Persisting activation in voluntary task switching: It all depends on the instructions

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We tested the hypothesis that persisting activation from a previous task execution does not contribute to the switch cost in voluntary task switching. We reasoned that voluntary task switching requires the selection of random task sequences, which necessitates the active inhibition of previously executed tasks. The asymmetric switch cost was used as a marker for persisting activation. Participants switched voluntarily between color naming and word naming. One group was instructed to select unpredictable task sequences. The other group was not instructed to do so. When participants were instructed to be unpredictable, no asymmetric switch cost was observed. When participants were not instructed to be unpredictable, an asymmetric switch cost was observed. We conclude that the amount of persisting activation in voluntary task switching is limited and that the switch cost in voluntary task switching reflects the time needed for reconfiguring the cognitive system from one task to another rather than the time needed to compensate for persisting activation.

An essential aspect of executive control is mental flexibility, which enables us to switch between different actions or tasks. Mental flexibility is often investigated using task-switching procedures in which participants are externally cued to repeat a task or to switch toward another task. Performance on task switches is inferior to performance on task repetitions (i.e., the *switch cost*). Many researchers assume that the switch cost indicates the presence of processes that reconfigure the cognitive system on task switches (Rogers & Monsell, 1995), such as the retrieval of the appropriate task goal and the activation of the corresponding task rules (e.g., Mayr & Kliegl, 2000, 2003; Rubinstein, Meyer, & Evans, 2001). Other researchers claim that the switch cost does not reflect task reconfiguration, but assumes that once a task has been performed, its activation persists over time. Such persisting activation facilitates responding when the same task is repeated, but interferes when a different task is imposed. In this view, the switch cost is related to processes that compensate for such interference (e.g., Allport, Styles, & Hsieh, 1994; Allport & Wylie, 2000; Gilbert & Shallice, 2002; Wylie & Allport, 2000).

Substantial evidence supporting the idea that the switch cost reflects the persisting activation from a previous task comes from task-switching studies using Stroop stimuli (Stroop, 1935), such as a color word printed in a particular color (e.g., the word “red” printed in blue). Two tasks can be applied to Stroop stimuli: naming the color word (word naming) or naming the color of the color word (color naming). Word naming (i.e., reading) is a highly practiced, nearly automatic task, whereas color naming is not automatic (Stroop, 1935). Allport et al. (1994) reasoned that because reconfiguring an automatic task is less

demanding than reconfiguring a nonautomatic task, the reconfiguration view predicts that switching toward color naming is harder than switching toward word naming. Yet studies in which participants have to switch between color and word naming observe the opposite: Word naming is associated with a higher switch cost than is color naming (Allport et al., 1994). This kind of *asymmetric switch cost* does not support the idea that the switch cost reflects task reconfiguration. In contrast, the asymmetric switch cost favors the idea that the switch cost reflects persisting activation. Gilbert and Shallice (2002; see also Yeung & Monsell, 2003) proposed that because color naming is less automatic, it must be activated to a large extent in order to be performed. This high amount of activation persists in the subsequent trial. If this subsequent trial is a switch toward word naming, a lot of interference needs to be overcome and a large switch cost occurs. In contrast, because word naming is nearly automatic, it needs less activation to be performed. Less activation thus persists in the subsequent trial. If this subsequent trial is a switch toward color naming, there is less interference to overcome and a smaller switch cost occurs.

The presence of an asymmetric switch cost offers clear support for the idea that switch costs are originated by processes that compensate for the activation issuing from a previous trial rather than by processes that are involved in the reconfiguration of a task on the current trial (Allport & Wylie, 2000). Yet, other findings suggest that processes of task reconfiguration also contribute to the switch cost (see Monsell, 2003, for a review) and some researchers assume that the switch cost is a combination of task reconfiguration and persisting activation (e.g., Meiran, Chorev, & Sapir, 2000). Nevertheless, the presence of per-

sisting activation in the switch cost complicates the study of reconfiguration processes underlying task switching and mental flexibility in general. A potential solution to this problem is offered by a variant of task switching in which participants are not externally prompted to switch, but switch on a voluntary basis—namely, *voluntary task switching* (Arrington, 2008; Arrington & Logan, 2004, 2005; Liefoghe, Demanet, & Vandierendonck, 2009; Mayr & Bell, 2006). On each trial, a task is randomly selected by the participants and the decision to repeat or switch tasks is now endogenously driven. This was demonstrated by Arrington and Logan (2005), who observed that task-choice behavior is not affected by contextual factors, such as the repetition of stimuli and responses or the occurrence of irrelevant cues. These authors argued that because task selections rely on endogenous processes, a switch cost that follows from a task selection is more likely to reflect task-reconfiguration processes. However, other research demonstrated that task selections in voluntary task switching can be affected by contextual factors (Arrington, 2008; Mayr & Bell, 2006) and, although Arrington and Logan (2005) did not exclude the possibility that persisting activation influences the switch cost in voluntary task switching, a direct test is lacking. In the present study, we provide such a test by investigating the presence of an asymmetric switch cost in voluntary task switching.

Our hypothesis is that the switch cost in voluntary task switching does not reflect persisting activation and that there is no asymmetric switch cost in voluntary task switching. The switch cost in voluntary task switching is qualitatively different from the switch cost in other variants of task switching, because it follows from processes related to a task selection (Arrington & Logan, 2005; Liefoghe et al., 2009). Importantly, the sequence of tasks selected in voluntary task switching is supposed to be random. Processes related to random generation are thus also present in voluntary task switching (Arrington & Logan, 2005). Baddeley, Emslie, Kolodny, and Duncan (1998) argued that in order to generate a random sequence of items (e.g., letters), items must be retrieved in a controlled way and previously retrieved items must be inhibited so that the currently retrieved item is independent from the previously retrieved item. Applied to voluntary task switching, this means that a previously selected and executed task is actively inhibited so that the selection of two consecutive tasks is independent. On the basis of the proposal of Baddeley et al. and the observation that task selection in voluntary task switching partly depends on the amount of inhibition exerted on the previously executed task (Lien & Ruthruff, 2008; Mayr & Bell, 2006), we hypothesize that in voluntary task switching, previously executed tasks are inhibited to such an extent that only a minimal amount of persisting activation is present. Because the asymmetric switch cost is basically the result of processes that compensate for persisting activation, we predict that the asymmetric switch cost is not or is only minimally present in voluntary task switching.

In order to test our prediction, we had two groups of participants switch voluntarily between color and word

naming. In one group (the standard condition), we used the standard instructions, which emphasize that participants have to select tasks randomly. In the second group (the modified condition), we did not present this instruction. If selecting random sequences of tasks reduces persisting activation, then no asymmetric switch cost should be present in the standard condition, whereas in the modified condition an asymmetric switch cost is expected because no random task selection is required. Such a pattern of results suggests, then, that persisting activation does not contribute to the switch cost in voluntary task switching and, by consequence, that the switch cost in voluntary task switching is more likely to reflect task-reconfiguration processes. This conclusion supports previous research on voluntary task switching (Arrington & Logan, 2005; Liefoghe et al., 2009). However, if an asymmetric switch cost is also present in the standard condition, this would indicate that persisting activation contributes to the switch cost in voluntary task switching as it does in other task-switching procedures. Consequently, voluntary task switching may not add anything new to the debate concerning the nature of task-reconfiguration processes.

METHOD

Participants

Fifty students of Ghent University participated for course requirements and credit. All participants had normal or corrected-to-normal vision, were right-handed, and were naive to the purpose of the experiment. Half of the participants were randomly assigned to the standard condition and the other half to the modified condition.

Materials

Stimuli were the Dutch color words *rood* (red), *geel* (yellow), *groen* (green), and *blauw* (blue), presented in the colors red, yellow, green, and blue. Color words were never presented in their matching color. Participants named either the color word or the color in which the color word was presented. Participants performed both tasks manually (e.g., MacLeod, 1991) and responded on a QWERTY keyboard. Both tasks were assigned to a different hand, and the task-to-hand mapping was randomly assigned across participants. For the left-hand task, the response keys “Q,” “W,” “E,” and “R” were used and for the right-hand task the response keys “U,” “I,” “O,” and “P.” For both sets of response keys, the response assignment from left to right was red, yellow, green, and blue.

Procedure

Participants were tested individually using a Pentium III personal computer with a 17-in. color monitor running Tscope (Stevens, Lammertyn, Verbruggen, & Vandierendonck, 2006). Instructions were presented on screen and paraphrased if necessary. In the standard condition, the instructions stated that participants could select which task to perform on each trial, that they should perform each task an approximately equal number of times, and that their pattern of task choices should not be predictable. In order to explain unpredictability, we translated the coin-flipping metaphor of Arrington and Logan’s (2004) initial study into Dutch. In the modified condition, the same instructions were provided except that participants were not instructed to produce unpredictable task sequences.

Five blocks of 80 test trials succeeded one block of 40 practice trials, with a short break after each block. During each break, feedback was provided about the proportion of color-naming and word-naming trials. If the difference in proportion between both tasks was larger than .5, an additional warning was provided indicating that participants should perform each task an approximately equal

Table 1
Outcomes of the ANOVAs Conducted on the Response Times (RTs), Accuracy, Proportion of Task Repetitions, and Proportion of Task Switches

		RT			Accuracy		
		MS_e	$F(1,48)$	η_p^2	MS_e	$F(1,48)$	η_p^2
Global Analysis	Condition	286,952	5.39*	.10	.0089	0.22	.00
	Task	19,870	6.17*	.11	.0037	0.44	.01
	Transition	52,526	95.61*	.67	.0015	31.33*	.39
	Task * condition	19,870	1.00	.02	.0037	1.55	.03
	Transition * condition	52,526	0.24	.01	.0015	0.54	.01
	Task * transition	3,856	14.19*	.23	.0016	1.91	.04
	Condition * task * transition	3,856	6.07*	.11	.0016	12.69*	.21
Standard Condition		MS_e	$F(1,24)$	η_p^2	MS_e	$F(1,24)$	η_p^2
	Task	18,757	1.17	.05	.0053	0.12	.00
	Transition	79,883	34.69*	.59	.0014	22.06*	.48
	Transition * task	3,483	0.94	.04	.0012	3.16	.12
Modified Condition		MS_e	$F(1,24)$	η_p^2	MS_e	$F(1,24)$	η_p^2
	Task	20,983	5.74*	.19	.0021	3.26	.12
	Transition	25,168	89.92*	.79	.0017	10.83*	.31
	Transition * task	4,229	17.70*	.42	.0020	9.79*	.29
		Proportion of Task Repetitions			Proportion of Task Switches		
		MS_e	$F(1,48)$	η_p^2	MS_e	$F(1,48)$	η_p^2
	Condition	.0086	7.05*	.13	.0086	7.05*	.13
	Task	.0013	1.97	.04	.0000	0.02	.00
	Task * condition	.0013	5.01*	.09	.0000	0.02	.00

* $p < .05$.

number of times. In the standard condition, an additional message was also displayed, which reminded participants that they had to produce unpredictable task sequences. In the modified condition, this message was not shown. On each trial, the stimulus was presented in the center of a black screen in 14-point Arial font. When a response was given or a maximum presentation time of 3,000 msec had elapsed, the stimulus disappeared. For incorrect responses, the screen turned red for 200 msec before the intertrial interval of 100 msec started.

RESULTS

Trials were first categorized according to the task that was chosen. Next, trials were classified as a task repetition or a task switch. Mean response times (RTs) of correct trials were analyzed after removal of trials following an error and trials with RTs shorter than 100 msec (data loss, 8.3%). Global analyses were conducted on the RTs and accuracies. These were subjected to a 2 (condition: modified or standard) $\times$ 2 (transition: task repetition or task switch) $\times$ 2 (task: word naming or color naming) mixed ANOVA, with repeated measures on the last two factors. The alpha level was .05. The outcome of these global analyses is presented in Table 1. RTs and accuracies of each cell of the design are shown in Figure 1.

Of primary importance in these global analyses is that the three-way interactions between task, transition, and condition were significant both for the RTs and the accuracies. As can be seen in Figure 1, the two conditions had different effects on switch performance. In order to clarify these results, we analyzed both conditions separately by means of two-way ANOVAs. The outcomes of these ANOVAs are also presented in Table 1. In the standard condition (left part of Figure 1), RTs on task repetitions were

smaller than were RTs on task switches. A switch cost was thus observed. RTs did not differ between color naming and word naming. The two-way interaction between task and transition was not significant. The switch cost was thus similar for word and color naming. In analogy, for the accuracy data, a switch cost was present but the interaction between task and transition was not significant. The switch cost measured by means of RTs and accuracy was therefore similar for word naming and color naming.

In the standard condition, there was thus no asymmetric switch cost. However, the switch cost in the standard condition was still 23 msec larger for word naming than for color naming. Possibly, the difference between word naming and color naming was attenuated due to a ceiling

Figure 1. Response times and accuracies as a function of transition type (repetition, switch), task type (word, color), and condition (standard, modified).

effect. In order to test for this possibility, we categorized RTs from fast to slow, in four bins. The interaction between task, transition, and bin was not significant ($F < 1$). The absence of an asymmetric switch cost in the standard condition therefore did not depend on response speed.

The modified condition is presented in the right part of Figure 1. RTs were smaller for task repetitions than for task switches. A switch cost was thus again present. RTs were larger for word naming than for color naming. Task and transition interacted. Additional planned comparisons performed on this interaction showed that for task repetitions, there was no difference in RTs between color naming and word naming ($F < 1$). In contrast, for task switches, RTs were longer for word naming than for color naming [$F(1,24) = 13.38$, $MS_e = 14,392$, $\eta_p^2 = .36$]. For the accuracy data, a switch cost was also present. Furthermore, task and transition interacted. Planned comparisons indicated that accuracy did not differ between the two tasks on task-repetition trials [$F(1,24) = 1.54$, $MS_e = .0011$, $p > .2$, $\eta_p^2 = .06$]. In contrast, for task switches, accuracy was higher for color naming than for word naming [$F(1,24) = 8.22$, $MS_e = .0030$, $\eta_p^2 = .26$]. In the modified condition, RTs and accuracies indicated a larger switch cost for word naming than for color naming (i.e., an asymmetric switch cost).

For reasons of completeness, we also report the main effects of the global analyses: RTs were faster in the modified condition ($M = 1,177$ msec; $SE = 53$) than in the standard condition ($M = 1,353$ msec; $SE = 53$); RTs were faster on task repetitions ($M = 1,107$ msec; $SE = 39$) than on task switches ($M = 1,424$ msec; $SE = 44$); and RTs were faster for color naming ($M = 1,240$ msec; $SE = 38$) than for word naming ($M = 1,290$ msec; $SE = 40$). With regard to accuracy, only the main effect of transition was significant: Accuracy was higher on task repetitions ($M = .93$, $SE = .01$) than on task switches ($M = .90$, $SE = .01$).

We also analyzed proportions of task selections. To this end, we considered all trials without exclusion. In each condition, we calculated the proportion of task repetitions and the proportion of task switches. Next, we subdivided each proportion into a subproportion of color-naming trials and a subproportion of word-naming trials. All these proportions appear in Table 2. The mean proportion of task repetitions across both conditions was $.639 \pm .039$ (95% confidence interval) and the mean proportion of task switches across both conditions was $.361 \pm .039$. Participants repeated tasks more often than they switched.

Table 2
Choice Proportions As a Function of Transition Type (Repetitions, Switches), Task Type (Color, Word), and Instruction Condition (Standard, Modified)

	Repetitions			Switches		
	Color	Word	Total	Color	Word	Total
Standard	.292 <i>.014</i>	.298 <i>.014</i>	.590	.205 <i>.013</i>	.205 <i>.013</i>	.410
Modified	.357 <i>.014</i>	.331 <i>.014</i>	.688	.156 <i>.013</i>	.156 <i>.013</i>	.312
Mean			.639			.361

Note—Standard errors are in italics.

This is a common finding in voluntary task switching (Arrington, 2008; Arrington & Logan, 2004, 2005; Liefooghe et al., 2009; Mayr & Bell, 2006).

We also tested whether the task-selection proportions differed across both tasks (word naming, color naming) and both conditions (standard condition, modified condition). Because the proportion of task repetitions and the proportion of task switches are not independent [$\text{prop}(\text{switches}) = 1 - \text{prop}(\text{repetitions})$], two ANOVAs were conducted: a first ANOVA on the proportion of task repetitions and a second ANOVA on the proportion of task switches. In both ANOVAs, task and condition were included as factors. The outcomes of these ANOVAs are presented in the lower part of Table 1.

For the ANOVA conducted on task repetitions, the main effect of condition was significant. The proportion of task repetitions was higher in the modified condition than in the standard condition. The main effect of task was not significant. Both main effects interacted. Planned comparisons indicated that, in the standard condition, the proportion of task repetitions did not differ between the two tasks ($F < 1$). In contrast, for the modified condition, the proportion of task repetitions was higher for color naming than for word naming [$F(1,48) = 6.63$, $\eta_p^2 = .12$]. In other words, in the modified condition, color naming was repeated more often than word naming. For the ANOVA conducted on the task switches, the main effect of condition was also significant: The proportion of task switches was lower in the modified condition than in the standard condition. The main effect of task and the two-way interaction were not significant.

DISCUSSION

The nature of the switch cost is under debate. Some researchers propose that switch costs reflect task-reconfiguration processes, whereas other researchers state that switch costs are related to processes that compensate for persisting activation. The latter view gained strong support from task-switching studies using Stroop stimuli. These studies observed an asymmetric switch cost, which cannot be accounted for by the reconfiguration view and is best explained in terms of persisting activation. Previous research nevertheless suggests that the switch cost is more likely to reflect reconfiguration processes when participants switch on a voluntary basis (Arrington & Logan, 2004, 2005; Liefooghe et al., 2009). Yet no direct test of the presence of persisting activation in voluntary task switching has been conducted so far. We hypothesized that less persisting activation is present in voluntary task switching, because in voluntary task switching, tasks are selected randomly, which necessitates the active inhibition of previously selected tasks (see also Baddeley et al., 1998). Accordingly, we predicted no asymmetric switch cost. Our results confirm this prediction. In the standard condition, there was no asymmetric switch cost. In contrast, in the modified condition an asymmetric switch cost was observed. Furthermore, in the standard condition, both tasks were selected equally often, whereas in the modified condition color naming was repeated more often

than word naming. When tasks are not selected randomly, switching toward word naming is harder than switching toward color naming, and word naming is even avoided. When tasks are selected randomly, however, no such effects occur, yet a significant switch cost was still present. Because this switch cost cannot be explained by persisting activation, it is thus probably more reflective of task-reconfiguration processes.

The results of the present study imply that there is less persisting activation in voluntary task switching than in task-switching procedures in which task sequences are indicated externally. To confirm this assumption, we ran an additional experiment, which is presented in the Appendix. This additional experiment was similar to our main experiment, except that the tasks were externally cued. Stimuli were presented in a 2×2 grid. Depending on the position of the stimuli in the grid, participants performed color naming or word naming (Rogers & Monsell, 1995). As can be seen in Figure A1, a clear asymmetric switch cost was present. The switch cost for word naming was 140 msec larger than the switch cost for color naming. By comparison, this difference was 109 msec in the modified condition and 23 msec in the standard condition of our main experiment. The asymmetric switch cost was thus smaller in voluntary task switching than in task switching with externally indicated task sequences.

The difference between the standard and the modified condition demonstrates that an important prerequisite for obtaining a switch cost that is only minimally affected by persisting activation is that participants must select random task sequences. Whereas previous research argued that the switch cost in voluntary task switching reflects task reconfiguration, because it follows a controlled task choice (Arrington & Logan, 2005; Liefoghe et al., 2009), the present study indicates that it is not the selection of a task in itself that is of importance but the selection of random (task) sequences and the active inhibition this requires (Baddeley et al., 1998). However, we cannot exclude the possibility that other factors besides inhibition also contributed to the difference between the standard and the modified condition. An important problem in the present study is that the only experimentally manipulated (independent) variable was the instruction provided to the participants. Although the variables transition (switch, repeat) and task (color naming, word naming) were treated as independent variables in our analyses (this is standard in the domain of voluntary task switching), these variables are actually dependent variables that are a consequence of the instructions provided to the participants. Additional factors may thus come into play. Furthermore, Mayr and Bell (2006) observed that the amount of inhibition participants exert when selecting a task in voluntary task switching is prone to individual differences, and Arrington and Yates (2009) suggested that different task-selection strategies are adopted depending on the amount of executive control that is available for the participants. Whereas active inhibition may thus be a crucial factor in obtaining a switch cost that is only minimally affected by persisting activation, our data may reflect a far more complex interrelation of additional

factors such as variability in task-selection strategies, motivation, mental fatigue, and so on.

To conclude, our study indicates that there is no contribution of persisting activation to the switch cost in voluntary task switching when random sequences of tasks are selected. However, persisting activation has a clear impact when tasks are not selected randomly. We propose that the selection of random task sequences elicits the active inhibition of persisting activation. Yet we do not exclude the possibility that additional factors also contributed to the effects we observed. Nevertheless, on the basis of the present findings and previous studies (Arrington & Logan, 2005; Liefoghe et al., 2009), we propose that voluntary task switching, with the use of standard instructions, can offer a breakthrough in understanding task reconfiguration by means of switch costs, without contamination of persisting activation.

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APPENDIX

Twenty-seven new participants took part in this additional experiment. Mean RTs (data loss, 7.7%) and accuracies were subjected to a 2 (transition) $\times$ 2 (task) repeated measures ANOVA. RTs and accuracy are presented in Figure A1. For the RTs, both main effects interacted [$F(1,26) = 33.49$, $MS_e = 3,947$, $\eta_p^2 = .56$]. As is shown in Figure A1, the switch cost was significantly larger for word naming (474 msec) than for color naming (334 msec). Accuracy on task repetitions was higher than accuracy on task switches [$F(1,26) = 10.20$, $MS_e = .00102$, $\eta_p^2 = .28$]. No other effect was significant.

Figure A1. Response times and accuracies as a function of transition type (repetition, switch) and task type (word, color).