The Role of Response Selection for Inhibition of Task Sets in Task Shifting

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Response selection in task shifting was explored using a go/no-go methodology. The no-go signal occurred unpredictably with stimulus onset so that all trials required task preparation but only go trials required response selection. Experiment 1 showed that shift costs were absent after no-go trials, indicating that response processes are crucial for shift costs. In Experiment 2, backward inhibition was absent after no-go trials. Experiments 3 and 4 demonstrated that response selection, rather than execution, causes backward inhibition. All 4 experiments showed effects of preparation time in go trials, suggesting that advance preparation must have also occurred in no-go trials. The authors concluded that inhibition of irrelevant task sets arises only at response selection and that residual shift costs reflect such persisting inhibition.

Control processes involved in human information processing enable flexible shifting from one task to another (see, e.g., Kluwe, 1997; Monsell, 1996). These processes configure the cognitive system to the currently relevant task. The term task set is used to refer to the internal constraints that need to be set to perform a particular task (see, e.g., Mayr & Keele, 2000; Monsell, 1996). In the context of choice reaction tasks, this is mainly the relevant stimulus dimension and the set of task-specific stimulus–response (S-R) mappings.

To investigate configuration processes, researchers have used the task-shifting paradigm. Performance when shifting to a task is compared with repeating the same task. Shifting tasks causes costs and because configuration processes must be involved in shift trials, such shift costs are assumed to reflect configuration processes (see Rogers & Monsell, 1995). Configuration can be partly completed prior to task performance (e.g., Meiran, 1996; Rogers & Monsell, 1995), as evidenced by the beneficial effects of prolonged preparation time. However, although shift costs decrease as a function of preparation time, they typically are not reduced to zero, so that some costs remain (see, e.g., De Jong, 2000; Meiran, 1996; Rogers & Monsell, 1995).

To account for such residual shift costs, Allport and colleagues (Allport, Styles, & Hsieh, 1994; Allport & Wylie, 1998, 2000) suggested that previous configurations interfere with the current configuration and that this persisting interference decays slowly over time (see also Mayr & Keele, 2000). Supporting evidence for this notion comes from the fact that shift costs decline as a function of remoteness from the previous trial (i.e., as a function of response–stimulus interval), even if the time for preparing the upcoming task is controlled (e.g., Koch, 2001; Meiran, 2000b; Meiran, Chorev, & Sapir, 2000).

Thus, it appears that shift costs may not be well suited to directly measure the setting up of a new configuration. Rather, they seem to reflect interference between conflicting configurations. However, even though the task-shifting paradigm may not provide a pure measure for the duration of control processes, it still provides a very promising method for investigating interference processes on the level of task sets (see Koch & Allport, 2001).

Does Proactive Interference Involve Inhibition?

Several researchers have suggested that proactive interference consists of persisting inhibition of task sets (e.g., Allport & Wylie, 2000; Mayr & Keele, 2000). To implement a new task set, the previous task set must be inhibited (“backward inhibition”; cf. Mayr & Keele, 2000). Because in the task-switching paradigm a to-be-established task set is always a recently abandoned one, persisting inhibition must be overcome. When switching between only two tasks, inhibition of task sets cannot be distinguished from activation of task sets. That is, proactive interference might result from persisting inhibition of the currently relevant task set and/or from persisting activation of the previously relevant task set. Shift costs between two tasks may be due to the relative activation of one task set as compared with the other, but it cannot be decided whether inhibition is involved as an extra component.

To focus exclusively on inhibition of task sets, Mayr and Keele (2000) recently created a modified task-switching paradigm (which they called “backward inhibition”). In this backward inhibition paradigm, persisting activation of the to-be-abandoned task set is held constant while persisting inhibition of the to-be-established task set is varied. Switching back to a task after only one intermediate trial (e.g., ABA) is compared with switching back to a task after at least two intermediate trials (e.g., CBA). In this way, Mayr and Keele have shown that the more recently a task has been switched away from, the harder it is to switch back to. It can...
thus be concluded that inhibition of task sets is a separate process that cannot be explained in terms of activation. Furthermore, Mayr and Keele suggested that backward inhibition might account for residual shift costs. They showed empirically that residual shift costs were present under conditions that included backward inhibition but disappeared under conditions of reduced persisting inhibition (see Mayr & Keele, 2000, Experiment 4).

The Functional Role of Inhibition

An inhibitory mechanism has been identified in task shifting. However, it is unclear as to which of the several processes involved in task switching the inhibition mechanism is related to. One possibility is that backward inhibition is related to preparation processes. Thus, the onset of a new task cue might trigger inhibition of the previous task set. Alternatively, however, backward inhibition could be related to response processes. If only response-related processes required inhibition of the competing task set, then this would imply that a new task set could be prepared without inhibiting the previous one. Mayr and Keele (2000) discussed both alternatives but were not able to decide between them on the basis of their data.

However, several findings in the literature provide support for the response-related alternative. For instance, in the domain of dual-task processing, the notion that tasks interfere with respect to response-selection processes is well established (e.g., Jolicœur, Tombu, Oriet, & Stevanovski, 2002; Pashler, 1994). Several researchers have suggested that the costs of performing two tasks at the same time, or in close temporal succession, result from delayed response selection in the second task. The delay is attributed to interference between response-selection processes for the first and second tasks (e.g., Pashler, 1994). A similar account might apply to the task-switching domain: When different tasks are performed in close succession, response selection might be impaired because of interference between the current and previous task sets.

In line with a response-selection account of task switching, it has been shown that residual shift costs are reduced under conditions that facilitate response selection. For example, Meiran (2000b) varied the degree to which the response sets of two tasks overlap. Residual shift costs occurred only when the same two response keys were used for the two tasks. If different sets of response keys were associated with the tasks, no residual shift costs were observed. This suggests that response-selection requirements indeed play an important role in task shifting.

Given that task sets interfere with respect to response selection, we could further assume that response conflict between the current and previous task sets is resolved by inhibiting the previous task set. This would imply that the previous task set becomes inhibited in the course of response selection; in other words, that backward inhibition is a function of response selection.

The Paradigm

The present experiments test the following two hypotheses: that backward inhibition is a function of response selection and that backward inhibition is functionally independent from preparation processes. To investigate these questions, we needed to separate the processes related to task-set preparation from response-related processes. To accomplish this, we used a cuing paradigm (see, e.g., Koch, 2001; Meiran, 1996, 2000b): A task cue is presented prior to the stimulus, thus allowing for activation of the current task set (advance preparation period). However, stimulus-specific processes, including response selection, cannot take place during this period of advance preparation because a stimulus has not yet been presented.

To manipulate response selection, we introduced a go/no-go signal, indicating whether response selection was required. Of importance, the go/no-go signal was provided only at the time of stimulus onset, and it was completely unpredictable. Thus, while preparing, participants could not know whether the current trial would be a go or no-go trial and thus had to prepare for the upcoming task in all cases. This way, the no-go manipulation affected only response selection, whereas advance preparation processes remained unaffected. To ensure that participants really engaged in preparation processes, we varied preparation time (i.e., the cue–stimulus interval [CSI]) in addition to response selection, allowing us to assess whether longer preparation time led to enhanced performance.

This combined cuing–no-go procedure allowed us to test the response-selection account of residual shift costs. We assumed that inhibition of the preceding task set only occurs at response selection of the current task set. We predicted that if response selection was unnecessary (i.e., in no-go trials), then inhibition of the previous task set would not take place. Consequently, there should be no persisting inhibition when shifting back to the previous task set (i.e., in trials after no-go trials). That is, there should be no backward inhibition and no residual shift costs after no-go trials.

Four go/no-go task-switching experiments were conducted to explore the role of response selection for inhibition of task sets. Experiments 1A and 1B investigated whether response selection is necessary for residual shift costs to occur in a two-task situation. To address inhibition of task sets more directly, we assessed backward inhibition in a three-task situation in Experiment 2. In Experiment 3, response selection was separated from response-execution processes by applying a slightly different no-go manipulation. Instead of giving no response at all, participants executed both possible responses simultaneously. Experiment 4 controlled for different trial lengths of go/no-go trials. The main conclusion from the four experiments was that response selection could be identified as the critical process for inhibition of task sets and thus for the performance costs resulting from persisting inhibition.

Experiment 1A

The paradigm we used involved shifting between numerical-classification tasks (see Sudevan & Taylor, 1987). Participants had to judge whether a digit was smaller or larger than five (smaller–larger task) or whether it was odd or even (odd–even task). The upcoming task was indicated by a task cue, and then, after a short or long cuing (i.e., preparation) interval, the stimulus (a numeral) appeared. The total time that passed between trials (i.e., the response–stimulus interval [RSI]) was constant in both CSI conditions. A high or low tone occurred simultaneously with stimulus onset, indicating whether participants were required to respond to the stimulus (go vs. no-go). No-go trials, however, were not predictable during the preparation interval, so that participants had to prepare in all trials. Thus, the only difference between go and no-go trials was that in no-go trials, the selection of a response was
not required. The question was whether shift costs would occur after no-go trials. We expected shift costs to be reduced after no-go trials because no inhibition would be triggered by response selection.

**Method**

**Participants.** Sixteen participants (8 female and 8 male; mean age = 26.4 years) took part in the experiment and received approximately U.S.$6.

**Apparatus and stimuli.** The experiments took place in a dimly lit cabin. Participants sat in front of a screen of an IBM-compatible PC. Viewing distance was 40 cm. Cues and stimuli appeared at the screen center in white on a black background. We used either a square or diamond frame with sides that were 3.5 cm in length as task cues to indicate the odd-even task or smaller-larger task, respectively. Stimuli consisted of the digits 1–9, excluding 5. The digits were 1 cm in height, 0.5 cm in width, and appeared centrally in the frame. The high and low tones as go/no-go trial signals occurred simultaneously with stimulus onset and were easily discriminable. Stimulus onset and tone onset were synchronized.

Participants were asked to respond manually. The same two response keys (left and right) were used for both the smaller-larger and odd-even tasks, so that each response key had two different meanings, depending on the task. Because each stimulus had two different meanings as well (i.e., it could be classified on both the smaller-larger and the odd-even dimension), S-R mappings of the two tasks were completely overlapping.

**Design.** In a $2 \times 2 \times 2$ within-subject design, no-go (go vs. no-go trials), CSI (100 ms vs. 1,000 ms), and trial type (task shift vs. repeat) were manipulated. Trials following a no-go trial (no-go condition) were compared with those following a go trial (go condition). The no-go trials themselves were not considered in the analysis, as no overt response had to be produced in these trials. CSI duration alternated between blocks. Whether the experiment started with the short or long CSI condition and which of the four possible S-R mappings were used was counterbalanced across participants, resulting in eight different conditions.

Task sequence was random. Twenty-five percent of the trials were randomly converted into no-go trials with the constraint that a no-go trial could not be followed by another no-go trial. Thus, in the no-go condition, trial $n$ was preceded by a no-go trial in $n - 1$ and by a go trial in $n - 2$ (go/no-go/go). In the go condition, only trials preceded by at least two other go trials were considered (go/go/go). Thus, go and no-go conditions only differed with respect to trial $n - 1$; they were identical with respect to trials $n$ and $n - 2$. The reaction times (RTs) and error rates that are reported always refer to trial $n$.

The variables task, trial type, no-go, CSI, and response type (response shift vs. repeat) were orthogonally combined in the random sequence. Both response repetition from trials $n - 1$ to $n$ and from trials $n - 2$ to $n$ were controlled because in the go condition, the last executed response was in trial $n - 2$. Stimulus sequence was random except that stimulus repetition could not occur. The stimulus from trial $n - 1$ could not be repeated, and the stimulus associated with the last execution of a specific task could not be repeated when switching back to that task.

**Procedure.** We verbally explained the tasks and the procedure to the participants, and they also read instructions on the screen. Participants were encouraged to make use of the preparatory interval and to respond as quickly and as accurately as possible. Participants started with two short practice blocks, each consisting of eight trials.

A trial started with presentation of the cue (i.e., frame). After 100 ms or 1,000 ms, depending on the CSI condition, a digit appeared inside the frame. A high or low tone sounded for 50 ms at the same time that the digit appeared. Participants were instructed not to execute any response when the low tone occurred. In no-go trials, frame and stimulus remained visible for 1,000 ms and then the next trial started automatically. In the event participants pressed a key in a no-go trial, an error message (the German words “Falsche Taste,” i.e., “Wrong key”) appeared for 500 ms. In go trials, both frame and stimulus stayed on the screen until participants responded. In the case of an incorrect response, an error message (the German words “Keine Taste drücken,” i.e., “Do not press any key”) appeared on the bottom part of the screen for 500 ms. In go trials, both frame and stimulus stayed on the screen until participants responded. In the case of an incorrect response, an error message (the German words “Falsche Taste,” i.e., “Wrong key”) appeared for 500 ms. The RSI was 1,600 ms in all go conditions. The response–cue interval (RCI) was 600 ms in the long CSI condition (CSI = 1,000 ms) and 1,500 ms in the short CSI condition (CSI = 100 ms). Thus, in both conditions, the RCI and CSI totaled 1,600 ms. During the RCI, the screen was blank.

At the beginning of a block, participants were informed whether the following block contained a short or long CSI. After each block, participants received feedback about their mean RT during the last block. Participants performed 8 blocks of 96 trials each, resulting in 768 trials.

**Results**

**Data analysis.** Significance was tested in an analysis of variance (ANOVA) for repeated measures. The alpha level of significance was set to .05. RTs and error proportions were analyzed as dependent measures.

**Error data.** Two kinds of errors were possible: pressing any key in a no-go trial or pressing the wrong key in a go trial. The mean error proportion was 5.5% in no-go trials ($SD = 4.4\%$) and 5.6% in go trials ($SD = 3.0\%$). We analyzed the go errors in an ANOVA, with the independent variables CSI, trial type (task switch vs. repeat), and go/no-go trial preceded by a go or no-go trial. There was a significant interaction of trial type and no-go, $F(1, 15) = 7.0, p < .05$, indicating that shift costs were larger in the go condition than in the no-go condition ($2.2\%$ costs in the go condition and $1.0\%$ costs in the no-go condition). The main effect of CSI was marginally significant, $F(1, 15) = 4.1, p = .06$, with a higher error rate in the short CSI condition. No other main effects or interactions were significant. Overall, the error data pattern corresponded to that found in RT.

**RT data.** For RT analysis, we excluded all errors and the two trials that followed an error (i.e., go or no-go error) as well as the first two trials of each block. RTs larger than 2,500 ms were defined as outliers (1.1% of the remaining trials). Overall, 80.5% of the go trials were submitted to RT analysis.

To address the question of whether shift costs would occur after no-go trials, we compared trials preceded by a no-go trial with trials preceded by a go trial. Table 1 shows RTs as a function of CSI and trial type, separately for the go and no-go conditions.

Table 1

<table>
<thead>
<tr>
<th>Condition</th>
<th>CSI and condition</th>
<th>Trial type</th>
<th>Repeat</th>
<th>Shift costs</th>
</tr>
</thead>
<tbody>
<tr>
<td>CSI = 100 ms</td>
<td>Go in $n - 1$</td>
<td>797</td>
<td>991</td>
<td>194**</td>
</tr>
<tr>
<td>Go in $n - 1$</td>
<td>No-go in $n - 1$</td>
<td>922</td>
<td>946</td>
<td>24</td>
</tr>
<tr>
<td>CSI = 1,000 ms</td>
<td>Go in $n - 1$</td>
<td>699</td>
<td>845</td>
<td>146**</td>
</tr>
<tr>
<td>No-go in $n - 1$</td>
<td>817</td>
<td>795</td>
<td>-22</td>
<td></td>
</tr>
</tbody>
</table>

**Note.** Go/no-go in the table title refers to trials preceded by a go or no-go trial. CSI = cue–stimulus interval.

**p < .01 (shift costs were tested with one-tailed t tests).**
An ANOVA with the independent variables CSI, trial type, and no-go yielded a significant main effect of CSI: Responses were faster in the long CSI condition than in the short CSI condition (789 ms and 914 ms, respectively), $F(1, 15) = 31.2, p < .01$, indicating that participants engaged in preparation processes. The CSI effect did not differ for the go and no-go conditions ($F < 1$ for the CSI × No-Go interaction). Responses were also faster in task-repetition trials than in task-switch trials (809 and 894 ms, respectively), $F(1, 15) = 27.7, p < .01$. There was a tendency for responses to be slower after no-go trials than after go trials, but this effect did not reach significance (870 and 833 ms, respectively), $F(1, 15) = 3.5, p = .08$.

Of most importance, there was a significant interaction of trial type and no-go, $F(1, 15) = 54.8, p < .01$, indicating that shift costs were smaller after no-go trials than after go trials. When averaged across short and long CSI, shift costs were 171 ms in the go condition, $t(15) = 7.6, p < .01$ (one-tailed), and only 2 ms in the no-go condition ($p > .40$). The interaction of CSI and trial type also reached significance, $F(1, 15) = 5.4, p = .03$, indicating that shift costs were smaller in the long CSI condition than in the short CSI condition. When the go and no-go conditions were analyzed separately, the interaction of CSI and trial type was still significant in the go condition (194 ms vs. 146 ms, respectively), $F(1, 15) = 7.1, p < .02$, but not in the no-go condition ($p > .10$). The three-way interaction was nonsignificant ($F < 1$).

Discussion

In Experiment 1A, shift costs were obtained in the go condition but disappeared after no-go trials. Large effects of CSI on RTs and on shift costs indicated that participants used the CSI to prepare for the upcoming task. Because the go/no-go information was not available during preparation time, preparatory processes must have taken place in both go trials and no-go trials. Because there were no shift costs after no-go trials, response-related processes were apparently necessary for shift costs to occur.

However, the data from Experiment 1A are not unequivocal with respect to a response-selection–based explanation of shift costs. For instance, one could also assume that the no-go manipulation led to inhibition of a prepared response. Participants could have selected a response in no-go trials on the basis of the task stimulus and then inhibited this response. This would be similar to what happens in the stop-signal paradigm (e.g., Logan, 1994), in which a stop signal occurs some time after the stimulus. In the present experiments, the stop-signal delay was zero. Participants could have processed the visual stimulus first, leading to response selection, and the auditory stimulus later on, leading to inhibition of the selected response. However, this is unlikely for two reasons. First, auditory stimuli are usually processed faster than visual stimuli. Second, if a response was inhibited in no-go, there should be an inhibition effect if the same response had to be executed on the next trial. However, no effect of response repetition from trial $n - 1$ to trial $n$ was observed in the no-go condition, even if the task was repeated. (We ran an ANOVA with the independent variables response repetition from $n - 1$ to $n$ and trial type for the no-go condition, and it yielded no significant effects.) Nevertheless, to explore further the possibility that a response was selected and then inhibited in no-go trials, we modified the no-go manipulation so that response selection was impossible in no-go trials and then reran the experiment. If we obtained the same data pattern in Experiment 1B as we did in Experiment 1A, then we would conclude that response selection most likely did not take place in the no-go trials of Experiment 1A either.

Experiment 1B

To explore whether response inhibition could account for the data pattern, we replicated the conditions of Experiment 1A with the only difference being that a neutral stimulus was presented in no-go trials. This way, it was impossible to select a response in no-go trials and thus response inhibition in no-go trials could not play any role.

Method

Participants. Sixteen new participants (13 female, 3 male; mean age = 22.4 years) were tested.

Stimuli, procedure, and design. These were identical to those used in Experiment 1A. The only difference was that in no-go trials, the stimulus was the letter $X$ instead of a digit. The letter was the same size as the digits.

Results

Error rates were 0.4% and 8.6% for no-go and go trials, respectively. The ANOVA for the go errors with the independent variables CSI, trial type, and no-go yielded a significant main effect of trial type, $F(1, 15) = 9.0, p < .01$, indicating more errors in switch trials than in repeat trials (9.9% vs. 7.6%). No other main effects or interactions were significant.

For the RT data, analysis proceeded as before. RTs larger than 2,500 ms (0.5% of trials) were defined as outliers and were excluded from analysis. Overall, 78.1% of the trials remained for RT analysis. An ANOVA with the variables CSI, task shift, and no-go yielded significant main effects of CSI, $F(1, 15) = 89.8, p < .01$; task shift, $F(1, 15) = 23.6, p < .01$; and no-go, $F(1, 15) = 6.1, p < .05$. Of most importance, there was a Task Shift × No-Go interaction, $F(1, 15) = 63.7, p < .01$, indicating that shift costs were present in the go condition but absent in the no-go condition. No other interactions reached significance. Table 2 shows RTs for the different conditions. Shift costs were found after go trials (156 ms and 109 ms in the short and long CSI conditions, respectively; both $p < .01$) but not after no-go trials (–26 ms and –4 ms; both $p > .40$). When the go condition was analyzed separately, the interaction of CSI and trial type was marginally significant, $F(1, 15) = 3.7, p = .07$, that is, shift costs tended to be larger in the short CSI condition than in the long CSI condition.

Discussion

The data pattern obtained was analogous to that obtained in Experiment 1A in that shift costs were observed after go trials but not after no-go trials. Thus, whether response selection was possible did not change the data pattern. This suggests that response selection did not take place in the no-go trials of Experiment 1A either, at least not in the majority of these trials.

1 The possibility of no-go trials did not seem to discourage participants from preparing because we observed preparation effects of about the same size in a pilot study that included go trials only.
Experiment 1B: Reaction Times (in Milliseconds) as a Function of CSI, Go/No-Go, and Trial Type (Switch vs. Repeat)

<table>
<thead>
<tr>
<th>CSI and condition</th>
<th>Trial type</th>
<th>Shift costs</th>
</tr>
</thead>
<tbody>
<tr>
<td>CSI = 100 ms</td>
<td>Repeat</td>
<td>Switch</td>
</tr>
<tr>
<td>Go in n − 1</td>
<td>761</td>
<td>917</td>
</tr>
<tr>
<td>No-go in n − 1</td>
<td>877</td>
<td>851</td>
</tr>
<tr>
<td>CSI = 1,000 ms</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Go in n − 1</td>
<td>583</td>
<td>692</td>
</tr>
<tr>
<td>No-go in n − 1</td>
<td>674</td>
<td>670</td>
</tr>
</tbody>
</table>

Note. Go/no-go in the table title refers to trials preceded by a go or no-go trial. CSI = cue–stimulus interval.

** p < .01 (shift costs were tested with one-tailed t tests).

Taking Experiments 1A and 1B together, it is unlikely that the no-go signal led to inhibition of a prepared response. We therefore conclude that shift costs were absent after no-go trials because there was less interference at the time of response selection in trials after no-go. On the basis of the results of Experiment 1B, we used a numeral stimulus in no-go trials (as in Experiment 1A) in the following experiments to keep go and no-go trials as similar as possible.

There is one aspect of the data, however, that requires thorough consideration. This aspect relates to the increased RT level after no-go trials (although this effect only reached significance in Experiment 1B). If there is less response-set interference after no-go, one would have expected performance on trials after no-go to be on the level of task-repetition trials rather than on the level of task-shift trials. We suggest that the effect of increased RTs after no-go may be due to priming of the go/no-go signal. That is, a previous go decision primes another go decision, whereas a previous no-go decision primes another no-go decision, thereby delaying go after no-go. We believe that this no-go priming leads to an additive component that generally increases RT. Thus, we conceive of the experimental setting as a two-step task: (a) Participants start with processing the go/no-go signal, deciding whether to respond, and (b) in the course of responding they proceed with processing the stimulus and selecting the appropriate response.

The focus of the present study was on the second step, that is, on response selection in the context of two different tasks with overlapping response sets. We would like to emphasize, however, that this two-step interpretation has to be taken cautiously in the context of Experiments 1A and 1B, for it relies crucially on the (yet-to-be-tested) assumption that the go/no-go switch and the task switch have additive effects. This clearly needs to be further explored. Also, it is important to note that in principle, Experiments 1A and 1B could be interpreted in terms of self-inhibition of task set. The no-go signal could have led to inhibition of the prepared task set. Thus, when repeating this task on the next trial, persisting inhibition would have to be overcome, similar to what happens in switch trials. We cannot exclude this possibility on the basis of the present data. However, although the self-inhibition account might hold for Experiments 1A and 1B, it does not hold for the following backward inhibition experiments; in contrast, the explanation we suggest is also effective for the following experiments. Thus, we favor the response-selection–based interpretation because it provides an integrated account of all observed data patterns.

To summarize, we conclude from the present data that residual shift costs result from response-selection processes and that they are not related to preparation processes. Assuming that residual shift costs result from persisting inhibition of a previously abandoned task set, the present findings suggest that response selection is the critical process for the previous task set to become inhibited. In the following experiments, we further investigated this idea of an inhibitory mechanism. With respect to Experiments 1A and 1B, persisting inhibition or persisting activation of the previous task set might equally well account for shift costs. Experiment 2 tested directly whether response selection is related to inhibition of task sets.

Experiment 2

In Experiment 2, we used a backward inhibition paradigm to assess persisting inhibition (see Mayr, 2001; Mayr & Keele, 2000). To obtain a backward inhibition paradigm, we added a third number classification task to the present paradigm. Participants judged whether a number was located centrally (i.e., 3, 4, 6, 7) or peripherally (i.e., 1, 2, 8, 9) in the interval from 1 to 9. The paradigm consisted of task-switch trials only. The critical comparison was between switching back to a task after only one intermediate trial and switching back to a task after two or more intermediate trials. Concerning Task A, for example, ABA was compared with CBA. The same comparison holds for Tasks B and C. In the following, the two conditions are referred to as the ABA and CBA conditions, but the comparison involved all tasks.

According to the notion of backward inhibition as proposed by Mayr and Keele (2000), ABA should be slower than CBA because there should be more persisting inhibition on Task A when it has been switched away from more recently. It is important to note that a persisting activation account would predict the opposite: If only activation was involved, then ABA should be faster than CBA because of more residual activation. Thus, the ABA–CBA contrast provides a measure of inhibition.

As in Experiments 1A and 1B, unpredictable no-go trials were inserted to explore the role of response selection for inhibition of task sets. We tested the hypothesis that response selection is necessary for backward inhibition to occur. If response selection is crucial, then no backward inhibition should be found after no-go trials. In particular, we compared the ABA and CBA conditions, and the preceding Task B was either a go trial (go condition) or a no-go trial (no-go condition). We expected that there should be persisting inhibition on Task A in the go condition but not in the no-go condition.

In addition to no-go, we also varied preparation time as in Experiments 1A and 1B. This allowed us to control whether participants engaged in preparation processes in go and no-go trials. However, we did not expect the inhibition effect to be affected by preparation time because this had not been found in any of Mayr and Keele’s (2000) experiments.

2 We thank Ulrich Mayr for pointing out this alternative explanation.
Method

Participants. Sixteen participants (14 female, 2 male; mean age = 24.8 years) were tested.

Stimuli and procedure. The cues, stimuli, and go/no-go signals were the same as those used in Experiments 1A and 1B. The task cue for the new central–peripheral task was a triangle frame. Stimuli were presented in random order with the same constraints on stimulus repetition as in Experiments 1A and 1B.

Design. The three variables no-go, CSI, and backward inhibition were manipulated. The backward inhibition condition, ABA, was compared with a control condition, CBA. Of importance, ABA and CBA refer to the abstract case; the critical comparison occurred equally often for each of the three numerical judgment tasks (A, B, and C).

Task sequence was random, excluding task repetition. Each task occurred equally often, and there was a roughly equal number of trials in every combination of the following variables: no-go, CSI, backward inhibition, task, and response repetition.

Again, response repetition from trials \( n - 1 \) to \( n \), as well as response repetition from trials \( n - 2 \) to \( n \), were controlled. Probability of a no-go trial was 25%, and a no-go trial could not be immediately followed by another no-go trial. As in Experiments 1A and 1B, the no-go condition (go/no-go/go) was compared with the go condition (go/go/go). The eight possible S-R mappings were counterbalanced across participants. As in the previous experiments, CSI alternated blockwise and CSI block order was counterbalanced orthogonally to S-R mapping.

Results

The mean error rate was 6.3% (SD = 5.1%) for the no-go trials and 7.6% (SD = 5.1%) for the go trials. An ANOVA for the go errors with the independent variables CSI, trial type (backward inhibition vs. control), and no-go yielded only a significant main effect of no-go, \( F(1, 15) = 15.0, p < .01 \). Participants made 9.3% errors in the no-go condition but only 6.5% errors in the go condition. There was also a backward inhibition effect in the go condition (7.2% vs. 5.8% errors in the backward inhibition and control conditions, respectively), \( t(15) = 1.7, p < .05 \) (one-tailed), that was absent in the no-go condition (9.2% vs. 9.4% errors in the backward inhibition and control conditions, respectively), \( t(15) > 1.0 \), but the interaction was not significant (\( F < 1 \)). In summary, error data showed an analogous pattern of results as RT data.

Analysis of RTs proceeded as in Experiments 1A and 1B, but we increased the outlier criterion to 4,000 ms (1.3% of trials) because of an overall higher RT level. This way, the proportion of trials excluded was comparable to the proportions in Experiments 1A and 1B. In total, 77.4% of the go trials were included in the RT analysis.

The main question was whether a backward inhibition effect would be obtained in the go and no-go condition. The three-way ANOVA yielded a significant interaction of no-go and backward inhibition, \( F(1, 15) = 13.2, p < .01 \), showing that backward inhibition was significantly stronger after go trials than after no-go trials. A main effect of CSI was found, \( F(1, 15) = 50.2, p < .01 \), indicating that preparation occurred. None of the other main effects and interactions reached significance. Table 3 shows RTs as a function of no-go, CSI, and backward inhibition.

Because backward inhibition was not affected by CSI, data were averaged across CSI conditions. Figure 1 shows the backward inhibition effect in the go and no-go condition, averaged across CSIs. There was a large backward inhibition effect in the go condition (82 ms), \( t(15) = 3.8, p < .01 \), but no such effect in the no-go condition. The effect tended to be reversed after no-go trials, but this did not reach significance, \( t(15) = 1.0, p > .10 \). This shows that the backward inhibition effect was eliminated after no-go trials.

Discussion

In analogy to the shift costs in Experiments 1A and 1B, backward inhibition was affected by no-go trials. A large backward inhibition effect was observed in the go condition that was absent in the no-go condition. We therefore conclude that response selection was critical for backward inhibition to occur. If response selection was required in trial \( n - 1 \), then the task on the previous trial \( (n - 2) \) became inhibited, and persisting inhibition was observed when switching back to this previous task. If, however, response selection was not required in trial \( n - 1 \), then the task in trial \( n - 2 \) was not inhibited, and, therefore, there was no persisting inhibition when switching back to this task. It should be noted that self-inhibition of no-go trials, as it was discussed in Experiments 1A and 1B, could not play any role in the present experiment because this experiment included switch trials only. Thus, even if no-go led to inhibition in trial \( n - 1 \), this could not account for the inhibition in trial \( n \), as there were always different task sets in trials \( n - 1 \) and \( n \).

As in Experiments 1A and 1B, the CSI effect indicates that participants engaged in preparation processes, and, because they could not know in advance whether the current trial would be go or no-go, it follows that they must have prepared in go as well as in no-go trials. Because no backward inhibition was found after no-go trials, we conclude that preparation processes do not involve backward inhibition. Thus, we can further specify the inhibition mechanism first proposed by Mayr and Keele (2000): The present data show that backward inhibition is related to response processes rather than to preparation processes. In line with this notion, backward inhibition did not interact with CSI, as in Mayr and Keele’s (2000) experiments, because response selection cannot start during CSI.

There are two issues that might be objectionable in this interpretation. First, the fact that backward inhibition does not interact with CSI (as in Mayr & Keele, 2000) makes it more difficult to...
neously activated. In go trials, the current task set becomes activated. According to our response-selection account, the experimental results are related to the number of task sets that are activated simultaneously.

In the go condition, the current task set becomes activated. In no-go trials, the current task set becomes activated but the previous task set is not inhibited and thus remains activated as well. Thus, two task sets are activated after a no-go trial. Assuming that as the number of task sets that are activated simultaneously increases, response selection becomes more difficult on a following trial, this account could explain the present data pattern: With respect to the CBA condition, there are two activated task sets in the CBA go condition at the time of response selection in A (namely, Task Sets B and A) as opposed to three activated task sets in the CBA no-go condition (namely, Task Sets C, B, and A, because C was not inhibited). Assuming that the more task sets activated at the time of response selection, the longer response selection takes, this can account for RTs being slower in the CBA no-go condition compared with the CBA go condition. Concerning the ABA case, go and no-go conditions do not differ with respect to the number of activated task sets: In both go and no-go conditions, Task Sets A and B are activated at the time of response selection in A. However, the relative activation of A must be larger in the no-go condition than in the go condition because there was no backward inhibition in the no-go condition. This is indeed reflected in RT data: The ABA no-go condition was faster than the ABA go condition (1,237 ms vs. 1,266 ms), $t(15) = 2.3$, $p < .02$ (one-tailed). Thus, our data are consistent with the response-selection account, assuming that response selection takes longer the more task sets are simultaneously activated.

In summary, we conclude that the data support a response-based account of backward inhibition. Still, one might argue that the no-go manipulation not only affected response selection but also response execution because no response had to be given in no-go trials. Thus, it might be that response execution, rather than response selection, was the crucial process for backward inhibition (in Experiment 2) and residual shift costs (in Experiments 1A and 1B). We addressed this issue in Experiments 3 and 4.

Experiment 3

Experiments 1A–2 varied not only response selection but also response execution: In the no-go trials used thus far, neither response selection nor response execution was required. To separate the influence of response selection and execution, we used a modified no-go manipulation. Instead of executing no response in no-go trials, both possible responses had to be executed simultaneously. Participants were asked to press the two response keys simultaneously when the no-go signal occurred (double-press trials). This way, all possible responses were executed without requiring the selection of one response against another competing response. Thus, the double-press trials required execution of all possible responses but no selection. If, indeed, response selection was the critical process, then we should observe the same data pattern as before, that is, backward inhibition should be absent after double-press trials. If, however, response execution was crucial for the inhibition to occur, then backward inhibition should be observed after double-press trials.

Method

Participants. Sixteen participants (12 female, 4 male; mean age = 22.9 years) were tested.

![Figure 1. Experiments 2–4: Backward inhibition (BI) in the go and no-go/double-press (DP) conditions, respectively, averaged over cue-stimulus interval conditions. Error bars refer to the standard error of the mean. Exp = experiment.](image-url)
Stimuli, procedure, and design. These were identical to those used in Experiment 2. The only difference from Experiment 2 was that participants were instructed to respond to the low tone (i.e., the no-go signal) by pressing the left and right response key simultaneously. Participants had to give the double-press response within 1,000 ms of stimulus onset or an error message appeared at the bottom of the screen. This was done to keep the double-press trials as similar as possible to the no-go trials of Experiments 1A–2. (In the no-go trials, the stimulus remained visible for 1,000 ms before the program continued.) In double-press trials, the program continued as soon as two responses were given.

Results

Participants made 9.8% errors in go trials and 14.6% errors in double-press trials. (An error in double-press trials meant that participants pressed only one key or no key at all in the 1,000-ms interval.) The go errors showed a backward inhibition effect in the go condition (10.1% vs. 8.5% errors in the backward inhibition and control condition, respectively), t(15) = 1.9, p < .05 (one-tailed), but no such effect in the no-go condition (10.1% vs. 10.5% errors in the backward inhibition and control condition, respectively; t < 1). In the three-way ANOVA, the interaction of trial type and no-go did not reach significance, F(1, 15) = 2.0, p = .18, and neither did any other effects. As in the previous experiments, error data corresponded to the pattern of RT data.

Analysis of RTs proceeded as before. Relative to Experiment 2, responses were faster but less accurate. (The overall RT level was 1,000 ms as compared with 1,250 ms in Experiment 2.) This might be due to participants having set a lower response criterion in Experiment 3. In line with this notion, the error rate was higher than in Experiment 2. Because of the lower RT level, we adjusted the outlier criterion to 3,000 ms in this experiment (0.6% outliers).

Double-press trials were analyzed separately. Akeypress was defined as simultaneous if the interval between first and second keypress did not exceed 50 ms. The second keypress was taken as the RT measure on double-press trials. Mean RT on double-press trials was 547 ms. All double-press trials with an interresponse interval larger than 50 ms (6.4% of the correct double-press trials) and the trial following double press were excluded from analysis. Overall, 70.3% of the trials were included in the analysis.

Table 4 shows RTs as a function of CSI, backward inhibition, and double press. The pattern of results was highly similar to that of Experiment 2. A three-way ANOVA with the variables CSI, backward inhibition, and double press showed the same pattern of significant effects as in Experiment 2. A main effect of CSI, F(1, 15) = 55.7, p < .01, indicated that RTs were shorter when long preparation time was provided. CSI did not interact with any of the other variables (all Fs < 1.5). The main effect of backward inhibition was significant as well, F(1, 15) = 15.8, p < .01. Of importance, there was a significant interaction between backward inhibition and double press, F(1, 15) = 9.6, p < .01, indicating that the double-press manipulation affected the inhibition effect (see Figure 1). Backward inhibition was found in the go condition (82 ms), t(15) = 6.7, p < .01, but the effect was considerably smaller and nonsignificant in the no-go condition (21 ms), t(15) = 1.1, p > .10.

Discussion

The pattern of results was completely analogous to that of Experiment 2: Backward inhibition was found after go trials, and the size of the effect was again in the order of 80 ms. As before, no inhibition was found after trials that did not require response selection. Because all possible responses were executed in these trials, we can rule out the notion that response execution was crucial for backward inhibition to occur. As in the previous experiments, a large CSI effect was obtained, suggesting that participants engaged in preparation processes.

In summary, the logic of the double-press manipulation was as follows: The double-press trials afforded task preparation, a stimulus occurred just like in go trials, and response execution was required. The only way double-press trials differed from go trials was that they did not require response selection. Thus, we can rule out the notion that refraining from executing a response led to the present results. We can also rule out the argument that participants first selected the correct response and then executed both responses because RTs were about twice as fast in double-press trials than in go trials. Therefore, we conclude that backward inhibition is a function of response selection.

However, one might argue that because of the fast responses in double-press trials, the overall duration of these trials was shorter than that of go trials, and this fact might have contributed to the data pattern. In particular, go trials took 1,600 ms + RT, that is about 2,600 ms, whereas double-press trials took only 2,155 ms on average (2,600 ms maximum). Thus, less time had passed from trials n – 2 to n in the double-press condition compared with the go condition. Therefore, persisting interference from previous trials might have been stronger in the double-press condition, and this might have affected the data pattern.

Experiment 4

To control for the effects of trial length, we conducted another experiment in which we adjusted the trial lengths of go trials and double-press trials. In one condition, double-press trials were prolonged to the overall duration of go trials. In a second condition, double-press trials remained the same but go trials were shortened by shortening the RCI. This way, we obtained two conditions with equal trial lengths in each condition.
Method

Participants. Sixteen participants (14 female, 2 male; mean age = 22.8 years) took part in the experiment.

Stimuli, procedure, and design. These were identical to those used in Experiment 3. Trial length was varied in addition to the variables CSI, double press, and backward inhibition. In the long trial condition, go trials remained the same but double-press trials were prolonged by adding 500 ms after the double-press response. Thus, the RCI after double-press trials was 1,100 ms in the long CSI condition and 2,000 ms in the short CSI condition. (The RCIs after go trials were 600 ms and 1,500 ms in the long and short CSI conditions, respectively.) In a second condition, go trials were shortened by 500 ms but double-press trials remained the same as in Experiment 3. This resulted in an RCI of 100 ms and 1,000 ms after go trials in the long and short CSI conditions, respectively. (The RCIs after double-press trials were 600 ms and 1,500 ms in the long and short CSI conditions, respectively.)

Trial length was varied orthogonally to all the other variables. There were always two blocks with short trial length, two blocks with long trial length, and so forth. CSI changed after every block, as in the previous experiments. The order of short and long RCIs and short and long CSIs was counterbalanced across participants. Task sequence was again random. Four of the eight possible S-R mappings were selected randomly, with the constraint that each of the possible stimulus dimensions (odd–even, smaller–larger, and central–peripheral) were mapped equally often to the left and right response key. Instructions mentioned that there were slow and fast trials, and trial length was indicated at the beginning of each block.

Results

The error rate was very similar to that in Experiment 3: It was 10.0% in go trials and 14.6% in double-press trials. As in the previous experiments, the go errors showed a backward inhibition effect in the go condition (10.8% vs. 7.6% errors in the backward inhibition and control conditions, respectively), t(15) = 3.0, p < .01 (one-tailed), but no such effect in the no-go condition (10.5% vs. 9.6% errors in the backward inhibition and control conditions, respectively; t < 1). In the three-way ANOVA, the interaction of trial type and no-go did not reach significance, F(1, 15) = 2.9, p = .11, and neither did any other interaction. There was a main effect of backward inhibition, F(1, 15) = 5.8, p < .05, and a marginally significant main effect of CSI, F(1, 15) = 4.2, p < .06, indicating slightly more errors in the short CSI condition than in the long CSI condition. Again, error data corresponded to the pattern of RT data.

With respect to RT analysis, again RTs longer than 3,000 ms were excluded (1.4%). Double-press trials and the following trial were discarded if the interresponse interval in the double press exceeded 50 ms (5.4% of the correct double-press trials). Overall, 69.3% of the trials were included in the analysis. The mean RT on double-press trials was 551 ms. The go and double-press trials were comparably long in this experiment (mean duration of go and double-press trials = 2,708 ms and 2,650 ms in the long trial condition, and 2,208 ms and 2,150 ms in the short trial condition).

We ran a four-way ANOVA with the factors trial length, CSI, double press, and backward inhibition to test whether trial length affected any of the other variables or interactions. However, trial length did not affect RTs and did not interact with any of the other variables (all Fs < 1). An analogous four-way ANOVA for the error data did not yield any effect of trial length. Therefore, the data were averaged across short and long trials.

The pattern of results was completely analogous to that of Experiments 2 and 3. Table 5 shows RTs as a function of CSI, backward inhibition, and double press. A three-way ANOVA with the variables CSI, backward inhibition, and double press showed the same pattern of significance as the previous experiments: CSI yielded a main effect, F(1, 15) = 67.4, p < .01, and did not interact with any of the other variables (all Fs < 1.8). Again, there was a significant interaction between backward inhibition and double press, F(1, 15) = 7.5, p = .02. Backward inhibition was about the same size as in the previous experiments (84 ms after go trials), t(15) = 6.8, p < .01, and there was no backward inhibition after double-press trials (~17 ms), t(15) = 0.5, p > .30 (see Figure 1).

Discussion

Experiment 4 showed that the difference in the trial length of go and double-press (or no-go) trials in Experiments 1A–3 did not bias the results. Rather, the pattern of results was clearly replicated when trial lengths were adjusted: Backward inhibition occurred after go trials but not after double-press trials. This shows that backward inhibition is neither a result of advance task preparation nor a result of response-execution processes. Instead, the data suggest that response-selection processes (i.e., response conflict) are crucial for inhibition of task sets to occur. Figure 1 provides an overview of backward inhibition in the go and no-go conditions in Experiments 2–4.

General Discussion

The present study addressed the role of response selection for inhibition of task sets in task shifting. Four experiments showed that response selection is necessary for this inhibition to occur. Both residual shift costs (Experiments 1A and 1B) and backward inhibition (Experiments 2–4) were absent after trials that did not require response selection. In the no-go trials of Experiments 1A–2, neither response selection nor response execution were required. To distinguish between selection and execution, we applied double-press trials in Experiments 3 and 4. These required executing both possible responses and thus included response execution but not selection of one response against a competing

<table>
<thead>
<tr>
<th>Table 5</th>
<th>Experiment 4: Reaction Times (in Milliseconds) as a Function of CSI, Go/Double-Press (DP), and Trial Type (ABA vs. CBA)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>CSI and condition</strong></td>
<td><strong>Trial type</strong></td>
</tr>
<tr>
<td></td>
<td><strong>CBA</strong></td>
</tr>
<tr>
<td>CSI = 100 ms</td>
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<tr>
<td>Go in n = 1</td>
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<tr>
<td>DP in n = 1</td>
<td>1,292</td>
</tr>
<tr>
<td>CSI = 1,000 ms</td>
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</tr>
<tr>
<td>Go in n = 1</td>
<td>949</td>
</tr>
<tr>
<td>DP in n = 1</td>
<td>1,005</td>
</tr>
</tbody>
</table>

Note. Go/double-press in the table title refers to trials preceded by a go or double-press trial. CSI = cue–stimulus interval; ABA = switching back to a task after one intermediate trial; CBA = switching back to a task at least two intermediate trials; BI = backward inhibition. **p < .01 (differences were tested with one-tailed t tests).
response. Again, backward inhibition was absent after double-
press trials, providing evidence that the inhibition does not depend
on response execution but on response selection. The pattern of
results was replicated when double-press trials were of comparable
length as go trials (Experiment 4).

After go trials, we found substantial backward inhibition in
Experiments 2–4, supporting Mayr and Keele’s (2000) notion of
inhibition of the previous to-be-abandoned task set. However, it
remained questionable in Mayr and Keele’s study as to which of
the several processes involved in task switching the inhibition is
related to. We observed that backward inhibition occurs with
response-related processes only and not during intentional prepara-
tion for a new task.

In the following, we aim to further characterize inhibition ef-
tects in task switching, addressing two important questions. The
first refers to what exactly is inhibited. The second refers to how
the inhibition process operates.

**Inhibition Effects in Task Switching**

What, then, is inhibited in the present experiments? First, it
might be inhibition of stimulus or response representations. For
instance, one might assume that simply the stimulus representation
of the last executed task becomes inhibited (see, e.g., Hoffmann,
Kiesel, & Sebald, in press, for stimulus-specific effects in task
switching). However, immediate stimulus repetitions were ex-
cluded in the present experiments so that the stimulus-specific
inhibition account can be ruled out in the present context. Alter-
natively, one might assume that the last executed response was
inhibited. However, we should then have found response-
repetition costs after a task switch, which we did not find: There
were no significant effects of response repetition after task switch
in any of the four experiments. Therefore, response inhibition
cannot account for the present effects.

Second, it could be that a task set becomes associated with the
particular stimulus or response with which it occurs (see, e.g.,
Allport & Wylie, 2000; Koch & Allport, 2001; Waszak, Hommel,
& Allport, 2002) and that the whole episode becomes inhibited.
However, inhibition of task-set stimulus episodes is also unlikely
because switching back to a task was never associated with switching
back to the same stimulus in the present experiments. Still, it
might be that task-set response episodes are inhibited. If this were
true, then switching back to a task should be harder when it is
associated with the same response as before than with the other
response. However, the opposite is true: Response repetition led to
smaller, not larger, inhibition effects. Backward inhibition tended
to be smaller when switching back to the same task was associated
with the same response (i.e., response repetition from trial n – 2 to
trial n) than with the other response (i.e., response shift from n –
2 to n). In Experiment 2, backward inhibition was only 56 ms with
response repetition but 117 ms with response shift, and the inter-
action of backward inhibition and response repetition was almost
significant, \(F(1, 15) = 4.5, p = .05\) (the analysis refers to the go
condition). In Experiment 3, backward inhibition was 51 ms with
response repetition versus 119 ms without response repetition, \(F(1,
15) = 5.5, p = .03\). (In Experiment 4, the inhibition effect was not
affected by response repetition; \(F < 1\).) Similar effects of response
repetition have also been reported by Mayr and Keele (2000).

Therefore, we can rule out the notion that task-set episodes were
inhibited in the present context.

The third possibility remains that it is the category–response
rules (e.g., odd–left) that become inhibited. More precisely, the
whole set of task-specific category–response rules (e.g., odd–left,
even–right) becomes inhibited. If only the last executed category–
response rule had been suppressed, then again we should have
found response-repetition effects. It is important to note that the set
of category–response rules (e.g., odd–left, even–right) could be
distinguished from the stimulus set of categories (e.g., parity). At
this point, we cannot decide whether it is useful to make this
distinction. If so, it remains an open question as to whether only
the category–response rules become inhibited or whether the rel-
evant set of categories is also inhibited. This question will be
addressed in future experiments. (We also return to this issue when
discussing other accounts of task switching.)

To account for our data, we suggest that backward inhibition
involves inhibition of the previous category–response mappings.
We believe that the inhibition occurs to support recoding of the
meaning of responses in overlapping S-R tasks (cf. Meiran,
2000b). It should be noted that in most task-shifting studies, the
same set of responses is used for all different tasks so that the
meaning of the responses changes depending on the task. Thus,
when switching from one task to another in typical task-switching
paradigms, a conflict arises between the previous and the current
category–response rules, and it becomes necessary to inhibit the
previous set of rules (cf. Fagot, 1994; Meiran, 2000b; Rubinstein,
Meyer, & Evans, 2001).

Besides the question of what exactly is inhibited in the present
study, it is also important to consider how the inhibition mecha-
nism might work. Two scenarios are possible. The first is that
inhibition of the no-longer-relevant response meanings is a neces-
sary precondition to enable response selection and therefore pre-
cedes response selection. If this were true, then backward inhibi-
tion would occur after the onset of a stimulus but before response
selection starts.

Alternatively, one might conceive of backward inhibition as a
kind of lateral inhibition on the level of response meanings (see
also Mayr & Keele, 2000). That is, selecting the correct category–
response rules is accompanied by inhibiting the competing
category–response rules to increase the relative activation of the
winning rule set.3 Because the category–response rules that were
relevant on the previous trial are the most interfering ones, they
become inhibited to the highest degree. Following this notion,
inhibition of the previous task set arises in the course of response
selection and is intricately linked to the selection process.

Presently, we cannot decide between the first and second alter-
native on the basis of our data. However, we favor the lateral
inhibition idea, for it provides the simpler account. A third alter-
native that is also discussed in the inhibition literature can be
excluded in the present context: The effect cannot be due to

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3 In network modeling, such a mechanism is called the “winner-takes-
it-all principle” (see, e.g., Kohonen, 1984). Selection of an element is
implemented in these models by a certain activation threshold. As soon as
one element reaches threshold activation, it becomes selected. This triggers
inhibition of the competing elements, thus increasing the signal-to-noise
distance.
self-inhibition. In principle, one could imagine that the category–response rules become inhibited after their application (see, e.g., MacKay, 1987). However, the present data show that inhibition of response meaning depends on response selection on the following trial and does not occur after application of the category–response rules on the current trial (otherwise, we should have found backward inhibition in the no-go condition just like in the go condition). Thus, we can rule out in the present context the argument that backward inhibition is a self-inhibition mechanism.

Preparation Processes and Response Processes in Task Switching

As for the nature of preparation processes, we can only draw preliminary conclusions from the present data because it was not the focus of this study. We can conclude, however, that advance preparation does not involve an inhibitory component in this study. In the literature on task shifting, it is widely assumed that advance preparation involves activating a task set or certain components of a task set (e.g., Goschke, 2000; Koch, 2001, in press; Koch & Allport, 2001; Mayr & Kliegl, 2000; Meiran, 1996; Meiran et al., 2000; Sohn & Carlson, 2000). With respect to the present experiments, we assume that the relevant stimulus dimension has been activated and, possibly, the corresponding category–response mappings as well. This assumption provides a simple account for both preparation and response-related processes in task switching: During task preparation, the new stimulus dimension and category–response rules become activated; however, none of the category–response rules reach threshold activation because a stimulus has not yet been presented. Consequently, the rules that were relevant on the previous trial are not yet inhibited but remain activated to some degree. (It must be assumed, however, that the current rules are more strongly activated than the previous rules; otherwise, one would perform the wrong task, which sometimes happens.) As soon as a stimulus occurs and is categorized into one of the possible categories (e.g., “odd”), the corresponding category–response rule reaches threshold activation and is selected. This triggers inhibition of all activated, and therefore competing, category–response rules (and, possibly, further activation of the selected rule). The selected rule is then applied, leading to execution of the specified response.

Such a notion would imply that several rule sets can be activated simultaneously, as long as they remain under threshold. However, once a particular rule set reaches threshold activation, it becomes selected, and activation of the competing rule sets decreases to make the signal more salient. Following this account, a set of category–response rules becomes activated during preparation time and inhibited during response selection. At first sight, this might seem incompatible with the finding that the backward inhibition effect does not interact with preparation time (which has been shown in the present experiments as well as in Mayr & Keele, 2000). One could assume that if both activation and inhibition operated on the same system (i.e., set of category–response rules), then the inhibition effect should be reduced with long preparation time. However, this is not necessarily so: As shown in Figure 2, a long CSI might lead to activation of the relevant rule set, but the prior activation level of this set of rules is lower in the ABA condition than in the CBA condition because of more persisting inhibition. Thus, preparation time would lead to an increased activation level but does not reduce the difference in activation levels between the ABA and the CBA conditions. Consequently, a long CSI would lead to faster RTs in both conditions but would not reduce the difference between these conditions.

Inhibition and Response Processes in Task Switching

The inhibition mechanism outlined above has been developed from a task-shifting paradigm in which different categories are mapped onto the same set of responses. It should be noted, however, that backward inhibition has also been reported with paradigms that involve less response conflict than the present one. For instance, Mayr and Keele (2000) used an odd-item-out paradigm in which participants were required to press one out of four response keys that were spatially compatible with four stimulus positions. The stimuli could differ on three different perceptual dimensions (color, orientation, and movement). For each of these dimensions, there was one stimulus that differed from the others. Thus, this paradigm involved high perceptual demands, but response conflict between the tasks was rather low. The meaning of the responses probably did not change because they always referred to the same four stimulus positions. Nevertheless, substantial backward inhibition was obtained with this paradigm. Arbuthnott and Frank (2000) reported backward inhibition in a paradigm with vocal responses. In each trial, three stimuli appeared on the screen (a number that could be odd or even, a letter that could be consonant or vowel, and a sign that could belong to a text or a math context). The category of the relevant stimulus was to be named verbally. Again, perceptual demands were high, but response conflict was small because a unique response was associated with each of the six possible categories. Moreover, the category–response rules were highly compatible.
How are these findings related to the inhibition effects observed in the present experiments? The above-mentioned paradigms differ from the present one in two aspects. First, there were no overlapping category–response rules and therefore response conflict was reduced. Second, in every trial, more than one stimulus appeared on the screen, with the relevant stimulus dimension being tied to one of these stimuli. Thus, these paradigms required visual search and perceptual filtering processes. In contrast, in the present study, there was only one stimulus at a time, and stimulus dimensions were purely cognitive, so that perceptual filtering could not have played any role. To account for backward inhibition in these different studies, we speculate that there might be different components of backward inhibition: one related to response processes and another related to perceptual processing (filtering). It would be interesting to explore whether and how backward inhibition with vocal responses or with an odd-item-out paradigm is affected by no-go trials. Possibly, these different components of backward inhibition could be dissociated within one experiment, similar to shift costs that also have been shown to consist of several different components (see, e.g., Goschke, 2000; Koch & Allport, 2001; Meiran et al., 2000). For the time being, we can only say that there is a response-related component of backward inhibition that is not tied to preparation processes.

**The Response-Selection Account**

The present response-selection account has been developed mainly from experiments focusing on backward inhibition, but we believe that it is not restricted to this particular phenomenon. Rather, we suggest that it provides a simple account for the costs observed in shifting tasks in general, at least in the large number of studies that used overlapping S-R rules. Of importance, Experiment 1 revealed that there are no shift costs after trials that do not require response selection. Although we have not investigated backward inhibition and shift costs in the same experiment, we suggest that residual shift costs reflect persisting inhibition, just like backward inhibition. Thus, we suggest that residual shift costs reflect persisting inhibition of category–response rules and result from lateral inhibition of response meanings as a consequence of a conflict in response selection.

With regard to preparation processes, our data show that preparation took place but did not include inhibition of the previous task set. On the basis of these findings, we suggest that two task sets can be activated at the same time. Converging evidence for simultaneous activation of task sets also comes from a study by Koch (2001) that demonstrated sequence learning on the level of task sets. To account for effects of task-sequence learning, Koch assumed that two consecutive elements become associated if they are activated at the same time. This suggests that two task sets can be activated simultaneously, at least to some degree.

There are several accounts in the task-switching literature that are compatible with the present response-selection account. In particular, Meiran (2000a, 2000b) and Allport and colleagues (Allport et al., 1994; Allport & Wylie, 1998, 2000) have emphasized the role of response-related processes for residual shift costs. We first turn to Meiran’s model. Meiran (2000a, 2000b) suggested distinguishing between different components of task sets. In particular, he considered a stimulus set and a response set. The response set leads to recoding of the mental representations of responses, which is equivalent to changing the response meaning, or category–response rules in the present account. However, presently, there is no inhibitory component in Meiran’s model so it cannot account for backward inhibition phenomena. 4 The second component, stimulus set, biases the mental representation of the stimulus so that the stimulus dimension relevant for the current task becomes more salient than the irrelevant dimensions. Of importance, Meiran suggested that the reconfiguration of stimulus set and response set (i.e., change of stimulus set and response set in the course of a task switch) takes place independently and at different points in time. Whereas the stimulus set is adjusted during preparation time, the response set is adjusted only in the course of response processes.

Applying Meiran’s (2000a, 2000b) model to the present paradigm, this would imply that the relevant stimulus category set (e.g., parity) is activated during CSI but that the corresponding category–response rules (e.g., odd–left, even–right) are only activated with response processes. Thus, the model differs from the mechanism proposed in the present study in that it distinguishes between category set and category–response rules and in that it assumes the latter to be activated during response processes and not during preparation processes.

Although Meiran’s (2000a, 2000b) model suggests a possible mechanism to account for the present data, we prefer our model outlined above for two reasons. First, it is difficult to see why participants should be able to prepare the stimulus dimension in advance but not the category–response rules. The question of whether this preparation deficit could be overcome in principle or whether it presents a more structural constraint arises. Second, and even more important, the present model is simpler: To account for preparation and response-related processes in task switching, we assume two processes (i.e., activation and inhibition) that operate on the same representation (i.e., sets of category–response rules). Meiran’s model, however, assumes two independent representations (i.e., representation of stimulus and representation of response), and to account for preparation effects and backward inhibition, one would have to assume two independent processes as well (activation and inhibition). It is important to note, however, that from a more global perspective, the two models are very similar, and it may be difficult to distinguish between them empirically.

The role of response selection, and interference from previous tasks, for shift costs has also been stressed by Allport and colleagues (e.g., Allport et al., 1994; Allport & Wylie, 1998, 2000). To account for residual shift costs, they suggested distinguishing between goal setting and S-R readiness (Fagot, 1994). Because participants are obviously able to switch from one task to another, they must have implemented the correct goal; otherwise, they would continue performing the old task. Goal setting, however, does in no way determine RTs; rather, these depend solely on S-R readiness, that is, “the time needed for the system to ‘settle’ to a unique response” (Allport & Wylie, 2000, p. 66). Although the correct goal is set, there might be interference from previous S-R

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4 The model may well be extended to include an inhibition component and a decay parameter to account for the temporal decay of inhibition. So far, the model has been applied to task switching in two-task situations, but it has not yet been applied to a backward inhibition paradigm.
rules that slows response selection. This notion is completely compatible with the present account. Goal activation refers to the relative activation of rule sets: The relevant category–response rules are more strongly activated than the irrelevant rules; otherwise, participants would perform the wrong task. S-R readiness, however, refers to the absolute activation of the relevant rule set; the closer the activation level is to the activation threshold, the faster response selection. S-R readiness is thus influenced by backward inhibition: The activation level is decreased because of persisting inhibition, and the more recently backward inhibition has been applied, the more the activation level is decreased.

In summary, there is converging theorizing in the task-switching literature emphasizing the role of response selection for shift costs. From a more general point of view, the present account holds that interference of cognitive sets is confined to response-related processes and does not occur with preparatory processes. This account is in line with theories suggesting that the cognitive system is not limited with respect to processing capacity but rather that constraints must be set on action selection to enable coordinated action (e.g., Allport, 1987; Neumann, 1990).

Conclusion

The present study investigated interference in switching between tasks that operate on the same stimuli and responses. The data show that the costs of switching tasks result from a conflict in action selection: Selecting a response causes inhibition of the previous response meanings because they are interfering, and such persisting inhibition must be overcome when switching back to this task. We conclude that interference results only from changing demands on action selection; there is no interference resulting from preparing for different tasks in close succession.

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