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Inhibitory processes in language switching: Evidence from switching language-defined response sets

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We used language-defined response sets (digit names from 1 to 9 in different languages) to explore inhibitory processes in language switching. Subjects were required to switch between two (Experiment 1) or among three (Experiment 2) languages. In Experiment 1, we obtained a shift cost when subjects switched between their first and second language, between their first and third language, or between their second and third language. For each language pairing, the shift cost was larger for the relatively dominant language than for the nondominant language (i.e., asymmetric shift cost). In Experiment 2, we assessed inhibition of response sets as reflected in n-2 repetition cost (i.e., the difference between ABA and CBA language sequences). We discuss both effects with respect to inhibitory processes in language switching. The results suggest different functional characteristics of the processes underlying asymmetric shift cost and n-2 repetition cost.

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In cognitive psychology, the task-switching paradigm is thought to be capable of addressing mechanisms underlying the flexible adaptation to changing situations. In task-switching experiments, subjects are introduced to different "tasks", which they perform in a changing sequence. When comparing the performance in a task repetition (i.e., the same task was performed in two successive trials) with that in a task switch, a relative performance benefit of repeating the same task can be observed. This performance difference in reaction time (RT) and error percentage is referred to as "shift cost" (see, e.g., Allport, Styles, & Hsieh, 1994; Meiran, 1996; Rogers & Monsell, 1995).

A possibility to account for the shift cost is to assume that proactive interference from the preceding trial plays a role (Allport et al., 1994; Allport & Wylie, 1999; Gilbert & Shallice, 2002; Koch & Philipp, 2005; Schuch & Koch, 2003). It can be argued that a part of the shift cost results from persisting task activation and inhibition of the preceding trial. Whenever two (or more) tasks are activated, the interference between competing tasks has to be resolved during response selection by activating the relevant task and by inhibiting the irrelevant task. The resulting bias in the activation level persists, at least to some degree, into the next trial (i.e., carryover effect) and leads to an advantage of repeating the task.

In a model of task switching, Meiran (2000) argued that specifically the carryover effects of a "response set" account for a substantial part of the shift cost. Response set, in this context, is defined by the set of all possible response categories for each task. An interesting finding to support the importance of response sets was provided by Hahn, Andersen, and Kramer (2003). In their study, a shift cost still occurred when a stimulus categorisation was repeated but a different response set had to be used in two successive trials (see also Philipp & Koch, 2005).

One possibility to study the role of response sets in task switching is found in "language-switching" studies, in which subjects name stimuli in one of two languages (see, e.g., Costa & Santesteban, 2004; Jackson, Swainson, Cunnington, & Jackson, 2001; Macnamara, Krauthammer, & Bolgar, 1968; Meuter & Allport, 1999). In these studies, switching between language-defined response sets can be studied because the perceptual input and the stimulus categories are kept constant. Usually, subjects are required to name objects (Costa & Santesteban, 2004) or digits (Jackson et al., 2001; Meuter & Allport, 1999) in their first and second language. Repeating a language (i.e., response set) was found to result in a better performance than switching from one language to another. Additionally, this shift cost was usually larger in the first language (L1) than in the second language (L2).

In the language-switching literature this shift cost is mainly attributed to persisting inhibition of a previously irrelevant language. In a model of language selection, Green (1998) argued that the selection of a language leads to the inhibition of momentary irrelevant languages. Adopting this idea, the difference between language-repeat and language-switch trials is explained by persisting inhibition of the language that was irrelevant in the preceding trial (Meuter & Allport, 1999). In the same way, the asymmetry of the shift cost (i.e., larger shift cost in L1 than in L2) is explained by persisting inhibition. Naming a digit in L2 has to go along with a strong inhibition of the more dominant L1, resulting in a strong persisting inhibition. As a consequence, it is relatively difficult to switch back to L1 in the subsequent trial. Naming a digit in L1, on the other hand, requires only little inhibition of the nondominant L2. This hypothesised difference in the amount of persisting inhibition is taken to account for the difference in the shift cost when switching to the dominant vs. nondominant language ("dominance-related inhibition account"). Note, however, that such an argument is not restricted to language switching but can also be found when switching between cognitive tasks (Allport & Wylie, 1999; Yeung & Monsell, 2003).

In this context, it is important to mention that an asymmetric shift cost was not observed in all language-switching studies. For example, Costa and Santesteban (2004) demonstrated that highly proficient bilinguals (which have presumably the same proficiency in L1 and L2) had no asymmetry in the shift cost when switching between L1 and L2. Proficient bilinguals also had no asymmetrical shift cost when switching between L1 and L3. Therefore, it was argued that highly proficient bilinguals show a qualitatively different data pattern when switching between language-defined response sets (Costa & Santesteban, 2004). Yet, although Costa and Santesteban did not find an asymmetric shift-cost pattern, they reported a general language-shift cost. Thus, it could still be argued that persisting inhibition of a recently irrelevant language plays a role in highly proficient bilinguals. In contrast, a dominance-related difference in this inhibition, resulting in asymmetric shift cost, might occur only in less skilled bilinguals (but see Orfanidou & Sumner, 2005, for a different result).

If dominance-related inhibition occurs in nonproficient bilinguals, we should expect to find an asymmetric shift cost whenever subjects switch between two languages that differ in their dominance. However, as regards the occurrence of asymmetrical shift cost in nonproficient bilinguals, to our knowledge, no study examined switching between L1 and L3 or between two non-native languages (L2 and L3). Therefore, it is difficult to generalise the finding of Meuter and Allport (1999) to different language pairings (e.g., switching between L2 and L3).

In our first experiment, subjects switched between either L1 and L2, L1 and L3, or L2 and L3. We defined L1 as being the native language. L2 and L3 were languages that subjects had learnt during school time (defined by the number of school years). With the empirical approach of applying different language pairings, we intended to replicate and extend the findings observed by Meuter and Allport (1999) and by Costa and Santesteban (2004). We expected that an asymmetrical shift cost should occur in each language pairing. The size of this asymmetry, however, might depend on the dominance difference between the two languages used in each language pairing. For example, switching between two non-native languages (L2/L3 language pairing) might lead to a smaller asymmetry than switching between a native (L1) and a non-native language (L2 or L3).

Additionally to the different language pairings, we also extended the experimental designs of previous language-switching studies by a within-subjects manipulation of preparation time. The manipulation of preparation time is informative because most studies in language switching (Jackson et al., 2001; Meuter & Allport, 1999) have not addressed the issue of cognitive preparation in the selection of language-defined response sets. As one exception, a manipulation of preparation time was used as between-subjects variable in the study of Costa and Santesteban (2004). In contrast, we manipulated the preparation time blockwise within subjects. Such a differentiation is important because several studies (Altmann, 2004; Koch, 2001, 2005) showed that a within-subjects manipulation of preparation time led to larger preparation effects than a between-subjects manipulation. Thus, we tested whether we could replicate the findings reported by Costa and Santesteban when using a within-subjects manipulation of preparation time.

The main goal of the present study, however, was to examine the proposed role of inhibition when switching between language-defined response sets. In this context, the shift cost in general was attributed to persisting inhibition of a previously irrelevant response set, whereas the asymmetry of shift cost was attributed to larger residual inhibition of the more dominant language (cf. Meuter & Allport, 1999). To further explore the role of inhibition in language switching, we conducted a second experiment. In this second experiment, we addressed the role of persisting inhibition in language-defined response sets in a different and more direct manner. This was done by studying an “n-2 repetition cost” (see, e.g., Arbuthnott & Frank, 2000; Mayr & Keele, 2000; Schuch & Koch, 2003). An n-2 repetition cost can be found with three different tasks, when performance (of a task *A*) in a task sequence AB*A* is compared to that in a task sequence CB*A*. The increased RT and error rate in a task sequence ABA is attributed to persisting inhibition of a task that was recently switched away from (see Mayr & Keele, 2000). Thus, when assuming an inhibitory process in language switching, one should be able to replicate an n-2 repetition cost in switching among language-defined response sets. Furthermore, if the inhibition of a specific language-defined response set is dependent on language dominance, the inhibition (and thus the n-2 repetition cost) should be larger for the native language (L1) than for non-native languages (i.e., L2 and L3). Here, the comparison of asymmetrical shift cost and the n-2 repetition cost might indicate whether inhibition measured as n-2 repetition cost also accounts for the asymmetric shift cost. In this way, the present study was intended to examine which role inhibitory processes play in switching between language-defined response sets.

EXPERIMENT 1

In Experiment 1, subjects switched between two languages. Each subject participated in three experimental sessions. In one experimental session subjects switched between L1 and L2 ("L1/L2 language pairing"), in one session subjects switched between L1 and L3 ("L1/L3 language pairing"), and in the third experimental session subjects switched between L2 and L3 ("L2/L3 language pairing").

We were specifically interested in the possible occurrence of asymmetrical shift cost. We expected to replicate an (asymmetrical) shift cost in all language pairings (L1/L2 vs. L1/L3 vs. L2/L3). Yet, the size of the asymmetry might differ depending on the dominance difference between languages. In this way, switching between the native and a non-native language (L1/L2 language pairing and L1/L3 language pairing) might lead to a larger asymmetry than switching between two non-native languages (L2/L3 language pairing). Additionally, we employed a cueing-paradigm (Meiran, 1996) and manipulated the cue–stimulus interval (CSI) to study whether preparation time affected the shift cost in general or the proposed asymmetry of shift cost.

Method

Subjects. Eighteen subjects (14 female, mean age 22.6 years) participated in the experiment and received €10.50. All subjects spoke German (as L1), English, and French. For 16 subjects, English was L2 and French was L3; for 2 subjects, French was L2 and English was L3. For most subjects, L2 and L3 were defined by the number of school years a language was learned, based on subjects self-reports. L2 had to be learnt at least 7 years and longer than L3. L3 had to be learnt for at least 4 years. Subjects learned L2 longer (on average 8.50 years) than L3 (5.36 years; the range of differences between L2 and L3 was 2–6 years). Two subjects learned both languages to a similar extent in school (between 5 and 7 years) but differed by more than half a year in the time they spent in a country with English or French as its native language. For those subjects, L2 and L3 were defined by the time spent in the foreign country.

Stimuli and tasks. Stimuli consisted of the Arabian digits 1–9. Subjects had to name each digit in L1, L2, or L3 (depending on the cue that indicated the correct language in each trial). Stimuli were presented one at a time in white in a frame at the centre of a black screen (15-inch monitor) connected to an IBM-compatible PC. The stimuli were 1 cm high and approximately 0.5 cm wide. The viewing distance was approximately 60 cm. The frame, which served as language cue, was white and had either the shape of a diamond (5.3 cm wide/high), indicating German, the shape of a square (width/height of 3.8 cm), indicating English, or the shape of a triangle (4.5 cm wide/ 4.0 cm high), indicating French.

Speech onset of the vocal responses was recorded using a voice-key. Errors were marked by the experimenter in a subject file.

Procedure. The experiment lasted approximately 90 min. Instructions were both given on the screen and orally at the beginning of each session and emphasised speed as well as accuracy. An instruction sheet indicating the cue to language mapping (e.g., square-English) was placed in front of each subject throughout the experiment. The shape of the frame indicating each language was held constant for all subjects in all language pairings (i.e., L1/L2, L1/L3, and L2/L3).

The experiment started with one pure block of 27 trials for each language so that subjects could get used to digit naming in different languages and to the use of a voice key. The order of the languages was counterbalanced across subjects.[1] After the pure blocks, subjects performed the three language-switching sessions (L1/L2, L1/L3, and L2/L3). For each language pairing, there was a separate introduction related to the two relevant languages for the next blocks. Each language-switching session had six blocks of 72 trials each (thus, in total the experiment consisted of 18 blocks with 72 trials each). Before each block, subjects were informed about the CSI in the next block. For each language pairing, blocks with short and long CSI alternated; CSI duration in the first block was counterbalanced across language pairings and subjects. Also, the order of language pairings was counterbalanced across subjects.

A trial started with a black screen followed by a cue. After a preparation time (CSI) of 100 ms or 1000 ms, the stimulus was presented in the middle of the cue frame. The interval between the response of the subject and the next cue (response–cue interval, RCI) was 1000 ms or 100 ms. The time between response and stimulus (response–stimulus interval; RSI) was constant 1100 ms (RCI 1000/CSI 100 vs. RCI 100/CSI 1000) in each trial.

The sequence of trials was controlled for an equal number of each language, digit, and language sequence (language repetition vs. language

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[1] On the level of individual subjects, we cannot use the pure block RTs as a measure of L1, L2, and L3 proficiency because unspecific practice effects were relatively large at the beginning of the experiment and the order of pure blocks was manipulated between subjects.

switch). Immediate repetition of a stimulus was excluded. Furthermore, a stimulus that had to be named in one language could not occur the next time when this language was required.

Design. For pure blocks, language (L1 vs. L2 vs. L3) was a within-subjects independent variable. As language is a variable with three levels, we report ε-values when different from 1.0 and use the Huynh-Feldt test to report *p*-values based on corrected degrees of freedom. However, we still report noncorrected degrees of freedom. RT and error percentage were measured as dependent variables. However, only a RT analysis will be reported for pure blocks because too few errors (1.5%) occurred in these blocks.

In language-switching blocks, language sequence (n-1 repetition vs. n-1 switch), dominance of language (dominant vs. nondominant language in the present language pairing), language pairing (L1/L2 vs. L1/L3 vs. L2/L3), and CSI (100 ms vs. 1000 ms) were within-subjects independent variables. For the variable language pairing, we report ε-values when different from 1.0 and use the Huynh-Feldt test. RT and error percentage were measured as dependent variables. In all analyses, significance was tested at alpha = .05.

Results and discussion

The first two trials of each block were discarded from analysis as well as RTs above 2500 ms or below 200 ms (0.9% of otherwise correct trials). In each analysis only trials preceded by at least two correct trials were included. For error analysis, we only analysed language and number-related errors (3.1%) and excluded all other types of errors (e.g., voice-key errors) from the analysis. The overall error rate (including voice-key errors) was 3.3%.

Performance in pure blocks. We ran a one-way analysis of variance with language (L1 vs. L2 vs. L3) as independent variable. The effect of language was significant, $F(2, 34) = 11.59$, $\varepsilon = .915$, $p < .01$. Post hoc *t*-tests revealed that L1 (585 ms) differed significantly from L2 (736 ms), $t(1, 17) = 3.98$, $p < .01$, and L3 (758 ms), $t(1, 17) = 5.50$, $p < .01$, whereas the difference between L2 and L3 was not significant, $t(1, 17) < 1.0$, $p > .1$. Thus, the performance in pure blocks shows that subjects named digits faster in their native language than in a foreign language.

Asymmetric shift cost and the effect of different language pairings. We conducted four-way analyses of variance (ANOVAs) with language sequence (n-1 repetition vs. n-1 switch), dominance of language (dominant vs. nondominant language in the present language pairing), language pairing (L1/L2 vs. L1/L3 vs. L2/L3), and CSI (100 ms vs. 1000 ms) as within-subjects independent variables on RT and error data. The analyses revealed significant effects of language sequence, $F(1, 17) = 101.42$, $p < .01$ for the RT analysis, and $F(1, 17) = 29.61$, $p < .01$ for the error analysis. A language repetition was faster (688 ms vs. 784 ms) and more accurate (1.9% vs. 4.3%) than a language switch, resulting in a shift cost of 96 ms and 2.4% (see Table 1). The interaction of language sequence and dominance of language was significant in the RT analysis, $F(1, 17) = 12.88$, $p < .01$, and in the error analysis, $F(1, 17) = 4.70$, $p < .05$, showing an asymmetrical shift cost with a larger cost for the dominant (113 ms/3.1%) than for the nondominant language (79 ms and 1.8%). The asymmetrical shift cost was not influenced by language pairing; *F*s < 2.4, *p*s $> .1$ for the three-way interaction of language sequence, dominance of language, and language pairing in RT and error data.

TABLE 1

Experiment 1: RT (in ms) and error percentage (PE) as a function of language pairing (L1/L2 vs. L1/L3 vs. L2/L3), language sequence (repetition vs. switch), dominance of language (dominant vs. nondominant in the present language pairing), and cue-stimulus interval (100 ms vs. 1000 ms)

	Cue-stimulus interval			
	100 ms		*1000 ms*	
	Mean	*PE*	*Mean*	*PE*
L1/L2 language pairing				
L1 switch trial	808	4.9	740	5.8
L1 repetition trial	700	1.2	595	0.9
L1 shift cost	108	3.7	145	4.9
L2 switch trial	753	3.2	740	4.4
L2 repetition trial	690	1.7	640	1.7
L2 shift cost	63	1.5	100	2.7
L1/L3 language pairing				
L1 switch trial	756	2.4	690	3
L1 repetition trial	684	1.1	594	0.3
L1 shift cost	71	1.3	96	2.7
L3 switch trial	752	2.8	732	4.6
L3 repetition trial	709	1.4	666	1.3
L3 shift cost	42	1.4	66	3.3
L2/L3 language pairing				
L2 switch trial	865	4.8	859	6.2
L2 repetition trial	754	2.3	711	2.7
L2 shift cost	111	2.5	148	3.5
L3 switch trial	862	4.3	849	5.6
L3 repetition trial	772	3.2	738	4.8
L3 shift cost	90	1.1	112	0.8

In sum, we found a substantial language shift cost in the RT and error data when subjects switched between two language-defined response sets. The shift cost was higher for the dominant language than for the nondominant language, replicating the asymmetry reported in previous studies (see, e.g., Jackson et al., 2001; Meuter & Allport, 1999). A comparison between language pairings in which subjects switched between L1 and L2, between L1 and L3, or between L2 and L3, revealed that the asymmetrical shift cost occurred in each of these language pairings but was not statistically different between language pairings.

The data pattern also indicates several effects of the specific language pairings. The RT analysis yielded a significant effect of language pairing, $F(2, 34) = 24.62$, $\varepsilon = .912$, $p < .01$, which was replicated in error data, $F(2, 34) = 13.44$, $p < .01$. The data pattern indicates that the performance was overall worse in the L2/L3 language pairing (802 ms and 4.2% errors) than in the L1/L2 (708 ms and 2.9%) or the L1/L3 language pairing (698 ms and 2.1%).

In the RT analysis, the interaction of language pairing and language sequence was significant, $F(2, 34) = 6.65$, $p < .01$. Pairwise post hoc comparisons revealed that the shift cost was smaller in the L1/L3 language pairing (68 ms) than in the L2/L3 language pairing (104 ms), $F(1, 17) = 11.74$, $p < .01$, and in the L1/L2 language pairing (115 ms), $F(1, 17) = 5.61$, $p < .05$. The difference between the L1/L2 and the L2/L3 language pairing was not significant ($F < 1$). Additionally, there was a significant interaction of language pairing and dominance of language, $F(2, 34) = 5.04$, $\varepsilon = .920$, $p < .05$, in the RT analysis. Pairwise post hoc comparisons revealed that the performance difference between dominant and nondominant language is larger in the L1/L3 language pairing (34 ms) than in the L2/L3 (8 ms), $F(1, 17) = 6.48$, $p < .05$, and in L1/L2 language pairing (-6 ms), $F(1, 17) = 6.95$, $p < .05$. The difference between the L1/L2 and the L2/L3 language pairing was not significant ($F < 1.3$). Taken together, these findings can be described as showing that in a language pairing in which the performance difference between the two languages was large (i.e., L1/L3 language pairing), the shift cost was relatively small at the same time. Put differently, language pairings with a relatively small performance difference between the languages showed a relatively large shift cost.

Effects of preparation time. As regards the effect of preparation time, the main effect of CSI was significant in the RT, $F(1, 17) = 42.65$, $p < .01$, and error analysis, $F(1, 17) = 7.55$, $p < .05$. However, whereas a long preparation time reduced RT (from 759 ms to 713 ms), a long CSI *increased* the error rate from 2.8% to 3.4%. Thus, a long preparation interval led to a performance benefit in the RT data but at the same time to a performance cost in error data. This speed–accuracy tradeoff was quite unexpected because a long preparation time is usually found to improve performance in both RT and error data (e.g., Koch & Philipp, 2005; Meiran, 1996). The speed–accuracy tradeoff might indicate that subjects reduced their response criterion with a long preparation time (faster but more error-prone responses). Therefore, preparation effects have to be treated rather cautiously in Experiment 1.

In the RT analysis, there were significant two-way interactions of CSI and language pairing, $F(2, 34) = 7.80$, $\varepsilon = .961$, $p < .01$, and of CSI and dominance of language, $F(1, 17) = 25.54$, $p < .01$. Additionally, the three-way interaction of CSI, language pairing, and dominance of language was significant, $F(1, 17) = 4.88$, $\varepsilon = .979$, $p < .05$. The data pattern shows that the preparatory-based reduction of RTs was larger in the dominant language than in the nondominant language in the L1/L2 language pairing (86 ms vs. 31 ms), $F(1, 17) = 14.48$, $p < .01$ for the interaction of CSI and dominance of language, and in the L1/L3 language pairing (78 ms vs. 31 ms), $F(1, 17) = 11.02$, $p < .01$. In the L2/L3 language pairing, the preparatory-based reduction was similar for L2 (25 ms) and L3 (23 ms) ($F < 1$). In general, the data pattern shows that when language switching involved L1 the preparation benefit was larger in L1 than in L2 or L3.

The interaction of CSI and language sequence was also significant in the RT analysis, $F(1, 17) = 9.23$, $p < .01$. The data pattern shows that the shift cost was, unexpectedly, *larger* with long preparation time (111 ms) than with a short preparation time (81 ms). Yet, there was no interaction of CSI, language sequence, and dominance of language. Thus, the data pattern does not indicate an influence of preparation time on the asymmetry of shift cost. However, the finding of an increased shift cost with long CSI is rather surprising. In tasks not defined by a language, when the preparation time was manipulated within subjects, it was usually observed that the shift cost was reduced with a long preparation time (Meiran, 2000; Rogers & Monsell, 1995). This reduction of the shift cost was mainly due to a preparation-based RT reduction in switch trials. In Experiment 1, however, we found that a long preparation time reduced RTs in language *repetition* trials more than in switch trials. In a recent language-switching study, Costa and Santesteban (2004) also showed that a long preparation time reduced the shift cost in highly proficient bilinguals. In contrast, Macnamara et al. (1968) found no effect of preparation time on language switching. Thus, the present finding is unexpected with respect to task switching in general and other language-switching studies. No other effect or interaction was significant in RT, Fs < 2.0, ps $> .1$, or error analysis, Fs < 2.7, ps $> .1$.

Summary. Experiment 1 demonstrated that a language-shift cost occurs when subjects switch between two language-defined response sets. Additionally, the shift cost was always larger for the dominant than for the nondominant language, replicating the increased shift cost for L1 that was reported by Meuter and Allport (1999). Note that we found the asymmetric shift cost in each of our three language pairings (L1/L2, L1/L3, and L2/L3). Therefore, our results indicate that an asymmetric shift cost occurs whenever subjects switch between two language-defined response sets that differ in their dominance. In this way, we extend the findings reported in previous language-switching studies with nonproficient bilinguals (e.g., Jackson et al., 2001; Meuter & Allport, 1999).

The manipulation of preparation time led to rather unexpected findings in Experiment 1. First, we observed a speed–accuracy tradeoff, indicating that subjects had faster but more erroneous responses with a long preparation time. This speed–accuracy tradeoff necessitates interpreting findings related to preparation time with extreme caution. Especially the additional finding that a long preparation time increased language-shift cost needs further replication before we can draw any conclusions why the result differed with respect to the other language-switching studies (Costa & Santesteban, 2004; Macnamara et al., 1968) and with respect to task-switching studies in general (e.g., Meiran, 1996).

In language-switching studies, shift cost as well as the asymmetry of shift cost is usually attributed to a dominance-related inhibition effect (cf. Meuter & Allport, 1999). In general, the present findings do not contradict this view. We found asymmetric shift cost, with a larger shift cost for the relatively more dominant language in all language pairings. Thus, the data pattern in Experiment 1 is in accordance with the idea that a competing language has to be inhibited when naming a digit in one language and that the amount of inhibition is larger toward the relatively more dominant language than toward the less dominant language. Yet, the dominance-related inhibition account should also predict that the asymmetry of shift cost is smaller when the dominance difference between two languages is relatively small (i.e., the L2/L3 language pairing). Numerically, as predicted by the dominance-related inhibition account, the asymmetry of shift cost was smaller in the L2/L3 language pairing (29 ms) than in the L1/L2 language pairing (45 ms) but this difference was not significant. Also, the asymmetry of shift cost was not different between the L2/L3 language pairing (29 ms) and the L1/L3 language pairing (30 ms). At the moment, it would be premature to interpret this finding as evidence indicating that the dominance difference between two languages in a language pairing has no effect on the asymmetry of switch cost at all. It might be that the power of the present experiment was not sufficient to show such effects.

However, we did observe an effect of language pairing. The data pattern shows that the performance difference in both languages was larger and the shift cost was smaller in the L1/L3 language pairing as compared to in the L1/L2 or L2/L3 language pairing. This finding could be attributed to a larger interference between two languages that are similar in their performance level, leading to an increase in shift cost. Thus, taken together, the results of Experiment 1 cannot be reconciled with a language-based inhibition account in all respects. Therefore, one might raise the question whether shift cost in general and the asymmetry of shift cost are indeed indicators for residual inhibition of a more dominant language.

EXPERIMENT 2

Experiment 2 was designed to specifically address the notion of inhibitory mechanisms at work when switching among languages. In this experiment, subjects were required to switch among all three languages in an unpredictable sequence. To test whether inhibition of language-defined response sets occurs, we compared performance in an n-2 repetition (e.g., L1–L2–L1) with that in an n-2 switch (e.g., L3–L2–L1), assessing n-2 repetition cost. The finding of n-2 repetition cost would indicate inhibition among response sets. This inhibition is assumed to arise when abandoning the no longer relevant response set, for example at the transition between L1 and L2 in an L1–L2–L1 sequence (see further Mayr & Keele, 2000; Schuch & Koch, 2003). As this inhibition is assumed to persist, it should lead to longer RT in an n-2 repetition compared to an n-2 switch. Furthermore, based on a dominance-related inhibition account (cf. Green, 1998; Meuter & Allport, 1999) one might expect that inhibition, and thus also the n-2 repetition cost, should be larger for L1 in trial n compared to L2 and L3 in trial n.

Method

Subjects. Eighteen new subjects participated in Experiment 2 (14 females, mean age 24.2 years). They were paid €8 for participation. All subjects had German as their L1; 15 subjects spoke English as their L2 (the other 3 subjects had French as their L2 and English as their L3). As L3, seven subjects reported French, three Italian, three Spanish, one Russian, and one Croatian. Subjects learnt L2 longer than L3 (8.41 years vs. 5.22 years; range 7–12 years for L2 and 4–7 years for L3). For 17 subjects, L2 and L3 were defined by the number of school years a language was learned, based on subjects self-reports. There was only one subject, who spend a longer time (3 years) in a foreign French-spoken country than in an English-spoken country (0.5 years), so that we defined L2 and L3 based on time spent in any of these countries for this subject.

Stimuli and tasks. Stimuli and tasks were the same as in Experiment 1. Subjects had to name each digit in their L1, L2, or L3. Subjects were asked to switch among all three languages as indicated by the cues (i.e., the same cues as in Experiment 1, with the triangle indicating either French or any of the other reported languages).

Procedure. The experiment was run in one session with one participant at a time and took about 45 min. The procedure was comparable to Experiment 1. Subjects performed three pure language blocks of 27 trials each before the main experiment to practice digit naming in all three languages. The order of the pure blocks was counterbalanced across subjects (see Footnote 1). The main experiment consisted of six blocks of 108 trials each, in which subjects switched among all three languages.

The sequence of trials was controlled for an equal number of each language, digit, and language sequence (n-2 repetition vs. n-2 switch). The same constraints concerning stimulus repetition as in Experiment 1 were fulfilled. Immediate repetition of a language was also excluded, because repetition is known to affect the occurrence of inhibitory mechanism (Philipp & Koch, 2006). Thus, the language sequence in each language-switching block was pseudo-random, due to the constraints outlined above.

Design. Pure blocks were again analysed using language (L1 vs. L2 vs. L3) as within-subjects variable. For the language-switching blocks, we used language (L1 vs. L2 vs. L3), language sequence (n-2 repetition vs. n-2 switch), and CSI (100 ms vs. 1000 ms) as within-subjects variables. RT and error percentage were measured as dependent variables. Significance was tested at alpha $= .05$. Again we report p-values as corrected by Huynh-Feldt test. However, we report the uncorrected degrees of freedom. As language is a variable with three levels, we again report ε-values if different from 1.0.

Results

The first two trials of each block were discarded from analysis. RT above 2500 ms or below 200 ms were considered as outliers and discarded from analysis (1.3% of otherwise correct trials). For the analysis only trials preceded by at least two correct trials were included. The mean error rate was 5.8%. For the error analysis, errors due to voice-key problems were not regarded in the analysis.

Performance in pure blocks. We ran a one-way analysis of variance with language (L1 vs. L2 vs. L3) as independent variable. The effect of language was significant, $F(2, 34) = 17.27$, $\varepsilon = .583$, $p < .01$. Post hoc t-tests revealed that L1 (519 ms) differed significantly from L2 (558 ms), $t(1, 17) = 2.42$, $p < .05$, and L3 (738 ms), $t(1, 17) = 4.32$, $p < .01$. The difference between L2 and

L3 was also significant, $t(1, 17) = 4.12, p < .01$. That is, we found a clearer difference between L2 and L3 in Experiment 2 compared to Experiment 1. Again, subjects were fastest when they named the digits in the L1.

Inhibition when switching language-defined response sets. To examine the assumption of inhibition when switching language-defined response sets, we conducted a 3 × 2 × 2 analysis of variance with language (L1 vs. L2 vs. L3), language sequence (n-2 repetition vs. n-2 switch), and CSI (100 ms vs. 1000 ms) as within-subjects variables. The RT analysis revealed a significant main effect of language sequence, $F(1, 17) = 20.76$, $p < .01$, indicating that an n-2 language repetition was slower than an n-2 language switch (902 ms vs. 865 ms), leading to an n-2 repetition cost of 37 ms. In error data, the main effect of language sequence failed to reach significance, $F(1, 17) = 1.76$, $p > .1$, but showed a trend in the same direction (0.7% for the difference between n-2 repetitions and n-2 switches).

Language itself did not yield a main effect ($F < 1$ in RT and error data). However, language interacted significantly with language sequence, $F(2, 34) = 14.90$, $\varepsilon = .873$, $p < .01$. Subjects exhibited a larger n-2 repetition cost for L1 (71 ms) than for L2 (−4 ms) and L3 (43 ms; see Table 2). Post hoc comparisons revealed that the n-2 repetition cost in L1 differed significantly from the n-2 repetition cost in L2 and L3, $F(1, 17) = 22.80$, $p < .01$, and

TABLE 2
Experiment 2: RT (in ms) and error percentage (PE) as a function of language (L1 vs. L2 vs. L3), language sequence (n-2 repetition vs. n-2 switch), and cue-stimulus interval (100 ms vs. 1000 ms)

	Cue-stimulus interval			
	100 ms		*1000 ms*	
	Mean	*PE*	*Mean*	*PE*
L1				
n-2 repetition	1002	5.2	819	3.9
n-2 switch	896	2.6	784	3.7
n-2 repetition cost	106	2.6	35	0.2
L2				
n-2 repetition	950	3.2	817	4.1
n-2 switch	928	2.3	847	5.3
n-2 repetition cost	22	0.9	−30	−1.2
L3				
n-2 repetition	965	3.9	858	3.4
n-2 switch	905	3.1	831	2.6
n-2 repetition cost	60	0.8	27	0.8

$F(1, 17) = 7.62$, $p < .05$, respectively. The difference between the n-2 repetition cost in L2 and L3 was also significant, $F(1, 17) = 9.62$, $p < .01$. In the error data, the interaction of language and language sequence failed to reach significance ($F < 1.1$), but mirrored RT data.

Effects of preparation time. Regarding the influence of preparation time, we found a significant main effect of CSI, $F(1, 17) = 38.23$, $p < .01$, in RT data. Subjects were faster with long than with short CSI (826 ms vs. 941 ms). This effect was not present in error data, $F < 1.1$, but as in Experiment 1, subjects tended to produce more errors with long CSI than with short CSI.

The preparation effect was again larger for L1 (147 ms) than for L2 (107 ms), $t(1, 17) = 2.33$, $p < .05$ for the comparison of preparation effects of L1 vs. L2, and L3 (91 ms), $t(1, 17) = 2.67$, $p < .05$ for the comparison of preparation effects of L1 vs. L3; $t(1, 17) < 1$ for the comparison of preparation effect in L2 and L3. This was also reflected in the interaction between language and CSI, $F(2, 34) = 4.45$, $\varepsilon = .873$, $p < .05$. Mirroring RT data, the error rates indicated that there was a different effect of preparation time for the different languages, which, however, fell short of significance, $F(2, 34) = 3.18$, $p > .05$, but showed the same trend as in RT data.

CSI was also found to modulate the inhibition effect, $F(1, 17) = 2.73$, $p < .001$. The inhibition effect decreased with long CSI (from 63 ms to 10 ms) in RT data. Preparation time modulated the inhibition effect in a similar manner also in error data, but this interaction failed to reach significance, $F(1, 17) = 3.33$, $p > .05$. The reduction of n-2 repetition cost with prolonged CSI was unexpected, as previous studies failed to find a significant influence of prolonged preparation time on n-2 repetition cost (Philipp & Koch, 2006; Mayr & Keele, 2000; Schuch & Koch, 2003). The modulation of the inhibition effect by preparation time has so far never been reported in the literature on inhibitory effects in the sequential control of tasks. Thus, the effect we found here should be treated carefully as long as it has not been established more firmly. Finally, the three-way interaction was far from significance in RT and error data (Fs < 1.5). Thus, like in Experiment 1, we found no evidence that preparation time affected the modulation of the inhibition effect by the dominance of the response set.

Summary. Using the n-2 repetition cost as empirical marker, Experiment 2 established and reconfirmed inhibitory mechanisms in switching among language-defined response sets. Our study established an n-2 repetition cost in language switching and, thus, contributes a novel finding. Furthermore, we could partially provide support for the claim made by the dominance-related inhibition account that the more dominant (i.e., native) language was inhibited to a larger degree than a less dominant (i.e., non-native) language. We found strong inhibition effects for L1 that differed from the inhibition exerted towards L2 and L3. However, the n-2 repetition cost for L2 and L3 also differed significantly from each other. Here, we obtained a larger n-2 repetition cost for L3 than for L2. This finding challenges the assumptions of the dominance-related inhibition account (Green, 1998; Meuter & Allport, 1999). Preparation time was found to decrease the inhibition effect for all three languages (or even reversed it as in L2; see Table 2).

GENERAL DISCUSSION

The present study addressed the notion of inhibition when switching among language-defined response sets. In the first experiment, we asked our subjects to name digits in one out of two languages in three different language pairings: L1/L2, L1/L3, and L2/L3. In the second experiment, we addressed inhibitory mechanisms more directly by using a slightly different paradigm. Here, subjects were required to name digits either in L1, L2, or L3 in rapid succession. Furthermore, in both experiments we varied preparation time. In the following discussion we first address the claim that an asymmetric shift cost arises because more inhibition is exerted towards a more dominant language respectively response set (Meuter & Allport, 1999). In the second part, we discuss the preparation effects we obtained.

The role of inhibition for the occurrence of asymmetric shift cost

With regard to the dominance-related inhibition account (Meuter & Allport, 1999), our results are supportive in most points. We replicated the finding of an asymmetric shift cost in all three language pairings assessed in Experiment 1, in that the shift cost was larger for the dominant language compared to the nondominant language. However, the asymmetric shift cost did not differ significantly between language pairings. This result contrasts with findings from Meuter and Allport (1999) as well as Costa and Santesteban (2004) who observed that the asymmetries are smaller when the proficiency of the languages did not differ so much (see also Orfanidou & Sumner, 2005).

In our study, we tested German subjects that learnt their L2 and L3 in school. Given this sample, we expected that subjects should differ in dominance by the time they learnt a language at school. However, we did not find a statistically significant modulation of asymmetric shift cost by the time a language was learnt during school time. As Yeung and Monsell (2003) showed recently, dominance of tasks (or response sets) can be introduced easily during an experiment, simply by practicing one task more than another. Given that our subjects were forced to name digits in two foreign languages, our experiments might also have led to a substantial practice effect in L2 and L3. L1, however, does not benefit as much from practice as L2 and L3 do because it is already more automatised than L2 and L3 and there is thus no further room for improvement of L1 performance. Therefore, one might speculate that language-specific practice effects when switching language-defined response sets counteracted existing dominance differences in both experiments, leading also to the unexpected difference between L2 and L3 in n-2 repetition cost. Note that this interpretation is post hoc and needs to be examined further.

Next to language-specific practice effects one may speculate that the stimulus material we used, that is digits from 1 to 9, might account for these unexpected results. Although there are accounts claiming that digits can be represented in a verbal format (Dehaene, 1992) and thus can be assumed to have access to language-specific processes, no study has systematically compared the language-switching performance for digits with that for non-numerical stimuli. Thus, it might well be that the stimulus material used in a study assessing subjects' ability to switch between languages is more likely to modulate the obtained effects as it is in other studies asking subjects to perform simple perceptual judgements, such as colour or form of a stimulus.

Note also that our study is—to our knowledge—the first study requiring subjects to switch between all possible combinations of three languages (i.e., L1 vs. L2, L1 vs. L3, and L2 vs. L3). So far, studies and theoretical accounts of the mechanisms underlying subjects' ability to switch between languages only considered the switching between L1 and one foreign language (e.g., Green, 1998; Meuter & Allport, 1999). Therefore it seems plausible to speculate that effects obtained when switching between L1 and L2 differ from those obtained when subjects are required to name digits in three languages which are combined variously, simply because of the need to activate not only two but three language-defined response sets in the course of the experiment.

All in all, we obtained asymmetric shift cost in all language pairings in Experiment 1. Meuter and Allport (1999; see also Green, 1998) explained this asymmetric shift cost by persisting inhibition that is exerted towards the different response sets. As the more dominant language is inhibited to a larger degree, there is more residual inhibition to overcome when switching to the more dominant response set. However, using only two tasks in a task-switching paradigm does not allow dissociating persisting activation and persisting inhibition properly (see, e.g., Koch & Philipp, 2005).

An alternative explanation for the asymmetric shift cost is based on persisting activation only. The rationale behind this alternative is as follows: when performing the nondominant task of two tasks, it has to be strongly activated. When subjects are then required to switch to the dominant tasks, the strong residual activation of the nondominant task hampers the implementation of the dominant task, resulting in asymmetric shift cost.

To provide evidence for inhibitory control mechanisms when switching among language-defined response sets, we assessed n-2 repetition cost as a marker of inhibition (Mayr & Keele, 2000) in Experiment 2. In this experiment, subjects showed a substantial n-2 repetition cost that was modulated by language. L1 yielded the largest inhibition effect, and in L2 and L3 the observed n-2 repetition cost was significantly smaller than in L1. Thus, at a first sight, this finding seems to support the claims made by the dominance-related inhibition account. However, although we found the strongest inhibition effect for the most dominant language, the inhibition effect was significantly larger for L3 than for L2. In fact, for L2, the n-2 repetition cost was even absent with long CSI. Thus, with regard to the question whether dominance of a task or response set determines the amount of inhibition exerted towards this task or response set, our results remain ambiguous. Therefore, it also seems to be premature to conclude that inhibition is the only source for the occurrence of asymmetric shift cost, at least those inhibition processes measured by n-2 repetition cost.

Inhibition has indeed been shown to contribute to shift cost found in usual task-switching experiments (Mayr & Keele, 2000). However, the effects were found to be small and mainly present in residual shift cost, that is, that cost that remains even after long preparation time. In our study, the asymmetry of shift cost was found to be insensitive to preparation time, whereas the inhibition effect decreased with long preparation time (see below). Thus, although we observed both asymmetric shift cost and inhibition within the same study, there is no hint showing that inhibition as measured by n-2 repetition cost is the source of asymmetric shift cost when switching between two languages. We therefore conclude that asymmetric shift cost is much better accounted for by persisting activation and that inhibition reflected in n-2 repetition cost contributes only marginally to this cost. However, this certainly does not rule out inhibition as a general mechanism in language switching, even though this inhibition is not systematically related to the dominance of the languages. Furthermore, it remains to be examined whether there is only one type of inhibitory process (i.e., the one reflected in n-2 repetition cost) or if there are several inhibitory processes at work in the control of task sequences and that the process measured by n-2 repetition cost does not contribute to the observed asymmetric switch cost.

Influence of preparation time

With regard to the preparation effects we obtained, we can conclude that preparation did not influence the asymmetry of shift cost. However, we obtained a preparation-based reduction in n-2 repetition cost. Thus, our preparation effects differed largely from those commonly reported in the task-switching literature (see Monsell, 2003, for a review) as well as from the study of Costa and Santesteban (2004).

Given our unexpected finding that preparation increased shift cost instead of decreasing it, a closer inspection of the data showed that preparation was especially beneficial for repetition trials. Thus, it may be that our subjects could prepare the large response set much better when they had to repeat the language than when switching it. In other task-switching studies the benefit may be more evident in switch trials, given the typically smaller response sets and the chance to retrieve the mapping of the stimulus categories onto the response categories during preparation time. Therefore we propose that preparation of such a stimulus–response rule is easier for subjects than preparing a response set as a whole. However, once a response set (i.e., language) has been successfully implemented, preparation of this response set seems to be possible (i.e., probably by rehearsal of the items).

With regard to the discrepancy of our preparation effects in Experiment 1 and those found by Costa and Santesteban (2004) when using comparably large language-defined response sets, it should be noted that the manipulation of preparation time between subjects does not necessarily yield the same effects as manipulating it within subjects (Altmann, 2004; Koch, 2001, 2005). Most studies using a within-subjects manipulation of preparation usually report stronger preparation effects (i.e., stronger reductions in overall RT and error rate as well as reduction in shift cost) as studies using a between-subject manipulation. Given that manipulation of preparation time has so far not been studied more systematically, studies that compare the influence of between- and within-subjects manipulation of preparation time systematically seem to be required (see, e.g., Koch, 2001).

In Experiment 2, we found that inhibition effects decreased with increasing preparation time. So far, inhibition has been shown to be largely insensitive towards intentional preparation (e.g., Mayr & Keele, 2000; Schuch & Koch, 2003). However, it might well be that switching between languages is more sensitive to show preparation effects on n-2 repetition cost than other paradigms. However, as this finding has not been reported so far, caution seems to be warranted in interpreting this finding.

Conclusions

In two experiments, we confirmed inhibition as mechanism when switching language-defined response sets and replicated the asymmetric shift cost that were reported to occur in language switching studies (Costa & Santesteban, 2004, Exp. 1; Jackson et al., 2001; Meuter & Allport, 1999) but which was also found in other cognitive task pairs, such as the for example colour naming and word reading on Stroop stimuli (Allport et al., 1994; Allport & Wylie, 1999; Yeung & Monsell, 2003). Contrary to former theoretical ideas about the source of this asymmetric shift cost, our findings suggest that inhibition measured by n-2 repetition cost is unlikely to account for asymmetric shift cost. Rather, an asymmetric shift cost seems to arise because of persisting activation of the less dominant language. Thus, our results did not support the dominance-related inhibition account as proposed by Meuter and Allport (1999).

Yet, we do not deny that inhibition as a general mechanism plays a role in language switching. By using an n-2 repetition cost as empirical marker we unambiguously demonstrate the occurrence of inhibitory processes when switching language-defined response sets. However, our results also indicate that the inhibition observed in the n-2 repetition cost cannot account for the occurrence of asymmetric shift cost.

As outlined in the introduction, our study provided further evidence for the role of response sets when switching between tasks. Finding both shift cost and n-2 repetition cost when switching among language-defined response sets suggests that response-related processes contribute to our ability to flexibly switch among different tasks (Koch & Philipp, 2005; Schuch & Koch, 2003).

Furthermore, we think that our study also contributes to the ongoing work done in bilingualism research. With regard to this large field of research, we provide further evidence that switching among languages can also be understood in the broad framework of task-switching research (see also Orfanidou & Sumner, 2005, for a similar conclusion). However, although this seems to be true for nonproficient bilinguals (as in our study), it remains to be proven for highly proficient bilinguals who may differ in the way they access and switch between their two languages (cf. Costa & Santesteban, 2004).

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