

Dissociating Stimulus-Set and Response-Set in the Context of Task-Set Switching

Paul D. Kieffaber
The College of William & Mary

John K. Kruschke
Indiana University Bloomington

Raymond Y. Cho
University of Pittsburgh and Center for the Neural Basis of
Cognition, Pittsburgh, Pennsylvania

Philip M. Walker
The College of William & Mary

William P. Hetrick
Indiana University Bloomington

The primary aim of the present research was to determine how *stimulus-set* and *response-set* components of task-set contribute to switch costs and conflict processing. Three experiments are described wherein participants completed an explicitly cued task-switching procedure. Experiment 1 established that task switches requiring a reconfiguration of both stimulus- and response-set incurred larger residual switch costs than task switches requiring the reconfiguration of stimulus-set alone. Between-task interference was also drastically reduced for response-set conflict compared with stimulus-set conflict. A second experiment replicated these findings and demonstrated that stimulus- and response-conflict have dissociable effects on the “decision time” and “motor time” components of total response time. Finally, a third experiment replicated Experiment 2 and demonstrated that the stimulus- and response- components of task switching and conflict processing elicit dissociable neural activity as evidence by event-related brain potentials.

Keywords: task-set, cognitive control, task-switching, ERP, EEG

Central to the adaptability of human behavior is our capacity to dynamically modify perceptual and cognitive processing in accordance with current goals. This cognitive flexibility does, however, appear to come with a time-cost associated with switching between tasks. Appreciation for the costs of task-switching is evidenced by modern industrial developments such as the assembly line. Psy-

chologists too have been intrigued by the time-costs of switching tasks and have sought to describe the nature of these “switch costs” for decades (Allport, Styles, & Hsieh, 1994; Jersild, 1927; Rogers & Monsell, 1995; Spector & Biederman, 1976). Common to this longstanding literature is the concept of mental set, which refers to a flexible, context-sensitive configuration of perceptual, cognitive, and response biases that can facilitate the performance of context-appropriate behavior (See Gibson, 1941; Shakow, 1962). Because the context is commonly defined by the task at hand, the term “task-set” is often used. Questions about the updating and switching of task-set are also at the heart of the ongoing debate over the nature of deficits of cognitive control and of context processing in clinical populations (Barch, Carter, MacDonald, Braver, & Cohen, 2003; Kieffaber, O’Donnell, Shekhar, & Hetrick, 2007; Meiran, Levine, Meiran, & Henik, 2000).

Contemporary interest in questions about the nature of cognitive control in the context of task-set switching has led to a number of important conclusions (See Kiesel et al., 2010, for a review), not the least of which is that there are a variety of mechanisms for cognitive control of task-switching that are likely to interact with one another in complex ways (J. W. Brown, Reynolds, & Braver, 2007). While much of current theorizing in the task switching literature relates to the nature of task-set updating, relatively few have addressed the internal structure of the relatively complex tasks which are commonly used in the literature on task-switching. Thus, the primary aim of the present research was to determine how two components of that

This article was published Online First September 17, 2012.

Paul D. Kieffaber and Philip M. Walker, Department of Psychology, The College of William & Mary; John K. Kruschke and William P. Hetrick, Department of Psychological and Brain Sciences, Indiana University Bloomington; Raymond Y. Cho, Department of Psychiatry, University of Pittsburgh, and Center for the Neural Basis of Cognition, Pittsburgh, Pennsylvania.

We express our appreciation to Roger Stanton and Anthony Bishara for their helpful comments on earlier versions of this article. This research was supported by National Institute of Mental Health (NIMH) grants MH070186-02 & 2T32MH018273 to Paul D. Kieffaber, a NARSAD Young Investigator Award & NIMH grant R03 MH066149 to William P. Hetrick, and R03 MH073955 & K08 MH080329 to Raymond Y. Cho. This work was performed in part using computational facilities at the College of William and Mary, which were provided with the assistance of the National Science Foundation, the Virginia Port Authority, Sun Microsystems, and Virginia’s Commonwealth Technology Research Fund.

Correspondence concerning this article should be addressed to Paul D. Kieffaber, Department of Psychology, College of William & Mary, 540 Landrum Dr., Williamsburg, VA 23185. E-mail: pdkieffaber@wm.edu

internal structure, stimulus-set and response-set, influence measures of control and conflict in task-switching.

The task-switching procedure remains a popular procedure for research regarding cognitive control because it yields two important conditions under which control is thought to be elicited. First, proactive control of task-set (i.e., task preparation) is thought to occur in anticipation of the need to switch tasks. Proactive control is typically thought to be elicited either between trials (the inter-trial interval) when the task order is predictable (e.g., “AABB” or alternating runs; see Rogers & Monsell, 1995) or, when the order of tasks is unpredictable, after an explicit cue indicating which task to perform. In healthy participants, responses are typically longer and more error-prone when the task performed on the previous trial is different from the task required on the current trial. However, increasing the duration of the intertrial interval (Rogers & Monsell, 1995) or the cue-target interval (Sudevan & Taylor, 1987) can significantly decrease the magnitude of these switch costs, supporting the hypothesis that the intertrial or cue-target intervals contain a task-set switching process (Rogers & Monsell, 1995; Kiesel et al., 2010). Importantly, however, many studies demonstrate that significant switch costs remain despite ample preparation for a task switch (Allport, Wylie, Humphreys, Duncan, & Treisman, 1999; Allport et al., 1994; Fagot, 1995; Rushworth, Hadland, Paus, & Sipila, 2002; Yeung & Monsell, 2003).

The presence of these residual switch costs has generated some debate over the nature of proactive preparation of task-set. For example, some theoretical models assume that the preparatory process is switch-specific, including a “task-reconfiguration” component that is not present on trials in which the task is repeated (e.g., Rogers & Monsell, 1995; Rubinstein, Meyer, & Evans, 2001), while others assume that the same processes take place on both switch and repeat trials, but to a greater extent on switch trials (e.g., Dreisbach, Haider, & Kluwe, 2002; Koch, 2005). Support for a general rather than switch-specific preparatory process can be garnered from the findings that either increasing a delay between cue and target stimuli or increasing the certainty (by manipulating target probability) with which a particular target appears will reduce response time and improve accuracy in *both* switch and repetition trials (Kiesel et al., 2010). Additionally, a positive event-related brain potential (ERP) over parietal recording sites has been reliably shown to be increased in amplitude after a cue to switch tasks (Hsieh, 2002; F. Karayanidis, Coltheart, Michie, & Murphy, 2003). This positivity, however, likely reflects a number of task-relevant processes given that some studies reveal that this positivity is also present to a lesser extent on repetition trials (Kieffaber & Hetrick, 2005; Jost, Mayr, & Rosler, 2008).

The second cognitive control-eliciting condition afforded by task-switching procedures is referred to as task-rule congruency or “conflict processing.” Because stimuli are typically bivalent with respect to the tasks, meaning that they afford decisions relevant to both tasks, cognitive control is thought to be needed to protect against the impingement of competing, task-irrelevant information on ongoing information processing. Conflict is said to occur when the currently irrelevant information in a stimulus display indicates a response that is incongruent with the correct response. Response time delays in the context of these incongruent stimuli are commonly observed and interpreted as a failure to gate-out irrelevant information amid the processing of both relevant and irrelevant features of a polyvalent stimulus (Ward, Roberts, & Phillips, 2001;

Schooler, Neumann, Caplan, & Roberts, 1997; Jensen & Rohwer, 1966).

As is the case with proactive cognitive control, there is some debate as to the nature of these conflict effects. For example, there is evidence that greater between-task interference is suffered when the same response-set is assigned to the two tasks (i.e., univalent response mapping) compared with when each task is assigned a unique response-set (i.e., bivalent response mapping; Klein, 1964; Yeung & Monsell, 2003). That is, the potential for conflict appears to be greater when the same abstract judgments (e.g., red/blue, same/different, etc.) are made about exemplars from each of the two tasks. Some have argued that this finding is suggestive of a gating mechanism capable of attenuating the interference from irrelevant decision-response mappings (Yeung & Monsell, 2003). This finding further suggests that between-task interference may be suffered at different levels depending the internal structure of their respective task-sets which defines how stimulus dimensions are mapped to abstract judgments, how judgments are mapped to decisions, and how decisions are mapped to responses.

One example of how the internal structure of task-set can be parsed is the distinction between stimulus-set and response-set. Stimulus-set refers to sensory/perceptual processes related to the discriminative selection and identification of relevant stimuli, whereas response-set refers to response-delegation processes governing the application of rules to the selection of relevant responses (Meiran, Chorev, & Sapir, 2000; Kopp, Tabeing, Moschner, & Wessel, 2006; Rushworth, Passingham, & Nobre, 2002). In cases where research has aimed to isolate stimulus-set (i.e., semantic; M. Brown & Besner, 2001; Klein, 1964) or response-set (Milham et al., 2001; West, Bowry, & McConville, 2004), in the context of between-task interference, each has been shown to lead to significant conflict-costs. However, efforts to simultaneously estimate their unique contributions using a Stroop task reveal only that both are likely to influence performance (De Houwer, 2003; van Veen & Carter, 2005). One caveat to interpreting such data from the Stroop task is that performance depends heavily on preexisting stimulus–response associations, making it difficult to make direct comparisons between the various types of conflict elicited.

Consideration of the dissociation between stimulus-set and response-set may also be informative in the context of task switching. Although similar distinctions appear in the task-switching literature (e.g., Barch et al., 1999; Crider, 1997; Elliott, McKenna, Robbins, & Sahakian, 1998; Henik et al., 2002), and in studies of focal brain lesions (Aron, Monsell, Sahakian, & Robbins, 2004), only a few studies have directly explored the explicit manipulation of stimulus- and/or response-set in the context of task switching (Meiran, Chorev, & Sapir, 2000; Kieffaber et al., 2006; Kopp et al., 2006; Rushworth, Passingham, & Nobre, 2002; Rushworth, Hadland, et al., 2002; Yeung & Monsell, 2003). In cases where efforts have been made to isolate the response-set component of task-set, both response-mapping reversals (Dias, Robbins, & Roberts, 1996; Dove, Pollmann, Schubert, Wiggins, & Cramon, 2000) and effector switches (Brass et al., 2003; West, Bailey, & Langley, 2009) have been demonstrated to produce significant switch costs, indicating that at least part of the switch cost is attributable to the need to overcome previously valid response mappings.

Historically, consideration of this distinction between stimulus-set and response-set has been complicated by the fact that many of the

reported set effects originate from experimental procedures that confound stimulus selection and response delegation. For example, a typical task-switching procedure will require participants to judge a compound letter/number stimulus (e.g., 5E) according to whether the number is odd or even, or whether the letter is a vowel or a consonant. Because odd, even, vowel, & consonant decisions are often assigned to two (left/right) responses, both stimuli and responses are bivalent, meaning that switching between tasks requires one to reconfigure stimulus-set so as to improve processing of the relevant stimulus attribute (i.e., letter or number) *and* reconfigure response-set so as to bias the appropriate set of decision-response mappings (e.g., Odd → Left and Even → Right, or Vowel → Left and Consonant → Right). A schematic of this conventional task-switching procedure is illustrated in Figure 1A.

There is evidence that this kind of response bivalency influences task performance as well as the recruitment of neural resources. For example, Brass et al. (2003) manipulated response mappings such that the same response was used to achieve different goals (e.g., response bivalency). They report increased switch costs for tasks with a bivalent response mapping along with imaging data suggesting that an interaction between task-switching and response valence is related to neural activity in regions of the lateral prefrontal cortex (Brass et al., 2003). In contrast, however, Mueller et al. (2007) later reported equivalent switch costs in bivalent and univalent conditions using a similar manipulation.

One difficulty with the interpretation of these findings with respect to the notion of response-set is that the two response-sets in Mueller et al.'s (2007) univalent condition were mapped to separate hands (i.e., effectors) for each of the two tasks. Thus, switches between univalent response sets were confounded with effector switches (See West et al., 2009). Because

response bivalency in the typical task-switching procedure requires the remapping of response meanings without changing the effector(s) (see Figure 1), we conceive of the response-set switching process as one that may occur independently of the selection of an effector with which to implement a given decision-response mapping.

Research by Hübner, Futterer, and Steinhauser (2001) similarly highlights the importance of considering the internal structure of the task-set implicit to procedures like that depicted in Figure 1. For example, Hübner et al. (2001) demonstrated that switch costs can be modulated by the number of task “components” being switched with larger switch costs incurred during switches of two by comparison with one component operation. Likewise, Arrington and colleagues (2003) demonstrated that switch costs were reduced for tasks which share component operations, suggesting that proactive control may operate in a multidimensional task-space defined by the internal structure of the task. While many parameters of the task-space may be task-general (i.e., shared by many tasks), these findings suggest that at least part of task-set preparation is specific to those parameters which uniquely define the task being switched to.

While much of current theorizing in the task switching literature relates to the processes of proactive control and conflict processing, relatively few have addressed the internal structure of the relatively complex tasks which are commonly used to elicit these control mechanisms. Thus, the primary aim of the present study was to test a distinction between stimulus-set and response-set in terms of the internal structure of task-set. To do so, a novel task was developed that interleaves trials with univalent and bivalent response-sets. This novel procedure required participants to alternate unpredictably between three tasks, each requiring the judgment of a pair of figures on one stimulus dimension (Shape, Size, or Color). Two of the tasks required a Comparison judgment wherein participants were asked to decide whether the figures in the pair were “same” or “different.” The third task required an Identity judgment wherein participants were asked to decide whether the figures in the pair had the (shared) value A or value B. In one group of participants, for example, the Shape and Size tasks required a judgment as to whether the pair of figures were the same or different on the task-relevant dimension of shape or size and the Color task required participants to judge whether the shared color of the pair of figures was red or blue. Because the assignment of the Shape, Size, and Color tasks to the Comparison or Identity judgments is made explicit to the participant, the cue informs the participant about both the relevant stimulus- and response-set. A schematic of the internal structure of this hypothetical task-set structure is presented in Figure 2.

Importantly, the pathways constituting the internal structure of task-set depicted in Figure 2 all represent arbitrary stimulus-decision and/or decision-response mappings. That is, rather than take advantage of inherent semantic or spatial relationships or preexisting task-set biases (e.g., a predisposition to read words), hypotheses regarding the present task rely entirely on differences between the task-sets that are defined by the internal structure depicted in Figure 2. This schematic is also illustrative of our assumptions regarding the role of stimulus & response bivalency and, by extension, switches of stimulus- and response-set. Thus, the first prediction that can be derived from

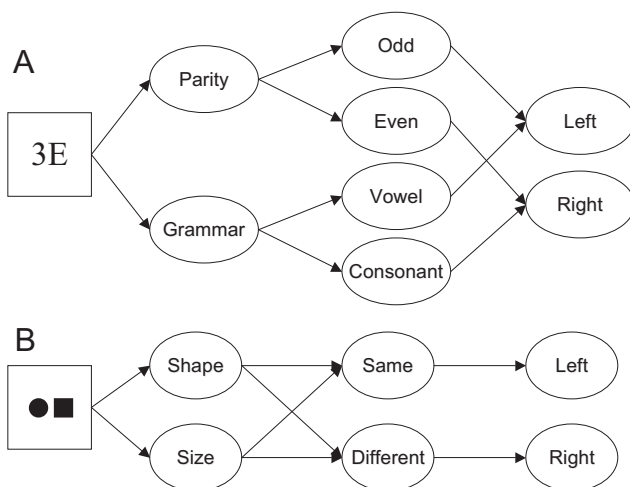


Figure 1. Schematic depiction of (A) a conventional task switching procedure and (B) a procedure used by Kieffaber and Hetrick (2005) to isolate stimulus-set switches. The boxes indicate target stimuli. Moving from left to right, the first and second set of arrows are intended to depict the internal structure of stimulus-set, selectively gating information that corresponds with the current task-relevant decisions. The third set of arrows depict the internal structure of response-set, selectively activating task and decision-appropriate responses.

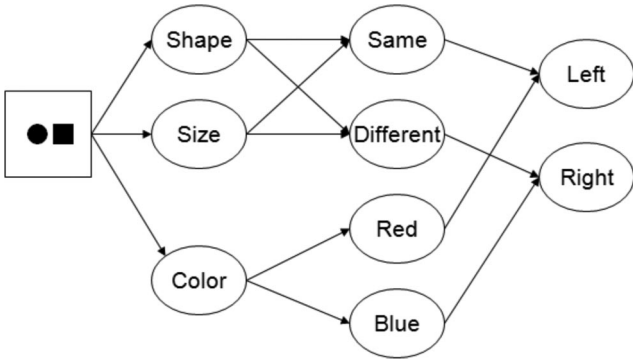


Figure 2. Schematic depiction of the current task. Again, arrows are intended to depict cognitive representations of attentional selection, decision-making, and response-mapping. Open symbols = red, closed symbols = blue.

the internal structure depicted in Figure 2 is that switches of stimulus-set (SW_S ; e.g., a switch from Shape to Size; see Figure 2) will require only a change to those pathways priming the perceptual judgment whereas switches of stimulus and response set (SW_{SR} ; e.g., a switch from Color to Size; see Figure 2) will require changes to those pathways priming the perceptual judgment and those pathways priming the decision-response mappings. Given previous research has illustrated that the costs of

task-set switching are correlated with the number of parameters being switched (Hübner et al., 2001; Arrington et al., 2003), we expect that SW_{SR} trials will incur larger switch costs than SW_S trials.

Predictions regarding between-task conflict can similarly be derived from the structure of Figure 2. When considering only those two judgments which share a response mapping (e.g., Shape and Size in Figure 2), an established stimulus-set will gate potentially conflicting, task-irrelevant information. However, when considering two judgments which do not share a decision-response mapping (e.g., Shape and Color in Figure 2), an established stimulus-set will gate task-irrelevant information and an established response-set will gate task-irrelevant response activation. Thus, it is expected that the cumulative gating of stimulus-set and response-set will protect against conflict effects when responses are bivalent by comparison with the gating of stimulus-set alone when responses are univalent. In fact, because there are two alternative tasks on each trial, each of which is associated with either stimulus-set or response-set conflict, there are four levels of conflict possible in the current task (See Figure 3): (1) Stimulus-set and response-set are both congruent with current task goals ($S_C R_C$). (2) There is congruency only at the level of stimulus-set ($S_C R_I$). (3) There is congruency only at the level of the response-set ($S_I R_C$). (4) There is incongruency in both stimulus-set and response-set ($S_I R_I$). Given the assumptions outlined above, it is expected that (1) shorter RTs to $S_C R_C$ trials than $S_C R_I$ trials will reflect the presence of significant response-set conflict, (2) shorter RTs to $S_C R_C$ trials than

Relevant Task = "Shape"

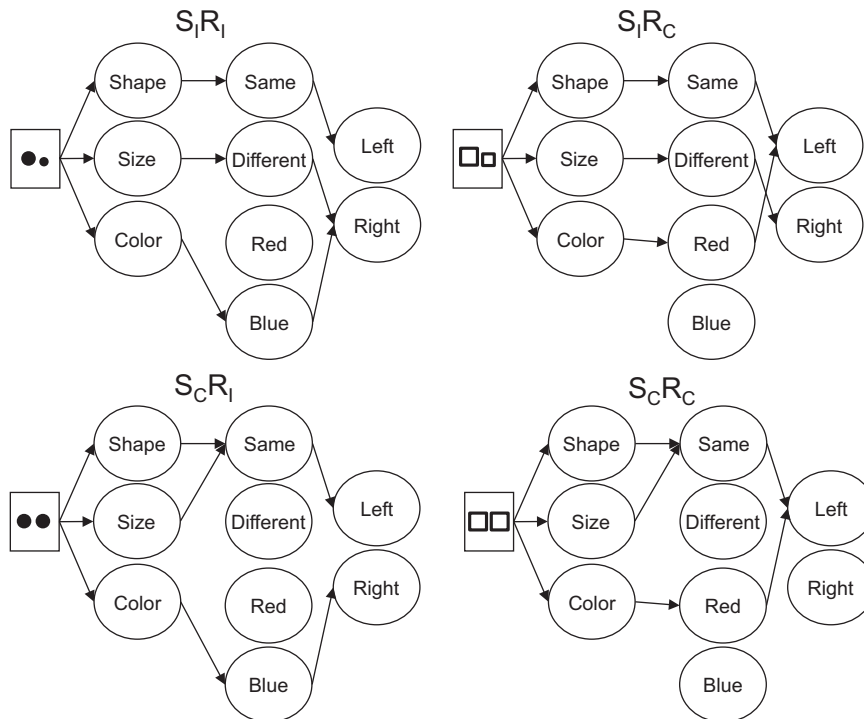


Figure 3. Schematic depiction of the four conflict types that are possible in the context of the current task. Note that the relevant task is "Shape" and that solid arrows depict only the correct routes for information processing. Open symbols = red, closed symbols = blue.

$S_I R_C$ trials will reflect the presence of significant stimulus-set conflict, and (3) Shorter RTs to $S_C R_I$ than $S_I R_C$ will reflect the critical prediction that the cumulative gating of stimulus-set and response-set will elicit smaller costs of between-task conflict.

Experiment 1: Stimulus-Set Versus Response-Set

Method

Participants. Forty-five (30 male, 15 female) participants from Indiana University received partial credit in an introductory psychology course for their participation. The average age of participants was 19.3 ($SD = 1.2$) years. The experiment was conducted with the understanding and consent of each participant (Indiana University, Bloomington, Study #00–4038). All participants reported normal or corrected-to-normal visual acuity and normal color vision.

Procedure and stimuli. Participants were individually seated in front of a standard CRT monitor in a small room. After giving informed consent, participants completed a brief demographic questionnaire and then began the task. Target stimuli consisted of figure-pairs that varied in shape (circle/square), size (large/small), and color (red/blue). On each trial, participants were instructed by an explicit cue (the word SHAPE, SIZE, or COLOR) to make a judgment about the figure pair according to the cued dimension. The cue remained on screen for 350 ms, and the target figures appeared after a 500-ms cue–target interval (see Figure 4. In addition to indicating the relevant stimulus dimension, each of the task-cues also indicated a task-relevant response-set. Two of the tasks required a Comparison decision (e.g., same/different) about the two figures (on the cued dimension), and one of the tasks required an Identity decision (i.e., circle/square, large/small, or red/blue) about the pair of figures. The assignment of the three stimulus dimensions (Shape, Size, & Color) to the two types of judgments was counterbalanced across subjects. Importantly, the

value of the two figures on the dimension assigned to Identity judgment was always the same within a trial. For example, if the shape and size dimensions were assigned to the Comparison judgment and color were assigned to the Identity judgment (i.e., Color-ID condition), then the two figures in any given stimulus display could vary in both shape and size, but were always the same color (either red or blue). Participants were randomly assigned to one of these three (Color-ID, $n = 17$; Shape-ID, $n = 12$; and Size-ID, $n = 16$) conditions and labels indicating the task-appropriate responses were placed over the Caps Lock and Enter keys of a standard QWERTY keyboard. Same, Square, Large, and Red decisions were mapped to one key and Different, Circle, Small, and Blue decisions were mapped to another key. The assignment of response labels to the Caps Lock and Enter keys was randomly assigned for each participant. A schematic of the task procedure is presented in Figure 4.

The task consisted of four blocks of 120 trials, and participants were permitted a brief break between each block. Task switches occurred following either one ($n = 120$) or three ($n = 120$) presentations of the previous rule. This staggered trial sequence yielded an overall task sequence wherein the global probability of a task switch is 0.5, and the local transitional probability of a switch is also 0.5 on 50% of the trials. Each of the three switch (SW_{SR} , SW_S , and ST (i.e., “stay”)) and four congruency ($S_C R_C$, $S_C R_I$, $S_I R_C$, $S_C R_C$) trial types were equally represented throughout the experiment.

Data analysis. Because judgments in the Comparison and Identity tasks are fundamentally different and because stimulus-set conflict could only occur in the context of the comparison judgments, tests of the primary hypotheses were addressed using data only from the comparison judgments. Response times and accuracy rates for the 12 trial types created by the factorial combination of the Switch (SW_{SR} , SW_S , and ST) and Congruency ($S_C R_C$, $S_C R_I$, $S_I R_C$, and $S_C R_C$) factors were submitted individually to a Switch ($3 \times$) Congruency (4) repeated measures ANOVA. Response times from the Identity task were analyzed separately and are presented in the Appendix. With respect to the Identity task, all trials involving a task switch are SW_{SR} trials and between-task conflict can only occur at the level of response-set. Thus, response times to the Identity task were analyzed by a Switch (2 ; SW_{SR} and ST) \times Congruency (3 ; R_C , R_{IC} , and R_I) repeated measures ANOVA where R_{IC} refers to those trials in which the correct response to only 1 of the alternative tasks was congruent with the currently relevant correct response. Because there were no significant between-groups differences across the three Response-Mapping conditions (see the Appendix), and because concerns regarding task-specific variability are assuaged by the fact that the mapping between task and identification/comparison judgments was counterbalanced across participants, the data were aggregated across subjects for the three Response-Mapping conditions. Moreover, data were aggregated within participants over the two comparison tasks. Greenhouse-Geisser corrected p values are provided where appropriate.

Results and Discussion

Accuracy. Mean accuracy for each of the conditions is illustrated in panel A of Figure 5. Overall performance on the task was good ($M = 92.6\%$, $SD = 5.7\%$). Accuracy rates were submitted to

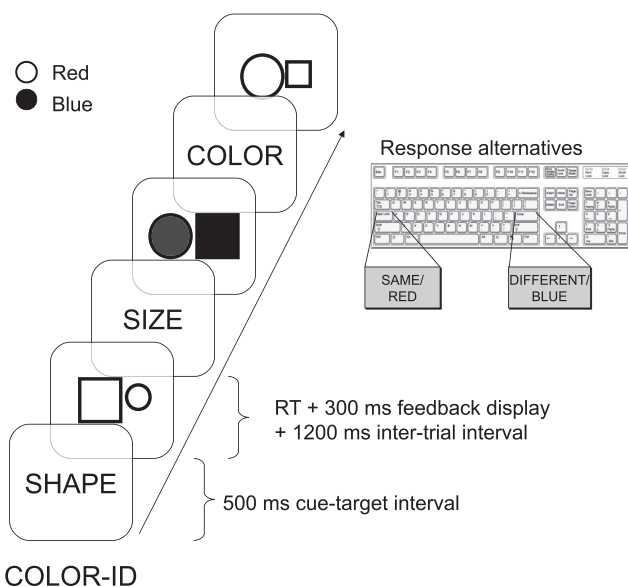


Figure 4. Procedural schematic of Experiment 1.

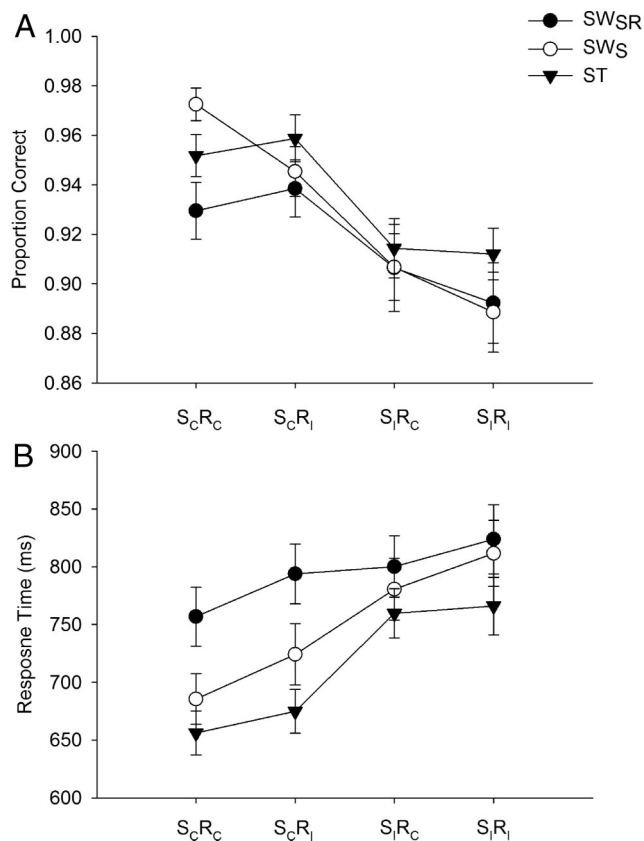


Figure 5. Accuracy (A) and response times (B) across conflict types for each of the three switch conditions.

a Switch (3) by Congruency (4) repeated measures ANOVA. A significant main effect of Switch indicated that there were omnibus accuracy costs associated with task-switching, $F(2, 88) = 4.69$, $p < .05$. However, planned comparisons revealed that accuracy on SW_S ($M = 0.93\%$, $SD = 0.06\%$) was not significantly different from ST trials ($M = 0.93\%$, $SD = 0.05\%$) and that accuracy on SW_{SR} trials ($M = 0.92\%$, $SD = 0.06\%$) was not significantly different from SW_S trials.

The main effect of Congruency was also significant in the accuracy rates, $F(3, 132) = 17.03$, $p < .001$. Planned comparisons revealed that there were not significant accuracy costs in $S_C R_I$ ($M = 0.95\%$, $SD = 0.06\%$) by comparison with $S_C R_C$ ($M = 0.95\%$, $SD = 0.05\%$) trials. However, accuracy costs were evident in the comparison of $S_I R_C$ ($M = 0.91\%$, $SD = 0.08\%$) and $S_C R_C$ trials, $p < .01$, indicating significant costs of stimulus-set conflict. Finally, accuracy costs were significantly larger in $S_I R_C$ by comparison with $S_C R_I$ trials, $p < .01$, indicating that the impact of response-set conflict was reduced by comparison with stimulus-set conflict. The interaction between Switch and Congruency was not significant.

Response time. Mean RTs for each condition are illustrated in panel B of Figure 5. Response times (RT; 10% trimmed), excluding error trials and trials immediately after an error, were submitted to a Switch (3) by Congruency (4) repeated measures ANOVA. A main effect of Switch indicated that there were significant RT switch costs, $F(2, 88) = 28.27$, $p < .001$. Planned comparisons

revealed that switch costs were significant in SW_S ($M = 750.40$ ms, $SD = 154.09$) compared with ST trials ($M = 714.15$ ms, $SD = 129.95$), $p < .01$. Moreover and in accordance with predictions, there were significant additional RT costs in SW_{SR} ($M = 793.62$ ms, $SD = 163.57$) trials by comparison with SW_S trials, $p < .001$.

A main effect of Congruency, $F(3, 132) = 42.12$, $p < .001$, reflected the impact of between-task conflicts. Planned comparisons revealed significant RT costs associated with both response-set conflict (e.g., $S_C R_I$ ($M = 730.91$ ms, $SD = 143.01$) $>$ $S_C R_C$ ($M = 699.49$ ms, $SD = 135.98$)), $p < .01$, and stimulus-set conflict (e.g., $S_I R_C$ ($M = 780.08$ ms, $SD = 150.90$) $>$ $S_C R_C$), $p < .001$. Critically, however, RTs were significantly faster to $S_C R_I$ by comparison with $S_I R_C$, $p < .001$, confirming the prediction that greater between-task interference would be suffered when between-task conflict is gated only at the level of stimulus-set.

Finally, the interaction between factors of Switch and Congruency was also significant, $F(6, 264) = 2.90$, $p < .05$. To better understand how SW_{SR} differed from SW_S and ST trials across the levels of Congruency, switch costs were computed as difference scores (e.g., $SW_{SR} - ST$ and $SW_S - ST$; hereafter referred to as SW_{SR} costs and SW_S costs, respectively). The pattern of these RT costs across the four levels of Congruency was then analyzed by a 2 (Switch; SW_{SR} , SW_S) by 4 (Congruency; $S_C R_C$, $S_C R_I$, $S_I R_C$, and $S_I R_I$) repeated measures ANOVA. The Switch by Congruency interaction was significant, $F(3, 132) = 2.73$, $p < .05$, and was clearly driven by an increase in the SW_{SR} costs on $S_C R_C$ and $S_C R_I$ trial types (see Figure 6).

Taken together, the data largely supported predictions. First, the finding that SW_{SR} trials by comparison with SW_S trials were associated with significantly greater switch costs (both RT and accuracy) validates the claim that arbitrary response mappings constitute an additional component of task-set that contributes significantly to the switch cost. Second, the finding that $S_C R_I$ trials by comparison with $S_I R_C$ incurred smaller congruency costs (both RT and accuracy) is consistent with the internal structure of task-set depicted in Figure 2 and with the hypothesis that stimulus-set and response-set act as cumulative filters for task-irrelevant information processing.

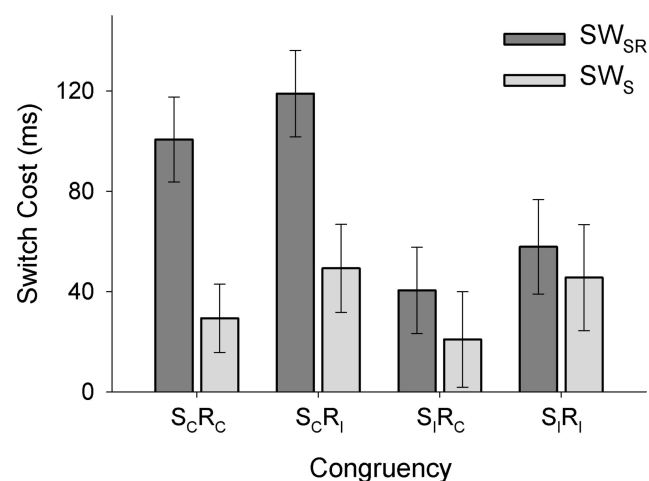


Figure 6. Task switching costs across levels of congruency (bars depict standard error of the mean).

The interaction between Switch and Congruency is more difficult to interpret. Task-set inertia (Allport et al., 1994; Wylie & Allport, 2000) and similar hypotheses of the switch costs assert that the priming of task-irrelevant pathways on previous trials will increase between-task interference following a task switch. The fact that SW_{SR} switches were associated with larger switch costs on $S_C R_I$ trials (which contain response-set conflict) is consistent with such residual priming, however the fact that similar increases were observed for $S_C R_C$ trials is incompatible with such explanations. It should also be noted, however, that while switch costs are often observed to be larger on incongruent trials, the anticipated interaction is typically slight (Meiran & Kessler, 2008). Moreover, there is evidence that the strength of the interaction dissipates with longer cue-target intervals that are similar to the range used in the current study (Goschke & Driver, 2000). Casting some doubt on the practical significance of this interaction, a similar interaction was nonsignificant in previous research using a nested version of the present task and long (1200 ms) cue-target intervals (Kieffaber et al., 2006, 2007). In light of these caveats, this finding will not receive further discussion.

Experiment 2: Decision Time Versus Motor Time

The data from Experiment 1 support the hypothetical internal structure of task-set depicted in Figure 2. However, implicit to that depiction is that stimulus-set and response-set impact dissociable points of information processing and may thus have dissociable effects on the selection and execution of responses. In fact, previous research using a nested version of this task that included *only* switches of stimulus-set (see Figure 1B) suggests that the effects of stimulus-set switches and stimulus-set conflict can be found selectively in the Gaussian component of the RT distributions which is typically associated with stimulus-based cognitive processing (Kieffaber et al., 2006).

Thus, Experiment 2 was designed with the intent to distinguish decisional processing occurring before response selection from response execution. To do this, the procedure from Experiment 1 was modified so that participants moved a cursor from a starting location at the bottom of the screen to one of two boxes representing the category judgments, rather than simply pressing a button corresponding to each decision. This permitted quantification of two components of the response time: 1) Decision time (DT) is the time it takes a participant to initiate action, and 2) Motor time (MT) is the time it takes to complete the selected action. The separation of RT into these two constituents was motivated by the following hypotheses: (1) Stimulus-set (SW_S) switching and stimulus-set conflict ($S_I R_C$) will be more likely to affect the DT component of RT because the cognitive representation of task-set depicted in Figure 2 implies that stimulus-set governs information processing related to perceptual input and abstract decisions about stimulus identity. (2) Response-set switching (SW_{SR}) and response-set conflict ($S_C R_I$) will be more likely to affect the MT component of response-time because the cognitive representation of task-set depicted in Figure 2 also implies that response-set governs information processing related to the mapping of abstract judgments to overt responses.

Predictions with respect to the dissociation between DT and MT are most compelling in the context of task-set conflict. Recall that a critical prediction of the internal task-set structure depicted in

Figure 2 is that the RT costs of response-set conflict will be substantially less than stimulus-set conflict as a result of the accumulation of task-set filters. Thus, if the DT component of RT is sensitive to stimulus, but not response-set conflict, then DTs on $S_C R_I$ trials will be significantly less than those on $S_I R_C$ trials and not different from $S_C R_C$ trials, replicating the results of Experiment 1. However, because MT is assumed to commence subsequent to stimulus identification/categorization, it may not benefit from the cumulative filtering of stimulus-set and response-set, relying primarily on the resolution of conflict at the level of the response-set. It is therefore predicted that increased susceptibility to response-set conflict will lead to similarity between $S_C R_I$ and $S_I R_C$ trials (attributable to RT slowing on $S_C R_I$ trials resulting from response-set conflict and RT acceleration on $S_I R_C$ trials resulting from the benefits of response-set congruency) as well as a significant difference between $S_C R_I$ and $S_C R_C$ trials (indicating significant costs of response-set conflict).

Method

Participants. Forty-five (30 female, 15 male) from the University of Pittsburgh received partial credit in an introductory psychology course for their participation. The average age of participants was 18.6 ($SD = 0.68$) years. The experiment was conducted with the understanding and consent of each participant and in accordance with the Institutional Review Board at the University of Pittsburgh. All participants reported normal or corrected-to-normal visual acuity and normal color vision.

Apparatus & stimuli. A schematic of the task is presented in Figure 7. The apparatus, stimuli, and procedure were the same as in Experiment 1 with the following two exceptions: (1) The Shape and Size rules were mapped to the Same/Different judgment and the Color rule was mapped to the Red/Blue judgment for all participants, and (2) Same/Different and Red/Blue responses were made by moving a mouse cursor from a central position at the bottom of the screen to one of two positions to the left and right of the target stimulus. These positions were indicated by black squares and contained the response labels in white letters. Cues remained on the screen for 500 ms and were followed by a blank screen for another 500 ms. Target figures remained on screen until a response was made by the participant. Feedback regarding accuracy was provided as soon as a response was made and remained on the screen until the participant returned the cursor to a central position at the bottom of the screen. This position was indicated by a small black box labeled with the word, Home. A 1000-ms intertrial interval preceded the onset of the next cue. The task included 480 trials (four blocks of 120) with each of the three Switch and four Congruency types equally represented across the experiment.

Response time measures. Decision Time (DT) was defined as the time between the presentation of the target figures and the initiation of cursor movement. Movement initiation was defined as any change in the vertical or horizontal position of the cursor of more than 8 pixels. This definition provided some tolerance for subtle cursor movement unrelated to response execution. Motor Time (MT) was defined as the time between the initiation of the movement and the completion of the movement. Movement completion was defined as the time at which the cursor crossed any of

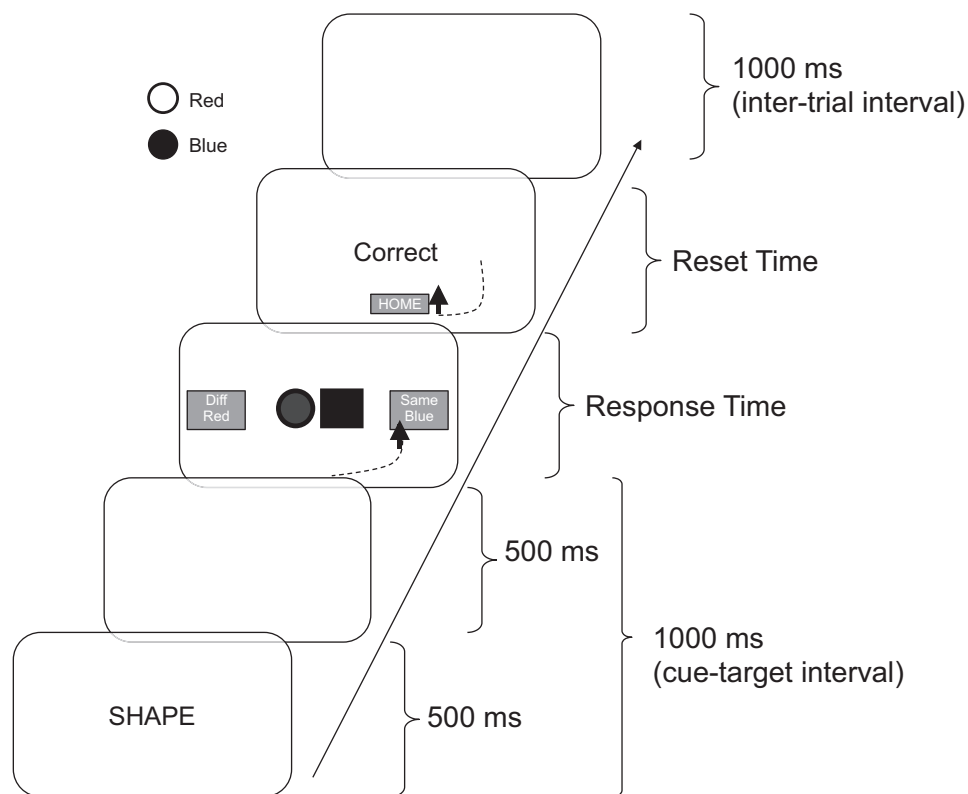


Figure 7. Procedural schematic of Experiment 2.

the boundaries defined by the response boxes to the left and right of the target figures.

Data analysis. Accuracy and response times were analyzed separately in the same way as in Experiment 1 except that an additional Response Component (DT, MT) factor was added to the analysis of RTs. Greenhouse-Geisser corrected p values are provided where appropriate.

Results and Discussion

Accuracy. Overall performance on the task was good ($M = 95.3\%$, $SD = 3.6\%$). Accuracy rates were submitted to a Switch (3: SW_{SR} , SW_S , ST) by Congruency (4: $S_C R_C$, $S_C R_I$, $S_I R_C$, $S_I R_I$) repeated measures ANOVA. A significant main effect of Switch indicated that there were accuracy costs associated with task-switching, $F(2, 88) = 13.5$; $p < .01$. Planned comparisons revealed that although accuracy was significantly reduced on SW_S ($M = 94.5\%$, $SD = 4.6\%$) compared with ST ($M = 96.4\%$, $SD = 5.0\%$) trials, $p < .001$, there were no differences in accuracy costs across SW_{SR} trials ($M = 94.7\%$, $SD = 4.6\%$) and SW_S trials.

The effect of Congruency was also significant in the accuracy rates, $F(3, 132) = 42.6$; $p < .001$. Planned comparisons revealed that there were significant accuracy costs associated with $S_C R_I$ ($M = 97.0\%$, $SD = 4.0\%$) by comparison with $S_C R_C$ ($M = 98.9\%$, $SD = 1.3\%$) trials, $p < .01$, reflecting the impact of response-set conflict. Significant accuracy costs were also observed in $S_I R_C$ ($M = 93.3\%$, $SD = 5.3\%$) by comparison with $S_C R_C$ trials, $p < .001$, reflecting the impact of stimulus-set conflict. Finally, there

were significant accuracy costs observed in $S_I R_C$ by comparison with $S_C R_I$ trials, $p < .001$, replicating Experiment 1 and reflecting the predicted increase in conflict processing associated with stimulus-set conflict. The interaction between Switch and Congruency was not statistically significant.

Response time. Means for each condition and response component (DT & MT) are illustrated in Figure 8. Response times (RT; 10% trimmed within each response component), excluding error trials and trials immediately after an error, were submitted to a Switch (3: SW_{SR} , SW_S , ST) by Congruency (4: $S_C R_C$, $S_C R_I$, $S_I R_C$, $S_I R_I$) by Response Component (2: DT, MT) repeated measures ANOVA. A main effect of Response Component indicated that DT ($M = 655$ ms, $SD = 204$ ms) accounted for a much larger proportion of the total response time than did MT ($M = 269$ ms, $SD = 100$ ms), $F(1, 44) = 291.9$, $p < .001$. There were also significant main effects of Switch, $F(2, 88) = 4.3$, $p < .05$, and Congruency, $F(3, 132) = 30.4$; $p < .001$, but these were each qualified by separate interactions with the Response Component factor. Neither the two-way interaction between Switch and Congruency nor the three-way interaction between Switch, Congruency, and Response Component were statistically significant.

The interaction between Switch and Response Component, $F(2, 88) = 7.0$; $p < .01$, revealed that the time costs of task-switching were significant only in the DT component of the total response times, $F(2, 88) = 9.9$, $p < .001$. Planned comparisons confirmed the expectation of significantly longer DTs to SW_{SR} trials ($M = 684$ ms, $SD = 213$ ms) than to SW_S ($M = 663$ ms, $SD = 213$ ms)

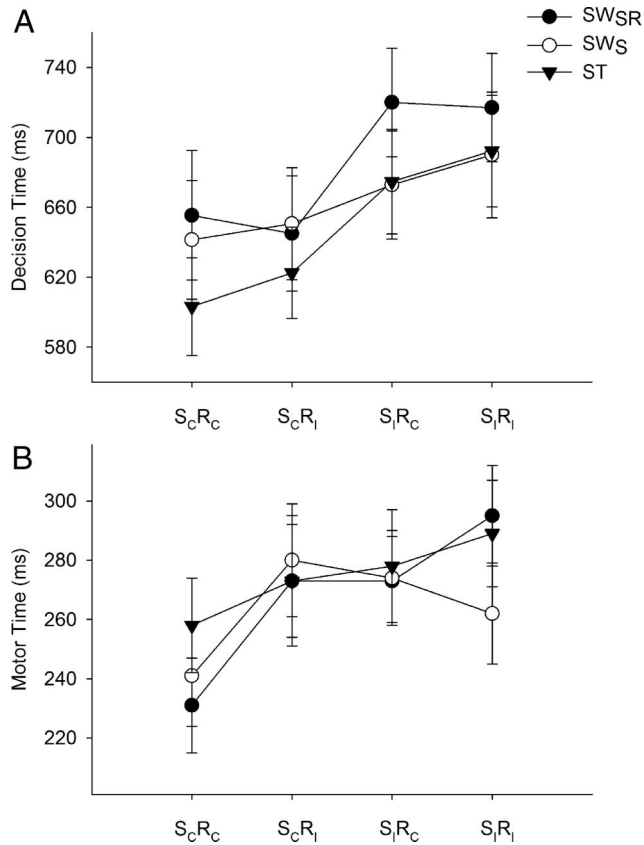


Figure 8. Experiment 2 response times shown separately for each of the three switch and four congruency conditions and for each of the DT and MT components (error bars reflect $\pm 1 SE$).

trials, $p < .01$, indicating an additional cost of switching the response component of task-set. However, the costs of switching stimulus-set alone ($SW_S - ST$; $M = 648\text{ms}$, $SD = 179\text{ms}$) were not significant in the DT component of RT.

The interaction between Congruency and Response Component, $F(3, 132) = 7.7$, $p < .001$, revealed differences in the way that stimulus- and response-conflict impacted the two components of total response time. Congruency effects in the DT component, $F(3, 132) = 25.8$; $p < .001$, replicated the findings in Experiment 1. Planned comparisons revealed that DTs to S_cR_c ($M = 633\text{ms}$, $SD = 216\text{ms}$) were not statistically different from S_cR_i ($M = 639\text{ms}$, $SD = 194\text{ms}$), indicating that response-set conflict was not significant in the DT component of RT. Moreover, DTs to S_cR_i were significantly shorter than those to S_iR_c ($M = 689\text{ms}$, $SD = 200\text{ms}$), $p < .001$, confirming the expectation that DT would be susceptible to stimulus-conflict.

Congruency effects were also significant in the MT component of response time, $F(3, 132) = 9.2$; $p < .001$, but the pattern of results suggested that both stimulus- and response-conflict had a significant impact on the time to execute a motor response. Planned comparisons revealed that MT in S_cR_i ($M = 276\text{ms}$, $SD = 123\text{ms}$) was significantly slower than MT in S_cR_c trials ($M = 244\text{ms}$, $SD = 106\text{ms}$), $p < .001$, indicating a significant MT cost associated with response-set conflict. Critically, the comparison of MT in S_cR_i and S_iR_c ($M = 276\text{ms}$, $SD = 107\text{ms}$) was

not statistically significant, consistent with the expectation that response execution is more vulnerable to the impact of response-conflict.

Taken together, the results from Experiment 2 replicate and extend those from Experiment 1. The DT component of response time, reflecting movement onset, closely replicated the data from Experiment 1 which used simple key-press responses in the following two ways. First, SW_{SR} trials were associated with a significant switch costs compared with SW_S trials. Second, response-set conflict elicited significantly smaller DT conflict costs as evidenced by shorter DTs on S_cR_i compared with S_iR_c trials and no difference between S_cR_c and S_cR_i trials. The data also indicate that response execution, reflected in the MT component of RT, is more susceptible to the effects of response-set conflict which is consistent with notion that the processes governing MT commence following stimulus identification/categorization and may thus not benefit from the cumulative filtering of stimulus-set and response-set.

Experiment 3: Event-Related Brain Potentials

The basis of Experiments 1 and 2 was the hypothetical cognitive representation (i.e., internal structure) of task-set depicted in Figures 2 and 3. Implied by this depiction of task-set is that dissociable neural circuits are recruited on the basis of task instructions. Thus, Experiment 3 was designed to determine whether the behavioral dissociations observed in Experiments 1 and 2 would also be reflected in brain activity using event-related brain potentials (ERPs). Combining measurement of ERPs and a cued task-switching procedure (such as those used in Exp. 1 and 2) introduces two opportunities to address questions about the neural basis of control and conflict in task-set switching. First, ERPs time-locked to the onset of the task cue provide an opportunity to determine whether neural activity at the moment of the task-switch is modulated by the nature of the operations being changed (e.g., SW_S vs. SW_{SR}). Second, the ERPs time-locked to the onset of the target stimuli provide an opportunity to determine whether neural indices of conflict processing are modulated by the nature of the conflict (e.g., S_cR_i vs. S_iR_c) encountered.

ERPs have been used on many occasions to investigate the neural basis of task-set switching. A common finding is that a posterior, late (i.e., 600–800 ms), positive component of the ERP is increased in amplitude when participants are cued to switch tasks (Hsieh, 2002; F. Karayanidis et al., 2003; Kieffaber & Hetrick, 2005). This positivity has been demonstrated to be sensitive to a variety of factors relevant to task switching, including memory retrieval, task-set configuration, and rule mapping (Jost et al., 2008; Travers & West, 2008; Swainson, Jackson, & Jackson, 2006). With respect to the goals of the current research, Karayanidis (2010) recently reviewed this literature and concluded that this switch positivity may be sensitive to both the stimulus-set and response-set components of task-set given that it can be elicited by (1) switching judgments on the same stimuli with bivalent stimuli and univalent responses (Kieffaber & Hetrick, 2005), (2) by switching judgments on the same stimuli with bivalent stimuli and bivalent responses (Nicholson, Karayanidis, Bumak, Poboka, & Michie, 2006), and (3) because its latency is prolonged when task preparation includes overt stimulus-response mappings (Astle, Jackson, & Swainson, 2008).

The task-cue is sometimes also associated with pretarget negativity that is likely to be associated with general task preparation processes (Karayanidis, 2010) but has also been shown to be increased in amplitude when an overt response is required (Astle et al., 2008). There is also evidence that the pretarget negativity is sensitive to the remapping of effectors to response category (see Karayanidis, 2010). Mueller, Swainson, and Jackson (2007) addressed this by comparing cue-locked ERPs to switches between tasks with bivalent response mappings with cue-locked ERPs to switches between tasks with univalent response mappings. A frontally distributed pretarget negativity was found to be larger in amplitude on switch trials, but *only* in the condition with bivalent response-mappings (Mueller et al., 2007).

In addition to the fact that univalent and bivalent task types were blocked in the procedure used by Mueller et al. (2007), precluding a direct statistical comparison between cue-locked ERPs to bivalent and univalent task-switches, switch trials in univalent response conditions always included an effector switch. The task-set switching procedure used in Experiments 1 and 2 addresses these limitations by permitting direct comparisons between SW_{SR} and SW_S trials *within* a single task block and without confounding effects of effector switching. One possible outcome, indicating a localized organization of the stimulus-set and response-set components of task-set, is that cues indicating a SW_{SR} switch will be associated with modulation of both the posterior parietal ERP positivity and a frontal ERP negativity whereas SW_S switches will be associated only with modulation of the posterior positivity. Alternatively, some have argued for a more general, dimensional representation of task-set in the brain (Kleinsorge & Heuer, 1999). Thus, the posterior positive component of the ERP, which is most commonly implicated in studies of task switching, may reflect a generalized switching operation, increasing in amplitude on SW_{SR} compared with SW_S switches because of the additional cognitive effort required.

The conceptual framework for conflict processing theory is more fully developed in the ERP literature than the framework for task-set switching. For example, there is a general consensus that the anterior cingulate cortex (ACC) participates in the cognitive control loop and may even serve the specific purpose of detecting conflict and subsequently signaling an increase in cognitive control from other brain areas in order to resolve conflicts when they occur (Botvinick, Braver, Barch, Carter, & Cohen, 2001; Jones, Cho, Nystrom, Cohen, & Braver, 2002). The N2 component of the ERP is most commonly identified with conflict processing. The N2 has been demonstrated to be larger in amplitude (more negative) under conditions of task conflict (Folstein & van Petten, 2008) and has even been shown to respond in a graded way to parametric manipulations of the level of conflict (Forster, Carter, Cohen, & Cho, 2011). Several other ERP components have also been implicated in conflict processing. For example, West and colleagues (2004) observed a conflict-modulated N450 in addition to N2 and Hsieh & Liu (2008) also demonstrated conflict-based modulation of ERPs in the 300–700ms latency range.

Related efforts to dissociate the variety of conflict processing mechanisms suggests that stimulus-conflict and response-conflict will both be associated with larger N2 amplitude (West et al., 2004; Wendt, Heldmann, Mnte, & Kluwe, 2007). Equivalent N2 amplitudes to $S_C R_I$ and $S_I R_C$ trials would be consistent with the conflict monitoring hypothesis of the N2 component (Botvinick et

al., 2001) given that conflict effects observed in RTs were so different. Alternatively, Forster et al.'s (2011) demonstration that N2 amplitude could be modulated parametrically with the level of stimulus-conflict suggests that N2 amplitude may be smaller to $S_C R_C$ and $S_C R_I$ stimuli and larger to $S_I R_C$ and $S_I R_I$ stimuli because of the additional cognitive conflict observed in the latter trial types. Such a finding would be more consistent with claims that the N2 component is related to outcome evaluation and decision-making (see Nieuwenhuis, Yeung, Holroyd, Schurger, & Cohen, 2004).

The fact that $S_C R_I$ trials did not elicit any significant conflict costs in total response time (Exp. 1) or in the DT component of RT (Exp. 2) has been interpreted as support for the hypothesis that response-set conflicts elicit less between-task interference. This interpretation depends on the assumption that the stimulus-conflict and response-conflict engendered by the arbitrary mappings depicted in Figure 2 are similarly processed by the brain. Thus, an important question is whether conventional ERP markers of conflict processing such as the N2 and N450 components are modulated by the types of conflict processing distinctions articulated in the present research.

Taken together, previous findings argue strongly for a neural dissociation between stimulus-set and response-set in task-switching and conflict processing, however previous results derive from indirect, block-wise comparisons of set-switching trials and from measures of conflict processing that capitalize on overlearned responses (e.g., word reading) or preexisting response predispositions. Thus, the primary aims of Experiment 3 were to (1) make direct comparisons between SW_{SR} and SW_S trials in the cue-locked ERP and (2) determine whether the behavioral dissociation between stimulus-set conflict and response-set conflict observed in Experiments 1 and 2 is also reflected in components of the stimulus-locked ERP.

Method

Participants. Thirty (22 male) participants from the College of William & Mary either received partial credit in an introductory psychology course for their participation or were compensated at the rate of \$10/hour. The average age of participants was 18.6 ($SD = .68$) years. The experiment was conducted with the understanding and consent of each participant and in accordance with the Institutional Review Board at the College of William & Mary. All participants reported normal or corrected-to-normal visual acuity and normal color vision.

Apparatus & stimuli. The apparatus, stimuli, and procedure were the same as in Experiment 2 with the exception that participants were seated in an electrically shielded booth and fitted with EEG cap. Movement was minimized by positioning the computer mouse on an adjustable laptop stand beneath the right arm so that participants could maintain a comfortable sitting position with his or her arm in a relaxed position and back against the chair throughout the recording session.

Behavioral data analysis. As in Experiments 1 and 2, the primary hypotheses were tested against the response time measures only from the two comparison tasks (Shape & Size). Accuracy rates for the 12 trial types created by the factorial combination of the Switch (SW_{SR} , SW_S , and ST) and Congruency ($S_C R_C$, $S_C R_I$, $S_I R_C$, and $S_I R_I$) factors were submitted to a Switch (3) \times Congruency (4) repeated measures ANOVA. Response times were

analyzed in the same way as the accuracy data except that an additional Response Component (DT, MT) factor was added. Greenhouse-Geisser corrected p values are provided where appropriate.

Electrophysiological recordings and analysis. Electrophysiological data were recorded continuously at 2000 samples per second using a DBPA-1 Sensorium bio-amplifier (Sensorium Inc., Charlotte, VT) with an analog high-pass filter of 0.01 Hz and a low-pass filter of 500 Hz (four-pole Bessel). Recordings were made using fabric caps bearing 72 Ag-AgCl sintered electrodes (Electrode Arrays, El Paso, TX) while participants were seated in an electrically shielded booth. EEG recordings were made using a forehead ground electrode and a reference at the tip of the nose. Vertical and horizontal eye movement was recorded from periocular electrodes placed on the superior and inferior orbits (centered with the pupil) and from electrodes placed at the lateral canthi, respectively. All impedances were adjusted to within 0–20 kilohms at the start of the recording session.

EEG data were decimated to 250 Hz and analyzed off-line using EMSE (Source Signal Imaging, San Diego, CA) and the Mass Univariate ERP Toolbox in MatLab (http://openwetware.org/wiki/Mass_Univariate_ERP_Toolbox). As a preliminary data screening, individual channels were inspected in 1-s segments over the entire recording epoch. Channels containing extreme values ($\pm 300 \mu\text{V}$) in more than 40% of the sweeps were automatically marked for replacement by interpolation. Additionally, individual segments in which more than 20 (28%) of the channels were contaminated by such extreme artifact were automatically marked for removal. The results of this procedure were verified and/or modified as necessary by an experienced user. The data were then corrected for ocular artifact using independent components analysis (Tzyy-Ping et al., 2000), smoothed using a low-pass filter with a half-amplitude at 20 Hz (18dB/Octave). The EEG Data were then segmented between -200 ms and 1000 ms with respect to stimulus onset. Individual segments containing voltages exceeding $\pm 100 \mu\text{V}$ were removed from the analysis. Data segments were then averaged for each subject within each condition.

The multichannel data were then analyzed using a massive univariate analysis (Lage-Castellanos, Martinez-Montes, Hernandez-Cabrera, & Galan, 2009). Briefly, this procedure involved the following steps: (1) For every channel and sample, differences in mean amplitude were tested across trial types using a repeated measures ANOVA. In the case of the cue-locked analysis, these tests included three levels of a Switch factor (SW_{SR} , SW_S , ST) and in the case of the target-locked analysis there were four levels of a Congruency factor ($S_C R_C$, $S_C R_I$, $S_I R_C$, $S_I R_I$). Analysis of the target-locked ERPs was limited to the levels Congruency in an effort to selectively address the current hypotheses. In addition to limiting the number of exploratory hypothesis tests, selective focus on the effects of Congruency was also motivated by the fact that the factorial combination of Switch and Congruency would have yielded only approximately 20 trials per cell on average and would have required separate massive univariate analyses for each of the main effects and interaction. (2) The resulting family of p values were then submit to the Benjamini, Krieger, and Yekutieli (2006) procedure for controlling the false discovery rate (FDR). (3) Only those channels/samples at which the p value exceeds a critical value defined by a FDR of $q < .05$ were considered. (4) Cluster-level statistics (e.g., means and SDs) were then computed by

defining “clusters” of activation using a spatial contiguity threshold of three consecutive sensors and a temporal contiguity threshold of two consecutive samples. Clusters were defined in the following way: (1) Groups of significant activations exceeding the spatial contiguity threshold were identified within each sample. (2) Groups in consecutive samples wherein the number of sensors common to the two groups exceeded 50% of the number of sensors in the group with the fewest sensors were clustered together. (3) Individual sensors within each cluster failing to meet the temporal contiguity threshold were removed from the cluster.

Results and Discussion

Behavioral data. Overall performance on the task was good ($M = 96.7\%$, $SD = 2.1\%$). Accuracy rates were submitted to a Switch (3: SW_{SR} , SW_S , ST) by Congruency (4: $S_C R_C$, $S_C R_I$, $S_I R_C$, $S_I R_I$) repeated measures ANOVA. Only the main effect of Congruency reached significant in the accuracy rates, $F(3, 87) = 22.9$, $p < .001$. Planned comparisons revealed significant accuracy costs associated with both response-set conflict ($S_C R_I$; $M = 97.8\%$, $SD = 2.1\%$, $p < .01$, and stimulus-set conflict ($S_I R_C$; $M = 95.7\%$, $SD = 3.8\%$, $p < .01$, by comparison with no conflict trials ($S_C R_C$; $M = 99.2\%$, $SD = 1.1\%$). Moreover, accuracy rates were significantly lower in $S_I R_C$ than $S_C R_I$ trials, $p < .01$, indicating that more errors were committed under conditions of stimulus-set conflict.

Response times (RT; 10% trimmed), excluding error trials and trials immediately after an error, were submitted to a Switch (3: SW_{SR} , SW_S , ST) by Congruency (4: $S_C R_C$, $S_C R_I$, $S_I R_C$, $S_I R_I$) by Response Component (2: DT, MT) repeated measures ANOVA. Means for each condition and response component are illustrated in Figure 9. The results largely replicated Experiment 2. A main effect of Response Component indicated that DTs ($M = 718$ ms, $SD = 192$ ms) accounted for a much larger proportion of the total response time than did MTs ($M = 314$ ms, $SD = 98$ ms), $F(1, 29) = 126.32$, $p < .001$. There were also significant main effects of Switch, $F(2, 58) = 6.52$, $p < .01$, and Congruency, $F(3, 87) = 28.68$, $p < .001$. Significant interactions with the Response Component factor were only observed for congruency.

Although the three-way interaction between Switch, Congruency, and Response Component was not significant, there was a significant interaction between Switch and Congruency (averaging over DT and MT), $F(6, 174) = 2.67$, $p < .05$. The pattern of results was similar the results of Experiment 1 which used only a measure of total response time. Considering the effects of task-switching at each level of the Congruency factor revealed a significant main effect of Switch only within $S_C R_C$, $F(2, 58) = 4.16$, $p < .05$, and $S_C R_I$, $F(2, 58) = 3.85$, $p < .05$. Similar to the results of Experiment 1, pairwise comparisons between the levels of Switch within the $S_C R_C$ and $S_C R_I$ levels of Congruency revealed that the effect of task-switching was driven by significant differences between SW_{SR} and ST trials, $p < .05$. Although the significant increase in response-time to SW_{SR} trials in $S_C R_I$ trials supports the hypothesis that response conflict will selectively impact switches of response-set, the fact that similar increases are observed in $S_C R_C$ trials is again inconsistent with the idea that task-conflict is related to the slowing of RTs on SW_{SR} trials.

In contrast with the results of Experiment 2 the interaction between Switch and Response Component did not reach signifi-

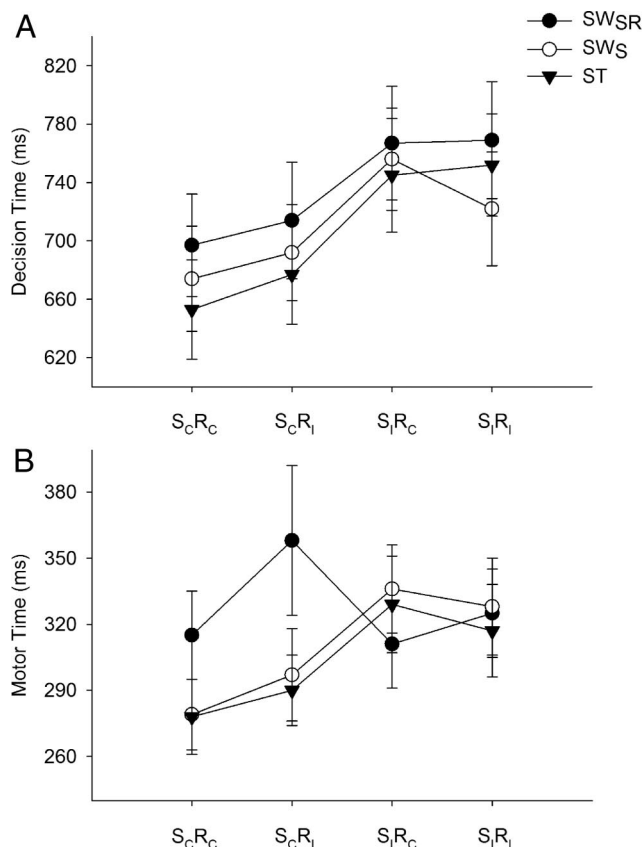


Figure 9. Experiment 3 response times shown separately for each of the three switch and four congruency conditions and for each of the DT and MT components (error bars reflect $\pm 1 SE$).

cance. However, similar to the results of Experiment 2, DT increased monotonically from ST ($M = 713\text{ms}$, $SD = 192\text{ms}$) to SW_S ($M = 711\text{ms}$, $SD = 187\text{ms}$) to SW_{SR} ($M = 737$, $SD = 204\text{ms}$). However, planned comparisons revealed that the difference between SW_S and SW_{SR} was only marginally significant, $t(29) = 1.92$, $p = .06$. Also similar to Experiment 2, consideration of MT alone revealed no significant differences in the omnibus comparison of the levels of the Switch factor.

An interaction between Congruency and Response Component, $F(3, 87) = 5.91$, $p < .01$, revealed differences in the way that stimulus- and response-conflict impacted the two components of total response time. Congruency effects in the DT component, $F(3, 87) = 25.84$, $p < .001$, replicated Experiments 1 and 2. DTs to S_cR_c ($M = 675$ ms, $SD = 187$ ms) and S_cR_l ($M = 694$ ms, $SD = 190$ ms) trials were not significantly different from one another, indicating that response-set conflict did not have a significant impact on DT. Moreover, DT in S_cR_l trials was significantly faster than in S_lR_c ($M = 756$ ms, $SD = 201$ ms), $p < .001$, again indicating that the only source of significant processing delays in DT were elicited by stimulus-conflict.

Congruency effects were also significant in the MT component of response time, $F(3, 87) = 5.13$; $p < .01$, with the pattern of results qualitatively identical to the results for MT in Experiment 2. MT in S_cR_l ($M = 315$ ms, $SD = 111$ ms) trials was significantly

longer than in S_cR_c trials ($M = 291$ ms, $SD = 89$ ms), $p < .05$, indicating a significant cost of response-set conflict. Also, and in accordance with predictions the difference between S_cR_l and S_lR_c trials was not statistically significant; a finding consistent with the hypothesis that response execution is more vulnerable to the impact of response-set conflict/congruency.

Electrophysiological data. Figure 10 depicts the cue-locked grand averages for a selection of midline channels. There were two significant clusters of activation indicated by the massive univariate analysis. The first cluster, hereafter referred to as N1_C, spanned the time between 172 and 184 ms, corresponded with the peak amplitude of the N1 ERP component, and possessed a bilateral posterior distribution (P9, P8, PO9, PO7, PO8). The second cluster, hereafter referred to as LPC_C, spanned the time between 624 and 960 ms, corresponded with the peak amplitude of the late positive component (LPC) of the ERP, and possessed a broad distribution over central and posterior scalp (C3, C1, C2, CP5, CP3, CP1, CPz, CP2, P5, P3, P1, Pz, P2, P4, P6, PO7, PO3, POz, PO4, PO8, O1, O2, Oz). Planned comparisons between each of the Switch conditions were carried out by calculating cluster means for each condition, averaging the conventional ERP voltage across the channels and samples included in the cluster. The mean amplitudes for each cluster and condition are presented in Figure 11. This analysis revealed that amplitudes of the N1_C in SW_{SR} ($M = -.09$, $SE = .55$) and SW_S ($M = .18$, $SE = .63$) trials were significantly smaller (more negative) than in ST ($M = .92$, $SE = .61$) trials, $t(28) = 3.7/2.8$, $p < .01$, but not significantly different from one another. This pattern of results suggests that the N1_C was modulated by a change in the cue (and thus task) type, but not by the specific requirements of the task switch. In contrast, pairwise comparisons between conditions on the LPC_C cluster revealed that the amplitude of the LPC_C increased significantly from ST ($M = -.75$, $SE = .53$) to SW_S ($M = .15$, $SE = .51$) trials, $t(28) = 3.27$, $p < .01$, and from SW_S to SW_{SR} ($M = .88$, $SE = .49$) trials, $t(28) = 2.64$, $p < .05$. This pattern of increasing amplitude with switch-type is consistent with the prediction that the LPC would be modulated by the specific requirements of a task switch.

Figure 12 illustrates the results of the analysis of the electrophysiological data time-locked to the onset of the target stimulus. There were three significant clusters of activation. The first cluster, hereafter referred to as N2_C, spanned the period of time between 260 ms and 276 ms, corresponded with the peak amplitude of the N2 component of the ERP and was distributed over frontal scalp sites (F1, F2, F4, FCz). The second cluster, hereafter referred to as P3_C, spanned 320 ms to 416 ms, and corresponded with the peak amplitude of an occipitally distributed, bilateral P3 component of the ERP (C4, CP2, CP4, CP6, P9, P7, P5, P3, P2, P4, P6, P8, PO9, PO7, PO3, POz, PO4, PO8, PO10, O1, Oz, O2). The third cluster, hereafter referred to as FCP_C, spanned 424 to 660 ms and corresponded with a fronto-central positive component of the ERP (FP1, FPz, FP2, AF7, AF3, AF4, AF8, F7, F5, F3, F1, Fz, F2, F4, F6, FC5, FC3, FC1, FCz, FC2, FC4, FC6, C5, C3, C1, Cz, C2, C4, CP3, CP1, CPz, CP2, CP4, CP6, P5, P3, P1, Pz, P2, P4, PO4). Planned comparisons of cluster means between levels of conflict were carried out in the same way as for the analysis of the cue-locked clusters. The cluster means and the results of the paired comparisons are presented in Table 1.

This cluster-level analysis (see Figure 13) indicated that the amplitude of N2_C was significantly smaller (more negative) for

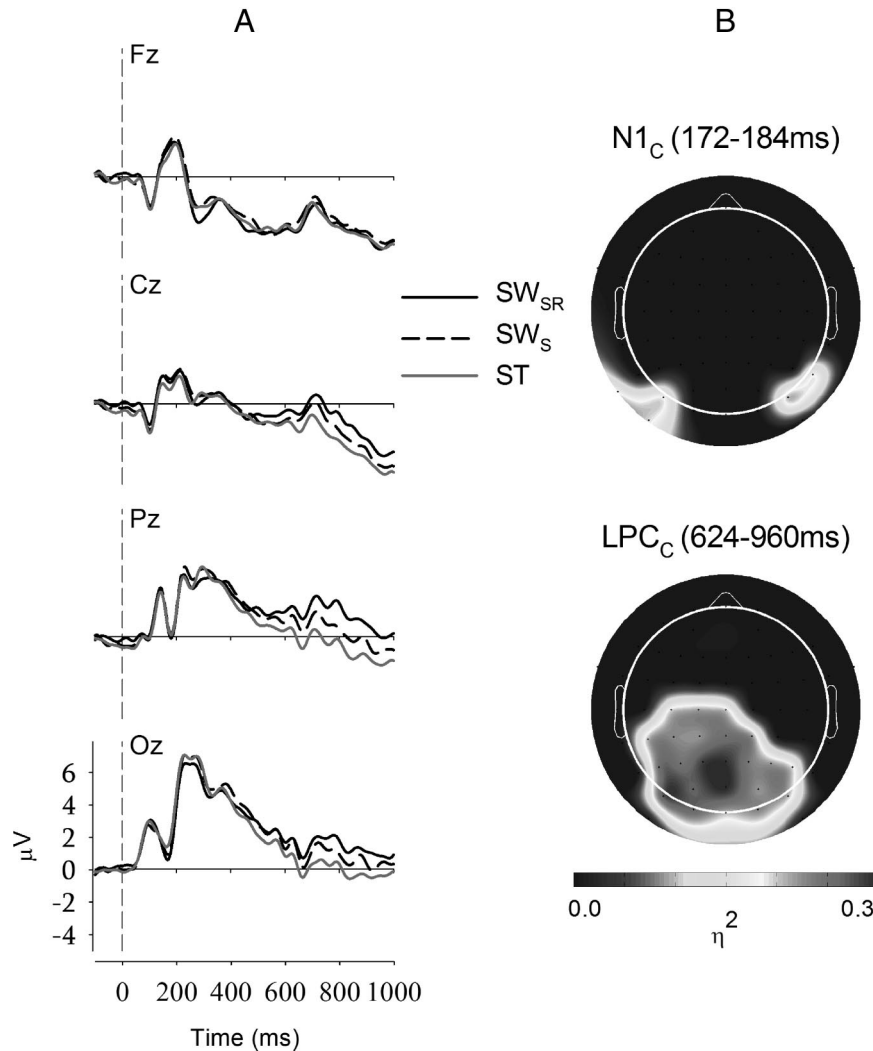


Figure 10. A, Grand-average, cue-locked ERPs from select midline channels. Highlighted regions correspond to the time courses of the N1 (N1_{C}) and LPC (LPC_{C}) clusters. B, Topographical distribution of the mean effect size (η^2) across samples for each of the electrodes included in the cluster (“halo” extending beyond head boundary represents electrodes on the lateral surfaces of the scalp).

each of the three ($\text{S}_{\text{C}}\text{R}_{\text{I}}$, $\text{S}_{\text{I}}\text{R}_{\text{C}}$, and $\text{S}_{\text{I}}\text{R}_{\text{I}}$) conditions containing task conflict compared with the no-conflict ($\text{S}_{\text{C}}\text{R}_{\text{C}}$) condition. This pattern suggests that N2_{C} reflects only the detection of conflict and is not sensitive to the quantity or nature of the conflict encountered.

The pattern of differences in the P3_{C} component also suggested a sensitivity to conflict, however, that sensitivity appears to be modulated by the nature of the conflict encountered. Amplitudes of the P3_{C} were significantly larger for both $\text{S}_{\text{C}}\text{R}_{\text{C}}$ and $\text{S}_{\text{C}}\text{R}_{\text{I}}$ trials compared with $\text{S}_{\text{I}}\text{R}_{\text{C}}$ and $\text{S}_{\text{I}}\text{R}_{\text{I}}$ trials.

The FPC_{C} cluster evidenced a statistical pattern that was similar to that of the P3_{C} cluster, however the polarity of the effect was reversed. Amplitudes for the $\text{S}_{\text{I}}\text{R}_{\text{C}}$ and $\text{S}_{\text{I}}\text{R}_{\text{I}}$ conditions were significantly larger than those in $\text{S}_{\text{C}}\text{R}_{\text{I}}$ and $\text{S}_{\text{C}}\text{R}_{\text{C}}$ conditions.

Taken together, these results replicate and extend the findings from Experiments 1 and 2. First, SW_{SR} trials were associated with a significant switch costs compared with SW_{S} trials in the DT

component of RT. Second, response-set conflict elicited significantly smaller RT conflict costs in the DT component as evidenced by reduced latencies on $\text{S}_{\text{C}}\text{R}_{\text{I}}$ compared with $\text{S}_{\text{I}}\text{R}_{\text{C}}$ trials and by the equivalence of $\text{S}_{\text{C}}\text{R}_{\text{C}}$ and $\text{S}_{\text{C}}\text{R}_{\text{I}}$ trials. Finally, the behavioral data indicate that response execution (MT) but not decision time (DT) may be increased when there is response-set conflict.

Examination of the cue-locked ERP data provided support for the hypothetical internal structure of task-set presented in Figure 2 given that SW_{SR} elicited a significant increase in the amplitude of a late positive component of the ERP. Moreover, the pattern of results in the target-locked analysis suggests the following: (1) stimulus-set and response-set conflict are similarly detected as reflected in the frontally distributed N2 component, (2) the presence of stimulus- but not response-conflict impacts perceptual processing and is associated with reduced ERP amplitude over occipital cortex between 320 and 416 ms, and (3) stimulus-conflict but not response-conflict significantly impacts response resolution

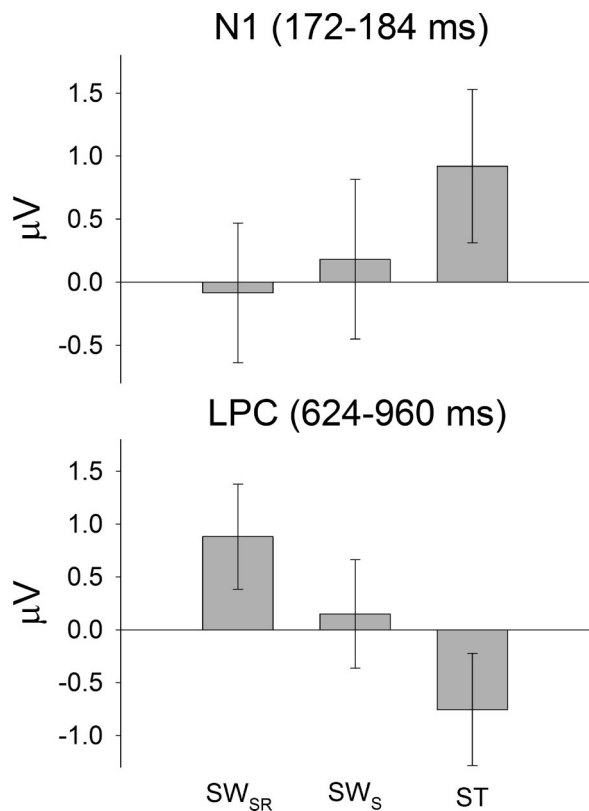


Figure 11. Mean (± 1 SE) cluster-level amplitudes averaged across time and electrodes for each cluster.

processes as evident in the amplitude of a fronto-central positivity between 424 ms and 660 ms.

General Discussion

The primary aim of the present research was to test the hypothesis that stimulus-set and response-set reflect distinct components of the internal structure of task-set. This hypothesis was supported in the findings that (1) task set-switches that included a switch of both stimulus-set and response-set resulted in larger residual switch costs than switches of stimulus-set alone, (2) response-set conflict resulted in significantly smaller response time costs than did stimulus-set conflict, (3) Stimulus-set conflict impacted the DT component of participant's response time, whereas the MT component was more sensitive to response-set conflict, and (4) finally, ERPs evidenced dissociations between stimulus-set and response-set both in the cue-locked measures of task-set switching and in the target-locked measures of conflict processing.

The arbitrary nature of stimulus-judgment and judgment-response mappings used in the present research is particularly important given that conflict processing may be both qualitatively and quantitatively different under conditions wherein stimulus-response congruency is determined by well-learned compared with novel judgment-response mappings (Meiran & Kessler, 2008). This is important because previous attempts to dissociate stimulus from response conflict tend to elicit conflict processing using Stroop stimuli wherein the effect relies on an overlearned predis-

position to read words rather than report the color in which they are printed.

Explicit consideration of the internal structure of the task-sets used to measure cognitive control in task-set switching research is seldom given. A notable exception is the taxonomy of "cognitive ensembles" developed by Kornblum & Lee (1995) in an effort describe the factors contributing to Stroop-like stimulus-response compatibility effects. By their account, stimulus-response (S-R) overlap occurs whenever there is a direct correspondence between the nature of the response and the semantic or physical properties of the stimulus. For example, responding to colors by verbalizing color names or responding to a stimulus' physical location by responding with the corresponding left or right hand (e.g., Simon & Wolf, 1963). Although cognitive ensembles are closely related to the concept of internal structure examined in the present research, there are important differences between the notion of S-R overlap (Kornblum & Lee, 1995), and the present notion of conflict processing (De Houwer, 2003; van Veen & Carter, 2006; Brass et al., 2003) wherein response-set interference is a product of arbitrary judgment-to-response mappings rather than a direct semantic and/or spatial association between stimuli and responses.

One potential caveat to the interpretation of the present data is that the predicted effects of task-set switching may also be interpreted with respect to the counterintuitive finding that switch costs are larger when switching from a weak to a stronger (i.e., dominant or well-practiced) task. Allport et al., (1994, see also; Wylie & Allport, 2000) reported that switch costs were largest when participants switched from color naming to word reading using incongruent Stroop stimuli. This finding is surprising because one might expect that the task-set for word reading (arguably the most familiar and dominant response to Stroop stimuli) would be almost effortlessly actuated. This asymmetry of switch costs has been interpreted to reflect a stronger residual inhibitory trace for word reading that previously maximized processing efficiency during color naming. Because the comparison judgments in the present task occurred more frequently throughout the present experiment (66% of trials), one might reasonably argue that the task set associated with the Comparison judgment must be more strongly inhibited during performance of the Identity task, resulting in larger switch costs when switching to comparison from identity judgments. However, the fact that SW_{SR} costs in the Identity task were similar in magnitude to SW_{SR} costs in the Comparison (see Experiment 1) task despite the fact that response times were generally much faster in the identity task, provides a significant challenge to this alternative explanation. Moreover, Monsell (2000) provide evidence that this asymmetry of switch costs is not a universal finding and, perhaps most relevant to the present task, Monsell (2003) reported that this asymmetry does not hold when the response-set also changes across tasks.

Analysis of the cue-locked and stimulus-locked brain potentials in Experiment 3 also motivate a compelling argument for the dissociation of stimulus-set and response-set processes using the present task. Amplitude of the LPC component of the ERP time-locked to the cue, indicating which dimension and response mapping were relevant on the current trial, was observed to increase monotonically from ST to SW_S to SW_{SR} trials. The time-course and distribution of the LPC are consistent with ERPs elicited by similar cues in previous research (Kieffaber & Hetrick, 2005; Kieffaber et al., 2007; Rushworth,

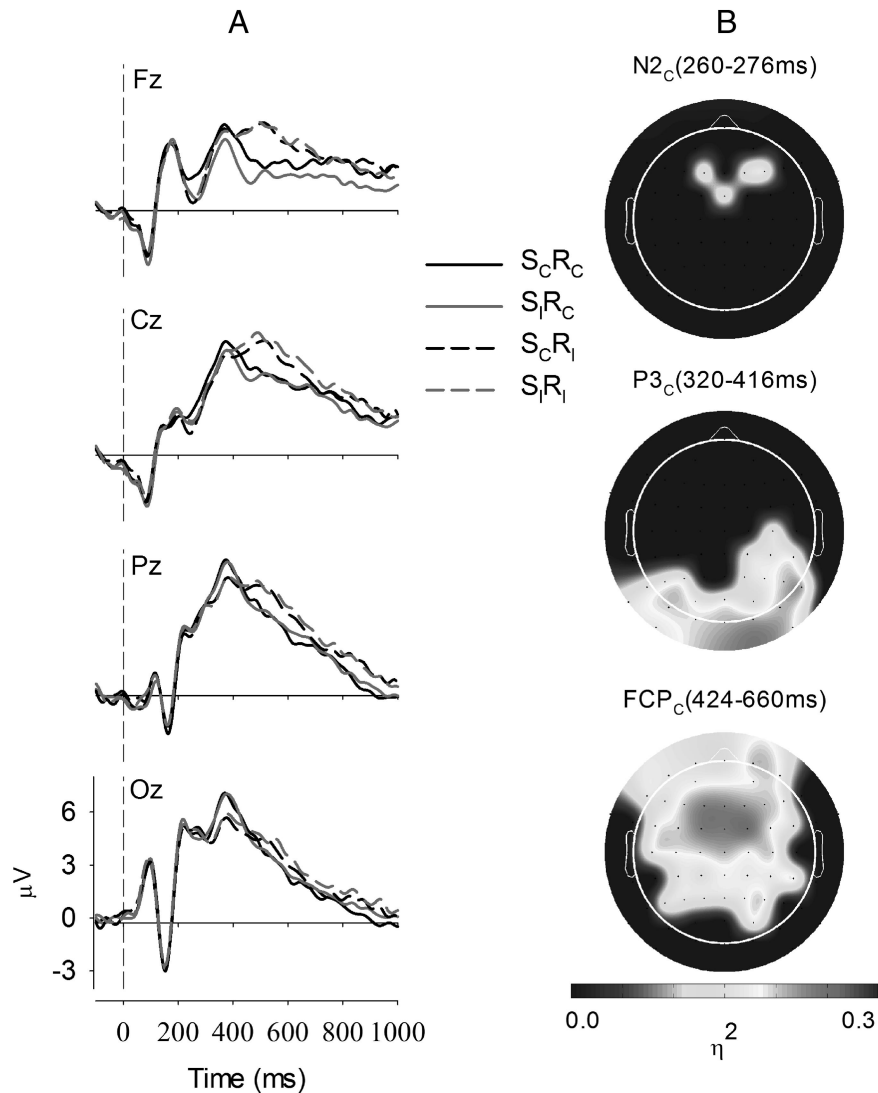


Figure 12. A, Target-locked grand-average ERPs from select midline channels. The time course of each cluster is highlighted in gray. B, Topographical distribution of the mean effect size (η^2) across samples for each of the electrodes included in the cluster ("halo" extending beyond head boundary represents electrodes on the lateral surfaces of the scalp).

Passingham, & Nobre, 2005; Swainson et al., 2006; Karayaniadis, 2010). Additionally, the LPC was modulated by the number of dimensions (i.e., stimulus & response) of the task-set being switched, a finding consistent with the claim that the cue-locked LPC reflects a forward-acting component of the neural response during task-switching. In addition to the fact that this increase in amplitude corresponded with similar monotonic increases in the switch costs, the fact that the amplitude of this component is significantly larger for SW_{SR} compared with SW_S trials is consistent with findings reported by Astle, Jackson, and Swainson (2008) and suggests that the LPC consists of a number of subcomponents that are sensitive to both stimulus-set and response-set switching.

Some prior research suggests that the cue-locked LPC component and ERP modulation over the frontal cortex reflect the

stimulus-set and response-set components task-set respectively (Molden et al., 1998; Rushworth, Passingham, & Nobre, 2002). However, the present findings with respect to the neural mechanisms of anticipatory task-switching are more consistent with the notion of a generalized switching operation over posterior parietal cortex. This generalized switching operation may reflect a dimensional representation of task-set in the brain, recruiting neural resources in accordance with the number of dimensions that are changed across a task switch (Kleinsorge & Heuer, 1999).

Analysis of the ERPs time-locked to the onset of the target stimulus also nicely complemented the behavioral data from all three experiments with respect to task-set conflict. Significant RT costs were associated with response-set conflict in Experiment 1 ($S_C R_I > S_C R_C$), but Experiments 2 & 3 demonstrated that this difference is limited to the MT component of RT. Response-set

Table 1
Uncorrected Pairwise Comparisons of Cluster Amplitudes (μV)
Across Levels of Conflict

	Mean (SD)	Conflict			
		$S_C R_C$	$S_C R_I$	$S_I R_C$	$S_I R_I$
$N2_C$		—	—	—	—
$S_C R_C$	2.04 (.96)	—	—	—	—
$S_C R_I$	0.69 (.87)	*	—	—	—
$S_I R_C$	0.54 (.87)	*	NS	—	—
$S_I R_I$	0.92 (.94)	*	NS	NS	—
$P3_C$		—	—	—	—
$S_C R_C$	6.72 (.80)	—	—	—	—
$S_C R_I$	6.48 (.90)	NS	—	—	—
$S_I R_C$	5.31 (.82)	*	*	—	—
$S_I R_I$	5.41 (.87)	*	*	NS	—
FPC_C		—	—	—	—
$S_C R_C$	3.14 (.71)	—	—	—	—
$S_C R_I$	2.76 (.70)	NS	—	—	—
$S_I R_C$	4.42 (.72)	*	*	—	—
$S_I R_I$	4.65 (.92)	*	*	NS	—

* $p < .01$.

conflict also elicited an increase in the amplitude of an N2 component of the stimulus-locked ERP. The N2 component, which is commonly linked with activity in the ACC, has been widely reported to be increased in amplitude under conditions of task-conflict (See Folstein & van Petten, 2008, for a review). For example, West et al. (2004) and Wendt et al. (2007) report that the N2 component is modulated by a variety of conflict types. The task used by Wendt et al. (2007) is most conceptually similar to the current procedure. Using arbitrary stimulus-response mappings and bivalent responses, Wendt et al. (2007) demonstrated that N2 amplitude was enhanced under conditions both stimulus and response conflict, but that the degree of enhancement was not modulated by the type of conflict. The present results replicate this finding, suggesting that the role of N2-related ACC activity is to detect conflict, irrespective of its source or magnitude. One caveat to this interpretation is the recent finding that N2 amplitude responds in a graded way to parametric manipulations of conflict (Forster et al., 2011). One possibility is that the amplitude of the N2 is modulated by the degree of conflict within but not across conflict types.

Stimulus-conflict elicited significantly greater RT costs in Experiment 1 ($S_I R_C > S_C R_I$) and this difference was only significant in the DT component of RT in Experiments 2 and 3, providing support for the claim that stimulus-set conflict selectively impacts cognitive processes related to stimulus classification but not response execution. Similarly, the P3 and FCP components of the stimulus-locked ERP were modulated by the type of conflict encountered. Conflict effects in these two components were both qualitatively and statistically similar to the conflict effects in the DT component of RT in Experiments 2 and 3, dissociating the four conflict types only on the basis of the presence of stimulus-conflict. The P3 component was maximal over occipital scalp and was reduced in amplitude on those trials containing stimulus-conflict (i.e., $S_I R_C$ & $S_I R_I$). The reduction in amplitude of the P3 in response to stimulus-conflict is consistent with similar findings using a Stroop task (West, Jakubek, Wymbs, Perry, & Moore,

2005), and the timing (310–416 ms) and topography of the P3 suggest that stimulus-set conflict impacted perceptual processes related to the extraction of relevant stimulus features.

Conflict effects in the FCP component over fronto-central scalp were similar to P3, but in the opposite direction. FCP amplitudes were significantly increased on trials containing stimulus-conflict. Taken together, the average DT of 718 ms and the timing (424–660 ms) and topography of FCP effects suggests that this component of the ERP may reflect increased effort in the selection of “action sets” in the superior frontal gyrus (Rushworth, Walton, Kennerley, & Bannerman, 2004) when faced with stimulus-conflict. Previous efforts to dissociate the components of conflict processing have indicated that an N450 component with a similar topography to the FCP is elicited by task-conflict. Using a numeric version of the Stroop task, West et al. (2004) demonstrated that

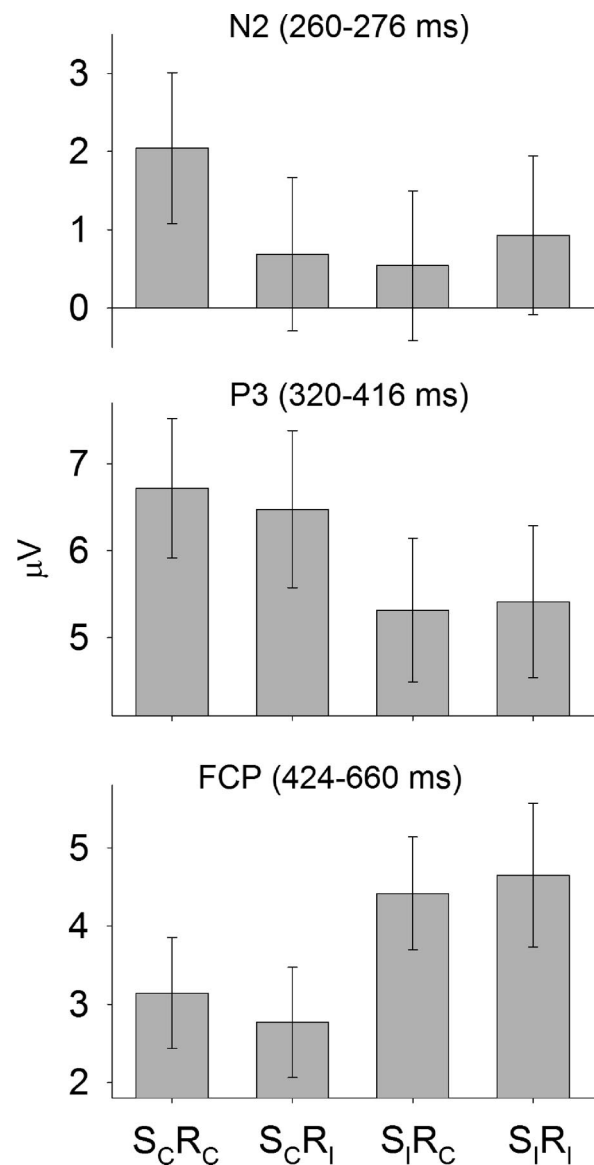


Figure 13. Mean (± 1 SE) cluster amplitudes for each Cluster across each condition.

greater negativity of the N450 was elicited by irrelevant attributes of a Stroop stimulus regardless of whether the irrelevant attribute was mapped to one of the currently relevant responses. The fact that the N450 appears sensitive to stimulus–conflict irrespective of response mappings complements the current finding that the FCP is selectively modulated by stimulus–conflict. However, a noteworthy difference is that the N450 is typically more negative in response to conflict (West et al. 2004, 2005; Chen, Bailey, Tierman, & West, 2011), whereas the FCP in the present data are more positive in amplitude on $S_C R_C$ and $S_I R_I$ trials. Future research may be needed to determine whether these differences reflect the activation of distinct neural circuitry engaged by the two tasks, or are simply attributable to EEG recording parameters such as the choice of a reference channel (e.g., nose-tip vs. common average).

Theoretical differences in the way stimulus-set and response-set are conceptualized may also contribute to differences between this and previous research. Variants of the Stroop task with bivalent responses wherein each response was correct for more than one of the color names have been used to dissociate “stimulus conflict” from “response conflict” (van Veen & Carter, 2005; Chen et al., 2011). However, van Veen and Carter (2005) defined semantic incongruence as those trials in which the two dimensions of the target stimulus (e.g., ink color and word identity) were different, but both indicated the same overt response. Similarly, Chen et al. (2011) defined “stimulus conflict” as those trials in which the two dimensions of the target stimulus were different, but the irrelevant dimension was not associated with any of the task-relevant responses. These conceptualizations of stimulus-set interference are critically different from stimulus-set conflict as it is presently defined wherein the two dimensions of a target stimulus share an overlapping set of abstract judgments (e.g., same/different) and judgment–response mappings, but indicate competing overt responses.

In fact, this important theoretical distinction may help to explain why van Veen et al. (2001) found an increased N2 amplitude for only “response-incongruence.” Chen et al. (2011) likewise report an increased (more negative) amplitude of medial frontal negativity (350 ms to 500 ms) for “response interference” by comparison with “stimulus interference.” The fact that, unlike “stimulus-incongruence” as defined by van Veen et al. (2001) and “stimulus interference” as defined by Chen et al. (2011), stimulus-set conflict in the present experiment *does* involve the activation of competing responses likely explains the present finding of an increased N2 amplitude for both $S_C R_I$ and $S_I R_C$ trials.

Some research also suggests that the N450 component of the ERP is sensitive to task conflict, but does not differentiate the stimulus and response conflict types (e.g., West et al., 2004). It is again difficult to integrate this finding with the present research because of differences in the way conflict types are defined. West (2004) used a definition of stimulus-conflict that is similar to Kornblum and Lee’s (1995) notion of S-R overlap wherein the conflict emerges because of a direct semantic correspondence between a stimulus (e.g., the word BLUE written in red ink) and the set of possible responses (e.g., the utterances “red” and “blue”), whereas response conflict in the present case was due to an arbitrary mapping between “Same,” “Different,” “Red,” and “Blue” decisions and the left/right response keys. It is also important to note that there were no significant differences between the response times to the various conflict conditions in West et al.,

(2004) whereas conflict types are distinguished on both RT and ERP measures in the current study.

Aiding interpretation of the present notions of stimulus-set and response-set amid prior research is the hypothetical task-set architecture depicted in Figure 2. Specification of this internal structure of task-set clarifies the way in which stimulus-set and response-set may be conceptualized as distinct cognitive biases which, when combined, cumulatively attenuate task-irrelevant information processing. The fact that stimulus-set conflict elicited longer response times than response-set conflict in Experiments 1–3 provides compelling support for this hypothetical architecture and the observed increase in amplitude of the LPC ERP time-locked to the task-cue indicates that each is a unique component of task-set that can be prepared in advance.

In summary, the present findings provide strong support for the notion that stimulus-set and response-set represent distinct components of the internal structure of task-set even when defined by completely arbitrary stimulus–response mappings. It is clear that the development of a more complete theoretical taxonomy of task-set is needed to establish a consistent vernacular regarding the various cognitive processes implied by the procedures used to explore set effects. The continued development of our understanding regarding the specific information processing mechanisms that constitute task-set effects is central to achieving resolution to the ongoing debate over the nature of cognitive control, executive functioning, and related deficits in clinical populations.

References

- Allport, D. A., Styles, E. A., & Hsieh, S. (1994). *Shifting intentional set: Exploring the dynamic control of tasks*. In Umiltà, C. & Moscovitch, M. (Eds.), *Attention and Performance XV* (pp. 421–452). Cambridge, MA: MIT Press.
- Allport, D. A., Wylie, G., Humphreys, G. W., Duncan, J., & Treisman, A. M. (1999). *Task-switching: Positive and negative priming of task-set*. In Attention, space and action: Studies in cognitive neuroscience (pp. 273–296). Oxford, UK: Oxford University Press.
- Aron, A., Monsell, S., Sahakian, B., & Robbins, T. (2004). A componential analysis of task-switching deficits associated with lesions of left and right frontal cortex. *Brain*, *127*, 1561–1573.
- Arrington, C. M., Altmann, E. M., & Carr, T. H. (2003). Tasks of a feather flock together: Similarity effects in task switching. *Memory & Cognition*, *31*, 781–789.
- Astle, D. E., Jackson, G. M., & Swainson, R. (2008). Fractionating the cognitive control required to bring about a change in task: A dense-sensor event-related potential study. *Journal of cognitive neuroscience*, *20*, 255–267.
- Barch, D. M., Carter, C., Perlstein, W., Baird, J., Cohen, J., & Schooler, N. (1999). Increased Stroop facilitation effects in schizophrenia are not due to increased automatic spreading activation. *Schizophrenia research*, *39*, 51–64.
- Barch, D. M., Carter, C. S., MacDonald, A. W., Braver, T. S., & Cohen, J. D. (2003). Context-processing deficits in schizophrenia: Diagnostic specificity, 4-week course, and relationships to clinical symptoms. *Journal of Abnormal Psychology*, *112*, 132–143.
- Benjamini, Y., Krieger, A. M., & Yekutieli, D. (2006). Adaptive linear step-up procedures that control the false discovery rate. *Biometrika*, *93*, 491–507.
- Botvinick, M., Braver, T., Barch, D., Carter, C., & Cohen, J. (2001). Conflict monitoring and cognitive control. *Psychological Review*, *108*, 624–652.

- Brass, M., Ruge, H., Meiran, N., Rubin, O., Koch, I., Zysset, S., . . . von Cramon, D. Y. (2003). When the same response has different meanings: recoding the response meaning in the lateral prefrontal cortex. *NeuroImage*, *20*, 1026–1031.
- Brown, J. W., Reynolds, J. R., & Braver, T. S. (2007). A computational model of fractionated conflict-control mechanisms in task-switching. *Cognitive Psychology*, *55*, 37–85.
- Brown, M., & Besner, D. (2001). On a variant of Stroop's paradigm: Which cognitions press your buttons? *Memory & Cognition*, *29*, 903–904.
- Chen, A., Bailey, K., Tiernan, B. N., & West, R. (2011). Neural correlates of stimulus and response interference in a 21 mapping Stroop task. *International Journal of Psychophysiology*, *80*, 129–138.
- Crider, A. (1997). Perseveration in schizophrenia. *Schizophrenia bulletin*, *23*, 63–74.
- De Houwer, J. (2003). On the role of stimulus-response and stimulus-stimulus compatibility in the Stroop effect. *Memory & Cognition*, *31*, 353–359.
- Dias, R., Robbins, T., & Roberts, A. (1996). Primate analogue of the Wisconsin card sorting test: Effects of excitotoxic lesions of the prefrontal cortex in the marmoset. *Behavioral neuroscience*, *110*, 872–886.
- Dove, A., Pollmann, S., Schubert, T., Wiggins, C., & von Cramon, D. (2000). Prefrontal cortex activation in task switching: An event-related fMRI study. *Brain Research. Cognitive Brain Research*, *9*, 103–109.
- Dreisbach, G., Haider, H., & Kluwe, R. (2002). Preparatory processes in the task-switching paradigm: Evidence from the use of probability cues. *Journal of Experimental Psychology-Learning Memory & Cognition*, *28*, 468–483.
- Elliott, R., McKenna, P., Robbins, T., & Sahakian, B. (1998). Specific neuropsychological deficits in schizophrenia patients with preserved intellectual function. *Cognitive Neuropsychiatry*, *3*, 45–70.
- Fagot, C. (1995). *Chronometric investigations of task switching*. Unpublished doctoral dissertation.
- Folstein, J. R., & van Petten, C. (2008). Influence of cognitive control and mismatch on the n2 component of the ERP: A review. *Psychophysiology*, *45*, 152–170.
- Forster, S. E., Carter, C. S., Cohen, J. D., & Cho, R. Y. (2011). Parametric manipulation of the conflict signal and control-state adaptation. *Journal of Cognitive Neuroscience*, *23*, 113.
- Gibson, J. (1941). A critical review of the concept of set in contemporary experimental psychology. *Psychological bulletin*, *38*, 781–817.
- Goschke, T., & Driver, J. (2000). *Intentional reconfiguration and involuntary persistence in task set switching*. In *Control of cognitive processes: Attention and performance XVIII*. Boston, US: MIT Press.
- Henik, A., Carter, C., Salo, R., Chaderjian, M., Kraft, L., Nordahl, T., & Robertson, L. (2002). Attentional control and word inhibition in schizophrenia. *Psychiatry Research*, *110*, 137–149.
- Hsieh, S., & Liu, H. (2008). Electrophysiological correlates of task conflicts in task-switching. *Brain Research*, *1203*, 116–125.
- Hsieh, S. (2002). Two-component processes in switching attention: A study of event-related potentials. *Perceptual & Motor Skills*, *94*, 1168–1176.
- Hübner, R., Futterer, T., & Steinhauser, M. (2001). On attentional control as a source of residual shift costs: Evidence from two-component task shifts. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *27*, 640–653.
- Jensen, A., & Rohwer, W. (1966). The Stroop color-word test: A review. *Acta Psychologica*, *25*, 36–93.
- Jersild, A. (1927). Mental set and shift. *Archives of Psychology*, *89*.
- Jones, A. D., Cho, R. Y., Nystrom, L. E., Cohen, J. D., & Braver, T. S. (2002). A computational model of anterior cingulate function in speeded response tasks: Effects of frequency, sequence, and conflict. *Cognitive, Affective, & Behavioral Neuroscience*, *2*, 300.
- Jost, K., Mayr, U., & Rosler, F. (2008). Is task switching nothing but cue priming? evidence from ERPs. *Cognitive, Affective, & Behavioral Neuroscience*, *8*, 74–84.
- Karayanidis, F., Coltheart, M., Michie, P., & Murphy, K. (2003). Electrophysiological correlates of anticipatory and poststimulus components of task switching. *Psychophysiology*, *40*, 329–348.
- Karayanidis. (2010). Advance preparation in task-switching: Converging evidence from behavioral, brain activation, and model-based approaches. *Frontiers in Psychology*. Available from http://www.frontiersin.org/Journal/Abstract.aspx?s=194&name=cognition&ART_DOI=10.3389/fpsyg.2010.00025
- Kieffaber, P., & Hetrick, W. (2005). Event-related potential correlates of task switching and switch costs. *Psychophysiology*, *42*, 56–71.
- Kieffaber, P., Kappenman, E., Bodkins, M., Shekhar, A., O'Donnell, B., & Hetrick, W. (2006). Switch and maintenance of task set in schizophrenia. *Schizophrenia Research*, *84*, 345–358.
- Kieffaber, P., O'Donnell, B., Shekhar, A., & Hetrick, W. (2007). Event related brain potential evidence for preserved attentional set switching in schizophrenia. *Schizophrenia Research*, *93*, 355–365.
- Kiesel, A., Steinhauser, M., Wendt, M., Falkenstein, M., Jost, K., Philipp, A. M., & Koch, I. (2010). Control and interference in task switching-A review. *Psychological Bulletin*, *136*, 849–874.
- Klein, G. S. (1964). Semantic power measured through the interference of words with Color-Naming. *The American Journal of Psychology*, *77*, 576–588.
- Kleinsorge, T., & Heuer, H. (1999). Hierarchical switching in a multi-dimensional task space. *Psychological Research/Psychologische Forschung*, *62*, 300–312.
- Koch, I. (2005). Sequential task predictability in task switching. *Psychonomic Bulletin & Review*, *12*, 107–112.
- Kopp, B., Tabeling, S., Moschner, C., & Wessel, K. (2006). Fractionating the neural mechanisms of cognitive control. *Journal of Cognitive Neuroscience*, *18*, 949–965.
- Kornblum, S., & Lee, J. W. (1995). Stimulus-response compatibility with relevant and irrelevant stimulus dimensions that do and do not overlap with the response. *Journal of Experimental Psychology Human Perception and Performance*, *21*, 855–875.
- Lage-Castellanos, A., Martinez-Montes, E., Hernandez-Cabrera, J. A., & Galan, L. (2009). False discovery rate and permutation test: An evaluation in ERP data analysis. *Statistics in Medicine*, *29*, 63–74.
- Meiran, N., Chorev, Z., & Sapir, A. (2000). Component processes in task switching. *Cognitive Psychology*, *41*, 211–253.
- Meiran, N., & Kessler, Y. (2008). The task rule congruency effect in task switching reflects activated long-term memory. *Journal of Experimental Psychology: Human Perception and Performance*, *34*, 137.
- Meiran, N., Levine, J., Meiran, N., & Henik, A. (2000). Task set switching in schizophrenia. *Neuropsychology*, *14*, 471–482.
- Milham, M. P., Banich, M. T., Webb, A., Barad, V., Cohen, N. J., Wszalek, T., & Cohen, N. J. (2001). The relative involvement of anterior cingulate and prefrontal cortex in attentional control depends on nature of conflict. *Brain research Cognitive brain research*, *12*, 467–473.
- 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*, 250–264.
- Monsell, S. (2003). Task switching. *Trends in cognitive sciences*, *7*, 134–140.
- Moulden, D. J., Picton, T., Meiran, N., Stuss, D., Riera, J., & Valdes-Sosa, P. (1998). Event-related potentials when switching attention between task-sets. *Brain & Cognition*, *37*, 186–190.
- Mueller, S., Swainson, R., & Jackson, G. (2007). Behavioural and neurophysiological correlates of bivalent and univalent responses during task switching. *Brain Research*, *1157*, 56–65.
- Nicholson, R., Karayanidis, F., Bumak, E., Poboka, D., & Michie, P. T. (2006). ERPs dissociate the effects of switching task sets and task cues. *Brain Research*, *1095*, 107–123.
- Nieuwenhuis, S., Yeung, N., Holroyd, C. B., Schurger, A., & Cohen, J. D. (2004). Sensitivity of electrophysiological activity from medial frontal cortex to utilitarian and performance feedback. *Cerebral Cortex*, *14*, 741–747.

- Rogers, R., & Monsell, S. (1995). Costs of a predictable switch between simple cognitive tasks. *Journal of Experimental Psychology: General*, *124*, 207–231.
- Rubinstein, J. S., Meyer, D. E., & Evans, J. E. (2001). Executive control of cognitive processes in task switching. *Journal of Experimental Psychology: Human Perception and Performance*, *27*, 763–797.
- Rushworth, M. F., Hadland, K. A., Paus, T., & Sipila, P. K. (2002). Role of the human medial frontal cortex in task switching: A combined fMRI and TMS study. *Journal of Neurophysiology*, *87*, 2577–2592.
- Rushworth, M. F., Passingham, R., & Nobre, A. (2002). Components of switching intentional set. *Journal of Cognitive Neuroscience*, *14*, 1139–1150.
- Rushworth, M. F., Passingham, R. E., & Nobre, A. C. (2005). Components of attentional set-switching. *Experimental Psychology*, *52*, 83–98.
- Rushworth, M. F., Walton, M. E., Kennerly, S. W., & Bannerman, D. M. (2004). Action sets and decisions in the medial frontal cortex. *Trends in Cognitive Sciences*, *8*, 410–417.
- Schooler, C., Neumann, E., Caplan, L., & Roberts, B. (1997). Stroop theory, memory, and prefrontal cortical functioning: Reply to Cohen et al. *Journal of Experimental Psychology-General*, *126*, 42–44, 1997.
- Shakow, D. (1962). Segmental set: A theory of the formal psychological deficit in schizophrenia. *Archives of General Psychiatry*, *6*, 1–17.
- Simon, J., & Wolf, J. (1963). Choice reaction times as a function of angular stimulus-response correspondence and age. *Ergonomics*, *6*, 99–105.
- Spector, A., & Biederman, I. (1976). Mental set and mental shift revisited. *American Journal of Psychology*, *89*, 669–679.
- Sudevan, P., & Taylor, D. (1987). The cuing and priming of cognitive operations. *Journal of Experimental Psychology: Human Perception and Performance*, *13*, 89–103.
- Swainson, R., Jackson, S., & Jackson, G. (2006). Using advance information in dynamic cognitive control: An ERP study of task-switching. *Brain Research*, *1105*, 61–72.
- Travers, S., & West, R. (2008). Neural correlates of cue retrieval, task set reconfiguration, and rule mapping in the explicit cue task switching paradigm. *Psychophysiology*, *45*, 588–601.
- Tzzy-Ping, J., Makeig, S., Westerfield, M., Townsend, J., Courchesne, E., & Sejnowski, T. J. (2000). Removal of eye artifacts from visual event-related potentials in normal and clinical subjects. *Clinical Neurophysiology*, *111*, 1745–1758.
- van Veen, V., & Carter, C. S. (2005). Separating semantic conflict and response conflict in the Stroop task: A functional MRI study. *NeuroImage*, *27*, 497–504.
- van Veen, V., & Carter, C. S. (2006). Conflict and cognitive control in the brain. *Current Directions in Psychological Science*, *15*, 237–240.
- van Veen, V., Cohen, J. D., Botvinick, M. M., Stenger, V. A., & Carter, C. S. (2001). Anterior cingulate cortex, conflict monitoring, and levels of processing. *NeuroImage*, *14*, 1302–1308.
- Ward, G., Roberts, M., & Phillips, L. (2001). Task-switching costs, Stroop-costs, and executive control: A correlational study. *Quarterly Journal of Experimental Psychology: Comparative & Physiological Psychology Special Issue*, *2*, 491–511.
- Wendt, M., Heldmann, M., Mnte, T. F., & Kluwe, R. H. (2007). Disentangling sequential effects of stimulus- and response-related conflict and Stimulus-Response repetition using brain potentials. *Journal of Cognitive Neuroscience*, *19*, 1104–1112.
- West, R., Bailey, K., & Langley, M. M. (2009). An investigation of the neural correlates of attention and effector switching using ERPs. *Cognitive, Affective & Behavioral Neuroscience*, *9*, 190–201.
- West, R., Bowry, R., & McConville, C. (2004). Sensitivity of medial frontal cortex to response and nonresponse conflict. *Psychophysiology*, *41*, 739–748.
- West, R., Jakubek, K., Wymbs, N., Perry, M., & Moore, K. (2005). Neural correlates of conflict processing. *Experimental Brain Research*, *167*, 38–48.
- Wylie, G., & Allport, A. (2000). Task switching and the measurement of “switch costs.” *Psychological Research/Psychologische Forschung Special Issue: Executive Control*, *63*, 212–233.
- Yeung, N., & Monsell, S. (2003). The effects of recent practice on task switching. *Journal of Experimental Psychology-Human Perception and Performance*, *29*, 919–936.

Appendix

Experiment 1: Supplementary Data Analysis

To address potential differences between the three tasks (i.e., Shape, Size, and Color) and the anticipated differences between the two judgment types (i.e., Comparison and Identity judgments) RTs (correct trials only) from each task and response mapping were submitted to a repeated measures ANOVA with Task (3) as a within-participants factor and Response-Mapping (3; Shape-ID, Size-ID, and Color-ID) as a between-participants factor. The main effect of Response-Mapping was not significant. The main effect of Task was significant, $F(2, 84) = 28.34, p < .001$, and attributable to significantly faster response times for judgments involving the Color dimension ($M = 651$ ms, $SE = 20$ ms) than to either the Shape ($M = 715$ ms, $SE = 20$ ms) or Size ($M = 732$ ms, $SE = 21$ ms) dimensions, which did not significantly differ from one another. However, this effect can be attributed, in part, to the anticipated interaction between Task and Response-Mapping, $F(4, 84) = 20.68, p < .001$, wherein RTs tended to be faster for the arguably simpler Identity judgment within each Response-Mapping condition (see Table A1). Although contrasts between the comparison and identity tasks were complicated by the discrepancy between these two judgment types, behavioral results from the identity task were analyzed separately by entering mean accuracy and correct RTs (10% trimmed) into separate Switch (2; SW_{SR} and ST) by Congruency (3; CON, CON_{R1} and INCON) repeated measures ANOVAs. Here, CON again refers to those trials in which both of the alternative tasks designated a congruent response, CON_{R1} refers to trials in which only one of the alternative tasks designated a congruent response, and INCON refers to trials in which both of the alternative tasks designated an incon-

gruent response. Recall that, in accordance with the schematic in Figure 2, response-set conflict is the only type of conflict that can impact performance of the Identity task.

Switch (i.e., SW_{SR}) trials were associated with a significant accuracy costs in the Identity task, $F(1, 44) = 16.95, p < .001$, with a 3% decrease in accuracy for SW_{SR} trials ($M = 90.5\%$, $SD = 8.6$) compared with ST trials ($M = 93.5\%$, $SD = 6.6$). There were no statistically significant effects of Congruency in the accuracy rates, but there was evidence for an interaction between Switch and Congruency, $F(2, 88) = 4.99, p < .05$. This interaction reflected the fact that mean accuracy declined monotonically with increasing conflict within SW_{SR} (i.e., CON [$M = 91.9\%$, $SD = 11.2$] > CON_{R1} [$M = 91.3\%$, $SD = 9.28$] > INCON [$M = 88.1\%$, $SD = 11.9$]) but not ST (e.g., CON [$M = 92.7\%$, $SD = 9.9$] < CON_{R1} [$M = 94.3\%$, $SD = 7.3$] > INCON [$M = 93.6\%$, $SD = 8.6$]) trials. Given the unusual qualitative nature of this pattern and the fact that the analysis of the Identification task was secondary to the analysis of the Comparison task, we do not comment further on this interaction.

SW_{SR} trials were also associated with significant RT switch costs in the Identity task, $F(1, 44) = 21.55, p < .001$, wherein RTs to switch trials ($M = 690.64$, $SD = 149.03$) were roughly 74 ms longer than RTs to stay trials ($M = 616.05$, $SD = 122.31$). Although the identity task is considered separately because of the inherent differences between the comparison and identity judgments, it is noteworthy that the SW_{SR} costs associated with this task are more similar in magnitude to the SW_{SR} costs (79 ms) than to the SW_S costs (43 ms) in the comparison task. There were no statistically significant effects of Congruency or in the interaction between Congruency and Switch for the Identity task. This finding is consistent with the results for the Comparison task, indicating a reduced vulnerability to the effects of between-task interference when the interference results from response-set conflict.

Table A1

Mean (SE) Response Times by Task and Response-Mapping

Response-mapping	Task		
	Shape	Size	Color
Shape-ID	644 (34)	717 (33)	657 (32)
Size-ID	764 (40)	656 (39)	654 (38)
Color-ID	795 (33)	791 (32)	625 (31)

Received May 18, 2011

Revision received March 5, 2012

Accepted April 13, 2012 ■