

Individual differences in multiple types of shifting attention

Tor D. Wager<sup>1\*</sup>

John Jonides<sup>2</sup>

Edward E. Smith<sup>1</sup>

Running Head: INDIVIDUAL DIFFERENCES IN SWITCHING

1 Columbia University, Department of Psychology

2 University of Michigan, Department of Psychology

\* Please address correspondence to:

Tor D. Wager  
Department of Psychology  
Columbia University  
1190 Amsterdam Ave.  
New York, NY 10027

Email: [tor@psych.columbia.edu](mailto:tor@psych.columbia.edu)  
Telephone: (212) 854-5318

Abstract

Many researchers consider costs in shifting attention and mental set to reflect a basic ability to use ‘top-down’ goal information to guide action. Although switch costs have been used as measures of individuals’ executive function, whether a common ability to efficiently switch perceptual and response sets across different types of shifting tasks has not been well studied. In 249 participants, we studied whether switch costs in a novel two-choice reaction time task were correlated across variations in two variables: the locus of representation (stimuli were either perceptually available or stored in working memory, WM) and which of two judgment tasks was performed. Switch costs were asymmetrical, in that it was easier to switch to the easier judgment, and related to overall and relative processing speed: Switch costs were higher when the task was more difficult. These factors should be accounted for when individual differences in switch costs is of interest. After controlling for these effects, we found evidence for a common ability underlying switch costs that involved both task-set preparation and response selection; however, ‘residual’ shift costs, which involve only response selection, were uncorrelated. Correlations among switch costs were substantially higher within task-type (e.g., WM shifting tasks with other WM shifting tasks, and perceptual tasks with perceptual ones), suggesting that there are also processes unique to switching within WM and switching among visible stimuli.

## Individual differences in multiple types of shifting attention

A number of research articles in recent years have focused on the reaction time (RT) costs incurred when previously irrelevant information—generally stimuli, stimulus attributes (dimensions), or responses—become relevant due to changing task demands (e.g., Garavan, 1998; Gopher, Armony, & Greenspan, 2000; Hsieh & Allport, 1994; Meiran, Chorev, & Sapir, 2000; Monsell, Yeung, & Azuma, 2000; Rogers & Monsell, 1995; Rubinstein, Meyer, & Evans, 2001; Shafiullah & Monsell, 1999; Yeung & Monsell, 2003). These are generally called ‘task switching’ paradigms, and they are thought to measure the ability to rapidly reconfigure perceptual and response sets to match changing environmental demands. Because a hallmark of such tasks is that they require flexible, context-dependent goal setting and execution, they may be useful as measures of a fundamental type of cognitive control (e.g., Baddeley, 1992; Hitch & Baddeley, 1976; Miller & Cohen, 2001; Norman & Shallice, 1986).

In a typical switching task, one is asked to respond to one of two or more attributes of a stimulus by making a speeded response. For instance, one might see the number/letter pair ‘5A’ and be asked on one trial to judge whether the number is even or odd (Rogers & Monsell, 1995). On the next trial, one may see a new stimulus (‘3C’) and be asked to make a vowel/consonant judgment on the letter (a ‘switch trial’) or make the same odd/even judgment (a ‘no switch’ trial). The increase in average response time on switch trials compared to no switch trials is the most common measure of switch costs.

Although the switching of attention demanded by these tasks is often referred to as an executive process (Garavan, Ross, Li, & Stein, 2000; Gopher, 1996; Kimberg, Aguirre, & D'Esposito, 2000; Miyake et al., 2000; Rubinstein et al., 2001; Sylvester et

al., 2003), there has been debate about what types of mental processes switch costs reflect. According to one view, switch costs are likely to be related at least in part to the time it takes to retrieve previously inactive task rules and goals from long-term memory (Mayr & Kliegl, 2000; Rogers & Monsell, 1995; Spector & Biederman, 1976).

According to a second view, previously performed but currently irrelevant tasks continue to capture attention or prime task goals or both, and switch costs reflect the time it takes to resolve interference from competing task sets (Allport, Styles, & Hsieh, 1994).

Whether observed switch costs are dominated by task-set retrieval or interference resolution may depend largely on the particular demands of the task, including practice on switched-from and switched-to tasks (Wylie & Allport, 2000; Yeung & Monsell, 2003). However, both interference-resolution time and task-set recall time are subsumed under the general idea that switch costs reflect the time it takes to reconfigure processing biases based on top-down goal information (Jersild, 1927; Rogers & Monsell, 1995), with the recognition that not all tasks and stimuli are equally easy to switch among. Thus, though it is still unclear whether switching tasks are composed of multiple controlled retrieval, selective attention, and inhibitory processes, switching tasks are good candidates for core measures of executive control of perception and action.

In this study, we are concerned with a fundamental property of task switch costs: the degree to which they reflect an underlying ability regardless of the type of switching task used. Most experimental studies use one task type per experiment; for instance, switching between number and letter tasks, as in the example above, between odd/even and number magnitude, between global and local judgments, between attended objects or locations, or between several of these at once. These studies vary the cue type (Coull,

Frith, Buchel, & Nobre, 2000), the target tasks (Allport et al., 1994; Rubinstein et al., 2001), and whether switching is among tasks themselves (i.e., both stimulus and response sets), operations (Spector & Biederman, 1976), S-R mapping rules (Rubinstein et al., 2001), objects stored in WM object attributes (Rogers & Monsell, 1995; Owen, Roberts, Polkey, Sahakian, & Robbins, 1991), or combinations of these. Another class of switching tasks involve switching between counters maintained in working memory (Garavan, 1998).

These are all referred to as studies of ‘task switching’ or sometimes ‘attention shifting,’ and theories attempt to account for phenomena discovered in these diverse tasks. However, the question of homogeneity across these tasks is critical if particular shifting tasks are used as measures of executive ability, or even if experimental findings are to be meaningfully integrated into a common theoretical framework. To what degree do these tasks reflect the same underlying core control processes, and to what degree do the ‘executive control’ mechanisms engaged depend on the particular stimuli and processing demands of the task?

We use two strategies to address this question. The first is to assess whether patterns of switch costs vary as a function of what is switched, the type of judgment required, and where information is represented (i.e., perceptually or in WM). The second is to examine how these variables affect individual differences in switch costs.

#### *Individual differences in task switching*

A potentially very informative way to provide information about whether different types of switch costs share common processes is to examine correlations among shift costs from various tasks. Stronger correlations are expected when two tasks share

more common processing requirements, so the magnitudes of correlations among switch costs could be used to garner evidence about which types of switch costs reflect common abilities. However, to date, studies of individual differences in attention shifting appear to constitute an almost entirely separate literature from the one on experimental manipulations of switch costs. The individual differences literature focuses on the concept of executive function, and has thus far largely ignored differences among types of switching.

The idea that switching costs reflect executive control operations suggests that individuals who show low switch costs (efficient performance) may also show better performance on other tests of executive function. Perhaps the most direct test of this theory was conducted by Miyake et al. (2000). They used confirmatory factor analysis to identify performance scores on three putative measures of executive function—switching, inhibition, and monitoring information in WM—and related these factors to performance on commonly used neuropsychological tests thought to measure executive and frontal lobe function. They found that a latent factor of switching, with contributions from switch costs in three different tasks, was moderately related to other measures of executive function. The Wisconsin Card Sorting Task (WCST), in particular, loaded most highly on the switching factor.

Other studies have concluded that putative tests of frontal lobe function share little in common (Burgess, Alderman, Evans, Emslie, & Wilson, 1998; Duncan, Johnson, Swales, & Freer, 1997; Rabbitt & Lowe, 2000; Ward, Roberts, & Phillips, 2001), raising the possibility of separate more specific mechanisms underlying each task. Furthermore, the shared variance across executive function tasks may not be unique to executive

function, but rather shared with performance across a wide range of tasks (i.e., any task that loads high on Spearman's (Duncan, Emslie, Williams, Johnson, & Freer, 1996; Duncan et al., 1997; Rabbitt & Lowe, 2000). An alternative view is that attentional control capacity underlying executive working memory or basic processing speed or both are core abilities underlying diverse types of performance (Bleckley, Durso, Crutchfield, Engle, & Khanna, 2003; Conway, Kane, & Engle, 2003; Kane et al., 2004; Salthouse, 1996; Salthouse, Fristoe, McGuthry, & Hambrick, 1998). Salthouse et al. (1998) found that an identifiable task switching construct was dissociable from processing speed and related to performance on an episodic memory task. However, Salthouse et al.'s switching tasks all involved similar stimuli and tasks – switching between odd/even and magnitude judgments on single-digit numerals – so the representativeness of performance on these tasks of a general switching ability could not be assessed. In fact, none of the studies mentioned above assessed whether switching could be fractionated into separate types.

### *The present study*

In the present experiment, we measured eight types of switch costs that varied on three variables. The first was the perceptual availability of stimuli or the 'locus of representation.' On some trials, participants switched between visible stimuli (e.g., external locus of representation), and on other trials, participants switched between stimuli stored in working memory (WM, internal locus). A second variable was *what* was switched between: Participants switched between whole objects, attributes of objects (i.e., 'dimensions' in the some papers, cf. Owen et al., 1991; Roberts & Wallis, 2000), both, or neither. Two attributes were judged: object shape and object orientation. For

each of external and internal object and attribute switching, we measured separate switch costs for shape and orientation judgments.

The question of interest is whether switch costs for shape and orientation judgments are comparable for external and internal object and attribute switching tasks. Thus, we focused on comparing both magnitudes of switch costs and correlations in switch costs within and across external and internal loci and across shape and orientation judgments. We were particularly interested in whether correlations across varying loci and judgment types were correlated at all, and whether holding each variable constant substantially increased correlations among switch costs. These comparisons were made for both object switches and attribute switches.

We chose these types of tasks (internal and external, object and attribute) because they are commonly used in switching tasks, but an analysis of the importance of variations in these types has not been performed. The classic switching paradigm of Rogers and Monsell (1995), for example, involves simultaneous switching between objects (number or letter) and attributes of those objects (the odd/even status or the vowel/consonant status) represented in an external locus (stimuli are onscreen), but this task is widely considered to be representative of 'task switching' generally. Likewise, we chose to study internal and external loci because there are separate literatures on each type of switch, and they are often assumed to reflect comparable 'task switching' processes; however, because one type involves perception and the other relies on working memory, we reasoned that there might well be separate mechanisms for shifting in each of these domains. In support of this view, an fMRI study using the same paradigm we employ here showed a double dissociation between switching costs in external and

internal loci, with the former producing greater event-related switching activation in bilateral extrastriate cortex, and the latter producing greater activation in left frontal cortex and intraparietal sulcus (Wager, Jonides, Smith, & Nichols, 2005).

Another important variable in switching tasks is whether the goal of responding to one particular attribute can be prepared in advance (e.g., Rogers & Monsell, 1995).

There is substantial evidence that switch costs can be reduced, but not eliminated, by cueing which task is to be performed before presenting the stimulus on which judgments are made (e.g., Mayr, 2003; Mayr & Kliegl, 2000; Meiran, 1996; Rogers & Monsell, 1995). The costs remaining after long preparation intervals are 'residual' switch costs. Based on this evidence, current theory suggests that goal-shifting (or 'endogenous' task-set engagement) and rule-activation are distinct stages of processing (Rubinstein et al., 2001). The first involves retrieval of task goals (e.g., judge the shape) based on cue information, and the second involves selection and application of mapping rules (e.g., rectangle = left response, ellipse = right response), which at least partially requires the presentation of the imperative stimulus.

One type of switching in our study involved no pre-cueing of task, and so switch costs reflected both stages of processing. A second type was divided into preparatory readiness times and residual switch costs. Thus, we could examine whether the patterns we observed applied to both switch costs that involve goal shifting and residual switch costs.

## Method

*Participants*

Participants were 268 adults aged 18 – 40 years, recruited at large from the Ann Arbor, MI area. The study was reviewed and approved by the University of Michigan human-subjects Institutional Review Board. To be included in the analysis, participants were required to be at least 80% accurate in all types of switch and non-switch trials (14 participants were excluded), and 5 participants were excluded as multivariate outliers due to an unusual pattern of reaction time (RT) data across conditions (Johnson & Wichern, 2002) as well, leaving a final sample for analysis of  $n = 249$ .

Participants were paid \$8 per hour for participation, in addition to a performance bonus calculated both on speed and accuracy. Bonus feedback was given after blocks of 48 trials, with 5 cents awarded per correct trial only if participants' mean reaction time was faster than on the previous block. To receive the bonus on the first block, participants had to be faster than 1000 msec on average. Total bonus values ranged from approximately \$3 to \$12.

*Task design*

The task consisted of multi-part trials each requiring two judgments about the same stimulus. Stimuli were images of two overlapping objects, one red and one blue, as shown in the first panel of Figure 1A. The color served as a cue for which object to attend. Each object was either an ellipse or a rectangle (two rectangles or two ellipses were allowed). One object was always oriented vertically, and the other horizontally.

On each self-paced trial, the objects appeared during an initial encoding phase, during which the participant was instructed to focus on the stimulus and prepare for the trial. When participants pressed the space bar, a cue appeared above the shapes with the

words, “Attend Red” or “Attend Blue,” which signaled the participant to attend to the corresponding shape (Orient phase). Upon another spacebar press, a judgment was required (J1 phase): either the words “Judge Shape” or “Judge Orientation” appeared. If shape judgment was indicated, participants pressed the right index finger if the attended shape was an ellipse, or the right middle finger if it was a rectangle. If an orientation judgment was indicated, participants pressed the right index finger if the attended shape was vertical or the right middle finger if it was horizontal.

Following the button press and an additional 200 msec delay (inserted after all remaining phases of the trial), the words “Switch object” or “Stay object” appeared on the screen, indicating whether the participant was to shift attention to the unattended object or remain on the same object (Object cue phase). Participants were instructed to press the spacebar when they completed the shift of attention. After the response and 200 msec delay, the participant was asked to either “Judge Shape” or “Judge Orientation” again (J2 phase). The task performed in J2 was the *Judgment Type* variable in the analysis.

*The Switch variable.* Attribute-switch trials were ones in which the relevant attribute (shape or orientation) for the second judgment was different from that for the first judgment of the trial. The critical RT measure for this was during the second judgment period for switch and non-switch trials. Object-switch trials were ones on which the participant was asked to shift between objects, and two RT measures for this shift were collected: Time to respond to the switch-cue “Stay” vs. “Switch”, and time to respond during the second judgment. Previous research has shown that even given quite a long time to prepare for an upcoming switch trial, responses to targets are still slower

on switch than no-switch trials (e.g., Meiran et al., 2000; Monsell et al., 2000; Rogers & Monsell, 1995).

*The Locus of Representation variable.* On external trials (Figure 1A), the stimulus remained on the screen throughout the trial, and cues appeared just above the stimulus. On internal trials (Figure 1B), the stimulus was present only for the initial viewing period so that it was necessary to refer to a representation of the object in WM to complete the trial. When the words “Attend red” (or blue) appeared, the shape disappeared for the rest of the trial. Blocks of 48 external (E) and internal (I) trials were alternately performed (E I E I E I), with two blocks of practice preceding test blocks. Trials were arranged in a fixed, pre-randomized order to minimize order effects on individual differences (e.g., Miyake et al., 2000).

### **Results and Discussion**

Mean reaction times (RTs) for correct trials in each condition were calculated for each participant after removing outliers greater than three standard deviations from the mean of the condition within participants (Kane & Engle, 2003). This procedure was chosen because it produced the highest overall split-half (odd-even trial) reliabilities and test-retest reliabilities for switching costs, compared to more extensive trimming procedures and log transformation (Rousseeuw, 1984).

We report two kinds of analyses: a) examination of the magnitude of switch costs and how they interact with Judgment Type and Locus of Representation, tested using analysis of variance (ANOVA), and b) pattern hypothesis tests on correlations among switch costs of different types, after controlling for overall and relative processing speed.

In the ANOVA, the three switch type variables were Object Switch Status (switch vs. no switch), Attribute Switch Status (switch vs. no switch), Locus of Representation (external vs. internal), and Judgment Type (shape vs. orientation). Mean RTs and

accuracies were analyzed for effects of each of these variables in a 2 x 2 x 2 x 2 factorial repeated measures ANOVA design. However, because of the large number of main effects and interactions, we present results from *a priori* hypotheses focused on whether switch costs and individual differences in switch costs vary by locus and Judgment Type. These hypotheses concerned attribute and object switch costs during J2 and object switch costs during the object cue period. Means for each trial type, and an explanation of how switch costs are estimated across types, are provided in Table 2. To avoid additional interactions with response compatibility, ANOVA analyses were restricted to incompatible trials; i.e., those on which the responses to the relevant attribute of both objects were different. Otherwise, switch costs and correlations among switch costs could be driven by interference effects on incompatible trials. Though previous studies have usually found these to be additive with switch costs, our goal was to examine switching without this additional complicating variable. Analyses on log RTs produced qualitatively identical results.

*Behavioral Data: RT and Accuracy ANOVAs*

*Main effects of Locus of Representation and Judgment Type.* We first describe main effects of task-type variables for each period of the trial, followed by a description of switch costs and switch-cost asymmetries.

**J1 period.** Processing speed for each task type (Table 1) provides information about the ease (or ‘strength’ of automaticity) of the tasks. A main effect of Locus on RT,  $F(1,248) = 88$ ,  $MSE = 134,000$ ,  $p < .001$ , and accuracy,  $F(1,248) = 63$ ,  $MSE = 0.00255$ ,  $p < .001$ , showed that surprisingly, responses were slower and less accurate in the external than the internal condition (126 msec, .012 difference in proportion correct). This slowing may reflect interference associated with visible cues or greater accessibility of stimuli that are already in WM. We also note that J1 times are slower than J2 times, which could reflect time spent orienting towards the judgment tasks at the beginning of trials or priming of the judgment tasks after J1. These effects were not of primary

interest, as we were concerned with switch costs during J2.

Analyses of Judgment Type (shape vs. orientation judgments) showed a main effect on RT ( $F(1,248) = 68$ ,  $MSE = 171,000$ ,  $p < .001$ ) but not on accuracy. Shape judgments were faster than orientation judgments (101 msec), and these results paralleled our subjective impressions that the shape was a more salient feature of the stimuli. As orientation judgments were slower, and slowness is one indicator of relative salience or automaticity of processing, these results suggest that orientation judgments are the 'weaker' task. There was no Locus x Judgment Type interaction.

**Object cue period.** RT data, presented in Table 2, showed a main effect of Locus ( $F(1,248) = 39$ ,  $MSE = 132,000$ ,  $p < .001$ ). External judgments were slower (by 80 msec). There was no main effect of Judgment Type. Accuracy data were not collected for this period.

**J2 period.** As before, we observed main effects of Judgment Type ( $F(1,248) = 150$ ,  $MSE = 137,000$ ,  $p < .001$ ; Table 2) and Locus ( $F(1,248) = 118$ ,  $MSE = 111,000$ ,  $p < .001$ ). Shape judgments were faster than orientation judgments (by 143 msec), and 'internal' judgments in WM were faster than 'external' perceptual judgments (by 115 msec). There was no Locus of Representation x Judgment Type interaction. Accuracy effects were significant for Locus,  $F(1,248) = 25.18$ ,  $MSE = .0138$ ,  $p < .001$ , indicating that internal judgments were more accurate, but not for Judgment Type. The speed-accuracy tradeoff suggests that neither external nor internal tasks were clearly easier in J2.

*Object and attribute shifting costs*

**J1 period.** Switch costs in J1 performance were not expected in the present analyses, as this period occurs before the presentation of cues to shift or maintain attention. As expected, neither main effects of Object Switch Status nor Attribute Switch Status were significant for either RT or accuracy, even with this large sample ( $n = 249$ ). The observed trends are over an order of magnitude smaller than switch costs observed

during J2. Because we used a fixed, pre-randomized trial order that did not vary across participants, some small differences in J1 cell means are expected due to trial history effects and imperfect random assignment of each of the 8 stimulus types and 2 initial color cues across trial types. These effects proved to be somewhat substantial in the present study, as the mean RTs for different considerably across trial types involving the same initial judgment. However, these effects do not impact the switch costs of interest, as no significant differences in J1 activity as a function of later switching demand were found.

**Object cue period.** We tested for object switch costs during this period, which would indicate that participants took longer to prepare when the cue indicated an object switch. Such costs are similar to 'readiness times' of Meiran et al. (Meiran, Hommel, Bibi, & Lev, 2002), and they are likely to reflect both the time required to reconfigure attentional focus to the unattended object and strategic choices about how completely participants shift attention before they are willing to proceed. We observed a main effect of object switch status ( $F(1,248) = 47$ ,  $MSE = 225,000$ ,  $p < .001$ ), but not attribute switch status, as expected (Table 3). Object switches were 121 msec slower than non-switches. There was no significant Locus x Object Switch interaction.

**J2 period.** This was the critical period in which we expected both attribute and object shift costs, though object shift costs are residual costs after preparation in the Cue period is completed. Here, we discuss whether shift costs were differed for internal and external loci. Subsequently, we discuss whether these shift costs are similar across judgment types (i.e., switch cost asymmetries in switches to shape vs. orientation judgments). Figure 2 shows mean RTs and error rates during J2 for all conditions, and switch costs are reported in Table 3.

We observed main effects of both attribute ( $F(1,248) = 264$ ,  $MSE = 143,000$ ,  $p < .001$ , 194 msec) and object switching ( $F(1,248) = 251$ ,  $MSE = 88,300$ ,  $p < .001$ , 149 msec). Both switch costs were observed in accuracy as well:  $F(1,248) = 198$ ,  $MSE =$

0.00461,  $p < .0001$  for attribute switching (a .0303 decrement), and  $F(1,248) = 113$ ,  $MSE = 0.00471$ ,  $p < .0001$  for object switching (a 0.0232 decrement), as shown in the right panel of Figure 2 and in Table 3.

Attribute switch status showed a trend towards interaction with Locus ( $F(1,248) = 2.94$ ,  $MSE = 253,000$ ,  $p = .08$ ), with RT switch costs of 179 and 211 msec for external and internal loci. Object switch status showed an interaction with Locus ( $F(1,248) = 10.80$ ,  $MSE = 89,000$ ,  $p < .001$ ), with switch costs of 180 and 118 msec for external and internal loci. Switch Status x Locus interactions were observed in accuracy as well: For attribute switch status,  $F(1,248) = 24.80$ ,  $MSE = 0.00373$ ,  $p < .001$ , with larger switch costs for internal (.0400 cost) than external (.0207 cost) loci. For object switch status,  $F(1,248) = 4.14$ ,  $MSE = 0.00373$ ,  $p < .05$ , with larger object switch costs for internal (0.0275 cost) than external (0.0190 cost) loci, although this effect was much less reliable than most effects observed in this study.

These interactions show that attribute switching was substantially more costly on internal representations, whereas object switching costs showed a speed-accuracy tradeoff (Pachella, 1974), with large RT cost differences for external vs. internal locus, and a small accuracy cost difference for internal vs. external locus. Overall, object switches were more difficult in the external locus, and attribute switches were more difficult in the internal locus. This suggests that internal and external shifting demand some different capacities.

If object and attribute shifting are performed serially, one might expect additive effects of object and attribute shifting on J2 RT and accuracy. However, we found a small but significant object Switch Status x Attribute Switch Status interaction in RT,  $F(1,248) = 6.15$ ,  $MSE = 69,800$ ,  $p < .05$ , which indicated that dual switches took longer than the sum of single switch costs (by 21 msec). In accuracy, the effect was stronger,  $F(1,248) = 7.56$ ,  $MSE = 0.00364$ ,  $p < .01$ , with a dual-switch accuracy cost of 0.0052. Object Switch Status x Attribute Switch Status x Locus Interactions were assessed to test

whether dual-switch costs were similar for external and internal loci. This interaction showed a trend in RT data,  $F(1,248) = 3.54$ ,  $MSE = 79,900$ ,  $p = .06$ , with larger Object x Attribute Switch interactions for internal (38 msec) than external (4 msec) loci. Accuracy data showed the same effect,  $F(1,248) = 8.33$ ,  $MSE = 0.00340$ ,  $p < .01$ , with larger Object x Attribute Switch interactions for internal (.0106) than external (.0001) loci. Thus, there was evidence for overadditive costs of dual switches in internal tasks, but almost perfectly additive effects in external loci, providing evidence that switching between stimuli that are visible vs. stored in WM involves different processes.

*Switch cost asymmetries (Judgment Type x Object/Attribute Switch)*

We examined asymmetries in switch costs in J2 depending on Judgment Type to test whether switch costs were similar across shape and orientation judgment tasks. Differences in attribute switching by Judgment Type are 'asymmetries' in task switch costs, which reflect the difference in switch costs when shifting from orientation to shape (referred to in Tables 4-6 as *sh*) compared with shifts from shape to orientation (referred to as *or*). Some previous work has found that it is easier to switch to the 'weaker' (slower) task (A. Allport et al., 1994; Monsell et al., 2000), but other studies have found the reverse (Monsell et al., 2000). The difference is thought to be a function of how much the strong task can interfere with the weak one (Yeung & Monsell, 2003). With much interference, the strong task may be actively suppressed when performing the 'weaker' task, causing greater difficulty in switching to the stronger task. For object shifts, effects of Judgment Type reflect asymmetries in shifting from object to object on the stronger task (shape, in the present experiment) compared with the weaker one (orientation). Asymmetries between switch costs were assessed by Judgment Type x Switch Status interactions.

Effects of Judgment Type on switch costs provide some support for the idea that cognitive processes may be differentially engaged in switching between strong and weak tasks (for attribute switches) or switching between objects depending on the ease of the

task (for object switches). One example of a process that may be more strongly engaged with harder tasks may be task-set retrieval from long-term memory (Dreher, Koechlin, Ali, & Grafman, 2002; Mayr & Kliegl, 2000), which may be more difficult for weaker tasks, particularly if the stimulus serves as a cue for task-set retrieval (Koch, 2003; Wylie & Allport, 2000). Here we tested for asymmetries in overall switch costs. Below, we provide more direct tests of the similarity of switching on stronger (shape) and weaker (orientation) tasks with correlation analyses.

The Judgment Type x Object Switch Status effect was significant for RT and accuracy. For RT,  $F(1,248) = 4.56$ ,  $MSE = 50,300$ ,  $p < .05$ , and for accuracy,  $F(1,248) = 14.90$ ,  $MSE = 0.00505$ ,  $p < .001$ . Object switch costs were higher when judging orientation (177 msec, .0290 accuracy costs) than shape (121 msec, .0145 accuracy costs). Thus, it is easier to switch among objects when the task is easier.

The Judgment Type x Attribute Switch Status was significant for RT and accuracy. For RT,  $F(1,248) = 31$ ,  $MSE = 82,500$ ,  $p < .001$ , and for accuracy,  $F(1,248) = 7.59$ ,  $MSE = 0.00509$ ,  $p < .01$ . Attribute switch costs were higher when switching from shape to orientation (245 msec, .0322 accuracy costs) than from orientation to shape (144 msec, .0241 costs). Thus, it was more difficult to shift to (and easier to shift away from) the weaker orientation judgment task.

Object switch cost asymmetries were similar for external and internal loci, as suggested by a nonsignificant Locus x Judgment Type x Object Switch Status interaction. However, in accuracy, there was a significant interaction:  $F(1,248) = 8.12$ ,  $MSE = 0.00409$ ,  $p < .01$ , indicating that asymmetries were greater for external (.0029 accuracy asymmetry) than internal (0.0059 asymmetry) loci. The Locus x Judgment Type x Attribute Switch Status interaction was not significant in either RT or accuracy.

In sum, we found that it was easier to switch to the weaker task, and that it was easier to switch among objects when the task was easier (particularly for the external locus).

*Individual Differences: Correlations*

*Analysis strategy and tests.* For switching attention to be a meaningful construct, switching costs should be correlated across different types of switching (e.g., across judgment types and loci). Significant correlations across different types (e.g. internal switching to shape judgments vs. external shifting to orientation judgments) would suggest common processes underlying even relatively diverse types of shifting attention, whereas null findings would provide evidence that switching costs involve different processes depending on where stimuli are represented and what task is performed. We also tested whether holding Locus and Judgment Type constant increased the magnitude of correlations among switch costs. If correlations between two external switch costs are greater than across external/internal, for example, then there are likely to be some mental processes that are unique to internal and external shifting. The same argument applies for correlations within vs. across judgment types. Significance tests on these hypotheses are perhaps most easily performed using pattern hypothesis testing on the correlation matrices (Steiger, 1980; Steiger, in press), which we employed here.

We analyzed switch costs for attribute switching in J2, object switching during the cue period, and object switching during J2 in separate analyses. Within each switch type (attribute-J2, object-J2, and object-cue), we calculated four separate switch costs, each derived from separate trials: shape judgment/external locus (shE), shape judgment/internal locus (shI), orientation judgment/external locus (orE), and orientation judgment/internal locus (orI). We assessed intercorrelations among these four switch types<sup>1</sup>. Attribute switch costs included task-preparation and residual switch costs. J2 object switch costs are largely residual costs after preparation has been completed, and allow us to test whether residual switch costs are correlated across types. Object switch costs during the cue period reflect a combination of preparatory switch costs and strategic slowing in preparation for efficient performance in J2.

Individual differences in overall and relative speed can artificially inflate

correlations in a manner unrelated to whether switching processes themselves are correlated (e.g., Salthouse et al., 1998). Thus, the analysis proceeded in two stages. First, we assessed whether each switch cost could be predicted by overall speed of processing and by relative speed of basic shape and orientation judgments (Table 4). If switch costs are correlated with overall speed, higher switch costs may have little to do with executive processing per se. If switch costs are correlated with relative shape vs. orientation speed, then high switch costs across different types may result simply from individual biases in attention towards one task or another. Our measure of overall speed was the average of shape and orientation judgment RTs in J1 and for relative speed was the difference in RT for [shape - orientation] in J1<sup>2</sup>. We adjusted switch costs by using the residual switch costs after controlling for overall and relative processing speed. This is an alternative to using an arbitrary scaling method--for example, dividing switch costs by no-switch RT. Whereas the fixed scaling method assumes a fixed ratio of switch costs to overall RT, which may or may not be correct, in our method this relationship is estimated using one free parameter.

We then performed correlation analyses on the adjusted switch costs (Table 5).<sup>1</sup>We used pattern hypothesis testing in WBCORR (Within-Between Correlational Tests software; Steiger, 2005) to test five a priori hypotheses on the correlation matrices for each switch cost (attribute, residual object, and cue object, Table 6). Pattern hypothesis testing allows the analyst to specify a pattern of free and fixed correlation estimates and constraints on equality of correlation estimates. For Tests 1 and 2, 2-stage generalized least squares was used to estimate correlations and standard errors, and chi-square goodness of fit tests were used to assess whether constrained models provided a significantly poorer fit to the correlation matrices, as is common in structural equation modeling. Tests 3 - 5 were planned contrasts across pairs of correlations, accounting for

---

the covariance among correlation estimates, using Z-tests. The hypothesis for each test is explained along with the results, below.

*Effects of overall and relative speed.* We first tested whether shift-cost asymmetries were correlated with relative processing speed on the tasks. Relative speed ([sh – or] in J1) was related to switch cost asymmetries for external and internal attribute switching: partial correlation ( $pr$ ) = .21,  $p = .002$  and  $pr = .31$ ,  $p = .0001$ , respectively. Thus, participants who were faster at the shape task had less difficulty switching to the shape task (and more difficulty shifting away from shape), paralleling the finding of lower switch costs switching to the easier task. For other periods (object-J2 and object-cue), relative speed did not predict asymmetries.

We next entered overall and relative speed as predictors of each type of switch cost in multiple regression, predicting shifts costs in this case rather than asymmetries. Regression coefficients (standardized to so that betas are partial correlations) and statistics are shown in Table 4.

**Effects of overall speed on switch costs.** For attribute switch costs in J2, overall speed was strongly predictive of switch costs in each switch type (shE, shI, orE, and orI, all  $pr \geq .21$ ,  $p < .001$ ). Betas were positive, indicating larger switch costs for participants who were slower overall in J1. Thus, slower participants showed higher switch costs. Correlations between basic speed and residual object switching (object-J2) were generally nonsignificant. OrE was significantly predicted by overall speed ( $pr = 0.14$ ), but this effect was much smaller than others reported here. For object switch costs in the cue period (preparatory costs), there were strong relationships between overall speed and switch costs in each switch type (all  $prs$  at least  $-0.36$ ,  $p < .0001$ ). Negative betas indicated that slower participants took less time to prepare object shifts in the cue period, perhaps reflecting a lack of strategic preparation. In sum, slower participants showed higher switch costs when the switch involved task-set preparation.

**Effects of relative speed on switch costs.** Expanding on the findings on

asymmetry above, relative speed [sh – or] predicted time to shift to the more difficult orientation task:  $pr = -.22$ ,  $p < .001$  for orE and  $pr = -.35$ ,  $p < .0001$  for orI, for attribute-J2. Significant negative betas indicated that participants with relatively slow orientation processing showed higher switch costs when switching to orientation. Relative speed did not significantly predict switch costs when switching to shape (shE and shI) or object switch costs in either Cue or J2 periods (Table 4).

*Correlations among switch costs.* Table 5 shows correlations among the four shift costs for raw data (left side) and residuals after controlling for overall and relative speed (right side). All analyses were performed on the adjusted correlation matrices. Pattern hypothesis tests on the adjusted correlation matrices were used to test whether switch costs were correlated across variations in Locus (external/internal) and Judgment Type (shape/orientation), and to assess the impact of these variables on correlation strength. The five planned tests on each correlation matrix are listed as Tests 1 - 5 in Table 6.

We first tested whether all correlations (among shE, shI, orE, and orI) were equal by fitting a single parameter for all correlation values and performing a goodness-of-fit test (Test 1 in Table 6). A failure to reject the null in this case would indicate that the equal-correlation model is plausible, whereas a rejection would indicate that variations in internal/external locus and shape/orientation Judgment Type significantly affect correlations, and that individual differences in different types of shifting probably reflect locus and task-specific processes. The null hypothesis was rejected for each type of switching:  $\chi^2(5) = 12.79$ ,  $p < .05$  for attribute switching,  $\chi^2(5) = 14.08$ ,  $p < .05$  for J2 object switching, and  $\chi^2(5) = 71.8$ ,  $p < .0001$  for object cue shifting.

We next tested whether there was *any* significant correlation when varying both Locus and Judgment Type (Test 2). We did this by setting parameter estimates for correlations between shI-orE and shE-orI to zero, fitting a separate free parameter to each of the other correlations, and performing a goodness-of-fit test on this model. A rejection

in this case indicates that the critical correlations are nonzero. For attribute switching, we rejected the zero-correlation across locus and judgment model,  $\chi^2(2) = 21.0$ ,  $p < .0001$ . For J2 object switching, we failed to reject,  $\chi^2(2) = 3.44$ ,  $p > .10$ , suggesting that there is not an appreciably large general switching ability in residual object switch costs. Notably, the cue shift costs were much more strongly correlated than the residual shift costs, with highly significant cross-task correlations,  $\chi^2(2) = 113$ ,  $p < .0001$ . As Cue period correlations could reflect strategy choices in deciding how completely to prepare as well as preparatory shift costs, the strong Cue period correlations suggest that the tendency to prepare is more stable across tasks than are shift costs.

We next tested whether correlations on switch costs holding Locus constant but varying Judgment Type (correlations b and e in Table 5) were significantly greater than those varying both Locus and Judgment Type (c and d, Test 3 in Table 6). This is a test of whether there are processes unique to internal and external switching. If there are, varying Locus should decrease the strength of the cross-task correlations. This test was significant in each switching type, with average increases in correlation values of 0.12, 0.19, and 0.14 for attribute, residual object, and cue object switching, respectively. Statistics are shown in Table 6, including parameter estimates for pairs of correlations, the contrast estimate, i.e.,  $(b + e) - (c + d)$ , and test statistics.

We also tested whether correlations on switch costs holding Judgment Type constant (a and f, varying Locus) were greater than correlations varying both Locus and Judgment Type (c and d, Test 4). For attribute switching and residual object switching, this difference was marginally significant (Table 6), with estimated increases in correlation values of 0.07 and 0.11. Although raw correlations (Table 5) were not analyzed with pattern hypotheses, they were substantially larger before removing the effects of relative processing speed, suggesting that systematic differences in switch costs due to Judgment Type were largely, but perhaps not completely, accounted for by relative processing speed. The test was not significant for cue object switching.

Finally, we compared correlation values holding Judgment Type constant (a and f) with those holding Locus constant (b and e) to determine which variable had the larger effects on switch costs (Test 5). For attribute and residual object switches, the test was not significant, indicating that neither variable was clearly more important than the other. For Cue object switches, Locus was the more important variable. Constant Locus increased the correlation by 0.15 compared with constant Judgment Type. Thus, overall, Locus emerged as a significant variable in each type of switching, whereas effects of Judgment Type appear to have been largely accounted for by relative processing speed.

### General Discussion

Overall, the results provide evidence for both commonalities and separability in the processes engaged in task switches across types of tasks. Evidence for common processes comes from correlations in switch costs across tasks, which were significant for switches that involved task-set preparation (but not residual switch costs). Evidence that task-switches in different tasks involve different processes comes from both correlational and ANOVA results.

When stimuli were maintained in WM (internal locus) vs. perceptually available (external locus), switch costs were apparent for both types of task. However, combining RT and accuracy, object switch costs were greater in the external task, and attribute switch costs were greater for the internal task. In addition, overadditive dual-switch costs were found in the internal task, but not in the external task. This result was found in spite of the fact that participants had as long as necessary to first complete the object switch. This implies that the ability to first select the object and then select the attribute (e.g., Sternberg, 1969), without interference, is diminished during switching in WM.

Asymmetries in switch costs existed for both loci, such that it was easier to switch to the more salient and faster-processed attribute (shape). These asymmetries existed in both internal and external tasks, and in both tasks they were predicted by relative basic processing speed. However, switch cost asymmetries were larger for the external task, consistent with the idea that asymmetries are partially created when visible stimuli prime associated task sets (Wylie & Allport, 2000). These findings are also consistent with models of task switching in which switch costs are determined by relative task strength (Gilbert & Shallice, 2002; Gilbert & Shallice, 2002). Such models can produce both the asymmetry pattern we report here and the “paradoxical” switch-cost asymmetries observed by Allport et al. (1994) and others (Monsell et al., 2000), but require additional input from a top-down task-selection mechanism to produce “paradoxical” asymmetry.

One explanation for why Attribute Shifting and Attribute x Object interactions are greater in internal tasks is this: Selecting an object stored in WM may require the selection and rehearsal of object attributes as well. For example, it is impossible to visualize a red square without representing its redness or its squareness. Thus, the attribute selection process may be more difficult in WM because both relevant and irrelevant attributes are selected along with the object, and the potential for interference is greater. By contrast, attribute selection when stimuli are visible can take advantage of visual spatial attention and object-based feature grouping to select objects without fully processing their attributes (e.g., Downing, Liu, & Kanwisher, 2001; Driver, 1996; Egly, Driver, & Rafal, 1994; Lamy & Egeth, 2002; Macaluso, Frith, & Driver, 2002; O'Craven, Downing, & Kanwisher, 1999). In support of this view, Vogel, Woodman, & Luck, (2001) found that people can typically store 3-4 attributes of objects in WM at a time, but

they can store two attributes each of 3-4 objects, suggesting that objects are units stored in WM and that multiple attributes are bound with object representations. Thus, switching objects stored in WM necessarily makes both the relevant and irrelevant attributes of the object salient, both increasing attribute shifting times and causing interference with the attribute-switching process when both object and attribute switches are performed together.

By contrast, object switching may create more interference when stimuli are visible, as the incorrect object is also visible and may attract attention. Thus, in external tasks in the literature, visible stimuli that afford both tasks (i.e., ‘bivalent’ stimuli) produce much greater switch costs (Jersild, 1927). Object selection may be rapid in WM because stimuli are stored and rehearsed object-by-object (Vogel et al., 2001).

*Correlational evidence for separable switching processes*

These data provide indirect support for the idea that locus and Judgment Type differentially engage controlled retrieval (comparable to the goal selection stage of Rubinstein et al., 2001) and interference resolution (comparable to rule activation) processes. More direct quantitative evidence for the degree of similarity in performance among these different variants of shifting tasks is provided by the individual differences analyses. Even after controlling for overall processing speed and relative processing speed—which may increase correlations among switching tasks if switch costs are proportional to overall RT or relative task difficulty, as we show here—correlations among tasks were significantly greater within locus (internal or external) than across loci. This result held for attribute switches, which involved both goal selection and rule activation stages, and for both goal-selection (preparatory) and rule-activation (residual)

stages of object switching. Thus, switch costs among visible stimuli and those stored in WM are, at least in part, measures of different abilities.

Two more points are worth noting. First, correlations within Judgment Type (shape and orientation) were marginally stronger than those across judgment types, suggesting that although controlling for relative speed appears to reduce the influence of judgment-specific switching processes, it does not do so completely. This pattern is consistent with the idea that relative speed is related to relative automaticity (Dyer, 1973), but is not sufficient to completely account for it (MacLeod & Dunbar, 1988). Second, the preparatory object shift costs in our experiment were self-paced, and so were influenced by strategy differences. This might explain the very high correlations among object switch costs generally, and underscores the point that strategic choices applied consistently across tasks are a major component of switch costs (\*\*cite braver\*\*). However, the larger correlations within internal and external loci compared with across loci is harder to explain in this manner, and we take it as corroboration of the unique processes involved in internal and external goal-shifting.

*Correlational evidence for common switching processes*

Having reviewed this evidence for separate processes for internal and external shifting, we turn next to the issue of whether switching processes are unique to particular task types, or whether evidence for common processes can be found even for the most dissimilar tasks we studied. We found that attribute switch costs were correlated even when the tasks were quite dissimilar, in that they varied in both locus and Judgment Type. These switch costs involved both goal selection and rule activation stages. However, residual shift costs (correlations on object switch costs after the goal shift was

largely completed) were uncorrelated. Thus, goal selection seems to involve common processes across diverse task types, but rule-application during residual shifting appeared to involve different cognitive processes for different tasks.

These findings parallel those from an fMRI study conducted recently in 39 participants on the same tasks (Wager et al., 2005). We found that external switching more strongly engaged extrastriate cortex bilaterally, and internal switching more strongly engaged frontal and parietal (particularly precuneus) regions associated with switching attention as identified in meta-analyses (Derrfuss, Brass, Neumann, & von Cramon, 2005; Wager, Reading, & Jonides, 2004). The regions more activated in internal switches have been implicated in executive control of WM more generally (Wager & Smith, 2003), suggesting a relationship between switching and manipulation of information in WM. One of these regions, the inferior frontal junction, has been related specifically to controlled updating of WM (Derrfuss et al., 2005). Although this is evidence for the separability of different kinds of task switching, we (Wager et al., 2005) found that although the magnitude of switching activations in these regions varied across tasks, each of these regions was still activated in shift – no shift comparisons in all tasks. This finding suggests that basic attention control processes are involved in each type of shift, but the degree to which they are required varies with task condition.

#### *Relation of switching to other cognitive abilities*

Unlike other studies that have focused on relating switch costs to other cognitive ability measures, we focused exclusively on taxonomy of processes within switching tasks. However, other studies have found that switching costs are related to other cognitive control processes. Miyake et al. (2000), for example, tested participants on

three different switching tasks. Using Confirmatory Factor Analysis (CFA), they found that switching costs were moderately intercorrelated, and were also moderately related to constructs of response inhibition and monitoring of information in WM. Ward, Roberts, Phillips (2001) also investigated the relationship among two similar switching tasks and two Stroop tasks and found that switching tasks were moderately correlated. However, that study was limited in its ability to relate switching to inhibition by low correlations between the two versions of the Stroop tasks. Salthouse et al. (1998) also identified a switching construct that was related to but dissociable from basic processing speed, as we found here. They found a relationship between the switching construct and a 'higher cognition' factor composed of more complex problem solving tasks; but this relationship was largely explained by common influences of basic processing speed on both switching and higher cognition. However, Salthouse et al. used three very similar switching tasks: All involved making judgments on visually available digits. Thus, although this choice of tasks was advantageous in producing a stronger 'switching' factor in that experiment than in Miyake et al. (2000), the 'switching' construct in Salthouse et al. may not be representative of task switching in general. Perhaps, as suggested by neuroimaging evidence for co-localization of switching and other executive control operations, complex measures of problem solving are more closely related to control of attention within WM than to the efficiency of perceptual shifting mechanisms.

This leaves us with three general points. First, basic processing speed and relative speed appear to influence measured switch costs, and these effects should be controlled for when examining correlations among switching tasks. Second, different switching tasks involve different processes, and are thus likely to involve different brain

mechanisms and relate to different processes. In particular, switching within WM is separable from switching in perception. Finally, individual differences analyses are an informative way to develop models of the structure of human performance.

Understanding how elementary control processes are grouped is essential for identifying the building blocks of cognitive abilities and developing the right constructs on which to test for selective impairments.

References

- Allport, A., Styles, E. A., & Hsieh, S. L. (1994). Shifting Intentional Set - Exploring the Dynamic Control of Tasks. *Attention and Performance Xv, 15*, 421-452.
- Allport, A., & Wylie, G. (1999). Task-switching: Positive and negative priming of task-set. In G. W. Humphreys & J. Duncan (Eds.), *Attention and action: Studies in cognitive neuroscience*.
- Baddeley, A. (1992). Working memory. *Science, 255*(5044), 556-559.
- Bleckley, M., Durso, F. T., Crutchfield, J. M., Engle, R. W., & Khanna, M. M. (2003). Individual differences in working memory capacity predict visual attention allocation. *Psychonomic Bulletin & Review, 10*(4), 884-889.
- Burgess, P. W., Alderman, N., Evans, J., Emslie, H., & Wilson, B. A. (1998). The ecological validity of tests of executive function. *Journal of the International Neuropsychological Society, 4*(6), 547-558.
- Conway, A. R. A., Kane, M. J., & Engle, R. W. (2003). Working memory capacity and its relation to general intelligence. *Trends in Cognitive Sciences, 7*(12), 547-552.
- Coull, J. T., Frith, C. D., Buchel, C., & Nobre, A. C. (2000). Orienting attention in time: behavioural and neuroanatomical distinction between exogenous and endogenous shifts. *Neuropsychologia, 38*(6), 808-819.
- Derrfuss, J., Brass, M., Neumann, J., & von Cramon, D. Y. (2005). Involvement of the inferior frontal junction in cognitive control: meta-analyses of switching and Stroop studies. *Hum Brain Mapp, 25*(1), 22-34.
- Downing, P., Liu, J., & Kanwisher, N. (2001). Testing cognitive models of visual attention with fMRI and MEG. *Neuropsychologia, 39*(12), 1329-1342.

- Dreher, J. C., Koechlin, E., Ali, S. O., & Grafman, J. (2002). The roles of timing and task order during task switching. *Neuroimage*, *17*(1), 95-109.
- Driver, J. (1996). Attention and segmentation. *Psychologist*, *9*(3), 119-123.
- Duncan, J., Emslie, H., Williams, P., Johnson, R., & Freer, C. (1996). Intelligence and the frontal lobe: The organization of goal-directed behavior. *Cognitive Psychology*, *30*(3), 257-303.
- Duncan, J., Johnson, R., Swales, M., & Freer, C. (1997). Frontal lobe deficits after head injury: Unity and diversity of function. *Cognitive Neuropsychology*, *14*(5), 713-741.
- Dyer, F. (1973). The Stroop phenomenon and its use in the study of perceptual, cognitive, and response. *Memory & Cognition*, *1*(2), 106-120.
- Egly, R., Driver, J., & Rafal, R. D. (1994). Shifting visual attention between objects and locations: evidence from normal and parietal lesion subjects. *J Exp Psychol Gen*, *123*(2), 161-177.
- Garavan, H. (1998). Serial attention within working memory. *Journal of Memory and Cognition*, *26*, 263-276.
- Garavan, H., Ross, T. J., Li, S.-J., & Stein, E. A. (2000). A parametric manipulation of central executive functioning. *Cerebral Cortex*, *10*, 585-592.
- Gilbert, S., & Shallice, T. (2002). Task switching and task-set inertia: A computational model. *Journal of Cognitive Neuroscience*, 76-76.
- Gilbert, S. J., & Shallice, T. (2002). Task switching: A PDP model. *Cognitive Psychology*, *44*(3), 297-337.

Gopher, D. (1996). Attention control: explorations of the work of an executive controller.

*Brain Res Cogn Brain Res*, 5(1-2), 23-38.

Gopher, D., Armony, L., & Greenspan, Y. (2000). Switching tasks and attention

policies. *Journal of Experimental Psychology: General*, 129(3), 308-339.

Hitch, G. J., & Baddeley, A. D. (1976). Verbal Reasoning and Working Memory.

*Quarterly Journal of Experimental Psychology*, 28(NOV), 603-621.

Hsieh, S., & Allport, A. (1994). Shifting Attention in a Rapid Visual-Search Paradigm.

*Perceptual and Motor Skills*, 79(1), 315-335.

Jersild, A. (1927). Mental set and shift. *Archives of Psychology*, 89.

Johnson, R. A., & Wichern, D. W. (2002). *Applied multivariate statistical analysis* (5th

ed.). Upper Saddle River, NJ: Prentice Hall.

Kane, M. J., & Engle, R. W. (2003). Working-memory capacity and the control of

attention: The contributions of goal neglect, response competition, and task set to Stroop interference. *Journal of Experimental Psychology: General*, 132(1), 47-70.

Kane, M. J., Hambrick, D. Z., Tuholski, S. W., Wilhelm, O., Payne, T. W., & Engle, R.

W. (2004). The Generality of Working Memory Capacity: A Latent-Variable Approach to Verbal and Visuospatial Memory Span and Reasoning. *Journal of Experimental Psychology: General*, 133(2), 189-217.

Kimberg, D. Y., Aguirre, G. K., & D'Esposito, M. (2000). Modulation of task-related

neural activity in task-switching: an fMRI study. *Brain Res Cogn Brain Res*, 10(1-2), 189-196.

Koch, I. (2003). The role of external cues for endogenous advance reconfiguration in task

switching. *Psychon Bull Rev*, 10(2), 488-492.

- Lamy, D., & Egeth, H. (2002). Object-based selection: the role of attentional shifts. *Percept Psychophys*, 64(1), 52-66.
- Macaluso, E., Frith, C. D., & Driver, J. (2002). Directing attention to locations and to sensory modalities: multiple levels of selective processing revealed with PET. *Cereb Cortex*, 12(4), 357-368.
- MacLeod, C. M., & Dunbar, K. (1988). Training and Stroop-like interference: evidence for a continuum of automaticity. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 14, 126-135.
- Mayr, U. (2003). Towards Principles of Executive Control: How Mental Sets are Selected. In R. H. Kluwe, G. Luer & F. Rosler (Eds.), *Principles of Learning and Memory* (Vol. 1, pp. 223-241). Basel, Switzerland: Birkhauser Verlag.
- Mayr, U., & Kliegl, R. (2000). Task-set switching and long-term memory retrieval. *Journal of Experimental Psychology-Learning Memory and Cognition*, 26(5), 1124-1140.
- Meiran, N. (1996). Reconfiguration of processing mode prior to task performance. *Journal of Experimental Psychology: Learning, Memory, & Cognition*, 22(6), 1423-1442.
- Meiran, N., Chorev, Z., & Sapir, A. (2000). Component processes in task switching. *Cognitive Psychology*, 41(3), 211-253.
- Meiran, N., Hommel, B., Bibi, U., & Lev, I. (2002). Consciousness and control in task switching. *Conscious Cogn*, 11(1), 10-33.
- Miller, E. K., & Cohen, J. D. (2001). An integrative theory of prefrontal cortex function. *Annu Rev Neurosci*, 24, 167-202.

- Miyake, A., Friedman, N. P., Emerson, M. J., Witzki, A. H., Howerter, A., & Wager, T. D. (2000). The unity and diversity of executive functions and their contributions to complex "Frontal Lobe" tasks: a latent variable analysis. *Cognit Psychol*, *41*(1), 49-100.
- Monsell, S., Yeung, N., & Azuma, R. (2000). Reconfiguration of task-set: Is it easier to switch to the weaker task? *Psychological Research/Psychologische Forschung: Special Issue: Executive Control*, *63*(3-4), 250-264.
- Norman, D. A., & Shallice, T. (1986). Attention to action: Willed and automatic control of behavior. In R. J. Davidson, G. E. Schwartz & D. Shapiro (Eds.), *Consciousness and self-regulation* (Vol. 4, pp. 1-18). New York: Plenum.
- O'Craven, K. M., Downing, P. E., & Kanwisher, N. (1999). fMRI evidence for objects as the units of attentional selection. *Nature*, *401*(6753), 584-587.
- Owen, A. M., Roberts, A. C., Polkey, C. E., Sahakian, B. J., & Robbins, T. W. (1991). Extra-dimensional versus intra-dimensional set shifting performance following frontal lobe excisions, temporal lobe excisions or amygdalo-hippocampectomy in man. *Neuropsychologia*, *29*(10), 993-1006.
- Rabbitt, P., & Lowe, C. (2000). Patterns of cognitive ageing. *Psychol Res*, *63*(3-4), 308-316.
- Roberts, A. C., & Wallis, J. D. (2000). Inhibitory control and affective processing in the prefrontal cortex: neuropsychological studies in the common marmoset. *Cereb Cortex*, *10*(3), 252-262.
- Rogers, R. D., & Monsell, S. (1995). Costs of a predictable switch between simple cognitive tasks. *Journal of Experimental Psychology: General*, *124*(2), 207-231.

- Rousseeuw, P. J. (1984). Least Median of Squares Regression. *Journal of the American Statistical Association*, 79, 871-881.
- Rubinstein, J. S., Meyer, D. E., & Evans, J. E. (2001). Executive control of cognitive processes in task switching. *J Exp Psychol Hum Percept Perform*, 27(4), 763-797.
- Salthouse, T. A. (1996). The processing-speed theory of adult age differences in cognition. *Psychol Rev*, 103(3), 403-428.
- Salthouse, T. A., Fristoe, N., McGuthry, K. E., & Hambrick, D. Z. (1998). Relation of task switching to speed, age, and fluid intelligence. *Psychol Aging*, 13(3), 445-461.
- Shafiullah, M., & Monsell, S. (1999). The cost of switching between Kanji and Kana while reading Japanese. *Language & Cognitive Processes: Special Issue: Processing East Asian languages*, 14(5-6), 567-607.
- Spector, A., & Biederman, I. (1976). Mental Set and Mental Shift Revisited. *American Journal of Psychology*, 89(4), 669-679.
- Steiger, J. H. (1980). Testing pattern hypotheses on correlation matrices: Alternative statistics and some empirical results. *Multivariate Behavioral Research*, 15, 335-352.
- Steiger, J. H. (2005). Comparing correlations. In A. Maydeu-Olivares & J. J. McArdle (Eds.), *Contemporary Psychometrics: A festschrift for Roderick P. McDonald*. Mahwah, NJ: Lawrence Erlbaum Associates.
- Sternberg, S. (1969). The discovery of processing stages: Extensions of Donders' method. In W. G. Koster (Ed.), *Attention and performance II* (pp. 276-315). Amsterdam: North-Holland.

- Sylvester, C. Y. C., Wager, T. D., Lacey, S. C., Hernandez, L., Nichols, T. E., Smith, E. E., et al. (2003). Switching attention and resolving interference: fMRI measures of executive functions. *Neuropsychologia*, *41*(3), 357-370.
- Vogel, E. K., Woodman, G. F., & Luck, S. J. (2001). Storage of features, conjunctions, and objects in visual working memory. *Journal of Experimental Psychology- Human Perception and Performance*, *27*(1), 92-114.
- Wager, T. D., Jonides, J., Smith, E. E., & Nichols, T. E. (2005). Towards a taxonomy of attention-shifting: Individual differences in fMRI during multiple shift types. *Cogn Affect Behav Neurosci*.
- Wager, T. D., Reading, S., & Jonides, J. (2004). Neuroimaging studies of shifting attention: a meta-analysis. *Neuroimage*, *22*(4), 1679-1693.
- Wager, T. D., & Smith, E. E. (2003). Neuroimaging studies of working memory: a meta-analysis. *Cogn Affect Behav Neurosci*, *3*(4), 255-274.
- Ward, G., Roberts, M. J., & Phillips, L. H. (2001). Task-switching costs, Stroop-costs, and executive control: A correlational study. *Quarterly Journal of Experimental Psychology: Human Experimental Psychology*, *54A*(2), 491-511.
- Wylie, G., & Allport, A. (2000). Task switching and the measurement of "switch costs". *Psychological Research*, *63*(3-4), 212-233.
- Yeung, N., & Monsell, S. (2003). The effects of recent practice on task switching. *J Exp Psychol Hum Percept Perform*, *29*(5), 919-936.
- Yeung, N., & Monsell, S. (2003). Switching between tasks of unequal familiarity: The role of stimulus-attribute and response-set selection. *Journal of Experimental Psychology: Human Perception & Performance*, *29*(2), 455-469.

Author Note

We would like to thank Dr. James Steiger for providing the WBCORR software, and Dr. Steiger and Jeremy Welland for extremely helpful advice and discussion on testing pattern hypotheses.

Footnotes

<sup>1</sup> Attribute and object switches involve the same trials, so are not independent; thus, correlating attribute with object switch costs is problematic.

<sup>2</sup> J1 and J2 speed measures were correlated ( $r = 0.91$ ) but we used J1 for speed measures because RTs for that period are independent from those used to calculate switch costs in J2.

Table 1.

Type	J1	Cue	J2	Sw. Type	J1			
					RT	SE	Acc	SE
<i>External switches</i>								
A	Shape (O1)	Stay	Shape (O1)	none	1186	40.2	0.973	0.005
B	Orientation (O1)	Stay	Orientation (O1)	None	1242	42.1	0.986	0.003
C	Orientation (O1)	Stay	Shape (O1)	Att	1294	38.6	0.979	0.003
D	Shape (O1)	Stay	Orientation (O1)	Att	1352	39.8	0.979	0.004
E	Shape (O1)	Switch	Shape (O2)	Obj	1278	43.6	0.977	0.004
F	Orientation (O1)	Switch	Orientation (O2)	Obj	1334	44.1	0.980	0.003
G	Orientation (O1)	Switch	Shape (O2)	DbI	1303	46.5	0.985	0.003
H	Shape (O1)	Switch	Orientation (O2)	DbI	1212	40.3	0.976	0.004
<i>Internal switches</i>								
A	Shape (O1)	Stay	Shape (O1)	none	1154	34.9	0.953	0.006
B	Orientation (O1)	Stay	Orientation (O1)	None	1160	39.1	0.966	0.006
C	Orientation (O1)	Stay	Shape (O1)	Att	1134	34.9	0.951	0.005

Table 3.

*Switching RT costs and reliability*

Switch type	RT (msec)		Accuracy		Reliability
	Effect	SE	Effect	SE	
<b>External shape task (shE)</b>					
Object switch (cue)	69	24	-	-	0.91
Object switch (J2)	138	15	-0.45	0.39	0.63
Attribute switch (J2)	134	16	-1.26	0.39	0.82
Object * Attribute (J2)	22	14	1.19	0.37	0.41
<b>Internal shape task (shI)</b>					
Object switch (cue)	141	23	-	-	0.86
Object switch (J2)	103	16	-2.45	0.42	0.51
Attribute switch (J2)	153	16	-3.56	0.43	0.61
Object * Attribute (J2)	20	16	-1.02	0.38	0.35
<b>External orientation task (orE)</b>					
Object switch (cue)	176	25	-	-	0.91
Object switch (J2)	222	23	-3.35	0.46	0.63
Attribute switch (J2)	223	22	-2.88	0.36	0.82
Object * Attribute (J2)	-14	21	-1.17	0.34	0.41
<b>Internal orientation task (orI)</b>					
Object switch (cue)	100	21	-	-	0.86
Object switch (J2)	133	19	-3.04	0.44	0.51
Attribute switch (J2)	268	24	-4.43	0.50	0.61
Object * Attribute (J2)	56	18	-1.10	0.44	0.35
<b>Overall (judgment period)</b>	1215	28	94.18	0.29	0.99

*Note.* Switching costs in reaction times (RTs) and accuracy, calculated as main effects.

SE = standard error ; Reliability = odd/even split-half reliability, adjusted using the

Spearman-Brown Prophecy Formula, computed collapsing across shape and orientation

judgments. Positive values in RT indicate that responses on switch trials were slower than those on non-switch trials. Positive interaction values indicate that double-switch trials showed a greater RT cost than the sum of switch costs single switches. Negative values for accuracy indicate switch costs in accuracy.

Table 4

*Switch costs predicted by processing speed*

<b>Switch</b>		<b>Beta</b>	<b>SE</b>	<b>t</b>	<b>p-value</b>
<b>cost</b>	<b>Predictor</b>				
<b>Attribute switching in J2</b>					
shE	Overall speed	0.312	0.064	4.91*	0.0000
	Sh - or speed	0.000	0.064	0.00	0.9965
shI	Overall speed	0.241	0.064	3.76*	0.0002
	Sh - or speed	-0.095	0.064	-1.48	0.1400
orE	Overall speed	0.213	0.063	3.38*	0.0008
	Sh - or speed	-0.217	0.063	-3.46*	0.0006
orI	Overall speed	0.389	0.054	7.26*	0.0000
	Sh - or speed	-0.354	0.054	-6.61*	0.0000
<b>Object switching in J2 (residual)</b>					
shE	Overall speed	0.066	0.067	0.99	0.3220
	Sh - or speed	0.060	0.067	0.90	0.3689
shI	Overall speed	0.098	0.066	1.48	0.1406
	Sh - or speed	0.099	0.066	1.50	0.1360
orE	Overall speed	0.139	0.066	2.11*	0.0358
	Sh - or speed	-0.081	0.066	-1.23	0.2186
orI	Overall speed	0.035	0.067	0.52	0.6027

Sh - or speed	0.088	0.067	1.31	0.1907
---------------	-------	-------	------	--------

**Object switching in cue period**

shE	Overall speed	-0.480	0.060	-8.11*	0.0000
	Sh - or speed	-0.050	0.060	-0.81	0.4214
shI	Overall speed	-0.450	0.060	-7.49*	0.0000
	Sh - or speed	-0.030	0.060	-0.56	0.5773
orE	Overall speed	-0.510	0.060	-8.71*	0.0000
	Sh - or speed	-0.090	0.060	-1.59	0.1128
orI	Overall speed	-0.360	0.060	-5.68*	0.0000
	Sh - or speed	-0.030	0.060	-0.46	0.6493

*Note.* Results of multiple regressions predicting each type of switch cost from overall processing speed and relative processing speed [shape – orientation] in J1. Betas are standardized so that values reflect partial correlations between predictors and switch costs. Positive betas indicate higher switch costs with slower overall processing or relatively faster shape than orientation judgments (i.e., a larger asymmetry in switch costs). Error *df* were 246 for all tests. I = internal locus, E = external locus, sh = shape judgment task, or = orientation judgment task, J2 = second judgment period. \* =  $p < .05$ .

Table 5. Correlations among switch costs

				<b>Controlling for overall and</b>			
<b>Raw correlations</b>				<b>relative speed</b>			
<b>Attribute switching in J2</b>				<b>Attribute switching in J2</b>			
	shE	shI	orE		shE	shI	orE
shE	-			shE	-		
shI	0.269*	-		shI	0.203*	-	
orE	0.357*	0.330*	-	orE	0.303*	0.262*	-
orI	0.287*	0.442*	0.486*	orI	0.173*	0.362*	0.371*
<b>Object switching in J2</b>				<b>Object switching in J2 (residual)</b>			
	shE	shI	orE		shE	shI	orE
shE	-			shE	-		
shI	0.182*	-		shI	0.175*	-	
orE	0.246*	0.104	-	orE	0.247*	0.102	-
orI	0.075	0.308*	0.198*	orI	0.070	0.303*	0.207*
<b>Object switching in cue</b>				<b>Object switching in cue period</b>			
	shE	shI	orE		shE	shI	orE
shE	-			shE	-		
shI	0.713*	-		shI	0.639*	-	
orE	0.854*	0.678*	-	orE	0.812*	0.592*	-
orI	0.712*	0.754*	0.649*	orI	0.663*	0.714*	0.587*

**Codes for pattern hypothesis**

<b>tests</b>			
	shE	shI	orE
shE			
shI	a		
orE	b	d	
orI	c	e	f

*Note.* Correlations among switching costs, raw (left table) and after removing linear effects of overall speed and relative shape – orientation judgment speed (right table). Adjusted correlations were used in pattern hypothesis tests. I = internal locus, E = external locus, sh = shape judgment task, or = orientation judgment task, J2 = second judgment period. Letters a-f are used to describe pattern hypothesis tests. Correlations c and d vary both locus and Judgment Type; b and e vary Judgment Type alone; and a and f vary locus alone. \* =  $p < .05$ .

Table 6.

*Pattern hypothesis tests*

<b>Null hypothesis</b>	<b>Contrast</b>	<b>Param. estimates (SE)</b>		<b>Contrast (SE)</b>	<b>Z</b>	<b>p</b>
<b>Attribute switching in J2</b>						
1. All switch costs are equal	a=b=c=d=e=f	.279		*		
2. Switch costs varying both locus and Judgment Type are uncorrelated	c=d=0	0		*		
3. Correlations within locus (external, internal) are no greater than across loci	(b=e) - (c=d)	.333 (.041)	.218 (.045)	.230* (.090)	2.56	0.005
4. Correlations within Judgment Type (shape, orientation) are no greater than across types	(a=f) - (c=d)	.287 (.043)	.218 (.045)	.109+ (.067)	1.63	0.051
5. Correlations within locus are equal to correlations within Judgment Type	(a=f) - (b=e)	.287 (.043)	.333 (.041)	-.092 (.098)	-0.098	0.82
<b>Object switching in J2 (residual)</b>						
1. Equal switch costs	a=b=c=d=e=f	.184		*		
2. Across types	c=d=0	0				
3. Within locus vs. across	(b=e) - (c=d)	.275 (.042)	.086 (.047)	.378* (.102)	3.69	0.0001
4. Within judgment vs. across	(a=f) - (c=d)	.191 (.045)	.086 (.047)	.105+ (.073)	1.43	0.077
5. Locus vs. judgment	(a=f) - (b=e)	.191 (.045)	.275 (.042)	-.168+ (.116)	-1.45	0.073
<b>Object switching in cue period</b>						
1. Equal switch costs	a=b=c=d=e=f	.668		*		
2. Across types	c=d=0	0		*		
3. Within locus vs. across	(b=e) - (c=d)	.763 (.020)	.628 (.032)	.270* (.053)	5.12	< .0001
4. Within judgment vs. across	(a=f) - (c=d)	.613 (.033)	.628 (.032)	-.005 (.037)	-0.15	0.56
5. Locus vs. judgment	(a=f) - (b=e)	.613 (.033)	.763 (.020)	-.300* (.052)	-5.76	< .0001

*Note.* Parameter estimates in pattern hypothesis tests. The same five tests were performed on

attribute switches, object switches in J2, and object switches in the object cue period. See Table 5 for explanation of letter codes a – f. Equal signs denote correlation estimates constrained to be equal in the model fit. Standard errors are in parentheses. \*,  $p < .05$ , + =  $p < .10$ , one-tailed.

## Figure Captions

Figure 1. Example trials from the task design (not drawn to scale). The panels illustrate successive events within the trial. In the actual experiment, the objects were colored blue (darker shading) and red (lighter shading). The eight different configurations of red and blue ellipses and rectangles in vertical and horizontal orientations were used in equal numbers, with a new stimulus configuration appearing on each trial. A) On external trials, the stimulus was visible continuously, as is depicted here. B) On internal trials, the stimulus was only visible in the first panel and language cues appeared in the center of the screen. C) The names of each phase of the trial are printed below the panels. Object switching RT costs in the object cue phase were calculated as RT for switch – stay trials. Trials were attribute switches if the attribute during J2 did not match that of the first judgment. In J2, RT measures were collected for each trial type (switch attribute and object, switch object only, switch attribute only, or no switch).

Figure 2. Behavioral performance data. A) Reaction times (RTs) for each condition during the second judgment period (the critical phase of the trial). I = internal locus; E = external locus; sh = shape judgment, or = orientation judgment. For example, shI columns show RTs for shape judgments preceded by shape judgments (for no attribute switch conditions) or orientation judgments (for attribute switch judgments) for the internal locus. B) Accuracy by condition. Error bars show standard errors of the means.

Figure 1

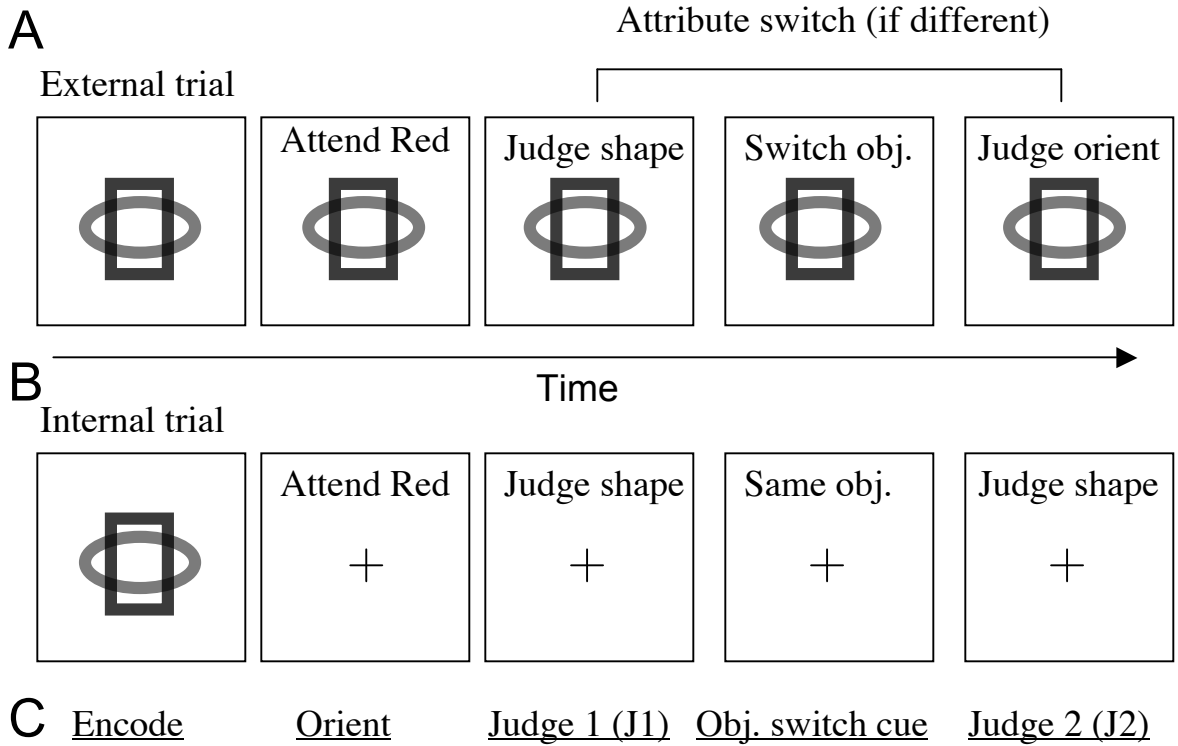
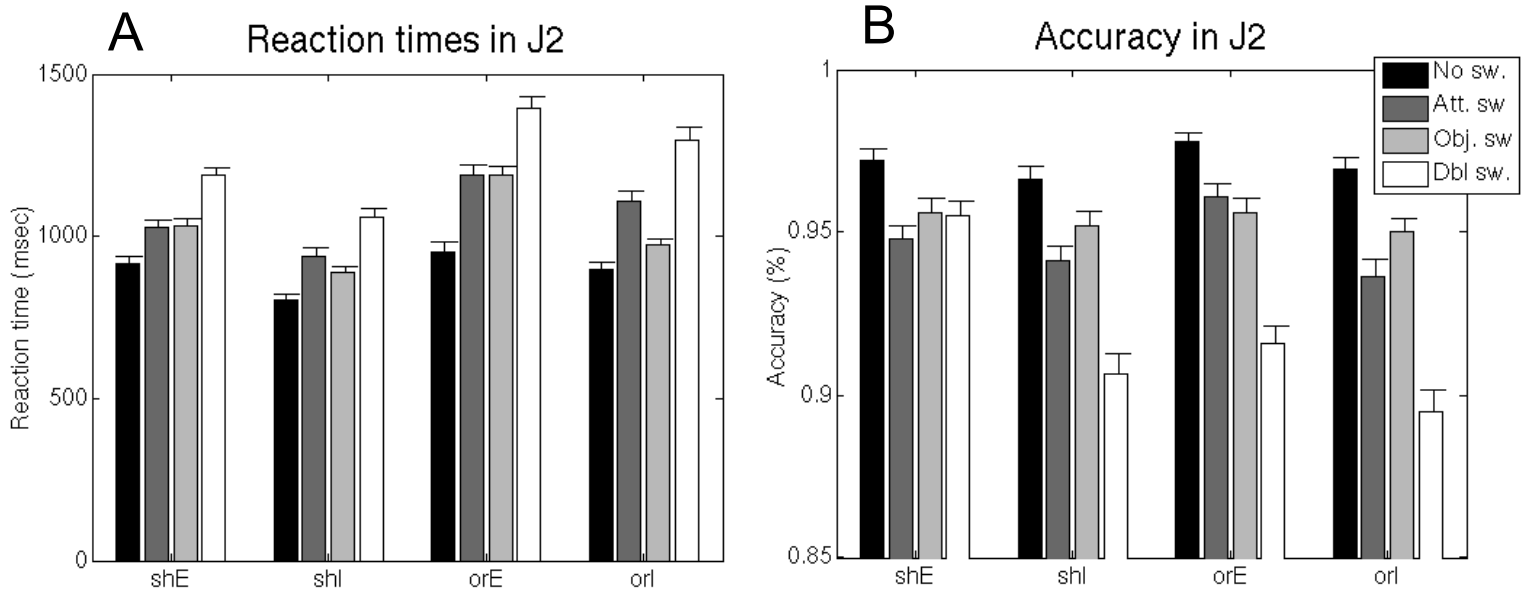


Figure 2





---

<sup>1</sup> Attribute and object switches involve the same trials, so are not independent; thus, correlating attribute with object switch costs is problematic.

<sup>2</sup> J1 and J2 speed measures were correlated ( $r = 0.91$ ) but we used J1 for speed measures because RTs for that period are independent from those used to calculate switch costs in J2.

D	Shape (O1)	Stay	Orientation (O1)	Att	1116	35.4	0.977	0.004
E	Shape (O1)	Switch	Shape (O2)	Obj	1081	36.0	0.952	0.007
F	Orientation (O1)	Switch	Orientation (O2)	Obj	1174	36.3	0.967	0.004
G	Orientation (O1)	Switch	Shape (O2)	Dbl	1164	46.8	0.965	0.005
H	Shape (O1)	Switch	Orientation (O2)	Dbl	994	34.0	0.967	0.005

*Note.* Means and standard errors for each trial type in the first judgment (J1) period, during which no switch costs were expected.

Judgments were made on object shape or orientation. Sw. Type: task switch type (None for no switch, Att for attribute switch only, Obj for object switch only, Dbl for double attribute-object switch). Switch indicates a cue to shift to the unattended object, and Stay indicates a cue to sustain attention on the same object. Obj. Cue: Object switch cue period. J2: Second judgment period. RT: Reaction time in msec. SE: Standard error. Acc: accuracy (proportion correct). O1 indicates response to the initially cued object, cued by color (red or blue). O2 indicates response to the initially uncued object.

Table 2.

Type	J1	Cue	J2	Sw. Type	Obj. Cue		J2			
					RT	SE	RT	SE	Acc	SE
<i>External switches</i>										
A	Shape (O1)	Stay	Shape (O1)	none	820	27.0	990	31.3	0.975	0.005
B	Orientation (O1)	Stay	Orientation (O1)	None	860	31.3	1036	36.0	0.978	0.003
C	Orientation (O1)	Stay	Shape (O1)	Att	875	28.5	1141	39.7	0.948	0.006
D	Shape (O1)	Stay	Orientation (O1)	Att	928	37.0	1241	40.0	0.955	0.006
E	Shape (O1)	Switch	Shape (O2)	Obj	1003	46.0	1142	37.2	0.944	0.008
F	Orientation (O1)	Switch	Orientation (O2)	Obj	1077	61.4	1224	40.9	0.952	0.007
G	Orientation (O1)	Switch	Shape (O2)	Dbl	1012	54.9	1443	45.1	0.943	0.007
H	Shape (O1)	Switch	Orientation (O2)	Dbl	967	55.5	1286	36.5	0.900	0.008
<i>Internal switches</i>										
A	Shape (O1)	Stay	Shape (O1)	none	751	23.7	911	40.7	0.958	0.006
B	Orientation (O1)	Stay	Orientation (O1)	None	789	24.2	924	31.7	0.967	0.006

C	Orientation (O1)	Stay	Shape (O1)	Att	785	25.4	1058	34.9	0.949	0.007
D	Shape (O1)	Stay	Orientation (O1)	Att	780	31.2	1168	41.3	0.923	0.008
E	Shape (O1)	Switch	Shape (O2)	Obj	907	42.0	1002	31.5	0.939	0.007
F	Orientation (O1)	Switch	Orientation (O2)	Obj	897	40.3	995	30.9	0.950	0.006
G	Orientation (O1)	Switch	Shape (O2)	Dbl	962	56.6	1478	63.1	0.879	0.010
H	Shape (O1)	Switch	Orientation (O2)	Dbl	868	41.8	1191	43.3	0.872	0.009

*Note.* Means and standard errors for object switch cue (Obj. Cue) and second judgment (J2) period. Sw. Type: task switch type (None for no switch, Att for attribute switch only, Obj for object switch only, Dbl for double attribute-object switch). Switch indicates a cue to shift to the unattended object, and Stay indicates a cue to sustain attention on the same object. J1: First judgment period. RT: Reaction time in msec. SE: Standard error. Acc: accuracy (proportion correct). O1 indicates response to the initially cued object, cued by color (red or blue). O2 indicates response to the initially uncued object. Object switch costs were defined as ABCD – EFGH, where ABCD indicates averaged performance across conditions A through D. Attribute switch costs were defined as CDGH – ABEF. The interaction between switch costs was defined as ABGH – CDEF. Asymmetries in switch costs in J2 were defined as orientation

– shape switch costs,  $(DH - FB) - (EG - AC)$  for attribute switches and  $(FH - BD) - (EG - AC)$  for object switches. Object switch costs were expected during the Cue period, and both attribute and object switch costs were expected during J2.

