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# 14

## Intentional Reconfiguration and Involuntary Persistence in Task Set Switching

Thomas Goschke

**ABSTRACT** Switching between different tasks often increases response time compared to repeated performance of a task. This switch cost has been thought to reflect either an executive process of task set reconfiguration or proactive interference from competing task sets. This chapter tries to reconcile these views by showing that switch costs are influenced both by voluntary preparation and involuntary carry-over of inhibition and stimulus-response-bindings from the previous trial. Three experiments are reported in which participants switched between responding to the color and responding to the identity of letters. Switch costs were reduced when participants verbalized each task before the stimulus, compared to when they performed a verbal distractor task, suggesting that intention retrieval supported advance reconfiguration. Switch costs increased when the two stimulus dimensions activated incongruent responses and when task switches *followed* incongruent trials, indicating persisting activation of preceding task sets and persisting inhibition of irrelevant perceptual dimensions, S-R mappings, or both. Findings suggest that voluntary actions are not controlled by a unitary central executive, but emerge from the interaction of separable component processes, some maintaining intentions, others reconfiguring task sets. According to the proposed model, seemingly dysfunctional aspects of cognitive control are manifestations of adaptive mechanisms that have evolved to satisfy partially incompatible constraints on action control.

### 14.1 INTENTIONAL RECONFIGURATION AND COGNITIVE CONTROL

A remarkable property of willed action is its flexibility: by receiving an instruction or forming an intention, we can transiently couple almost any response to almost any stimulus or aspect of a stimulus, even when there are neither innate nor acquired connections between stimulus and response. For instance, if you, as a participant in a psychological experiment, are instructed to press a response key when the word "Green" is presented, or if you form the intention to lift your left index finger at the end of this sentence, your response dispositions are reconfigured such that your intended action is usually triggered by the stimulus condition specified in the instruction or intention. Although seemingly trivial, even such simple instances of voluntary action require that various processing systems be coordinated from moment to moment in novel ways, that new couplings between stimuli and action schemata be set into readiness, that skills be recombined into new behavioral sequences, and that a specific

mode of interaction between various processing systems be established. Following similar proposals, I will use the term *task set* to denote such transient configurations of response dispositions and processing modes, and the term *intentional reconfiguration* to denote the processes underlying the formation and change of task sets (cf. Allport, Styles, and Hsieh 1994; Kuhl 1996; Meiran 1996; Monsell 1996; Rogers and Monsell 1995). Whereas in everyday life, "task sets" may involve long-term goals whose realization lies hours, days, or even years in the future, in this chapter, I restrict my analysis to much simpler task sets, ones that consist of transient couplings of elementary stimulus features and immediate behavioral responses.

Although the problem of cognitive control was acknowledged early in cognitive psychology (cf. Neisser 1967), as evidenced by the influential distinction between automatic and controlled (or control) processes (e.g., Atkinson and Shiffrin 1968; Posner and Snyder 1975; Schneider and Shiffrin 1977), until recently there has been little systematic research on the mechanisms underlying intentional reconfiguration. Whereas sophisticated models have been developed to account for performance in tasks such as naming, categorizing, and visual search, the question of how the cognitive system is configured for a given task in the first place still represents what Monsell (1996) has aptly called the "heart of darkness" of cognitive psychology.

This chapter reports three new experiments that use task switching to investigate processes underlying intentional reconfiguration. After a brief review of theoretical controversies in the task-switching literature (see also Allport and Wylie, chap. 2, De Jong, chap. 15, and Meiran, chap. 16, this volume; Monsell 1996; Pashler, chap. 12, this volume), I will try to show that the switch cost observed when individuals alternate between different tasks is influenced both by active preparatory processes (in particular, retrieval of verbal task representations) and by involuntary processes (in particular, *persisting activation* of the previously relevant task set and *persisting inhibition* of previously task-irrelevant perceptual dimensions, S-R mappings, or both). Finally, I will outline a theoretical framework, according to which voluntary control is a multiple constraint satisfaction problem, which affords a dynamic balance between maintaining and switching intentions, and between inhibition of distracting information and continuous background monitoring (Goschke 1996, 1997; cf. Allport 1989; Brandtstädter, Wentura, and Rothermund, forthcoming; Kuhl, 1985, 2000)

## 14.2 TASK SWITCHING AS A TOOL FOR STUDYING VOLUNTARY CONTROL

The experimental investigation of intentional reconfiguration has recently received renewed attention in the study of task switching, intro-

duced as early as 1927 by Jersild, but seldom used (most notably by Spector and Biederman 1976) until recently (e.g., Allport, Styles, and Hsieh 1994; Allport and Wylie, chap. 2, De Jong, chap. 15, Keele and Rafal, chap. 28, this volume; Kluwe 1997; Mayr and Keele forthcoming; Meiran 1996, chap. 16, this volume; Rogers and Monsell 1995; Rubinstein, Meyer, and Evans forthcoming). The rationale of the method is to compare a condition or trials in which participants repeatedly perform the same task (for instance, subtracting 3 from successive digits in a list), with a condition or trials in which subjects have to alternate between different tasks (for instance, between subtracting 3 and adding 3 to successive digits in a list). Alternating between tasks usually results in a switch cost, that is, a prolonged response time compared to that for task repetition.

### **Task Switch Cost as a Manifestation of Proactive Interference**

At first sight, the time cost incurred by a task switch may be taken to reflect the time required for executive control processes that configure the cognitive system for the new task. However, Allport, Styles, and Hsieh (1994, 436) have suggested that the switch cost does not directly reflect the duration of a stagelike executive process, but rather is due to proactive interference from previously executed task sets—"task set inertia" (TSI). In their experiment 4, participants first performed a block where they read color words printed in conflicting colors, named the digit in a stimulus such as "3333," or alternated between the two tasks. In a subsequent block, they had to perform different tasks with the same stimuli (naming the print color and counting the number of digits). Whereas in the first block, switch costs dissipated almost completely across 8 runs of trials, at the beginning of the second block they were significantly greater than in the first block and remained significant throughout the block. The authors interpreted this as evidence that the stimulus-response mappings from the first block persisted for at least some minutes and interfered with the tasks in the second block (p. 436). From this and other findings, they concluded that switch costs "cannot be understood as the reflection of a discrete processing stage that must be completed before execution of the next S-R- task can begin. Rather, ... they appear to represent the additional time needed for the system to settle to a unique response decision (or response retrieval) *after* the next imperative stimulus has arrived" (p. 436; see Allport and Wylie, chap. 2, this volume, for further elaboration of this view).

### **Task Switch Cost as a Manifestation of Advance Reconfiguration**

That proactive interference influences switch costs does not exclude the possibility that there are endogenous executive processes as well, which may reconfigure processing systems before or after the stimulus.

Evidence for advance reconfiguration has been obtained by Rogers and Monsell (1995, exp. 3), who used an alternating-runs method in which two tasks were presented in a predictable sequence (AABB). The switch cost was reliably reduced when the response-stimulus interval (RSI) was increased from 150 to 1,200 msec, provided the RSI was constant throughout a block. Because the time for advance preparation was confounded with the temporal distance from the preceding response, one might suspect that fast decay of the previous task set was in part responsible for the switch cost reduction. This appears unlikely, however, because in their experiment 2, Rogers and Monsell found no reduction of the switch cost with a variable RSI. Nor can passive decay be easily reconciled with results reported by Meiran (1996), who presented subjects instructional cues before each stimulus and varied the response-cue interval and the cue-stimulus interval independently. The switch cost was reliably reduced when the cue-stimulus interval was increased from 216 to 1,716 msec, even when the RSI was held constant, which strongly suggests advance reconfiguration before the stimulus (see also De Jong, chap. 15, this volume; Rubinstein, Meyer, and Evans forthcoming).

### 14.3 OPEN QUESTIONS AND AIMS OF THE PRESENT STUDY

In the following sections, I defend the view that proactive interference and advance reconfiguration are not mutually incompatible explanations, but denote separable component processes influencing overall switch costs (see also Meiran 1996, chap. 16, this volume; Rogers and Monsell 1995; Rubinstein, Meyer, and Evans forthcoming). Three task-switching experiments were performed to elucidate processes underlying advance reconfiguration and to investigate the interaction of advance preparation and involuntary aftereffects of previous task sets. Three main issues were addressed and three corresponding hypotheses proposed.

#### **Hypothesis 1: Advance Reconfiguration and Intention Retrieval**

The first hypothesis states that an important component of advance reconfiguration is the retrieval of an abstract intention or task representation. It assumes that—at least in the case of nonautomatized actions—abstract intentions are preferentially represented in a verbal format, that is, in terms of self-instructions like “respond to the color” (cf. Goschke and Kuhl 1996; Kuhl and Kazén 1999). This assumption is consistent with the long-standing idea that the ability to represent intentions in a linguistic format and to generate self-instructions endogenously is an essential precondition for volitional self-control (Ach 1910; Luria 1961; Vygotski 1962). To test the task retrieval hypothesis in the following experiments, the length of the RSI was varied (14 versus 1,500 msec). Moreover, in conditions with the long RSI, participants either had to

overtly verbalize the next task before each stimulus, or they had to say task-irrelevant words during the RSI in order to prevent them from retrieving the next task. The task retrieval hypothesis predicts a reduction of the switch cost when subjects retrieve the next task before the stimulus, compared to conditions in which task retrieval before the stimulus is prevented because the RSI is too short or a distractor task must be performed during the RSI.

### **Hypothesis 2: Persisting Activation of Task Set**

The second hypothesis states that *persisting* activation of a previous task set can interfere with or facilitate a subsequent task switch, depending on whether it activates a response that is the same as or different from the response activated by the new task set. To test this hypothesis, task-relevant and -irrelevant stimulus dimensions were variously mapped to the same (congruent) or different (incongruent) responses. This manipulation allowed me to investigate possible interactions between advance reconfiguration and persisting task set activation, in particular, to determine whether proactive interference from a previous task set is suppressed when a new intention is retrieved.

### **Hypothesis 3: Persisting Inhibition of Task-Irrelevant Perceptual Dimensions or Stimulus-Response Mappings**

The third hypothesis concerns the role of inhibitory processes in task switching. When a task requires responding to a particular stimulus dimension such as form, color, or location, one important function of task sets is presumably to enhance the sensitivity of task-relevant perceptual processing modules (cf. Hommel, chap. 11, this volume; Meiran, chap. 16, this volume). When, however, task-irrelevant stimulus features activate incompatible competing responses, it may also be necessary to inhibit or selectively decouple from action irrelevant perceptual information (Houghton and Tipper 1994; see also Mayr and Keele forthcoming). The third hypothesis states that the degree of inhibition is adjusted depending on the amount of response conflict evoked by a stimulus. More specifically, if one conceives of response selection in terms of a constraint satisfaction process, to settle into a maximally coherent state, the system will tend to suppress irrelevant information that imposes incompatible constraints on the activation of response codes. By contrast, no inhibition will be triggered when a stimulus imposes compatible constraints (cf. Houghton and Tipper 1994).

Two forms of inhibition will be distinguished. First, inhibition may affect stimulus *feature values* (for instance, when the task is to respond to the identity of the letter A printed in red, the color red may be inhibited). Inhibition of feature values should show up in increased switch costs

when, on a subsequent trial, the stimulus feature to be responded to happens to have the same value as the task-irrelevant feature on the preceding trial, compared to switch trials on which a different feature value must be responded to (e.g., green). This form of inhibition is similar to the negative priming effect, that is, the increase in response time (RT) when one responds to a stimulus that was a distractor on the preceding trial (see Fox 1995; May, Kane, and Hasher 1995 for review). Second, inhibition may affect irrelevant stimulus *dimensions* (e.g., color) as a whole. According to hypothesis 3, dimensional inhibition should show up in longer RTs on task switch trials following incongruent than on those following congruent trials, whether or not specific feature values are repeated.

#### 14.4 EXPERIMENT 1

##### Participants

Twelve undergraduates from the University of Osnabrück participated in the experiment.

##### Apparatus

Stimulus presentation and reaction time measurement were controlled by an IBM-compatible PC; presentation was synchronized with the vertical retrace signal of the monitor.

##### Procedure

Stimuli were the uppercase letters *A*, *B*, *C*, and *D*, which could appear in the colors red, green, blue, or yellow. Participants were instructed to respond to the color or to the identity of the letters as fast and accurately as possible by pressing one of two response keys with their left and right index fingers. For half of the participants, the letter *A* and the color red were mapped to the left key ("y"), and the letter *B* and the color green were mapped to the right key ("-"), whereas the other half received the reverse mapping. The remaining colors and letters were not mapped to any responses and occurred only as values of the irrelevant stimulus dimension.

Each trial started with a 200 Hz tone lasting 50 msec. After a delay of 500 msec, a letter was presented at the center of the screen and remained there until the participant pressed one of the response keys. After an RSI of either 14 or 1,500 msec the second letter was presented and remained on the screen until the second response was made. After a delay of 1,500 msec, the next trial started.

There were four different types of blocks, each consisting of 144 such trial pairs. Before each block, participants were informed about the task to be performed throughout the block. There were two task repeat blocks, in which participants either had to respond only to the color (task repeat "color") or to the identity of the letters (task repeat "letter") throughout the block. In task switch blocks, they either had to respond to the color of the first letter and the identity of the second letter in each trial pair (task switch "color-letter"), or to the identity of the first letter and the color of the second letter (task switch "letter-color"). Each participant performed each of the four blocks with both the long and the short RSI. Both the order of the RSI conditions and the order of the four types of blocks within each RSI condition were counterbalanced.

In one-third of the trials of each block, the task-relevant and task-irrelevant stimulus dimensions were mapped to the same response (*congruent trials*); in one-third of the trials, the two stimulus dimensions required different responses (*incongruent trials*); and in one-third of the trials, the value of the task-irrelevant dimension was not mapped to any response (*neutral trials*). Within each experimental condition resulting from the orthogonal manipulation of task switch, RSI, and congruence, all possible combinations of colors and letters appeared equally often across subjects. For each combination of the experimental variables, half of the trial pairs required the same response to the two stimuli, and half involved a response switch.

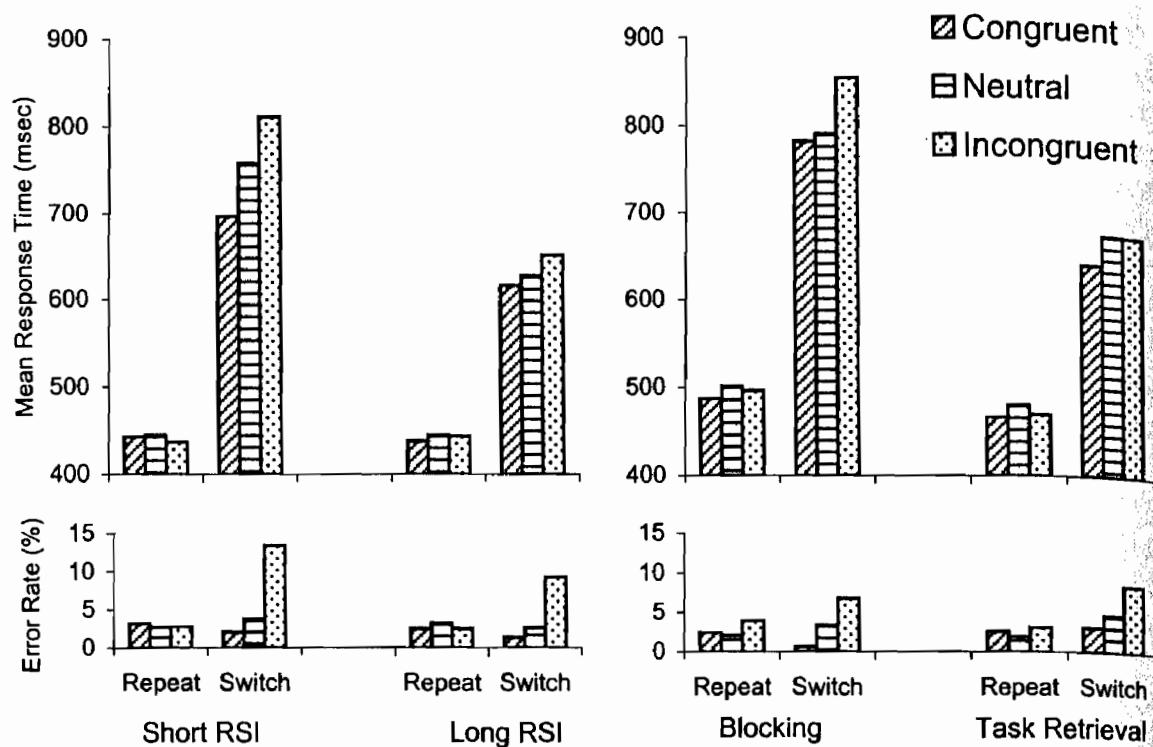
## Results

Reaction times (RTs) below 200 msec or more than 3 standard deviations above a participant's mean RT were discarded from the analyses (a stricter criterion for outliers did not substantively alter the results). Means of the remaining RTs for correct responses were computed for each participant and each experimental condition. Data from color-color and letter-letter trials were averaged to obtain mean RTs for task repeat trials, and trials from color-letter and letter-color trials were averaged to obtain mean RTs for switch trials.<sup>1</sup>

### Effects of Task Switch, Response-Stimulus Interval, and Congruence

Figure 14.1 (left panel) shows mean RT for correct responses (as well as error rates) on the second trial of each trial pair for the different experimental conditions. A  $2 \times 2 \times 3$  repeated-measure analysis of variance (ANOVA) with the independent variables task switch, RSI, and congruence yielded a reliable effect of task switch, indicating that mean RT was longer on task switch than on task repeat trials:  $F(1, 11) = 115.47$ ,  $p < 0.001$ . This main effect was qualified by a reliable interaction of task switch and RSI, indicating that the switch cost was markedly reduced





**Figure 14.1** Mean response time for congruent, incongruent, and neutral task switch and task repeat trials in the short- and long-RSI conditions of experiment 1 (left panel), and in the blocking and task retrieval groups of experiment 2 (right panel).

after the long versus the short RSI:  $F(1, 11) = 26.39, p < 0.001$ . Even after the long RSI, however, there was still a reliable residual switch cost:  $F(1, 11) = 199.68, p < 0.001$ .

There was also a reliable effect of congruence:  $F(2, 22) = 17.89, p < 0.001$ , which was qualified by a reliable interaction with task switch:  $F(2, 22) = 19.49, p < 0.001$ . Congruence had a reliable effect on RT on task switch trials:  $F(2, 22) = 20.25, p < 0.001$ ; but not on task repeat trials:  $F < 1.1, p = 0.35$ . Planned comparisons showed that RT on congruent, neutral, and incongruent nonswitch trials did not reliably differ from each other (all  $ps > 0.09$ ), whereas congruent switch trials produced shorter RTs than neutral and incongruent switch trials (both  $ps < 0.001$ ), and incongruent switch trials produced longer RTs than neutral trials ( $p < 0.03$ ). The two-way interactions described thus far were further qualified by a reliable three-way interaction between task switch, RSI, and congruence:  $F(2, 22) = 9.11, p < 0.001$ . This reflects the fact that the interaction between task switch and congruence was reliable only for the short RSI:  $F(2, 22) = 22.42, p < 0.001$ ; not for the long RSI:  $F(2, 22) = 2.71, p = 0.09$ . Thus the congruence effect on switch trials was strongly attenuated after the long RSI.

**Error Rates** Showing an analogous pattern, error rates increased on incongruent switch trials, especially after a short RSI. An ANOVA

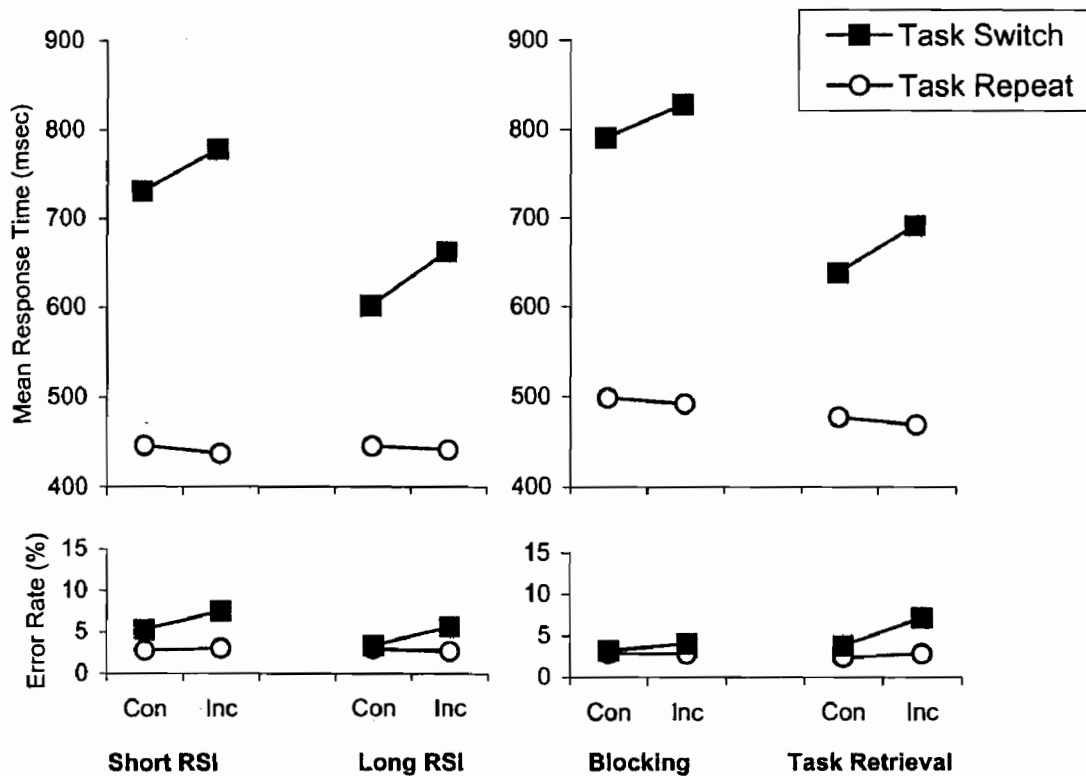


Figure 14.2 Mean response time for task switch (solid squares) and task repeat (circles) trials preceded by congruent (Con) and incongruent (Inc) trials in experiment 1 (left panel) and experiment 2 (right panel).

revealed reliable effects of task switch:  $F(1, 11) = 20.04, p < 0.001$ , congruence:  $F(2, 22) = 11.90, p < 0.001$ , and a reliable interaction of congruence and task switch:  $F(2, 22) = 18.06, p < 0.001$ .

**Effects of Congruence on the Preceding Trial** To investigate inhibition effects (hypothesis 3), all trial pairs were classified depending on whether the task-relevant dimension of the second stimulus had the same value as or a different value from that on the first trial (for instance, when color was task relevant on the second trial, trials were classified depending on whether the first and the second stimulus had the same or a different color). In addition, all trial pairs were classified depending on whether the first stimulus was congruent or incongruent. An ANOVA with the independent variables task switch, feature value repetition, previous congruence, and congruence on the second trial, and mean RT on the second trial as the dependent variable, yielded no evidence for feature-specific inhibition. The interaction of task switch and feature value repetition was not reliable:  $F(1, 11) = 2.41, p = 0.15$ . Mean RT for task switch trials on which participants responded to a feature value identical to the irrelevant feature value on the preceding trial was not longer than for switch trials in which the stimulus feature had changed (656 versus 668 msec).

There was, however, a highly reliable interaction of task switch and previous congruence:  $F(1, 11) = 24.08, p < 0.001$ . As can be seen in figure 14.2 (left panel), task switch trials following incongruent trials produced longer RTs (720 msec) than switch trials following congruent trials (666 msec):  $F(1, 11) = 20.73, p < 0.001$ . By contrast, mean RT on task repeat trials was slightly, though reliably *shorter* after incongruent than after congruent trials:  $F(1, 11) = 5.98, p < 0.04$ .

The analogous ANOVA for the error data yielded an almost reliable interaction of task switch and previous congruence:  $F(1, 11) = 4.47, p = 0.058$ , indicating that slightly more errors were made on task switch trials following incongruent trials than on those following congruent trials, whereas no such difference was present on task repeat trials.

Because incongruent first trials in task switch blocks produced longer RTs than did congruent trials (807 versus 721 msec), one might object that the effect merely reflects a tendency to produce slower responses following long RTs (RTs on first and second trials were indeed positively correlated:  $r = 0.24, p < 0.001$ ). To address this objection, an analysis of covariance was performed at the level of individual trials with RT on switch trials as the dependent variable and with RT on the first trial as the covariate. Although this analysis yielded a reliable effect of the covariate, the effect of previous congruence also remained highly reliable:  $F(1, 6,640) = 387.37, p < 0.001$ ; and  $F(1, 6,640) = 15.72, p < 0.001$ , respectively.

## Discussion

Experiment 1 yielded three main findings. First, the task switch cost was reliably reduced, albeit not eliminated, after a long (1,500 msec) versus a short (14 msec) RSI. One possible explanation for this effect is that participants in the long-RSI condition had the opportunity to retrieve the next task prior to the stimulus. A majority of participants in fact reported that they had covertly said the words "color" or "letter" at least on a portion of trials with the long RSI. This interpretation was tested more directly in experiment 2.

Second, there was a reliable congruence effect. Switch costs were reliably greater on incongruent than on neutral trials, whereas they were smaller on congruent than on neutral trials, which indicates that the task set from the previous trial persisted in a state of residual activation (at least after a short RSI). It is noteworthy that Rogers and Monsell (1995, expts. 1 and 3) also obtained greater switch costs in mixed blocks, when congruent and incongruent stimuli were presented, than in pure blocks containing only neutral stimuli. Although incongruent stimuli produced longer RTs and higher error rates than congruent stimuli on switch trials, both congruent and incongruent trials produced longer RTs and greater

switch costs than did neutral trials. The authors suggest that this may indicate that stimuli in mixed blocks not only activated an S-R-association defined by the recently performed task, but also evoked the complete competing task set, thus causing interference whether or not the irrelevant task set happened to trigger the same response as the relevant task set. Although not incompatible with this interpretation, the findings of my experiment 1 are evidence for more specific, trial-to-trial after-effects of recently activated task sets. Interestingly, in contrast to previous studies (e.g., Meiran 1996; Rogers and Monsell 1995), the congruence effect was almost completely attenuated after the long RSI, which may indicate that preparatory processes during the RSI helped to suppress the preceding task set. This possibility was further addressed in experiment 2.

Third, switch costs were reliably larger when task switches were preceded by incongruent versus congruent trials, whether or not task-relevant feature values were repeated. This effect did not reflect an unspecific slowing after long RTs, but was reliable even if response speed on the preceding trial was statistically controlled. Results are thus consistent with the interpretation that the task-irrelevant perceptual dimension was inhibited or selectively decoupled from the response system on incongruent trials. It is noteworthy that the persisting inhibition effect was not affected by the RSI. Inhibition of distracting perceptual information was obviously released only after the next imperative stimulus had been processed. Experiment 2 investigated whether inhibition persists until the next stimulus, even when task retrieval is explicitly induced.

#### 14.5 EXPERIMENT 2

In addition to the questions noted above, experiment 2 addressed two obvious objections against the interpretation of the RSI effects in experiment 1. First, both the reduction of the switch cost and the attenuation of the congruence effect after the long RSI might have been due, not to active preparation, but merely to rapid dissipation of the previous task set. Second, although it may seem plausible that task retrieval is an important component of advance preparation, the results of experiment 1 provided no direct evidence for this. However, hypothesis 1 predicts that there should be no reduction of the switch cost even after a long RSI if task retrieval is prevented prior to the stimulus. To test this prediction in experiment 2, only a long (1,500 msec) RSI was used, and participants had either to verbalize the next task before the stimulus, or to perform a verbal distractor task during the RSI. According to hypothesis 1, verbalizing the task should produce the same reduced switch cost as observed with the long RSI in experiment 1, whereas a distractor task that prevents task retrieval should yield a switch cost of about the same magnitude as after the short RSI in experiment 1. If, on the other hand, the decrease in

switch cost after a long RSI merely reflected passive decay of the previous task set, or if a previous task set is suppressed by *any* kind of intervening activity, there should be no differences between the task retrieval and blocking conditions.

### Participants and Apparatus

Sixteen undergraduates from the University of Osnabrück participated in the experiment, which used the same equipment as in experiment 1.

### Procedure

The procedure and response time analyses were the same as in experiment 1, with the following exceptions. Only the long RSI of 1,500 msec was used. Half of the participants were assigned at random to a *task retrieval* group; half were assigned to a *blocking* group. Participants in the task retrieval group were instructed to say either the word "color" or "letter" once during the interval between the warning signal and the first stimulus of each trial, and once during the RSI and prior to the second stimulus, depending on what the next task was. Participants in the blocking group were instructed to say one of two task-irrelevant words ("Monday" or "Tuesday") prior to each stimulus.

### Results

**Effects of Task Switch, Task Retrieval, and Congruence** Means of the RTs for correct responses served as the dependent variable in a  $2 \times 3 \times 2$  ANOVA with the independent variables: task switch, congruence, and group (task retrieval versus blocking). This analysis yielded a reliable effect of task switch:  $F(1, 14) = 80.89, p < 0.001$ ; and a reliable interaction of task switch and group:  $F(1, 14) = 4.73, p < 0.05$ . Mean RT was markedly longer in task switch than in task repeat blocks (see figure 14.1, right panel). Most important, the switch cost was reliably smaller in the task retrieval than in the blocking group, although there was still a reliable residual switch cost in the task retrieval group:  $F(1, 7) = 14.93, p < 0.01$ . Planned comparisons showed that there was no reliable difference between the blocking and task retrieval groups for task repeat trials ( $p > 0.40$ ), whereas RTs on task switch trials were reliably shorter in the task retrieval than in the blocking group:  $t(14) = 1.94, p < 0.05$  (one-tailed test).

There was also a reliable main effect of congruence:  $F(2, 28) = 15.48, p < 0.001$ , as well as a reliable interaction between task switch and congruence:  $F(2, 28) = 5.43, p < 0.01$ . In task repeat blocks, incongruent and neutral trials differed only by a nonreliable  $-8$  msec:  $t(15) = -1.64, p = 0.12$ ; mean RT was 14 msec shorter on congruent than on neutral

trials:  $t(15) = -4.23, p < 0.01$ . By contrast, in task switch blocks, mean RT was on average 31 msec longer on incongruent than on neutral trials:  $t(15) = 2.54, p = 0.03$ ; and RT was 22 msec shorter on congruent than on neutral trials:  $t(15) = -2.13, p = 0.05$ .

As can be seen in figure 14.1 (right panel), the effect of congruence on the switch cost was greater in the blocking than in the task retrieval group. A  $2 \times 3$  (group  $\times$  congruence) ANOVA, with RT on switch trials as the dependent variable, yielded a reliable interaction of the two variables:  $F(2, 28) = 4.51, p < 0.02$ . Whereas the effect of congruence was highly reliable in the blocking group, it was at best marginally reliable in the task retrieval group:  $F(2, 14) = 12.84, p < 0.001$  versus  $F(2, 14) = 3.57, p = 0.06$ . Analogous results were obtained when the switch cost served as the dependent variable: the effect of congruence was reliable in the blocking group, but not in the task retrieval group:  $F(2, 14) = 8.82, p < 0.01$  versus  $F(2, 14) = 1.48, p > 0.26$ .

**Error Rates** Corresponding analyses of error rates yielded reliable effects of task switch:  $F(1, 14) = 7.05, p < 0.02$ ; of congruence:  $F(2, 28) = 12.43, p < 0.001$ ; and a reliable interaction of congruence and task switch:  $F(2, 28) = 8.31, p < 0.001$ . Error rates increased on task switch trials, and this increase was more pronounced on incongruent trials.

**Effects of Congruence on the Preceding Trial** The data were further analyzed depending on whether the relevant stimulus dimension on the second trial had the same value as on the first trial or a different value, and depending on whether the first trial was congruent or incongruent (see figure 14.2, right panel). As in experiment 1, there was no evidence for inhibition on the level of specific feature values. Mean RT for task switch trials on which participants responded to a feature value identical to the irrelevant feature value on the preceding trial was virtually identical to mean RT for task switch trials on which the stimulus feature value had changed (739 versus 735 msec). There was, however, a reliable interaction of task switch and previous congruence:  $F(1, 14) = 15.72, p < 0.001$ . Whereas RT on task switch trials was reliably longer after incongruent trials than after congruent trials (759 versus 714 msec), mean RT on task repeat trials was slightly, but reliably *shorter* after incongruent than after congruent trials:  $F(1, 14) = 14.19, p < 0.002, F(1, 14) = 5.29; p < 0.04$ .

Because RTs produced by the first and the second stimuli of the trial pairs were positively correlated in task switch blocks ( $r = 0.33; p < 0.001$ ) the effect of previous congruence may again have been due merely to longer RTs on incongruent first trials. Although an analysis of covariance with RT on switch trials as the dependent variable and with RT on first trials as the covariate yielded a reliable effect of the covariate, the effect of previous congruence remained reliable:  $F(1, 4,193) = 488.10, p < 0.001$ ; and  $F(1, 4,193) = 4.19, p < 0.05$ , respectively.

**Error Rates** Corresponding analyses of error rates yielded no reliable results.

## Discussion

The results of experiment 2 replicate and extend the findings of experiment 1. When participants verbalized the next task before the stimulus, the switch cost was reliably smaller than in the blocking group, for whom task retrieval was interfered with by a verbal distractor task. In fact, the magnitude of the switch cost in the task retrieval group (192 msec) was almost identical to that in the long-RSI condition of experiment 1 (189 msec), whereas the switch cost in the blocking group (315 msec) was practically identical to that in the short (14 msec)-RSI condition of experiment 1 (313 msec), despite the long (1,500 msec) RSI.

There was again a reliable congruence effect, as indicated by greater switch costs on incongruent than on neutral or congruent trials. This effect was reliable only in the blocking group, but not in the task retrieval group, which speaks against an interpretation in terms of passive decay of the previous task set. The preceding task set neither decayed in a passive manner as a function of the length of the RSI, nor was it deactivated by an unrelated intervening activity; it was suppressed only by retrieval of a new intention.

Finally, switch costs were again reliably greater after incongruent than after congruent trials, whereas previous congruence had a small reverse effect on task repeat trials. This further supports the assumption that the task-irrelevant perceptual dimension was inhibited when it activated an incompatible response. It is noteworthy, that—in contrast to the congruence effect—the dimensional inhibition effect persisted even after the new task was retrieved.

**Dimensional Inhibition or Episodic Stimulus-response Binding?** Up to this point, I have interpreted the effect of previous congruence as evidence for inhibition of task-irrelevant perceptual dimensions (or the decoupling of perceptual dimensions from the response system). There is, however, an alternative interpretation that deserves consideration. With the two-choice reaction tasks used, it was inevitable that previous congruence was confounded with particular combinations of switches and repetitions of the response and the task-relevant stimulus feature. Consider the case in which the previous trial  $n - 1$  is congruent and both stimulus dimensions are mapped to the same response. On a following task switch trial  $n$ , either the task-relevant stimulus feature will have the same value as on trial  $n - 1$  and the response must be repeated, or both the stimulus feature and the response will switch. Consider now an incongruent trial  $n - 1$ , in which the two stimulus dimensions are mapped to different responses. When on a following task-switch trial  $n$  the rele-

**Table 14.1** Example of Different Stimulus Combinations on Two Successive Trials

			Trial $n - 1$ : Task = COLOR	
			Congruent Red <sub>L</sub> A <sub>L</sub>	Incongruent Red <sub>L</sub> B <sub>R</sub>
Trial $n$ : Task = LETTER	Con	Red <sub>L</sub> A <sub>L</sub>	S=R=	S≠R=
	Inc	Green <sub>R</sub> A <sub>L</sub>	S=R=	S≠R=
	Con	Green <sub>R</sub> B <sub>R</sub>	S≠R≠	S=R≠
	Inc	Red <sub>L</sub> B <sub>R</sub>	S≠R≠	S=R≠

*Note:* Stimuli are letters ( $A, B$ ) with different colors (green, red). The task on trial  $n - 1$  is to respond to the color, the task on trial  $n$  is to respond to the letter. Subscripts ( $L, R$ ) attached to stimulus values denote the response (left, right) associated with a given stimulus value. Symbols  $S =$  and  $S \neq$  denote whether the task-relevant stimulus value on trial  $n$  is or is not repeated from trial  $n - 1$ ; symbols  $R =$  and  $R \neq$  denote whether the response on trial  $n$  is or is not repeated from trial  $n - 1$ .

vant stimulus feature has the same value as on trial  $n - 1$ , it will require a response switch, whereas a switch of the stimulus feature will be accompanied by a response repetition (see table 14.1 for an illustration).

When RT on switch trials was analyzed, not in terms of previous congruence, but in terms of the orthogonal combination of stimulus feature switch and response switch, this yielded in both experiments a highly reliable interaction of the two variables:  $F(1, 11) = 20.73$ ;  $p < 0.001$ , for experiment 1;  $F(1, 14) = 14.19$ ;  $p < 0.002$ , for experiment 2. The effect of previous congruence may thus alternatively be explained in terms of *episodic bindings* of stimulus and response codes (cf. Hommel 1998, chap. 11, this volume). According to this explanation, task-relevant and -irrelevant stimulus features together with the current response will be encoded as an integrated episode. If the task-relevant feature on the following switch trial is repeated, the previous S-R configuration will be reevoked. This will facilitate the task switch when the same response is produced as on the preceding trial, whereas it will interfere with the production of a different response, which requires an unbinding of the previously established S-R configuration. If, on the other hand, the task-relevant stimulus feature is different from that on the preceding trial, this should facilitate a switch to a different response, one not previously bound to a different stimulus feature, whereas it should interfere with a repetition of the response, which again requires an unbinding of the previously established S-R episode (see Hommel 1998, chap. 11, this volume, for empirical evidence for automatic stimulus-response bindings).

### 14.6 EXPERIMENT 3

Experiment 3 was performed to unconfound previous congruence from the effect of particular stimulus-response bindings. This was achieved by using four-choice instead of two-choice reaction tasks, so that there could



be task switch trials preceded by congruent and incongruent trials, in both cases accompanied by a switch of the relevant stimulus feature and a switch of the response. If the effect of previous congruence is due to the confounding described above, it should disappear under these conditions.

### **Participants and Apparatus**

Sixteen undergraduates from the University of Osnabrück participated in the experiment, which used the same equipment as in experiment 1.

### **Procedure**

Participants had to respond to the color or identity of four uppercase letters (*A, B, C, D*), which could appear in four colors (red, green, blue, yellow), by pressing one out of four response keys on the computer keyboard ("y", "x", ":", "-"). In contrast to the experiments 1 and 2, the two tasks appeared in a computer-generated pseudorandom sequence of 500 trials. Each trial started with a blank screen for 250 msec, followed by an instructional cue (the word "color" or "letter") at the center of the screen. After a cue-stimulus interval of 1,500 msec, the imperative stimulus appeared and remained on the screen until a response was made. Half of the trials were task repeat trials; half required a task switch. After 250 trials, participants were given a brief rest. The first three trials after the break were not included in the data analyses. Prior to the main block, participants performed 40 practice trials to become familiar with the task and the S-R mapping.

### **Results and Discussion**

Trimmed mean RTs for correct responses were computed as in the previous experiments. The analyses included only those trials on which both the response and the value of the task-relevant stimulus dimension differed from the immediately preceding trial (there were too few data points to analyze other possible combinations). This selection did not result in any confoundings of previous congruence with some other variable. In particular, previous congruence and congruence on the current trial were orthogonal. A  $2 \times 2 \times 2$  ANOVA with the independent variables task switch, congruence on the current trial, and congruence on the preceding trial yielded a reliable effect of task switch, indicating that RT was longer on task switch than on task repeat trials (844 versus 815 msec):  $F(1, 15) = 4.63$ ;  $p < 0.05$ . The switch cost was smaller than in experiments 1 and 2, which presumably reflects beneficial effects of the instructional cues and the fact that the randomized presentation of tasks unfounded task switch from intention memory load, which may increase

switch costs in a blocked design (cf. Rogers and Monsell 1995). There was also a reliable effect of current congruence, indicating that RT was longer on incongruent trials than on congruent trials (870 versus 788 msec):  $F(1, 15) = 30.71, p < 0.001$ . Most important, there was a reliable interaction of task switch and previous congruence (no other main effects or interactions were reliable):  $F(1, 15) = 5.35, p < 0.04$ . RT was longer on task switch trials preceded by incongruent trials than on task switch trials preceded by congruent trials (866 versus 822 msec):  $F(1, 15) = 7.12, p < 0.02$ . By contrast, no such difference was present on task repeat trials (810 versus 819 msec):  $F < 1$ . Given that the two categories of trials were both accompanied by a response and a stimulus feature switch, this shows that the dimensional inhibition effect cannot be accounted for in terms of episodic S-R binding.

It should be noted, however, that there was also evidence suggesting an effect of episodic S-R binding. Task switch trials that required a response switch produced longer RT when accompanied by a stimulus feature repetition (889 msec) than when accompanied by a stimulus feature switch (866 msec), whereas task switches accompanied by a response repetition produced longer RT when the stimulus feature was switched (883 msec) than when it was repeated (843 msec). Although the interaction of response switch and stimulus feature switch was only marginally reliable:  $F(1, 15) = 3.63, p < 0.08$ , the present results suggest that dimensional inhibition and episodic S-R binding constitute separate influences on task switching.

**Error Rates** Corresponding analyses of error rates yielded a reliable interaction of current congruence and task switch:  $F(1, 15) = 16.28, p < 0.001$ . Error rates for congruent and incongruent trials were 1.5% versus 5.3% for task repeat trials and 5.3% versus 8.8% for task switch trials.

#### 14.7 GENERAL DISCUSSION: ACTION CONTROL AS A MULTIPLE CONSTRAINT SATISFACTION PROBLEM

The present results have shown that task switch costs are influenced by various separable processes, including advance preparation in the form of task retrieval, proactive interference from recently activated task sets, persisting inhibition of distracting perceptual dimensions, and episodic stimulus-response bindings. In discussing implications of these findings for the interaction of intentional and involuntary processes, this final section outlines a tentative theoretical framework according to which seemingly dysfunctional aspects of cognitive control, such as proactive interference, can be seen as manifestations of an adaptive design, evolved to cope with partially incompatible constraints in the control of action.

## On the Nature of Advance Reconfiguration

One aim of the present study was to provide evidence for advance reconfiguration in terms of retrieval of verbal task representations. The most serious objection against the present interpretation is that the reduction of the switch cost in the task retrieval group could merely have reflected fast dissipation of task set inertia. This objection deserves serious consideration, given that the time for advance preparation was confounded with the temporal distance from the previous response. But it is not easily reconciled with the complete absence of a switch cost reduction in the blocking group. Obviously, neither the length of the RSI nor the presence of an intervening task as such was responsible for the switch cost reduction, but rather the *content* of what was verbalized. This conclusion fits with other evidence against a passive decay account of the reduction of switch costs with a long RSI (Meiran 1996; Rogers and Monsell 1995). It is also consistent with the suggestion that the endogenous aspect of task switching consists in the deletion of old and insertion of new goals in a declarative working memory before activation of specific condition action rules (Rubinstein, Meyer, and Evans forthcoming; see also Kieras et al., chap. 30).

Given that the results demonstrate active preparation, one may further ask whether preparation actually consisted in the retrieval of a *verbal* task representation. One might argue that the distractor task in the blocking group need not have specifically interfered with retrieval of a verbal task representation, but may rather have impaired other, yet-to-be-specified nonverbal executive processes. This interpretation, however, raises the question of why such nonverbal executive processes were completely blocked by saying the words "Monday" and "Tuesday," while they were not at all impaired by saying the words "color" and "letter." Again, it was not that participants said *something* during the RSI, but whether they verbalized the next task, that accounts for the results.<sup>2</sup> Converging evidence for the role of verbal processes in task switching has recently been reported in a neuropsychological study (Mecklinger et al. 1999). Although patients with left-brain damage showed greater switch costs than patients with right-brain damage, this difference was exclusively due to a subgroup of left-brain-damaged patients suffering from central speech disorders, who showed disproportionately great switch costs. The authors suggest that articulatory processes may be important for suppressing interference from previously activated task sets, which fits nicely with the present finding that task retrieval attenuated the congruence effect.<sup>3</sup>

This brings us to why and how task retrieval facilitated task switching. At first sight, one might interpret the difference in the RT cost of a switch between the task retrieval group and the blocking group as a measure of the time it takes to retrieve a task representation, time that augments the

RT if task retrieval can only be initiated after the stimulus. On the other hand, as has been noted by Allport and Wylie (1999), the switch cost reduction caused by a process performed before the stimulus need not be a direct measure of the duration of that process, but may reflect additional *effects* of this process on subsequent response selection. Loading an intention into working memory presumably has a number of such effects, in particular (1) it may increase in an anticipatory way the sensitivity of task-relevant perceptual processing modules (cf. Corbetta et al. 1990; Cohen, Dunbar, and McClelland 1990; Posner and Peterson 1990; see also Meiran, chap. 16, this volume); (2) it may set specific stimulus-response connections into readiness; and (3) it may suppress representations of competing intentions.

### **Varieties of Involuntary Priming in Task Set Reconfiguration**

While the present results suggest that retrieval of an intention into working memory constitutes a strong top-down constraint for subsequent processing and response selection, they also demonstrated involuntary aftereffects of preceding task sets. These findings are consistent with other reports of involuntary priming in task switching (e.g., Allport and Wylie, chap. 2, this volume). Taken together, these findings suggest that competing task sets may influence response selection for a number of reasons, in particular, because they were recently activated, because they must be maintained in a state of readiness, or because they were consistently associated with the same stimuli in the past. It will be important in future research to investigate differences and commonalities between different sources of interference and cross talk. For instance, while slowly dissipating task set inertia effects may result from competing stimulus-task associations (Allport, Styles, and Hsieh 1994), much shorter-lived aftereffects of recently executed tasks as observed in the present experiments may reflect more transient changes in the activation level of task sets. In this respect it is also noteworthy that the present results showed that persisting task set activation was attenuated by task retrieval, whereas the inhibition (or decoupling from the response system) of task-irrelevant perceptual dimensions persisted even after task retrieval. Although this dissociation clearly needs to be replicated, it suggests that different kinds of facilitatory and inhibitory aftereffects of task sets differ in their resistance to top-down control (cf. Mayr and Keele forthcoming). It should be noted, however, that other studies have reported no reduction of congruence effects with an increasing opportunity for preparation (e.g., Meiran 1996; Rogers and Monsell 1995). At least with respect to experiment 2, this discrepancy may reflect the fact that in the present experiment subjects were forced to retrieve the next task before the stimulus on each trial; in other experiments, merely providing the opportunity to prepare may not have been sufficient to motivate subjects to pre-

pare on each trial (see De Jong, chap. 15, this volume). On the other hand, such an account cannot explain the reduction of the congruence effect in experiment 1, and further research is needed to clarify the discrepancy.

From a more general perspective, the foregoing conclusions are consistent with the view that automatic and controlled (intentional) processes do not constitute an either-or distinction. Rather than conceiving of automatic processes as necessarily triggered by a stimulus, and of controlled processes as directly initiated by conscious intentions, we should see intentions rather as constituting constraints that set the stage for later processing and that modulate the readiness of responses to be activated more or less "automatically" by subsequent stimuli (Cohen, Dunbar, and McClelland 1990; Exner 1873; Gollwitzer 1996; Goschke 1996, 1997; Hommel, chap. 11, this volume; Neumann 1984, 1987; Neumann and Prinz 1987). Thus intentions modulate or "configure" automatic processes for voluntary action, whereas the selection of responses, though dependent on prior intentions, is influenced by various forms of involuntary priming.

### **Control Dilemmas and Adaptive Constraints: Toward a Functional Analysis of Action Control**

In a sense, the present results may appear to reveal the suboptimal design of the cognitive system. Humans neither switch between tasks without a cost nor inhibit competing intentions efficiently, but are obviously prone to various kinds of interference from irrelevant information or competing task sets. I propose, however, that these seemingly dysfunctional features are manifestations of an adaptive design and reflect competing mechanisms, which have evolved to satisfy partially incompatible constraints on intelligent action. I have described these constraints as "control dilemmas" (Goschke 1996, 1997, 1998; see also Kuhl 2000 for a related view) and will briefly relate some of them to the problem of task switching.

**The Selection-Orienting Dilemma** On the one hand, an acting organism should select intention-relevant information to specify parameters of immediate action and should inhibit irrelevant information to avoid cross talk (Allport 1989). On the other, the organism should continuously monitor the environment for potentially significant information, even if this information is not directly relevant for the ongoing action. For this reason, it would not be adaptive if attentional selection operated so efficiently as to suppress irrelevant information completely (cf. Allport 1989; Houghton and Tipper 1994). Ignored information should be processed to a level at which threats or affordances relevant for higher-level goals or vital needs can be recognized (e.g., the smell of fire while working on an important paper). Thus what is considered interference and cross talk in the light of the current intention is a necessary by-product of continuous

*background monitoring* and thus a precondition for flexible reorientation (Goschke 1996, 1997; cf. Allport 1989; Dibbelt 1996; Brandtstädter, Wentura, and Rothermund forthcoming; Kuhl and Goschke 1994).

**The Persistence-Interruption Dilemma** On the one hand, the system should shield a current intention against competing intentions and motivational tendencies in order to persist in pursuing long-term goals (Kuhl 1985). On the other, an organism must be able to interrupt an ongoing action and to switch to a different action if necessary. Indeed, animals incapable of responding to the sudden appearance of, say, a predator with a fast switch from the ongoing activity (e.g., eating) to a very different behavior (e.g., flight) are most probably not numbered among our evolutionary ancestors. From this perspective, task set inertia and the related finding that uncompleted intentions persist automatically in a state of high activation in long-term memory (Goschke and Kuhl 1993, 1996) may be manifestations of an inherent tendency of intentions to persist in the face of distractions. Although this persistence promotes the realization of a selected intention, it incurs a cost when fast and flexible switching is required.

**The Stability-Flexibility Dilemma** On the one hand, the system should incrementally strengthen fixed stimulus-response and stimulus-task associations in order to respond to invariant or recurrent situations with well-established habits (Goschke 1998). On the other, the system should be able to flexibly reconfigure response dispositions from moment to moment. From this perspective, long-lasting task set inertia effects after prolonged performance of competing tasks, as observed by Allport, Styles, and Hsieh (1994), may reflect the formation of relatively stable stimulus-task associations. Although such associations will allow for efficient responding under invariant conditions, they will interfere when reconfiguration of response dispositions is required.

It is beyond the scope of this chapter to describe these dilemmas in greater detail. Suffice it to say that the foregoing analysis supports a view of action control as an optimization problem, which requires a dynamic, context-sensitive balance between competing constraints (Goschke 1996, 1997; cf. Allport 1989; Brandtstädter, Wentura, and Rothermund forthcoming; Kuhl 2000; Kuhl and Goschke 1994). Insofar as these constraints pose functionally incompatible demands, they presumably promoted the evolution of a functional architecture in which different control operations are subserved by separable competing and cooperating subsystems (Baars 1988; Goschke 1996; Hayes-Roth 1985; Kieras et al., chap. 30, this volume), as opposed to being controlled top-down by a unitary central executive (central processor, intention system, or operating system). Although admittedly speculative, this account receives support from recent neuropsychological and brain-imaging studies suggesting that the

prefrontal cortex, long considered to be the anatomical locus of executive control, appears to exhibit an unanticipated degree of functional specialization (for reviews, see Della Sala and Logie 1993; Fuster 1989; Goldman-Rakic 1995; McCarthy and Warrington 1990; Robbins 1998; Roland 1984; Shallice and Burgess 1998). Although our knowledge about the neurocognitive systems underlying cognitive control is still very restricted, a functional analysis of adaptive constraints on action control may serve as a fruitful framework for further experimental explorations.

## NOTES

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1. Responses to the first stimulus of each trial pair showed a pattern of results similar to responses to the second stimulus. Because, however, reaction times to the first stimuli are uninformative concerning the effect of the response-stimulus interval, I will report results only for second responses.

2. This is not to say that *overt* verbalization is crucial; covert task retrieval should produce similar effects. In addition, it should be noted that, while the present results show that retrieval of a verbal task representation is sufficient to facilitate preparation for the next task, it is an open question whether verbal task retrieval is also *necessary* for intentional reconfiguration.

3. It may be asked why a reliable residual switch cost was observed in the task retrieval group. One possibility is that the blocked presentation of task switch and repeat trials confounded task switching with the number of stimulus-response mappings in working memory (Rogers and Monsell 1995). Consistent with this possibility, in experiment 3, where switch and repeat trials were intermixed, the residual switch cost was much smaller. A second possibility is that further reconfiguration processes (for instance, the activation of specific condition action rules) can only be completed after the imperative stimulus (cf. Rogers and Monsell 1995), or that participants do not initiate these processes before the stimulus due to a lack of motivation (De Jong, chap. 15, this volume).

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