Research Article

The Cost of a Voluntary Task Switch

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ABSTRACT—*Task-switching paradigms are widely used to study executive control. However, standard paradigms may not require active control to switch tasks. We examined voluntary task switching by having subjects choose which task to perform on a series of bivalent stimuli. Subjects performed parity or magnitude judgments on single digits. Instructions were to perform the two tasks equally often and in a random order. The response-to-stimulus interval (RSI) was either 100 or 1,000 ms, manipulated between blocks. Task alternations were slower than task repetitions, and this switch cost was greater at the short RSI than at the long RSI (310 and 94 ms, respectively). Additionally, subjects produced more task repetitions than expected if the tasks were performed in a random sequence. These results show costs associated with a voluntary task switch, when subjects must actively control the choice of the task to be performed.*

People intuitively feel that humans have a basic degree of control over their actions (but see Wegner, 2003). This control is evident in the fact that a person may choose to respond in various ways when presented with the same environmental input. People assume that the choice to behave in one way versus another depends on the goals of the individual, which may change over time. The coordination of perceptual, cognitive, and motor processes and the ability to reconfigure these processes in response to a change in goals are thought to be functions of executive control (Logan, 1985; Meyer & Kieras, 1997; Norman & Shallice, 1986). Executive control is an important issue in many areas of psychology, including cognitive science, cognitive neuroscience, child development, aging, psychopathology, and individual differences.

Executive control, which is manifest in a number of different phenomena, is often investigated using task switching (Jersild, 1927). Subjects are given a series of target stimuli and asked to perform various tasks on them. The task they must perform changes periodically, and reaction time (RT) is typically slower on trials in which the task alternates than on trials in which the task repeats. This RT difference between repetitions and alternations is called a *switch cost*.

The basis for switch costs has become a controversial topic. Some researchers interpret these costs as reflecting active processes (e.g., Arrington, Altmann, & Carr, 2003; Logan & Gordon, 2001; Mayr & Kliegl, 2000; Meiran, 1996; Rogers & Monsell, 1995; Rubinstein, Meyer, & Evans, 2001), and others interpret them as reflecting passive processes (Allport, Styles, & Hsieh, 1994; Allport & Wylie, 2000; Logan & Bundesen, 2003).

Investigators who interpret switch costs as reflecting active processes generally assume that the requirement to change tasks on alternations evokes a time-consuming control process that is instigated by an executive process and results in a reconfiguration of the subordinate processes that perform the task. For example, Logan and Gordon (2001) modeled this act of control in terms of an executive process that derives control parameters from task-level instructions in working memory and transmits them to subordinate visual attention processes. Similarly, Rubinstein et al. (2001) proposed separate control processes of goal shifting and rule activation. Goal shifting involves updating working memory, whereas rule activation involves either retrieving information from long-term memory or activating the production rules associated with a particular task (also see Mayr & Kliegl, 2000). In this view, because these processes are not required on repetitions, repetitions are faster than alternations. Switch costs reflect the duration of the active processes.

Other researchers suggest that switch costs reflect passive interference from memories of past task sets (*task-set inertia*; Allport et al., 1994) or interference from associations between the current stimulus and its interpretation under the last task set (*task-set priming*; Allport & Wylie, 2000; Wylie & Allport, 2000). These memories interfere on alternations because the last task set and associations to it are no longer appropriate. They do not interfere on repetitions because the last task set and associations to it are appropriate. The time taken to resolve the interference on alternations appears in switch costs. It is not clear whether task-set inertia and task-set priming are resolved by active or passive processes. Allport and his colleagues have suggested that the resolution may be passive, in which case switch costs do not reflect the duration of active processes. However, in order to simulate these passive effects on switch costs, Gilbert and Shallice (2002) had to assume that active processes were engaged on both repetitions and alternations.

One common method for separating active and passive processes is the *explicit task-cuing* procedure (Sudevan & Taylor, 1987). In this procedure, before each target stimulus is presented, subjects are given

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cues that specify which task to perform. Tasks are presented in random order, and trials are divided into repetitions and alternations post hoc. Cuing allows for independent manipulation of the time between the cue and target during which active preparation for the upcoming task can occur and of the overall delay between trials when passive influences from the previous task set dissipate. Cuing procedures produce switch costs that are large and reliable when the interval between the cue and the target is short and that diminish and sometimes disappear as this interval increases (Meiran, 1996). These results support active-reconfiguration accounts of switch costs. However, the explicit task-cuing procedure confounds cue repetitions with task repetitions—both the cue and the task are the same on repetitions, and both the cue and the task are different on alternations—so it is not clear whether switch costs reflect an active process of task switching or an encoding benefit for repeated cues (Logan & Bundesen, 2003; Mayr & Kliegl, 2003).

In the present experiment, we developed a method for studying task switching in the absence of explicit task cues. We presented subjects with a series of single digits on which parity judgments (deciding whether the digit was odd or even) and magnitude judgments (deciding whether the digit was larger or smaller than 5) could be performed. Subjects were told to choose at random which task to perform. Key presses for each task were unique. Thus, the key a subject pressed on each trial revealed the task performed, and the keys pressed on successive trials revealed whether the subject repeated or alternated tasks. In this manner, we were able to identify voluntary task switches and calculate switch costs. We assumed that unlike responding to an externally provided cue to switch tasks, which may not involve an act of control, voluntary task switching necessarily involves active processing. Thus, we were able to determine whether switch costs are observed when subjects actively change task sets.

We manipulated the interval between the response on one trial and the appearance of the stimulus on the next trial—the response-to-stimulus interval (RSI). Switch costs are often smaller the larger the RSI (Rogers & Monsell, 1995) or the larger the interval between the cue and the target (Meiran, 1996). Investigators who assume task switching is an active process interpret this reduction as evidence that the active process can be carried out, at least in part, before the target stimulus occurs (Logan & Gordon, 2001; Mayr & Kliegl, 2000; Meiran, 1996; Rogers & Monsell, 1995). Thus, with voluntary task switching, which engages active processes, any switch costs observed should be smaller the longer the RSI.

In addition to examining the difference between repetitions and alternations, we examined the trials leading up to a task switch to see if we could determine what influenced subjects' decision to switch. Altmann and Gray (2002) argued that task sets decay over trials, and it is possible that subjects are more likely to switch the more the current task set has decayed. We also examined the trials following task switches to see if switches were completed in a single trial, as Rogers and Monsell (1995) suggested, or whether performance continued to speed up over multiple trials following a switch (Monsell, Sumner, & Waters, 2003).

METHOD

Subjects

Seventeen individuals from the Vanderbilt University community participated. Subjects received either class credit or $5 for partici-

pation. We excluded data from 2 subjects because their accuracy was below 90% and from 3 subjects because they failed to produce enough task switches to allow for adequate data for the analyses. Data from the remaining 12 subjects were analyzed.

Apparatus and Stimuli

Presentation of stimuli and recording of responses were controlled by E-Prime 1.1 software (Schneider, Eschman, & Zuccolotto, 2002) running on a Dell Dimension computer with a Trinitron screen. The stimuli were the digits 1, 2, 3, 4, 6, 7, 8, and 9 presented in black on a white background. All digits were 9 mm tall and 6 mm wide. The stimuli appeared in the center of the display, remaining on the screen until a response was recorded. The screen was then blank for either a short (100 ms) or a long (1,000 ms) RSI. Responses were made on the "d" and "f" (left hand) or "j" and "k" (right hand) keys of a QWERTY keyboard using the index and middle fingers. The hand-to-task mapping was counterbalanced across subjects. For the high/low judgment, the key mapping to "lower than 5" was always the key to the left ("d" or "j") for the appropriate hand; the key mapping of the even/odd task varied across subjects.

Procedure

The experiment began with two single-task practice blocks of 16 trials to familiarize subjects with the response mappings for each task. Subjects then received the following instructions:

> Now that you have practiced each task individually, you will do blocks of trials where you will be mixing together these two tasks within a single block of trials. You only need to do one task on each trial—press one button for each digit you see. You have to choose which task to perform on each trial. You should perform each task on about half of the trials and should perform the tasks in a random order. For example imagine that you had a coin that said EvenOdd on one side and LowHigh on the other. Try to perform the tasks as if flipping the coin decided which task to perform. So sometimes you will be repeating the same task and sometimes you will be switching tasks. We don't want you to count the number of times you've done each task or alternate strictly between tasks to be sure you do each one half the time. Just try to do them randomly.

The experimenter probed the subjects to see whether they understood the task-switching procedure and clarified the instructions as necessary. Subjects then completed six blocks of 80 trials each, with self-paced breaks between blocks. The RSI varied between blocks, and the order was counterbalanced across subjects.

RESULTS AND DISCUSSION

For each trial, we categorized the task performed on the basis of the hand subjects used to respond. Error trials were categorized according to the hand subjects used rather than the finger used on the assumption that subjects used the correct hand but wrong finger for the intended task (Miller, 1982; Rosenbaum, Kenny, & Derr, 1983; Scheffers & Coles, 2000). Once task labels were assigned to trials, the trials were categorized into repetitions and alternations on the basis of

the task performed on trial n and trial $n - 1$. In addition to the repetition-versus-alternation classification, trials were labeled on the basis of their position in a run of trials of a given task. The first trial in a run was labeled "S" for "switch." The first repetition was labeled "P1" for "Positive Position 1," the second was labeled "P2," and so forth. Trials were also labeled on the basis of their position leading up to a switch, their negative run position. The trial preceding a switch was labeled "N1" for "Negative Position 1," the prior trial was labeled "N2," and so forth. Error trials, the first trial of each block, and trials with RTs less than 150 ms or greater than 3,000 ms were excluded from the RT analyses.

Switch Costs

The simplest measure of switch costs is the comparison of RTs for repetitions and alternations. Figure 1 shows the mean RTs for alternations and repetitions separated by RSI and task. Alternations were slower than repetitions in all conditions, and these switch costs were greater at the short RSI than at the long RSI. This pattern is typical of results from standard task-switching experiments, showing switch costs that decrease as time between targets increases. This finding demonstrates that when individuals have active control over the choice to switch tasks, there is still a substantial cost in carrying out that switch. This cost is particularly prominent when the task switch is performed under time pressure.

The effect of alternations versus repetitions was analyzed in a 2 (task transition: alternation, repetition) × 2 (RSI: short, long) × 2 (task: even/odd, high/low) repeated measures analysis of variance (ANOVA). RTs were slower for alternations ($M = 998$ ms) than for repetitions ($M = 798$ ms), $F(1, 11) = 63.4$, $p < .01$, $\eta_p^2 = .852$; slower for the even/odd task ($M = 928$ ms) than for the high/low task ($M = 867$ ms), $F(1, 11) = 10.1$, $p < .01$, $\eta_p^2 = .479$; and slower for the short RSI ($M = 1,004$ ms) than for the long RSI ($M = 791$ ms), $F(1, 11) = 24.3$, $p < .01$, $\eta_p^2 = .688$. The effect of task transition interacted significantly with RSI, $F(1, 11) = 31.5$, $p < .01$, $\eta_p^2 = .852$,
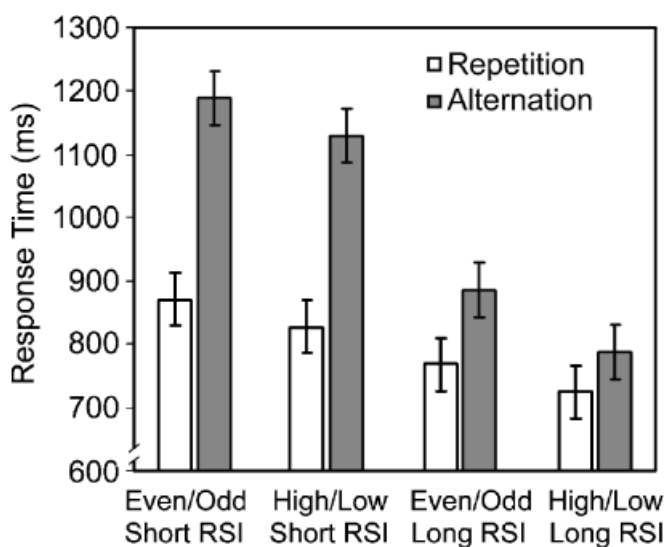
with the switch cost larger at the short RSI than at the long RSI (310 vs. 94 ms, respectively). However, analyzing the two RSI conditions separately showed that the cost associated with switching tasks was significant at both the short and long RSIs, $F(1, 11) = 76.1$, $p < .01$, $\eta_p^2 = .873$, and $F(1, 11) = 6.4$, $p < .05$, $\eta_p^2 = .369$, respectively. The comparable ANOVA for response accuracy showed only a main effect of task, $F(1, 11) = 22.7$, $p < .01$, $\eta_p^2 = .958$, with responding more accurate on the high/low task ($M = .98$) than on the even/odd task ($M = .959$).

Beyond the binary categorization of trials as alternations versus repetitions, position in a run was also considered. The only positions with six or more trials for every subject were switches (S), the two trials following a switch (P1 and P2), and the two trials leading up to a switch (N1 and N2). Figure 2 shows mean RTs for these five positions separated by RSI. Positive and negative run positions were entered into a 2 (RSI: short, long) × 2 (position relative to switch: 1, 2) × 2 (side relative to switch: negative, positive) ANOVA. Responding was slower for the short RSI ($M = 874$ ms) than for the long RSI ($M = 752$ ms), $F(1, 11) = 8.8$, $p < .05$, $\eta_p^2 = .446$. In looking at the effects of position and side relative to switch, we are concerned with whether the switch costs seen in the earlier analysis reflect discrete events or whether there are markers in responding leading up to a switch or lingering effects following a switch. Overall, the two trials prior to a switch (N1 and N2) were slower ($M = 822$ ms) than the two trials following a switch (P1 and P2; $M = 804$ ms), $F(1, 11) = 4.7$, $p = .05$, $\eta_p^2 = .3$, suggesting that a decrease in efficiency over a run may influence the choice to switch (see Altmann & Gray, 2002; Sohn & Anderson, 2001). In addition, the two positions immediately adjacent to the switch (P1 and N1) were slower ($M = 827$ ms) than the two further positions (P2 and N2; $M = 800$ ms), $F(1, 11) = 10.0$, $p < .01$, $\eta_p^2 = .475$, suggesting that the cost of a voluntary switch may not be completely absorbed in a switch trial, but rather may be reflected in slower RTs both leading up to the switch (N1) and following the switch (P1). Moving away from a switch (P1 to P2), there was a decrease in RT that was smaller at the long than at the short RSI. Leading up to a switch (N2 to N1), there was a slight increase in RT for the short RSI and no difference in RT for the long RSI. However, the interaction among these variables was not significant, $F(1, 11) < 1$.

Task-Production Probabilities

Along with the RT analyses, we also considered the probabilities with which different tasks, task transitions, and runs of tasks were produced by the subjects. Subjects complied fairly well with the instruction to perform each task "on about half of the trials," with no subject performing a given task with a probability greater than .57. The even/odd task was performed slightly more often than the high/low task. Averaged across subjects, the probability of performing the even/odd task was .524 for the short RSI and .513 for the long RSI. The difference between RSIs was not significant, $F(1, 11) < 1$. A probability of .5, which would indicate equal performance of the two tasks, was within the 95% confidence interval of the mean probability for the long but not the short RSI. Although performed slightly more often than the high/low task, the even/odd task also resulted in slower RTs, suggesting that subjects did not choose to perform the faster task more often. The choice of task did not vary as a function of the target digit, suggesting that subjects were not making the decision about which task to perform on the basis of particular target stimuli.
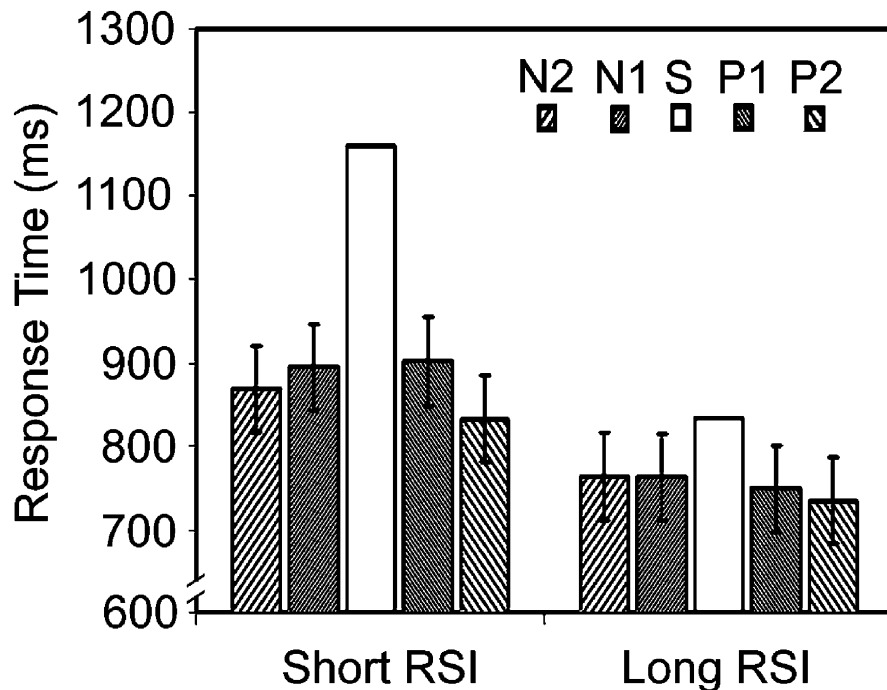

Fig. 1. Mean response times for repetitions and alternations separated by response-to-stimulus interval (RSI) and task. Error bars are 95% confidence intervals calculated from the error term for the interaction.

Fig. 2. Mean response times for switch trials (S), for the trials in the first (P1) and second (P2) positions following a task switch, and for the trials one (N1) and two (N2) trials before a task switch. Results are shown separately for short and long response-to-stimulus intervals (RSIs). Error bars are 95% confidence intervals calculated from the error term of the interaction across these conditions (see the text for details of this analysis).

If subjects performed the tasks in a truly random sequence, the probability of a task repetition should have been .5. The probability of repeating a task was calculated for each subject for each RSI. Across subjects, the mean probability of a repetition was .678 for the short RSI and .595 for the long RSI. The chance probability of a repetition fell outside the 95% confidence interval of the mean probability for each RSI. The probability of a repetition was greater for the short than for the long RSI, $F(1, 11) = 7.0$, $p < .05$, $\eta_p^2 = .39$. Subjects often deviate from randomness when asked to generate random sequences, but there is typically an alternation bias. Repetitions occur with a probability around .4, less often than expected by chance (Nickerson, 2002).[1] In our study, the probability of a repetition deviated from chance in the opposite direction. The deviation from randomness toward more repetitions than alternations may have resulted from subjects avoiding the cost associated with switching tasks.

We also considered the length of runs of the same task. Figure 3 shows the distribution of run lengths (for run lengths of 1 to 10 trials) averaged across subjects for the short and long RSIs, as well as the proportions expected if task production was truly random (i.e., probability of repetition was .5). As the graph shows, the run lengths deviated from expected values, with fewer very short runs and more longer runs than expected. At the level of individual subjects, the
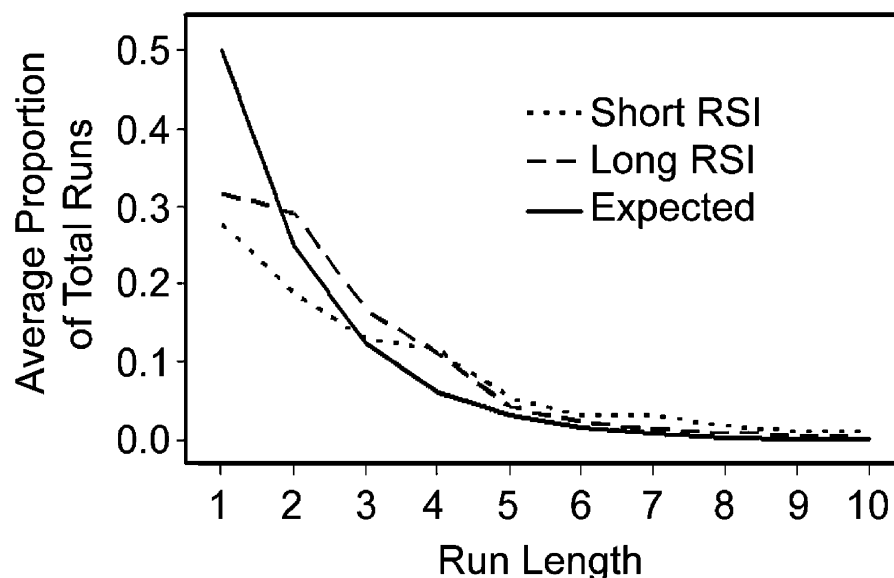
deviation from the expected values was significant for 9 out of 12 subjects at the short RSI and 10 out of 12 subjects at the long RSI. Summed across subjects, this effect was highly significant for both the short RSI, $\chi^2(99, N = 894) = 1,260.3$, $p < .05$, and the long RSI, $\chi^2(99, N = 1,139) = 686.0$, $p < .05$. An analysis of the mean run length across all runs showed that on average subjects produced longer runs when the RSI was short ($M = 5.2$) than when it was long ($M = 2.8$). This difference approached significance, $F(1, 11) = 3.6$, $p < .1$, $\eta_p^2 = .244$. The mean run length predicted by random production of the two tasks ($M = 2$) fell outside the 95% confidence interval for the short RSI and on the 95% confidence interval for the long RSI.

Taken together, these analyses of task-production probabilities suggest that subjects show a reluctance to switch tasks that is pronounced at short RSIs. In the current experiment, the "random production" instructions given to subjects were intended simply to make it possible to look at task switching when subjects actively make the decision to switch tasks rather than follow an external cue to switch tasks. However, the data suggest that the executive processes involved in performing a task switch may hamper subjects' ability to generate random sequences (see also Baddeley, Chincotta, & Adlam, 2001). The voluntary task-switching paradigm introduced here may prove useful in examining the relation between executive processes involved in task switching and random generation.

CONCLUSIONS

We developed a new procedure for studying task switching that requires that an act of executive control be involved in the process of

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[1]Following the task-switching experiment, half of the subjects completed a pencil-and-paper task in which they were asked to write a series of *H*s and *T*s ("*H* for heads" and "*T* for tails") that would represent what they considered to be a typical sequence of flips of a fair coin. The mean probability of a repetition for this sample was .37, in line with the results of other studies on production of random sequences, but different from the probability in the sequences produced by those same subjects when performing the task-switching experiment.

Fig. 3. Distribution of run lengths (1 to 10) averaged across subjects for the short and long response-to-stimulus intervals (RSIs) and the expected distribution in a random sequence of tasks.

switching from one task to another. Subjects were instructed to choose at random which of two possible tasks to perform on a series of bivalent stimuli. This procedure required that subjects engage an active process of control in the decision to switch tasks. The RT results showed switch costs that were greater at the short RSI than at the long RSI, replicating general findings from a wide variety of task-switching procedures. Voluntary task switches slowed performance much as externally cued task switches do.

Our experiment shows that voluntary task switching results in a switch cost, but it does not resolve the controversy over the nature of the cost. A voluntary switch may instigate an active reconfiguration process, the duration of which is reflected in the switch cost (Logan & Gordon, 2001; Meiran, 1996; Rogers & Monsell, 1995). Alternatively, a voluntary switch may create conflict from past task sets. This conflict may be resolved by an active process that suppresses past task sets (Mayr & Keele, 2000), or the conflict may be resolved passively as the system settles into a new mode of processing (Allport et al., 1994; Allport & Wylie, 2000; Gilbert & Shallice, 2002). The reduction in switch cost with increasing RSI (from 310 to 94 ms) is of a magnitude more similar to that seen when manipulating cue-to-target interval (CTI) than that seen when manipulating response-to-cue interval (RCI; see, e.g., Logan & Bundesen, 2003, Experiment 5; Meiran, Chorev, & Sapir, 2000, Experiment 2). Because manipulations of CTI vary time available for active preparation and manipulations of RCI vary time for dissipation of passive processes, the pattern of switch costs seems more compatible with active than with passive processes. However, our results cannot distinguish between two potential active processes that may be involved in voluntary switching: the decision about which task to perform and the subsequent reconfiguration of task set (Logan & Gordon, 2001). Future research is needed to distinguish between them.

Although the similarity of the current behavioral results with those of experiments using explicitly cued task switches suggests that voluntary task switches may involve the same processes as externally cued switches, this conclusion may prove to be false. Using single-cell recordings of monkeys switching from one type of manual response to another, Shima and Tanji (1998) found cells in the cingulate motor area that were active when monkeys made a voluntary shift in response, but not when the response shift was cued externally. Voluntary task switches may involve acts of executive control not involved when task switching is guided by an external cue. Further investigations of voluntary task switching, which may reveal differences in behavior guided by volition and behavior stimulated by the environment, will add to understanding of the processes of executive control.

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