
THEORETICAL AND REVIEW ARTICLES

The role of inhibition in task switching: A review

IRING KOCH

*RWTH Aachen, Aachen, Germany
and Max Planck Institute for Human Cognitive and Brain Sciences, Leipzig, Germany*

MIRIAM GADE

*Max Planck Institute for Human Cognitive and Brain Sciences, Leipzig, Germany
and University of Zürich, Zürich, Switzerland*

STEFANIE SCHUCH

RWTH Aachen, Aachen, Germany

AND

ANDREA M. PHILIPP

*RWTH Aachen, Aachen, Germany
and Max Planck Institute for Human Cognitive and Brain Sciences, Leipzig, Germany*

The concept of inhibition plays a major role in cognitive psychology. In the present article, we review the evidence for the inhibition of task sets. In the first part, we critically discuss empirical findings of task inhibition from studies that applied variants of the task-switching methodology and argue that most of these findings—such as switch cost asymmetries—are ambiguous. In the second part, we focus on $n-2$ task-repetition costs, which currently constitute the most convincing evidence for inhibition of task sets. $n-2$ repetition costs refer to the performance impairment in sequences of the ABA type relative to CBA, which can be interpreted in terms of persisting inhibition of previously abandoned tasks. The available evidence suggests that inhibition is primarily triggered by conflict at selection of stimulus attributes and at the response level.

Inhibition is a fundamental psychological concept with a venerable history (see, e.g., Smith, 1992). The concept of inhibition plays a central role in many areas of psychological research, such as developmental psychology (e.g., Davidson, Amso, Anderson, & Diamond, 2006; Kramer & Madden, 2008), child psychiatry (e.g., Barkley, 1997; Nigg, 2001), and clinical research on personality and psychopathology (e.g., Nigg, 2000). In cognitive psychology, inhibition has been hypothesized to play a major role in many areas, such as memory (e.g., Levy & Anderson, 2002) and attention (e.g., Johnson & Proctor, 2004).

The concept of inhibition has been invoked for explaining a variety of attentional and perceptual-motor phenomena. For example, the observation that performance in visual detection tasks is worse at cued locations when the cue-target interval is long as compared with when it is short has been attributed to “inhibition of return” of visual attention to locations that have just been attended very recently (see, e.g., Klein, 2000; Posner & Cohen, 1984). Likewise, the instructed stopping of a prepared response that can be observed in variants of the no-go or stop-signal paradigm has been

attributed to a process of response inhibition (e.g., Logan, 1994; Verbruggen & Logan, 2009). Moreover, the phenomenon of negative priming (e.g., Neill, 1997, 2007; Tipper, 1985), which denotes worse performance when attending to previously ignored stimuli as compared with new stimuli, has been attributed to a process of persisting inhibition of distractor stimuli (e.g., Tipper, 2001). Furthermore, some phenomena in sequential motor performance have been attributed to the inhibition of just executed responses (e.g., Dell, Burger, & Svec, 1997; Houghton & Tipper, 1996).

However, although explanations in terms of inhibitory mechanisms are plausible for these phenomena, it has been argued that there may be alternative, noninhibitory accounts that view the observed empirical phenomena as interference effects, which can have many different causes (e.g., MacLeod, Dodd, Sheard, Wilson, & Bibi, 2003; Neill, 2007; Tipper, 2001). Therefore, it is important to critically review the existing empirical evidence before a contribution of inhibition can be inferred.

In the present article, we will provide a review of recent evidence on task inhibition. To enable an assessment of

task inhibition, variable task contexts are required, which can be introduced using variants of the task-switching methodology (for reviews, see Meiran, in press; Monsell, 2003). Task switching represents a major research topic in current cognitive psychology, and several theoretical accounts invoke inhibition as an explanatory concept. Particularly, it has been argued that there must be a mechanism that reduces activation of the current task representation in order to enable the cognitive system to switch to a different task. This deactivation of task representations could possibly take place in the form of rather unspecific activation decay (e.g., Altmann & Gray, 2008; Horoufchin, Philipp, & Koch, 2009, for a discussion) or in the form of inhibition, which is presumably a faster process that is triggered by some specific event (e.g., Mayr & Keele, 2000).

In this review article, we will first describe “switch costs” as a basic interference effect in task switching, and we will review theoretical accounts that refer to task inhibition. Then, we will critically discuss the validity of empirical phenomena with respect to inhibitory accounts. In particular, we will review evidence on $n-2$ task-repetition costs, which is a phenomenon that suggests persisting inhibition of the previously abandoned tasks. We will then discuss theoretical frameworks with particular reference to an account suggesting that task inhibition is mainly triggered by response conflict.

The Role of Inhibition in Task Switching

The study of task switching has become one of the major research tools in studying the dynamic and flexible control of task sets. A task set is typically assumed to include a representation of a task goal (e.g., attend to stimulus color), a set of task-relevant stimuli (e.g., red and blue), a set of possible responses (e.g., press a left or a right key), and a mapping of stimuli—or stimulus categories—to responses (see, e.g., Monsell, 1996). In typical task-switching studies, participants switch between two tasks. For example, subjects might switch between a color discrimination task and a word-reading task, in which the words RED and BLUE can appear in red or blue colors, respectively, and are mapped onto left and right response keys. Word reading is the more dominant task, as demonstrated by the Stroop effect (e.g., MacLeod & MacDonald, 2000; Stroop, 1935); subjects need to rely on a strong task set when they are required to respond to stimulus color. That is, when subjects switch between color naming and word reading, they need to switch between competing task sets (e.g., Allport, Styles, & Hsieh, 1994; Gilbert & Shallice, 2002; Masson, Bub, Woodward, & Chan, 2003).

In the following subsections, we will first discuss switch costs and review theoretical accounts that propose a role of inhibition in task switching. Then, we will critically discuss several empirical phenomena with respect to whether they do or do not support inhibitory accounts of task switching.

Switch costs. The basic phenomenon in task switching is called *switch cost*, which is the typically observed drop in performance (i.e., higher reaction times [RTs] and

error rates) in task switches relative to that in task repetitions (see, e.g., Allport et al., 1994; Jersild, 1927; Rogers & Monsell, 1995; Spector & Biederman, 1976). Switch costs have also been found in studies of language switching (see Kroll, Bobba, Misrab, & Guoc, 2008; Meuter, 2005, for reviews). Generally, switch costs have been observed with numerous combinations of tasks and represent a highly robust empirical phenomenon (see Meiran, in press; Monsell, 2003, for reviews).

There are many theoretical accounts of switch costs, and some of them do not refer to inhibitory mechanisms (see, e.g., Altmann & Gray, 2008; Meiran, 2000a; Schneider & Logan, 2005; Yeung & Monsell, 2003b), but some of these authors concede a likely contribution of inhibitory processes to task switching. For example, Yeung and Monsell (2003b) argued that “it is likely that a complete model of task switching will need to incorporate inhibitory effects” (p. 468). In fact, in a review of task switching, Monsell (2003) proposed that switch costs “result from both transient and long-term carry-over of ‘task-set’ activation and inhibition as well as time consumed by task-set reconfiguration processes” (p. 134). Reviewing the existing accounts of switch costs in detail would be beyond the scope of this article. Instead, we will focus on those accounts that include inhibition as a central explanatory construct.

In their “task set inertia” account, Allport and colleagues (Allport et al., 1994) suggested that switch costs arise from proactive interference resulting from having previously performed a competing task (see also Yeung, Nystrom, Aronson, & Cohen, 2006). According to Allport and Wylie (1999), the nature of this proactive interference can be specified as “continued priming of the previous task (competitor priming) and suppression (negative priming) of the currently intended task” (p. 293). Thus, inhibitory processes (i.e., “suppression”) could contribute to switch costs in a simple way. Suppose that, when performing a task, the tendency to perform a competing task needs to be suppressed, and this occurs by inhibiting the corresponding task set. Presumably, the inhibition of an irrelevant task set persists over time, so that it is more difficult to perform this task when it becomes relevant again. Thus, persisting inhibition could produce “inertia” on the level of task sets (Allport et al., 1994; Allport & Wylie, 1999).

A similar contribution of inhibitory processes in task switching has been proposed by a variety of authors (see, e.g., Arbuthnott, 2005; Goschke, 2000; Masson et al., 2003; Mayr & Keele, 2000; Philipp, Kalinich, Koch, & Schubotz, 2008; Schuch & Koch, 2003). For example, Goschke (2000) suggested that “the degree of inhibition is adjusted depending on the amount of response conflict evoked by a stimulus” (p. 335). Also, some computational models of task switching encompass inhibitory mechanisms. For example, the parallel distributed processing model of Gilbert and Shallice (2002) proposes lateral inhibition of “task demand units” to reduce or prevent the simultaneous activation of two competing task sets. Likewise, the more recent model of Brown, Reynolds, and Braver (2007) included a mechanism that detects task

conflicts “when the new task set representation becomes active *and the previous one has not yet been deactivated by lateral inhibition*” (p. 54, emphasis added).

However, because it has been argued that many seemingly inhibitory phenomena in attention research are equally well explained by noninhibitory accounts (MacLeod et al., 2003), the same appears to be the case with respect to switch costs. That is, persisting activation accounts (see, e.g., Altmann & Gray, 2008; Yeung & Monsell, 2003b) could explain switch costs just as well as could persisting inhibition accounts, so that it is important for one to critically review the empirical findings with respect to whether they provide unambiguous support for a role of inhibitory processes in task switching. In the next subsections, we will discuss two important empirical findings: switch-cost asymmetries and the effects of $n-1$ congruence on switch costs.

Switch-cost asymmetries. A prominent phenomenon in task switching is the observation of a switch-cost asymmetry. Allport et al. (1994) observed that switch costs are higher when participants switch to the stronger, more dominant task of a pair of tasks. For instance, when participants switch between word reading and color naming using incongruent color–word Stroop stimuli (e.g., the word “red” printed in blue color), switch costs are higher for word reading than for color naming. Such switch-cost asymmetries have been observed with different types of stimuli and responses (see, e.g., Arbuthnott, 2008a; Koch, Prinz, & Allport, 2005; Monsell, Yeung, & Azuma, 2000; Yeung & Monsell, 2003a, 2003b). Switch-cost asymmetries have been observed also in the context of language-switching studies. These studies typically report greater switch costs when switching into the first, more dominant language than for switching to the second language (e.g., Campbell, 2005; Costa & Santesteban, 2004; Costa, Santesteban, & Ivanova, 2006; Finkbeiner, Almeida, Janssen, & Caramazza, 2006; Meuter & Allport, 1999; Philipp, Gade, & Koch, 2007).

To account for such switch-cost asymmetries, one needs to combine the task-set inertia idea of Allport et al. (1994) with the idea that the degree of task control is adjusted in a context-sensitive way (Goschke, 2000; Yeung & Monsell, 2003b). Thus, when performing the weaker of two tasks—for example, color naming with incongruent Stroop stimuli—the dominant word-reading task is a very strong competitor and needs to be inhibited. In contrast, when performing the word-reading task, the inhibition of color naming is hardly required because color naming is the less dominant task anyway. If that scenario is true, then the relative difference in the carryover of inhibition can easily explain higher switch costs when returning to the more dominant task, because this task has been the stronger competitor and thus suffers from more residual inhibition. Similar accounts are also discussed in language switching (see Kroll et al., 2008, for a review; Meuter & Allport, 1999; Philipp, Gade, & Koch, 2007; Philipp & Koch, 2009).

However, Monsell et al. (2000) argued that sometimes reversed switch-cost asymmetries can be observed, which appears to be difficult to reconcile with the inhibitory ac-

count. In fact, the switch-cost asymmetry could be explained without invoking a specific inhibitory process that targets competing task sets or languages. To account for asymmetrical switch costs, Yeung and Monsell (2003b) proposed a model that has “task priming” as the core concept. In the model, task priming interacts with both task strength and the current control input. Task priming represents the aftereffects of previous task performance, and task strength is modeled as the baseline level of activation of a particular task. Importantly, task priming is asymmetrical in pairs of tasks with different strength, with priming being proportionally larger following performance of the weak task than following the strong task, because the weak task has a lower baseline activation. Active control processes serve to increase the activation of the currently relevant task set in order to ensure that this task is actually performed. Additionally, the authors assumed that control is dynamically adjusted to the level of task interference (e.g., Brown et al., 2007; Goschke, 2000). Task interference is highest when switching to the weak task, but because of strong task priming, this interference is greatly reduced in a task repetition, calling for less control input, which in turn reduces the repetition benefit of the weak task relative to that of the stronger task. That is, Yeung and Monsell (2003b) modeled the switch-cost asymmetry as a priming-based modulation of task-repetition benefits. More importantly, however, they conceived of priming as the persistence of increased activation (i.e., positive priming). Persisting inhibition is not needed to explain switch-cost asymmetries in this account, even though the authors conceded that it would be easy to reformulate their model in order for it to include inhibitory control.

As we have seen, the issue of whether switch-cost asymmetries require the theoretical assumption of task inhibition is difficult to resolve empirically. Yet, the notion of inhibition is highly pertinent in research on bilingual control, in which switch-cost asymmetries are discussed as a hallmark of inhibitory control of the mental lexicon (see, e.g., Costa & Santesteban, 2004; Meuter & Allport, 1999; and Philipp & Koch, 2009, for a discussion). Therefore, it is important for one to acknowledge that switch-cost asymmetries do not necessarily imply inhibition. Since inhibitory accounts of task switching are not unequivocally supported by these findings, it is important to look out for converging empirical evidence for inhibitory processes in task switching.

$n-1$ congruence effects on switch costs. Another phenomenon that has been discussed in the context of the possible involvement of inhibitory processes in task switching is the $n-1$ congruence effect (see, e.g., Goschke, 2000; Monsell, Sumner, & Waters, 2003). This effect is based on a sequential analysis of congruence effects. Congruence effects in task switching arise when a stimulus needs to be processed differently, depending on the instructed task. Such “bivalent” stimuli can afford the same response in both tasks (“congruent” stimuli), or they can afford different responses in the two tasks (“incongruent” stimuli). For example, if participants switch between a color discrimination task (e.g., red vs. blue) and a shape task (e.g., circle vs. square) and the color red and a circle

were mapped to the same response key in both tasks (congruent), a red circle would be a congruent stimulus and a blue circle would be an incongruent stimulus. It has been shown that both RT level and switch costs are higher for incongruent stimuli than for congruent stimuli (e.g., Meiran & Kessler, 2008; Rogers & Monsell, 1995), suggesting that incongruent trials increase response conflict and task conflict (e.g., Koch & Allport, 2006; Meiran & Kessler, 2008; Monsell, Taylor, & Murphy, 2001). The phenomenon of the $n-1$ congruence effect refers to the observation that switch costs are also higher after trials with incongruent stimuli than with congruent stimuli (Brown et al., 2007; Goschke, 2000; Monsell et al., 2003).

To account for this $n-1$ congruence effect, Goschke (2000) suggested that incongruent stimuli produce more response conflict, which then calls for both additional online strengthening of the current task set and inhibition of the competing task set. This pattern of increased activation and inhibition carries over to the next trial (proactive interference), leading to increased switch costs. This idea of an online recruitment of additional cognitive control is currently an area of intense research in the domain of response control in conflict situations (see, e.g., Botvinick, Braver, Barch, Carter, & Cohen, 2001; Botvinick, Cohen, & Carter, 2004; Egner, 2008; Gratton, Coles, & Donchin, 1992; Stürmer, Leuthold, Soetens, Schröter, & Sommer, 2002; Wendt, Kluwe, & Peters, 2006). Such sequential congruence effects in task switching led Brown et al. (2007) to propose a model that includes a within-trial incongruence “detector” that reacts to response conflicts. This incongruence detector is also accompanied by an across-trial change detector, which monitors for task switches (see also Monsell & Mizon, 2006).

The observation of $n-1$ congruence effects is consistent with the notion of (1) a context-sensitive mechanism that regulates the strength of inhibitory control, and (2) an inertia of the cognitive system, so that inhibition, once exerted, persists and leads to proactive interference when switching back to the previously inhibited task. However, again it could be argued that response conflict in incongruent trials is resolved not by the increased inhibition of competing tasks, but by the stronger activation of the currently relevant task. That is, $n-1$ congruence effects in task switching might as well be explained by assuming that incongruent trials require extra activation of the currently relevant task, which then carries over to the subsequent trial, producing increased switch costs. Thus, there is an alternative noninhibitory interpretation for the $n-1$ congruence effect in task switching, just as it is the case with many other putative inhibitory phenomena in cognitive psychology (see, e.g., MacLeod et al., 2003, for a review). In the next section, we will describe more unambiguous evidence for task inhibition.

$n-2$ Task Repetition Costs

It has been proposed that task inhibition can be assessed using a method that requires switching between three tasks (see, e.g., Mayr & Keele, 2000). In this method, the critical comparison is between switching back to a particular task after one intermediate task (i.e., sequences of the ABA

type, “ $n-2$ task repetitions”), and switching back after at least two intermediate tasks (i.e., CBA sequences).

Importantly, persisting-activation accounts and persisting-inhibition accounts make opposite predictions for the difference between $n-2$ repetitions and $n-2$ switches: Persisting-activation accounts predict a performance benefit in $n-2$ repetitions relative to $n-2$ switches, whereas persisting-inhibition accounts predict a performance cost in $n-2$ repetitions. In fact, many studies report $n-2$ repetition costs (see, e.g., Arbuthnott & Frank, 2000; Lien & Ruthruff, 2008; Mayr & Keele, 2000; Philipp, Jolicœur, Falkenstein, & Koch, 2007; Schuch & Koch, 2003), and this paradigm has also been employed in the context of psychopathology to assess task inhibition (Moritz, Hübner, & Kluwe, 2004; Whitmer & Banich, 2007). To date, $n-2$ repetition costs appear to be the most convincing demonstration of task inhibition (Mayr, 2007).

$n-2$ repetition costs can be taken to represent an empirical signature of task inhibition, since these costs can be observed for a large variety of different tasks. $n-2$ repetition costs occur when subjects switch between tasks that differ in stimulus-related aspects (e.g., different stimulus dimensions) as well as in response-related aspects (e.g., different response modalities).

Inhibition of task-specific stimulus dimensions. Mayr and Keele (2000) introduced a visual search paradigm, in which participants had to localize a deviant stimulus in a display consisting of four stimuli and to press one of four response keys that were spatially compatible with the positions of the individual stimuli on the screen. The stimuli varied along the dimensions of color, orientation, and movement, and the currently relevant dimension was indicated prior to stimulus onset by a task cue. Mayr and Keele found that participants’ performance was impaired in $n-2$ repetitions of the relevant dimension (e.g., ABA), relative to $n-2$ switches of the relevant dimension (CBA). These authors termed this effect *backward inhibition* to indicate the idea that task-related stimulus dimensions become the target of an inhibitory process once these dimensions are actively abandoned. However, we will use the theoretically more neutral term “ $n-2$ repetition costs” to refer to this inhibitory phenomenon (cf. MacLeod et al., 2003).

The inhibition of task-irrelevant stimulus dimensions has also been shown in studies by Arbuthnott and colleagues (e.g., Arbuthnott, 2005; Arbuthnott & Frank, 2000; Arbuthnott & Woodward, 2002). These studies had participants switch between attending digits, letters, or symbols in a display containing all of these different types of stimuli. Subjects named the category of the stimulus in the relevant dimension (e.g., they said “vowel” or “consonant” in the letter-categorization task). Switching between these stimulus types in this multidistractor environment was associated with $n-2$ repetition costs.

When researchers have used more simple perceptual categorization tasks that were mapped to manual key-press responses, robust $n-2$ repetition costs have also been demonstrated (see, e.g., Gade & Koch, 2005, 2007; Mayr, 2001, 2002, 2009; Philipp & Koch, 2006; Sdoia

& Ferlazzo, 2008). Moreover, $n-2$ repetition costs have been demonstrated with cognitive categorizations in numerical judgment tasks. For example, Schuch and Koch (2003) used digits from 1 to 9 (excluding 5) as stimuli and had participants switch among parity judgments (odd vs. even), magnitude judgments (smaller vs. larger), and interval judgments (near vs. far from 5).

Inhibition of response mode: Modality switching and language switching. The aforementioned studies have suggested that inhibition can be observed when the difference between tasks is associated with stimulus processing. However, there is also evidence for inhibition associated with response-related aspects of task set. For example, using a numerical judgment task that remained constant across the entire experiment, Philipp and Koch (2005) had their subjects switch among different effectors (manual, vocal, or foot-pedal responses). This resulted in $n-2$ repetition costs, suggesting that inhibition can also be observed for task sets that differ in terms of the response modality. Moreover, Koch, Gade, and Philipp (2004) had participants switch among three tasks; two of them were numerical judgment tasks (i.e., parity and magnitude), whereas the third task was a simple-response task that required pressing both response keys simultaneously upon stimulus onset. These authors found $n-2$ repetition costs even for the simple-response task.

Finally, $n-2$ repetition costs have been observed in language switching, in which the same kind of stimuli (e.g., digits) have to be named in different languages (Philipp, Gade, & Koch, 2007; Philipp & Koch, 2009). The study of Philipp and Koch (2009) also showed that inhibition does not necessarily refer to a particular subset of responses but that it can generalize to other responses, too.

Taken together, these studies show that inhibition can be targeted also at output-related aspects of processing, which complements the existing evidence for inhibition at input-related task aspects (e.g., stimulus dimensions). Hence, it appears that inhibition can occur at many different levels of task processing (Houghton, Pritchard, & Grange, 2009).

Do $n-2$ Task-Repetition Costs Reflect Task-Set Inhibition?

Inhibition of task sets versus inhibition of cue representations. In the previous discussion, we have implicitly assumed that inhibition refers to the task sets, or to components of the task set. However, it is possible that inhibition is, in fact, targeted at the task cues. In the studies described previously, the tasks were always indicated by cues. Hence, $n-2$ task repetitions are also associated with $n-2$ cue repetitions, and the assumed inhibitory process might be targeted at the representation of the task cue rather than at the task set itself. If so, a cue representation that has been the target of an inhibitory process would be more difficult to process (i.e., to encode) in an $n-2$ cue repetition relative to an $n-2$ cue switch, and such a cue-encoding inhibition effect could account for the robust $n-2$ task-repetition costs.

The existing evidence, however, strongly favors an account in terms of the inhibition of task sets rather than of

cue representations. Mayr and Kliegl (2003) examined this issue by using two cues for each of three tasks (see also Logan & Bundesen, 2003, for an application of the 2:1 cue-to-task mapping procedure). This procedure enabled the authors to dissociate $n-2$ task repetitions and $n-2$ cue repetitions. The authors found significant $n-2$ repetition costs even when the task was indicated by a different cue, suggesting that the inhibition effect is not targeted at cue-encoding processes or cue representations. However, these authors failed to observe the expected $n-2$ repetition costs under standard conditions, in which there is an $n-2$ repetition of both cue and task. This was possibly due to the large number of cues used in this study (six different cues in total), which might have led to a situation in which repetition priming of cue encoding produced positive priming effects at the cue level that were strong enough to outweigh inhibition effects at the task level. This post hoc account is plausible, but it already presupposes the existence of $n-2$ task inhibition, whereas the goal of that experiment was to actually demonstrate this existence. Hence, these data are clearly suggestive but not fully conclusive.

More conclusive evidence comes from a study by Altmann (2007). In this study, subjects performed a task several times without intervening cues until a cue indicated a new task that had to be performed with the subsequent stimuli. Using two cues per task, Altmann found robust $n-2$ repetition costs with both $n-2$ repetitions of cue and task and $n-2$ repetitions of task only. Likewise, Gade and Koch (2008), presenting cues on every trial, found comparable $n-2$ repetition costs irrespective of whether the cue did or did not repeat. Finally, Philipp and Koch (2009) found that $n-2$ repetition costs in language switching are not associated with the specific cues but with the languages themselves.

Taken together, these studies showed that there is no evidence for the notion that $n-2$ repetition costs are related to cue representations. The difference in the pattern of results in Mayr and Kliegl's (2003) study and the studies of Altmann (2007) and Gade and Koch (2008) is probably due to the fact that Mayr and Kliegl used completely arbitrary cues, whereas the two other studies used cues that were easier to decode. Note that the distinction of processes at the level of cue encoding and of task sets has generated a fruitful discussion in the literature on switch costs (see, e.g., Altmann, 2007; Forstmann, Brass, & Koch, 2007; Logan & Bundesen, 2003; Mayr, 2006; Mayr & Kliegl, 2003; Monsell & Mizon, 2006; Schneider & Logan, 2005), in which the results seem to indicate some role of repetition priming on the level of cue processing in the generation of switch costs. In contrast, there is no clear evidence for the idea that the inhibition of cue representations significantly contributes to $n-2$ task repetition costs (see Gade & Koch, 2008).

Inhibition of task sets versus sequential expectancies. In the previous sections, we argued that $n-2$ repetition costs could not be explained by persisting activation accounts. However, it is worth considering another possible alternative noninhibitory explanation. In the context of sequential choice behavior, people sometimes entertain

a heuristic of expecting that all possible events are about equally distributed even in short runs of events (see, e.g., Kahneman & Tversky, 1972). Applied to the methodology of assessing $n-2$ repetition costs, this would suggest that participants would develop some kind of expectancy that a CBA sequence is more representative and thus more likely to occur than an ABA sequence, which in turn might cause an expectancy-based performance benefit in CBA sequences relative to that in ABA sequences. If that were true, then $n-2$ repetition costs would be due to the violation of expectancies rather than to task inhibition. However, there are at least three arguments that speak against this account (see also Mayr, 2007; Mayr & Keele, 2000, for discussion).

First, studies using a 2:1 cue-to-task mapping revealed that $n-2$ repetition costs are largely unaffected by whether the cue switches or repeats as well from trial $n-2$ to trial n (Altmann, 2007; Gade & Koch, 2008; Mayr & Kliegl, 2003), even though an expectancy bias account would probably predict that $n-2$ repetitions of cue and task should be even more unexpected.

Second, several studies have shown that $n-2$ repetition costs are not affected by manipulations of the preparation interval (e.g., Bao, Li, Chen, & Zhang, 2006; Gade & Koch, 2008; Mayr & Keele, 2000; Schuch & Koch, 2003). However, it seems plausible for one to assume that sequential expectancies should lose their influence when there is sufficient time to process a cue indicating the upcoming task, so that the next task can be explicitly expected.

Third, $n-2$ repetition costs have been shown to occur even when the whole sequence of tasks is fully predictable (Koch, Philipp, & Gade, 2006; Mayr, 2009; Mayr & Keele, 2000; Schneider, 2007), even though complete predictability in short task sequences should be a condition in which sequential expectancies, in the form of an alternation bias, are strongly discouraged. Interestingly, it has been shown that there can be additional noninhibitory contributions to $n-2$ task repetition costs in the quite specific case of to-be-memorized sequences that are explicitly instructed in advance, but robust inhibitory effects remain even if these contributions are taken into account (see Mayr, 2009).

Taken together, the sequential expectancy account does not seem to be a viable candidate for explaining $n-2$ task repetition costs. Additionally, it appears to be unclear how such an account could explain the whole pattern of rich empirical findings that were reviewed in the preceding sections and that will be discussed in the following sections (see below), which will show that $n-2$ repetition costs are sensitive to the degree of processing conflict in trial $n-1$.

To summarize, the data indicate that $n-2$ repetition costs can be found with a large variety of different tasks. Additionally, the evidence suggests that cue representations are probably not the target of inhibition (Altmann, 2007; Gade & Koch, 2008; Mayr & Kliegl, 2003; Philipp & Koch, 2009), and that $n-2$ task repetition costs cannot be reduced to sequential expectancy effects. Given this pattern of empirical evidence, we will now ask how the mechanisms underlying task inhibition can best be described. In doing so, we primarily rely on $n-2$ repetition

costs, because this currently appears to be the most convincing evidence for task inhibition.

Mechanisms of Task Inhibition

We will organize the discussion of the mechanisms of task inhibition along two theoretically relevant questions, in two separate sections. First, we will discuss whether task inhibition is necessarily tied to “top-down” selection of task sets. Second, we will discuss whether inhibition is primarily triggered by processing conflicts during actual task performance.

Task inhibition as a top-down triggered process? Consistent with the account of Mayr and Keele (2000), our operational definition of “top-down” processing is that it is based on specific cues that reveal the identity of the upcoming task, whereas performing tasks that are based on the information given by the actual stimulus display itself is, by definition, based on “bottom-up” processing (e.g., Hübner, Dreisbach, Haider, & Kluwe, 2003; Mayr & Keele, 2000). In the following two subsections, we will discuss evidence for the influence of task-specific versus switch-specific cuing, and of the duration of the cuing interval, on task inhibition.

Task-specific versus switch-specific cues. Although empirical evidence strongly indicates that cue-encoding processes themselves are not targets of inhibition, one might argue that specific task cues nevertheless play a crucial role for task inhibition in that they might trigger top-down inhibition of a specific task set. Evidence for the notion that inhibition is triggered by top-down processes comes from studies that manipulated the information value of cues. For example, Mayr and Keele (2000) suggested that task inhibition is a means of top-down control of a task set that directly serves to control target selection. According to these authors, “inhibition should occur only during endogenously controlled shifts between relevant perceptual dimensions, but not when target dimensions are activated through external stimulation only” (p. 13).

In their Experiment 2, Mayr and Keele (2000) compared two conditions that presumably differed in the degree to which top-down control occurs. To this end, they modified their visual search paradigm, in which a perceptually defined deviant target stimulus on a specified dimension needs to be located. In a bottom-up condition, the distractor always occurred on a dimension that was never task relevant, so that the target could be unambiguously identified even without a cue indicating the relevant dimension. In contrast, in the top-down condition, participants received an informative cue as to the relevant perceptual dimension prior to stimulus onset. The authors observed significant $n-2$ task repetition costs only in the latter condition, suggesting that the top-down selection of perceptual dimensions is necessary to trigger inhibition of competing tasks, or task-relevant dimensions, whereas purely bottom-up triggered selection of dimensions does not lead to inhibition.

However, Mayr and Keele (2000) conceded that a potential problem with this manipulation is that participants in the top-down condition could have reverted to a bottom-up approach because the task-relevant information was

completely specified in the actual stimulus display. Hence, strictly speaking, processing of the informative cue was not necessary even in the so-called top-down condition. In fact, the observed $n-2$ repetition costs in the top-down condition were very small (7 msec), and the effect was significant only in the group of the fastest participants, who were assumed to have used the cue to prepare for the upcoming dimension. Therefore, it appears to be important to gather more conclusive evidence for the notion of task inhibition as being triggered by top-down control.

There is indeed complementary evidence for top-down contributions to task inhibition. Hübner et al. (2003) used a task-switching variant of the flanker compatibility paradigm (see, e.g., Eriksen & Eriksen, 1974) to measure task inhibition. Importantly, these authors did not measure $n-2$ task repetition costs proper, but measured an effect that is conceptually related to $n-2$ repetition costs. Specifically, they observed a reduced flanker interference effect when the flanker belonged to the previously relevant stimulus dimension (which is assumed to have been the target of inhibition) relative to a dimension that had been relevant less recently (and therefore should have been less strongly inhibited). Importantly, in Hübner et al.'s (2003) Experiment 2, the cue was not task specific, but simply indicated a task switch without revealing information about the identity of the upcoming task (e.g., Dreisbach, Haider, & Kluwe, 2002; Koch, 2008; Nicholson, Karayanidis, Davies, & Michie, 2006), and there was no significant inhibition effect in RT. That is, these authors found evidence for task inhibition only when there was an explicit task cue that indicated the identity of the upcoming task in a switch trial, whereas there was no inhibition effect when the cue merely indicated an upcoming task switch without revealing the identity of the upcoming task itself. These data appear to confirm Mayr and Keele's (2000) observation that $n-2$ repetition costs are found only in situations in which the selection of upcoming task sets occurs in a top-down manner.

However, in Hübner et al.'s (2003) Experiment 2, there was a reduced flanker-interference effect after task-unspecific switch cues in the error rates (even though the authors do not report whether this particular critical contrast was significant). Moreover, Kuhns, Lien, and Ruthruff (2007) failed to replicate the reduced flanker effect in one experiment but found it in a second experiment. However, that experiment differed from the Hübner et al. (2003) study in several aspects.

In sum, the current evidence is mixed with respect to whether task-unspecific cues do or do not lead to task inhibition. Therefore, the role of top-down control in task-set selection still needs further examination before clearer conclusions can be drawn.

Time-based task preparation. The notion of inhibition as a top-down triggered process implies that inhibition can act in a preparatory way prior to stimulus onset. If so, one might ask whether the inhibitory effect, measured as $n-2$ repetition costs, is affected by a manipulation of the cuing interval.

Several studies have examined this issue, but most of these studies did not find an effect of the cuing interval on

$n-2$ repetition costs (Bao et al., 2006; Gade & Koch, 2008; Mayr, 2002; Mayr & Keele, 2000; Schuch & Koch, 2003), although there are also studies that report mixed findings (Koch et al., 2004; Philipp, Gade, & Koch, 2007). However, the cuing effects in all of these studies are not conclusive, for both theoretical and methodological reasons.

First, on a theoretical level, one might assume that the trigger for inhibition acts in a "ballistic" manner, so that it would not matter whether the duration of the cuing interval is short or long. Second, on a methodological level, it is critical for one to note that the cuing interval was blocked in the aforementioned studies. Therefore, increased inhibition in the preceding trial could have been compensated during preparation in the current trial. That is, if cue-based task preparation in a task switch triggers the inhibition of the previous, competing task set, then the aftereffect of preparatory inhibition should be partially compensated by increased preparation in the current trial. To dissociate these two opposing influences, it would be necessary to manipulate the preparation intervals independently in the corresponding conditions, but this evidence is not yet available.

In summary, the evidence in favor of task inhibition as a top-down process is currently mixed. Further research is needed to unequivocally demonstrate that $n-2$ repetition costs are related to top-down control processes.

In the next section, we will come to the role of processing conflict in task inhibition. Before doing so, however, we would like to clarify an important issue. We refer to inhibition in the present context as the inhibition of the competing task. That is, we assume that the preceding task becomes the target of inhibition when performing a new task (Mayr & Keele, 2000). This idea can be contrasted with the idea discussed in the literature on sequential motor inhibition that elements in a sequence get inhibited immediately after use, as a form of "self-inhibition" (see, e.g., Houghton & Tipper, 1996; Mayr & Keele, 2000, for discussion). $n-2$ task-repetition costs do not appear to represent a case of self-inhibition for three reasons. First, it has been shown that $n-2$ task-repetition costs also occur when immediate repetitions are possible (Arbuthnott, 2008b; Mayr & Keele, 2000), even though the effect can get smaller in such circumstances (Philipp & Koch, 2006). Second, an automatic self-inhibition mechanism should produce costs of immediate repetitions, which were not observed in task switching. Third, if $n-2$ task repetitions represented a case of self-inhibition, then in a sequence of the type ABA, the characteristics of the B-task would not affect $n-2$ task-repetition costs, and there would be no way of explaining the rich evidence demonstrating that the size of $n-2$ task-repetition costs is sensitive to conflict in the task performed in trial $n-1$. We will discuss this evidence in the next section.

The role of processing conflict in task inhibition. A variety of evidence points toward a crucial role of conflicts during task processing in task inhibition. First, we will review evidence of $n-2$ repetition costs being affected by manipulations of the intertrial interval. Then, we report evidence suggesting that conflict during processing of the cue and stimulus is important in task inhibition. We will

then discuss in some more detail evidence for a critical role of conflicts at the response level.

Dissipation of inhibition: Temporal decay or event-based release? It has been found that $n-2$ repetition costs were smaller when the duration of the interval between the previous response and the next cue (response-cue interval, RCI) was long as opposed to when it was short (see, e.g., Grange & Houghton, 2009; Koch et al., 2004; Mayr, 2002; Mayr & Keele, 2000). This finding is important with respect to the theoretical idea underlying the measure of $n-2$ repetition costs, which is that the persistence of inhibition is stronger when the previously inhibited task was performed only two trials before ($n-2$ repetitions) rather than three or more trials before ($n-2$ nonrepetitions). That is, the observed decrease of $n-2$ repetition costs as a function of increasing RCI appears to suggest that task inhibition, once exerted, decays as a function of the time elapsed between the inhibitory episode and the “probe” trial (i.e., the $n-2$ repetition).

However, Gade and Koch (2005) noted that the existing studies manipulated RCI in blocks of trials, so that the duration of the immediately preceding RCI was always the same as that of the RCI between trial $n-2$ and trial $n-1$. Gade and Koch (2005) reasoned that the critical factor for inhibition to be exerted in the first place is the degree of task conflict when switching the task. Hence, the degree of persisting activation of the just-preceding task (i.e., the $n-2$ task) should determine the strength of inhibition exerted in trial $n-1$, which in turn is measured as $n-2$ repetition costs in trial n . On the basis of this reasoning, the RCI between trials $n-2$ and $n-1$ should be crucial to determine the size of $n-2$ task repetition costs: The shorter the RCI, the more competition and conflict, and hence the larger the $n-2$ repetition costs.

To test this idea, the authors assessed $n-2$ task repetition costs when the RCIs varied randomly from trial to trial. In two independent experiments, they found that it was primarily the RCI between trials $n-2$ and $n-1$ that affected $n-2$ repetition costs, whereas the RCI between trials $n-1$ and n had only little systematic effect, even though such an effect would have been expected on the basis of the decay-of-inhibition hypothesis. Therefore, the data suggest that RCI effects in $n-2$ repetition costs are primarily due to task conflict in trial $n-1$ rather than to the decay of inhibition in trial n .

Hence, task inhibition, once triggered, appears to be quite persistent and does not decay quickly as a function of the passage of time. This raises the critical issue of what the basis for $n-2$ task repetition costs is in the first place, if it is not more advanced time-based decay of inhibition in the $n-2$ nonrepetition condition relative to that in $n-2$ task repetitions.

Although it would be premature to exclude altogether time-based decay of inhibition as an explanation for $n-2$ task repetition costs on the basis of just a single study, we believe that inhibition does not decay passively. Instead, we suggest that inhibition is gradually released as a function of processing new tasks. According to this event-based release of inhibition account, when subjects perform a task (e.g., Task A), they will inhibit the previous

task (e.g., Task B), which is the most competing task. We now speculate that this will lead to a situation in which the inhibition of other, less competing tasks (Task C) is reactively released to some degree. Because of this release, it is easier to switch to Task C than to Task A, which had just been inhibited in the preceding trial. Note that this account relates relative differences in task inhibition not to the time elapsed but, rather, to the consequences of conflict resolution during task processing. A similar debate can be found in the literature on negative priming, in which it has been found that the effect is much more stable over time than would be suggested by a decay-of-inhibition account (see Neill, 2007; Tipper, 2001, for discussion). We believe that it will be important to further examine the idea of event-based release of task inhibition in future studies.

The issue of the actual basis of $n-2$ task-repetition costs leads to the related issue of whether $n-2$ task-repetition costs represent inhibition in absolute terms or in relative terms. In the strictest sense, the concept of inhibition might imply that activation of a representation is suppressed below some baseline value (MacLeod et al., 2003). However, since it is notoriously difficult to define proper baselines (Jonides & Mack, 1984), there is also no easy way of doing so in task switching. If we defined single-task performance as baseline, in which task competition should be minimal, then we would need to take into account that performance in mixed tasks (i.e., task switching) is generally much worse even in task repetitions—a finding that has been termed *mixing costs* (see, e.g., Koch et al., 2005; Los, 1996; Philipp et al., 2008; Poljac, Koch, & Bekkering, 2009; Rubín & Meiran, 2005). Hence, we can assume that task competition is very strong, particularly when switching among three tasks, because all tasks need to be kept active to some degree, which is presumably above baseline level. If that is true, it appears unlikely that inhibition would suppress the activation level of a competing task to a below-baseline level. On the basis of this reasoning, it seems that $n-2$ task-repetition costs most likely represent inhibition in relative terms; that is, these costs reflect relative activation differences that help to resolve task-selection conflicts in a situation in which all tasks have a heightened activation level. In that sense, inhibitory processes that are targeted at the preceding, most competing task would be a means to increase the signal-to-noise ratio more quickly than by only activating the relevant task, or they might help to create functionally important activation differences in tasks that are all close to ceiling in activation.

Clearly, this characterization of task inhibition in relative terms is speculative, but the idea that $n-2$ repetition costs reflect differences in the event-based release of inhibition fits well with the findings of Gade and Koch (2005), which suggest that inhibition does not decay as a function of time. Also, the event-based release account suggests a strong role of processing conflicts that trigger inhibition in a context-sensitive manner (see, e.g., Arbutnot, 2008b; Brown et al., 2007; Gade & Koch, 2005, 2007; Goschke, 2000). Note that this account is agnostic as to where, in terms of processing stages, these conflicts are functionally located. Below, we will discuss further

evidence that allows us to specify the functional locus of processing conflicts.

Conflicts at the level of cue processing. In a previous subsection, we have already described evidence suggesting that inhibition is not targeted at cue representations (Altmann, 2007; Gade & Koch, 2008; Mayr & Kliegl, 2003). Nevertheless, it appears that inhibition is influenced by the way tasks are cued. For example, Druey and Hübner (2007) found that $n-2$ task-repetition costs were significantly larger when there was temporal overlap between task cue and target stimulus than when the cue disappeared before the target appeared. However, this influence of temporal cue–target overlap on $n-2$ task-repetition costs could not be replicated by Grange and Houghton (2009) across three experiments. Hence, temporal characteristics of how tasks are cued might have an influence on $n-2$ repetition costs, but this influence still needs to be confirmed in future studies.

More convincing evidence exists for an influence of the spatial characteristics of task cues. Arbutnott and Woodward (2002) found that $n-2$ repetition costs were strongly reduced when the task cues were presented in separate spatial locations, and this result has been replicated in several studies (Arbutnott, 2005, 2008b, 2009; Druey & Hübner, 2007). To account for this finding, Arbutnott (2009) suggested that with distinct cue locations, “location-task representations are retrieved, and these representations do not interfere sufficiently with other location-task representations during response retrieval and selection to evoke inhibition” (p. 526). She suggested that task inhibition is a flexible process that is responsive to the degree of task interference that occurs as a function of overlap of task components. The notion that task inhibition is a function of the degree of task conflict has also been proposed by a number of other authors (e.g., Gade & Koch, 2005, 2007; Goschke, 2000; Schuch & Koch, 2003), and it appears that cue characteristics can contribute to task conflict. This is further supported by findings from Houghton and colleagues (Houghton et al., 2009), who found that $n-2$ repetition costs are larger when the cue-task associations are weak rather than when they are strong (i.e., when the cues are “transparent”). This suggests that cue-based task retrieval, if sufficiently hard, can be a trigger for the inhibition of competing tasks. Note, however, that the observation of cue-specific influences on $n-2$ task-repetition costs is not informative as to whether task inhibition can act as a “top-down” preparatory process, because these studies do not allow one to specify the point in time at which inhibition is actually triggered.

In sum, there is evidence that cue characteristics can influence $n-2$ task-repetition costs. However, some of this evidence needs further empirical support (i.e., the role of temporal cue–target overlap). Also, although the influence of spatially distinct task cues appears to be well established by now, it is still not clear exactly how this influence can be functionally integrated in a more comprehensive model of task inhibition. Finally, it currently seems that the observed influence of cue-task association strength is difficult to reconcile with two findings that will be discussed in more detail in the next subsection: that

$n-2$ task repetition costs were not affected by manipulations of the cue–target interval (see, e.g., Bao et al., 2006; Gade & Koch, 2008; Mayr & Keele, 2000; Schuch & Koch, 2003), and that there were no $n-2$ repetition costs even with nontransparent cues after trials that did not require a response (Philipp, Jolicœur, et al., 2007; Schuch & Koch, 2003). It is possible, though, that differences in tasks and methodology can account for this latter discrepancy. To summarize, the data referring to the influence of cue characteristics seem to show that task inhibition “is employed wherever and whenever the locus of conflict appears” (Houghton et al., 2009, p. 475), but more work is needed to fully understand the effects and interactions of conflict at different processing stages.

Conflicts at the level of stimulus processing. Another possible functional trigger of task inhibition is conflict at the level of stimulus-attribute selection (e.g., Arbutnott & Woodward, 2002; Hübner et al., 2003; Sdoia & Ferlazzo, 2008). For example, Sdoia and Ferlazzo found that conflict at stimulus selection during intentional encoding of stimuli into short-term memory in trial $n-1$ can result in $n-2$ repetition costs. This finding suggests that stimulus conflict plays a role in $n-2$ task-repetition costs.

As we have discussed previously, there is suggestive evidence that the resolution of conflict is rather generic and can trigger the inhibition of competitors at different levels of information processing (see Houghton et al., 2009). Nevertheless, it appears that most of the evidence currently available speaks for conflict at the response level as a trigger of task inhibition (see, e.g., Gade & Koch, 2005, 2007, 2008; Koch et al., 2004; Koch & Philipp, 2005; Philipp, Jolicœur, et al., 2007; Schuch & Koch, 2003). We will discuss this evidence next.

Conflicts at the response level: 1. Response-set overlap. Evidence in favor of conflict at the response level as the trigger of inhibition comes from a study by Gade and Koch (2007). These authors manipulated the degree of overlap at the level of the response requirements across tasks. They used four perceptual judgment tasks, which all called for a vocal response (i.e., overlapping response modality). Three of these tasks (shape, color, and size judgments of a visual stimulus) had trivalent stimuli and responses (saying “left” or “right”). That is, these tasks overlapped in the response mappings, so that each of two responses changed their functional “meaning,” depending on the current task (Meiran, 2000b; Schuch & Koch, 2004). This response-set overlap ought to produce strong task competition and response conflict during response selection. In contrast, the fourth task, which referred to the “fill” of the stimulus (i.e., outline shape vs. filled shape) had univalent stimuli (i.e., affording only one task) and required responses that had no direct overlap with the responses in the other tasks.

Gade and Koch (2007) found $n-2$ task-repetition costs only with the trivalent, fully overlapping tasks in three experiments. However, responding with “full” versus “empty” (Experiment 1) or “up” versus “down” (Experiment 2) in the fill task did not produce significant $n-2$ task-repetition costs when this task was performed in trial $n-1$, suggesting that it did not interfere strongly

enough to trigger measurable inhibition of the preceding task set. Significant $n-2$ task-repetition costs, however, were found when the fill task was mapped to “left” and “right” responses, which created full overlap in response categories across the four tasks. This suggests that task inhibition acts on the level of response mappings (see also Schneider & Verbruggen, 2008) and that, more generally, similarity of the response sets across tasks is a crucial determinant of response conflict and thus determines the size of $n-2$ repetition costs (see, e.g., Yeung & Monsell, 2003b, for a similar argument with respect to switch-cost asymmetries).

Conflicts at the response level: II. Response selection and execution. Even stronger evidence for the role of conflict at the response level as a trigger for $n-2$ repetition costs comes from studies using completely overlapping stimulus sets across tasks while varying response requirements. These studies applied variants of the go/no-go (or stop signal) methodology to task switching (see, e.g., Koch & Philipp, 2005; Philipp, Jolicœur, et al., 2007; Schuch & Koch, 2003; Verbruggen, Liefoghe, Szmalec, & Vandierendonck, 2005; Verbruggen, Liefoghe, & Vandierendonck, 2006). However, only two of these studies focused on $n-2$ repetition costs (Philipp, Jolicœur, et al., 2007; Schuch & Koch, 2003).

Schuch and Koch (2003) had participants switch among three numerical judgment tasks. An auditory go versus no-go signal was presented simultaneously with stimulus onset, transforming 25% of all trials unpredictably into no-go trials. Importantly, the CSI was also manipulated. The authors observed substantial cue-based preparation effects with long CSI in go trials, in which a response was executed. This CSI effect indicated that participants had effectively used the cuing interval for active task preparation despite the fact that the go versus no-go signal occurred unpredictably only with stimulus onset. Thus, participants definitely processed the cue and most likely encoded the target stimulus, but it is unlikely that they selected a task-specific response.

The most critical result was that although substantial $n-2$ repetition costs were obtained after go trials, these were significantly reduced or even eliminated after no-go trials. This elimination of $n-2$ repetition costs following no-go trials suggests that conflict during response selection or execution in trial $n-1$ is crucial to trigger $n-2$ repetition costs.

Hence, the findings from Schuch and Koch (2003) suggest that it is not cue-based task preparation that creates the critical conflict triggering $n-2$ repetition costs; rather, conflict during response-related processes seems to be crucial. It might be objected, however, that stimulus processing was probably rather shallow in no-go trials, so that there might have been less conflict not only at response selection but also at the level of stimulus-attribute selection. However, this potential objection can be disconfirmed on the basis of the results of a study by Philipp, Jolicœur, et al. (2007).

Philipp, Jolicœur, et al. (2007) devised a new paradigm they called the “go-signal paradigm.” In that paradigm, participants are required to prepare the task-specific re-

sponse but are not allowed to execute the prepared response until a go signal is presented. In 25% of all trials, the go signal was replaced with a no-go signal, so that the already-prepared response must be withheld. Importantly, the authors manipulated the go-signal delay (GSD). With a short GSD, the results mimicked those of Schuch and Koch (2003), showing greatly reduced $n-2$ task repetition costs after no-go trials. Moreover, the manipulation of the GSD resulted in substantial response preparation effects. RTs were very short in go trials with a long GSD, and $n-2$ task repetition costs were completely eliminated in such trials, suggesting that full response preparation can completely resolve the conflict that gives rise to task inhibition (see also Koch et al., 2004). Most critically, these findings also indicate that participants actually used the GSD in go trials very effectively for response preparation, so that the effects of no-go trials with a long GSD on subsequent task performance could not reflect the absence of either response selection or shallow stimulus encoding. However, $n-2$ task repetition costs were significantly smaller after no-go trials with long GSD than after go trials with long GSD, confirming the role of conflict at response processing in $n-2$ repetition costs.

Note that the reduction of the size of the $n-2$ task-repetition costs after no-go trials with long GSD suggests that conflict during response selection is probably not the only triggering factor for $n-2$ repetition costs. In addition, it appears that processes even later than response selection can play an important role (Philipp, Jolicœur, et al., 2007).

The conflict that appears to drive $n-2$ task-repetition costs in the studies using variants of no-go or stop-signal methodology (Philipp, Jolicœur, et al., 2007; Schuch & Koch, 2003) is not about whether to perform a response (in trial $n-1$), but rather is about whether the required response in trial $n-1$ conflicts with the response that would be afforded by the $n-2$ task. Hence, the consequence of conflict during selecting and executing a task-specific response in trial $n-1$ is that the preceding task becomes the target of an inhibitory process.

On the basis of this consideration, one might ask whether other “conflict” manipulations that have been found to influence ($n-1$) task-switch costs are also relevant for $n-2$ task-repetition costs. For example, we might ask whether congruence in trial $n-1$ plays a role, as has been found for switch costs (see, e.g., Goschke, 2000). However, since it is difficult to define congruence unambiguously with three tasks (i.e., 50% of the stimuli would be partly congruent and partly incongruent), there is, to our knowledge, no study so far that has directly examined this issue. Likewise, it has been reported that switch costs are increased with response repetitions (e.g., Meiran, 2000a; Rogers & Monsell, 1995), but again, we are not aware of a study that has investigated this issue with respect to $n-2$ repetition costs. This lack of evidence is most likely due to the fact that some manipulations that are straightforward with just two tasks become increasingly complex when three tasks are involved, which renders these manipulations less useful for examining adaptive responses to conflict in task switching.

On the basis of the empirical findings on $n-2$ task-repetition costs, we speculate that task inhibition is invoked by a conflict-monitoring mechanism similar to the one postulated in the study of response conflict in single-task contexts (see, e.g., Botvinick et al., 2004; Egner, 2008, for reviews). One mechanism to overcome response conflict in task switching may be to inhibit the competing response alternatives, or the competing task set that includes the set of response alternatives. That is, the inhibition of task sets may be triggered by conflict-monitoring processes. According to Yeung, Botvinick, and Cohen (2004), the monitoring continues until after response execution. Such a mechanism would explain the role of response selection as a trigger of task inhibition (Schuch & Koch, 2003). It would also be able to account for findings showing that processes that are associated with actual response execution can be a trigger as well (Philipp, Jolicœur, et al., 2007).

The role of processes associated with the actual execution of a response can be described in two different, mutually nonexclusive ways. First, it might be that inhibition is triggered, or further fueled, by postresponse evaluation processes (Botvinick et al., 2004). Alternatively, the role of performing the response could be to provide actual performance feedback. In turn, this drives processes of reinforcement learning (Holroyd & Coles, 2002), assuring a positive bias toward the performed task, as well as a negative bias—in the form of inhibition—toward competing tasks.

To better understand these mechanisms, it would be important for one to integrate the two largely independent research areas of conflict monitoring in single-task settings on the one hand (Botvinick et al., 2004; Egner, 2008), and response-related processes in settings with task variability (i.e., task switching) on the other hand. First steps toward an integration of conflict monitoring and task switching have been made by Steinhäuser and Hübner (2006, 2008), who analyzed performance in task switching following a task error. These authors found that the typically observed switch costs are inverted after a task error, suggesting that the wrong task set has been strengthened. To date, it is not clear, however, how exactly the mechanisms underlying switch costs relate to those of $n-2$ repetition costs (see Philipp, Jolicœur, et al., 2007, for a discussion). Hence, it will be important to continue to pursue such an integrative research approach.

In addition, it will be important to relate the existing knowledge based on cognitive-behavioral work to the growing literature in the cognitive neurosciences. To this end, we will provide a brief review of the neuroscience evidence on task inhibition. It would be beyond the scope of the present article to provide full coverage of this literature, so we will rather focus on those studies that have a clear relation to task inhibition as measured via $n-2$ task repetition costs.

The Neural Basis of $n-2$ Task-Repetition Costs

Recent neuroscience studies have provided supportive evidence for a role of response-related mechanisms in task inhibition. Aron, Robbins, and Poldrack (2004) summarized the neuroscience literature on various forms

of inhibition, including response inhibition and task inhibition. This review covered neuroimaging studies, ERP studies, neuropsychological patient studies, and monkey lesion studies. They concluded that all of these studies point toward the relevance of right inferior frontal cortex (IFC) for inhibitory processes. For example, Aron et al. reported that patients with a right IFC lesion showed increased switch costs and that this apparent switching deficit increased with the magnitude of the lesion. Assuming that switch costs also represent, among other processes, inhibitory components of cognitive control (Mayr & Keele, 2000; Schuch & Koch, 2003), these data suggest that right IFC is involved in task inhibition. Yet, Aron et al. did not specifically refer to $n-2$ repetition costs in their review.

Mayr and colleagues (Mayr, Diedrichsen, Ivry, & Keele, 2006) dissociated the effects of left and right prefrontal brain damage by assessing both switch costs and $n-2$ task-repetition costs. These authors found reduced $n-2$ task-repetition costs in right-frontal patients relative to those in a control group and to left-frontal lesion patients, whereas switch costs were relatively normal. In contrast, patients with left-frontal lesions showed $n-2$ task repetition effects that were comparable to those of a control group, but these patients clearly showed increased switch costs. This functional dissociation suggests separate neural loci of $n-2$ repetition costs and switch costs. However, the sample of right-frontal patients was very small ($n = 4$), and the lesions covered large parts of prefrontal cortex. Furthermore, 2 of the patients numerically showed $n-2$ repetition costs. Hence, although these findings are consistent with those from a growing body of other neuroscience studies, further evidence is desirable to confirm the dissociation observed by Mayr et al.

In fact, such supportive evidence has been reported by Dreher and Berman (2002) in a study using fMRI to examine $n-2$ repetition costs. These authors found that the ABA versus CBA contrast was associated with increased activation in a right-frontal brain area, supporting the hypothesis that this area is involved in task inhibition.

However, at present, it is not clear whether right prefrontal cortex contributes to triggering inhibition or to resolving the conflict due to persisting inhibition. In fact, Dreher and Berman (2002) speculated that right-prefrontal areas are primarily recruited when dealing with the aftereffects of inhibition. Future research will have to tackle this difficult question.

In summary, there is already some recent work on the neural basis of $n-2$ task-repetition costs (see also Fales, Vanek, & Knowlton, 2006; Sinai, Goffaux, & Phillips, 2007). The evidence suggests an involvement of right-frontal cortex in $n-2$ task-repetition costs (Dreher & Berman, 2002; Mayr et al., 2006), but further empirical support would be highly desirable.

Conclusion

In the present article, we reviewed recent empirical evidence on the role of inhibitory processes in task-set switching. We discussed several inhibitory phenomena, such as switch costs, switch-cost asymmetries, and $n-1$

congruence effects. We argued that these seemingly inhibitory phenomena are disputable, and that, to date, $n-2$ task-repetition costs seem to represent the most convincing evidence for task inhibition. Robust $n-2$ task-repetition costs have been observed with many different tasks and when switching between languages. Hence, $n-2$ task-repetition costs can be taken as evidence for an inhibitory mechanism that serves to reactively deactivate task sets if these create conflict when implementing a new task set.

On the basis of a review of the empirical evidence, we suggest that the primary trigger of task inhibition is conflict during response selection, even though conflict at other processing stages may contribute to $n-2$ task-repetition costs as well. An important goal for future research will be to disentangle whether various forms of processing conflicts in task switching (i.e., at the stimulus level vs. at the response level) have functionally similar roles in generating $n-2$ task-repetition costs, or whether these can be dissociated.

AUTHOR NOTE

The authors thank Erik Altmann, Judith Kroll, Nachshon Meiran, Stephen Monsell, Tram Neill, Darryl Schneider, and an anonymous reviewer for helpful comments on this article and Vera Lawo for her help in preparing the manuscript. This research was supported by Grants KO2045/4-1, KO2045/4-2, and KO2045/4-3 of the Deutsche Forschungsgemeinschaft (German Research Foundation). Correspondence concerning this article should be addressed to I. Koch, Institute of Psychology, RWTH Aachen University, Jägerstr. 17-19, D-52056 Aachen, Germany (e-mail: koch@psych.rwth-aachen.de).

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(Manuscript received October 9, 2008;
revision accepted for publication September 18, 2009.)