that has been executed in the preceding trial becomes inhibited after a task switch.

A well established finding in the task switching literature is the task-rule congruency effect, which indicates imperfect filtering of the information related to the currently irrelevant task. Sudevan and Taylor (1987) were the first ones to document this effect. They studied switching between two numerical classification tasks. They asked subjects to press the left key in response to odd numbers (in an odd-even classification) and in response to numbers higher than 5 (in a high-low classification). Right hand responses were required for even numbers and for numbers smaller than 5. As a consequence, there were numbers that required a left-key press in both tasks (e.g., "7," which is both ODD and HIGH). These are congruent targets. Other targets required different responses in each task. For example, "8" required a left-hand response in the High-Low task (because it is high) and a right-hand response in the odd–even task (because it is even). These were *incongruent* targets. More generally, congruency relates to whether the target stimulus requires the same response according to both rules. The fact that congruence effects are highly replicable indicates filtering failure. They show that the currently irrelevant task rule is operative and affects response choice. It should be mentioned here that Meiran and Daichman (2005) have recently suggested that the congruency effect found in errors represents the erroneous execution of the wrong task. In contrast, Meiran and Kessler (2008) show that the RT congruency effect reflects the activation of overlearned stimulus category codes.

Biederman's (1972) study, described in Historical Foundations, shows that subjects are only partly successful in filtering out information that is relevant for one task rule but is irrelevant for the task rule that is currently required. Additional evidence that information filtering is used for task control comes from studies comparing univalent stimuli with bivalent stimuli. These studies show smaller switch costs for univalent stimuli (e.g., Mayr, 2001; Meiran, 2000b). A similar role of information filtering has been noted with respect to the responses. When the responses used in the two (or more) tasks overlap, each response becomes associated with multiple meanings. For example, when switching between an ODD–EVEN task and a HIGH–LOW task, a given key press might be used to indicate ODD when the first task is required and HIGH when the second task is required. One way in which control could be achieved is by selectively attending to one response meaning and temporarily ignoring the other response meaning. To study this information filtering function, researchers compared univalent response setups (in which the responses for the two tasks are disjointed) with bivalent response setups (in which the responses for the two tasks overlap). Further evidence suggests that the link between the motor act and its symbolic meaning is adjusted by each task execution (Meiran, 2000b, Philipp et al., 2007) or even by the mere activation of the relevant response representation (R. Hübner & Druey, 2006).

Monitoring

By monitoring, I refer to ongoing recording of changes in control demands and consequent behavioral adjustments. A relevant piece of evidence is the increase in switch costs following incongruent trials (Goschke, 2000). Brown et al. (2007) have recently replicated and extended this finding. Importantly, their formal model attributes this change to monitoring effects. Indirect evidence for the involvement of monitoring comes from brain imaging studies in which the dorsal anterior cingulate gyrus is often implicated (especially Dosenbach et al., 2006), because this region is believed to involve monitoring in a variety of other paradigms (for review, Botvinick et al., 2001).

Preparation

I mention "preparation" here although it is a process that is not described at the same level of analysis as task decision, inhibition, and monitoring. Preparation reflects the changing in advance of any of those, plus additional, non switch-related task aspects, such as phasic alertness (Posner & Bois, 1971) and stimulus timing (Los & Van Der Heuvel, 2001; Meiran et al., 2000). In fact, evidence for anticipatory change has been found regarding task identity (Gade & Koch, 2007; Meiran & Daichman, 2005; Sohn & Anderson, 2001; Sohn & Carlson, 2000), the retrieval of the stimulus-response mapping from episodic memory (Mayr & Kliegl, 2000; *see also* Lien et al., 2005, A-L. Cohen et al., in press), the direction of attention to the relevant stimulus dimension (Meiran, 2000b), the blocking of irrelevant information (M. Hübner et al., 2004) and the order of sub-tasks making a multi-step task (Luria & Meiran, 2003, 2006; Luria et al., 2006).

This anticipatory preparation was considered to be a hallmark of executive functioning by some authors (Allport et al., 1994; Rogers & Monsell, 1995; Meiran, 1996). One surprising finding that keeps intriguing researchers is the persistence of switch cost even after ample preparation time. For example, Meiran and Chorev (2005) found that switch costs were only slightly and non-significantly smaller after 10 seconds of advance preparation as compared to 1.4 seconds. There are some notable exceptions to this rule, showing that switch costs can be eliminated by advance preparation. These include using nonoverlapping responses for the two tasks (Meiran, 2000b), switching between two eye-movement tasks: a pro-saccade task (orient towards the stimulus) and an anti-saccade task (orient away from the stimulus, Hunt & Klein, 2002), presenting the task cue only briefly (Verbruggen et al., 2007, but *see* Gotler & Meiran, 2001, for a different result with a similar procedure), and avoiding a response in the pre-switch trial (e.g., Schuch & Koch, 2003).

There are numerous hypotheses regarding the nature of this "residual switch cost". Most of these hypotheses share the idea that some, but not all of the task set is prepared in advance. The theories differ as to when the remaining preparation or adjustment is being made. Advance preparation theories suggest that preparation (if used) precedes task execution processes. Rogers and Monsell (1995), who were the first to show the residual switch cost, suggested that preparation is postponed until the target stimulus is presented ("stimulus-cued reconfiguration"). de Jong (2000, *see also* Nieuwenhuis & Monsell, 2002; Brown et al., 2006) argued that the participants prepare fully but do so only on a subportion of the trials. Lien et al. (2005), who observed preparation effects for some but not all the responses, argued that subjects prepare some response rules but not others.

Another idea is that the residual switch cost results from the persistent nature of the inner obstacles. Allport et al. (1994), for example, suggested that preparation barely affects the switch cost and the cost is mainly due to task set inertia. Mayr and Keele (2000; *see also* Arbuthnott & Frank, 2000; Schuch & Koch, 2003) suggested that the residual cost results from a carryover of task inhibition that took place in previous trials. I suggested that the residual cost is a form of negative transfer because of retroactive adjustment (Meiran 1996, 2000a, 2000b; *see* above).

Luria et al. (2006) contrasted these two accounts using multistep tasks that required subjects to make three responses to each stimulus according to the three dimensions of the stimulus. They found switch costs in the second response in the response triplet, suggesting that the task preparation was not completed after the stimulus was presented because it persisted beyond the first response. This result is incompatible with the postponed preparation idea of de Jong (2000) and Rogers and Monsell (1995) but is in line with the idea concerning a carryover of inner obstacles.

Conclusion

There are numerous processes that contribute to cognitive flexibility. They include the decision of which activity to execute, the vivid representation of goals, the inhibition of previous goals, and the filtering of no-longer relevant information. The goals are usually arranged in hierarchies so that more global goals (such as completing writing this chapter) are subdivided into smaller goals (such as completing writing this section). Flexible performance is ensured by online monitoring and consequent behavioral adjustments. Finally, many of these processes can be carried out in preparation for the activity. This preparation, although useful, is rarely complete, and in most circumstances, the inner obstacles influence (but do not dictate) behavior, at least until the first execution of the next task or activity.

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AQ1: Please provide year of publication for Reference Botvinick et al.
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