A brain-potential correlate of task-set conflict

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Abstract

Brain-potential correlates of response conflict are well documented, but those of task conflict are not. Task-switching studies have suggested a plausible correlate of task conflict—a poststimulus posterior negativity—however, in such paradigms the negativity may also reflect poststimulus task-set reconfiguration postulated in some models. Here, participants alternated between single-task blocks of classifying letters and digits; hence, no within-block task-set reconfiguration was required. Presenting letters alongside digits slowed responses to the digits and elicited an ERP negativity from ~350 ms, relative to task-neutral symbols presented alongside digits, consistent with task conflict. The negativity was also present for congruent digit-letter stimuli; this and the lack of behavioral response congruency effects indicate conflict at the level of task-set rather than response selection.

Descriptors: Task-set, Conflict, EEG, ERP, Task switching

Conflict and Task-Set

Conflict can arise in the context of a single (and simple) categorization or identification task if the stimulus is a compound whose irrelevant part(s) afford(s) response alternatives—as in the above example with taking the wrong turn at a busy junction and classic flanker paradigms. Or, conflict can arise because the stimulus or parts of it afford more than one task—as in the above example with the web browser and the Stroop paradigm. The latter, task conflict, has been the focus of intense scrutiny, especially in the domain of task switching, in which stimuli affording two or more tasks are presented in a rapid sequence of trials in which the participant is required to perform one task or another. Indeed, task conflict is commonly seen as one of the primary sources of the switch cost (Rogers & Monsell, 1995)—the performance overhead of changing the task relative to repeating it. In an influential account of the switch cost, the activation of the previously relevant task and the inhibition of the previously irrelevant task carry over into the subsequent trial, a phenomenon referred to as task-set inertia (TSI, Allport, Styles, & Hsieh, 1994). These after effects of the preceding trial result in conflict when the task changes. Providing an opportunity to prepare for the imperative stimulus usually results in a substantial reduction in switch cost, even if the interval from the previous response, and thus the dissipation of TSI, is held constant (Meiran, 1996; Monsell & Mizon, 2006). This is taken by many as evidence for another source of the switch cost—endogenous task-set control (task-set reconfiguration, TSR, e.g., Monsell, 2003; Rogers & Monsell, 1995), which can be exerted prestimulus onset given the opportunity (e.g., De Jong, 2000; Meiran, 1996; Rogers & Monsell, 1995).

Sources of Task Conflict

The fact that performance recovers to asymptote very soon after a switch—over one trial in predictable switching (Rogers & Monsell, 1995) and over three to four trials in unpredictable switching (Monsell, Sumner, & Waters, 2003)—suggests that TSI, or at least its contribution to the switch cost, is transient. However, task conflict may also be elicited by longer-lasting associations between stimuli and task-sets: if the stimulus was previously encountered in the context of the irrelevant (competing) task, performance is impaired, particularly on switch trials (Allport & Wylie, 2000; Waszak, Hommel, & Allport, 2003). Subsequently, this effect was shown to be due mainly to stimuli retrieving the competing
tasks-set via previously formed associations, though with small stimulus sets there was also a contribution of negative learned associations: responses were slower for previously irrelevant stimuli (distractors) that became relevant in the current task (Waszak, Hommel, & Allport, 2005). Waszak and colleagues also showed associative effects of transfer to other (semantically related) stimuli (Waszak, Hommel, & Allport, 2004).

Levels of Task Conflict

TSI and stimulus-driven associative retrieval of task-set may cause conflict on at least two levels. First, they may result in some activation of the response appropriate to the previous task. When this response is different from that in the current task—as for incongruent stimuli—the result is response conflict, relative to the case of congruent stimuli, for which the response is the same in both tasks, so that activation of the irrelevant task’s response will facilitate, or at least not compete with, the appropriate response. Second, task conflict may also arise in other components of the task-set, for example at the level of attentional selection of the relevant stimulus dimension, or in other hypothetical components of the task-set (e.g., task goals). For example, there is lateral inhibition between task-set units in Brown, Reynolds, and Braver’s (2007) connectionist model of task-set control. We will refer henceforth to conflict between tasks at this superordinate level as set or set-level conflict, and use the term task conflict as an umbrella term for both response-level and set-level conflict.

There is evidence of both response-level and set-level conflict. Performance for incongruent stimuli is almost always worse than for congruent stimuli, indexing conflict at the level of response selection. The congruence effect tends to be larger on switch compared to repeat trials, indicating greater activation of the irrelevant stimulus-response (S-R) rules immediately following a switch, though congruence effects remain substantial well beyond the transient effects of a task switch (e.g., Monsell et al., 2003). To examine set conflict, researchers have compared bivalent stimuli that afford both the relevant and irrelevant task with univalent stimuli that afford only the relevant task (e.g., Aron, Monsell, Sahakian, & Robbins, 2004; Elchlepp, Lavric, Mizón, & Monsell, 2012; Karayanidis, Coltheart, Michie, & Murphy, 2003; Rogers & Monsell, 1995). In particular, one can contrast congruent bivalent stimuli, which afford both tasks and require the same response in both (hence creating the possibility for set-level conflict but also facilitation at the response level), with univalent stimuli, which afford neither the other task, nor another response. Longer response times (RTs) and larger RT switch costs for congruent bivalent stimuli suggest that conflict at the set level can outweigh any benefit of response-level facilitation (Aron et al., 2004; Rogers & Monsell, 1995; Steinhauser & Hubner, 2007).

Electrophysiological Correlates of Conflict

There is persuasive behavioral evidence concerning the sources and the levels of task conflict. However, relevant electrophysiological evidence is scarce, especially with regard to the distinction between response-level and set-level conflict suggested by behavioral studies. There is a substantial literature on electrophysiological correlates of response conflict. A growing body of studies have linked modulations of the amplitude of event-related potentials (ERP) with central-anterior scalp distribution (N2 and error-related negativity) to response conflict in go/no-go, flanker, and other paradigms (Yeung, Botvinick, & Cohen, 2004). In contrast, an unequivocal brain-potential correlate of task conflict has not yet been identified. One potential candidate that has emerged in task-switching studies is a protracted switch-induced negative polarity deflection over the central and posterior scalp starting from ~300 ms following stimulus onset and extending into (but not limited to) the range of the P3 component of the ERP (e.g., Astle, Jackson, & Swainson, 2006; Elchlepp et al., 2012; Karayanidis et al., 2003; Lavric, Mizon, & Monsell, 2008; Nicholson, Karayannis, Poboka, Heathcote, & Michie, 2005; Swainson, Jackson, & Jackson, 2006). We (Elchlepp et al., 2012; Lavric et al., 2008) and others (Nicholson et al., 2005) have proposed that this component reflects enhanced conflict/interference on switch trials, an interpretation in part motivated by reports of a similar conflict-related negativity with a parietal distribution (N450) in some ERP studies of Stroop interference (West, 2003).

The Present Investigation

Although the poststimulus switch-related negativity reported in task-switching studies is likely to reflect set-level conflict, there are alternative interpretations. The fact that univalent stimuli cause less task-set conflict but still result in a nontrivial negativity (Elchlepp et al., 2012; Karayanidis et al., 2003) can be seen as an indication that this brain potential is a reflection of poststimulus TSR rather than task conflict. Indeed, in some accounts TSR consists of two stages, of which the first can be started and (if there is opportunity) completed before the stimulus, whereas the second stage can start only after stimulus onset, thus leading to a switch cost even when there is ample opportunity for preparation (Meiran, 2000; Meiran, Kessler, & Adi-Japha, 2008; Rogers & Monsell, 1995; Rubinstein, Meyer, & Evans, 2001). The second stage has been argued to involve rule activation—loading the S-R rules associated with the relevant dimension into working memory (Rubinstein et al., 2001)—and/or response-set biasing—changing the meaning of the response set (Meiran, 2000).

To identify a brain potential that can be unequivocally attributed to task conflict, we chose to exclude TSR as a source of ERP effects in a design in which tasks switched not within, but only between, relatively long blocks of trials. Evidence from predictable switching (alternating runs) shows that recovery from a task switch is complete on the second trial of a task run (Rogers & Monsell, 1995) and even with unpredictable switching recovery is asymptotic after three or four trials (Monsell et al., 2003). Therefore, we would expect task-set reconfiguration to be completed within the first few trials of a block. We could thus examine the brain-potential correlates and ask what brain-potential modulation(s) would be elicited by manipulations of task conflict arising from relatively long-term associations between stimulus attributes and tasks in the absence of transient task switches (and hence of TSR). Furthermore, we could analyze the effects of response congruency to distinguish between response-level and set-level conflict and manipulate the associative history of specific stimuli to examine the role of stimulus-response/stimulus-task bindings in task conflict.

Experiment 1

We expected conflict to arise even in single task blocks for bivalent stimuli if a strong association had been formed between their irrelevant attribute and a competing task. To accomplish this, we adapted a letter/digit task pair widely used in both behavioral and ERP task-switching paradigms (e.g., Karayanidis et al., 2003; Nicholson et al., 2005; Rogers & Monsell, 1995). In an initial
training session, participants classified a single letter presented on each trial as consonant or vowel. In a subsequent session, there were blocks of single-letter classification trials to reinforce the associations created by performing the letter task. In addition, there were blocks in which the stimulus was a pair of characters (letter and digit), and the task was to classify the digit as odd/even. Hence, these bivalent stimuli (e.g., 1a, v5) afforded a task that was in competition with the previously practiced letter task (although the letter task was never required in a digit-task block). To create a comparable univalent stimulus, a nonalphabetic symbol was combined with the digit (e.g., #3) so that the stimulus afforded only one task. We expected task conflict on digit-letter trials, but not on digit-symbol trials. To examine effects of response conflict, we contrasted bivalent incongruent stimuli (digit-letter stimuli whose component characters required different responses in the two classification tasks) with bivalent congruent stimuli (digit-letter stimuli whose component characters required the same response in the two tasks). To investigate effects of set-level conflict, we compared bivalent congruent stimuli to univalent (digit-symbol) stimuli.

In addition to investigating the effects of valence and congruency, we also manipulated the association between specific letters and performance of the letter task (and the resulting response) to examine the role of stimulus-specific associations in any effects of task conflict that we might observe (cf. Waszak et al., 2003). Of the letters used as the irrelevant character in the digit-task blocks, some had been repeatedly classified in previous letter task blocks (“old” letters) and some occurred only as irrelevant characters in the digit-task blocks (“new” letters). To the extent that the associations causing task conflict are stimulus-specific, one would expect old letters to elicit more conflict than new letters. To the extent that associations are formed only between classes of stimuli (e.g., letters) and tasks, old and new letters should elicit similar degrees of conflict.

Method

Participants. Twenty-four right-handed students (8 female) aged 18–47 ($M = 24, SD = 6.7$) gave written informed consent to participate in the experiment, whose procedure was approved by the local Ethics Committee (School of Psychology, University of Exeter). Participants were paid £13 for completing two testing sessions.

Apparatus. The testing was run and behavioral data collected using E-prime 1.1 software (Psychology Software Tools, Sharpsburg, PA) running on a standard PC with a 17” CRT monitor; responses were recorded using a standard computer keyboard. The electroencephalogram (EEG) was acquired using 64 active Ag/AgCl electrodes embedded in a cap connected to EEG amplifiers (ActiCap and BrainAmp, Brain Products, Munich, Germany).

Stimuli, tasks, and procedure. To exploit the beneficial effect of sleep on consolidation of content learned in simple tasks with motor responses (Nishida & Walker, 2007), the testing was run over 2 consecutive days: a 20-min training session on Day 1 and a 1 1/4-hr session on the following day; EEG data were collected only in the second session.

On Day 1, participants performed four blocks (see Figure 1) of 144 trials each, classifying a single letter as vowel or consonant by pressing the left or right arrow key, with the assignment of keys to the vowel/consonant categories counterbalanced over participants. Each trial started with a blank (white) screen for 500 ms, followed by display of a black fixation cross in the center for 500 ms, followed by presentation in the same location of one of four letters in lower case Lucida Console font (subtending between 0.5°–1° of visual angle). The stimulus remained on the screen until a response was made. Feedback was given only following an error: “ERROR” displayed for 1,500 ms.

On Day 2, three 72-trial blocks (Blocks 2, 4, 6) of the vowel/consonant classification task practiced on Day 1 were interspersed among four blocks (1, 3, 5, 7) in which the task was to classify a digit from the set 1–6 as odd (left key) or even (right key). In Block 1 (48 trials), the digit classification task was introduced by presenting a single digit. Blocks 5 and 7 (144 trials each) were critical for investigating task-set conflict. Here, the digit to be classified was paired with either a letter (bivalent stimulus) or with one of six nonalphabetic characters, or symbols: # * ; € { } . No classification responses to symbols were required at any point during the experiment, so digit-symbol stimuli were univalent. Among the bivalent (digit-letter) stimuli, two thirds contained old letters presented on Day 1 and extensively re-exposed in the letter classification blocks on Day 2 (17 times each per block) and one third contained new letters not seen on Day 1 and presented only twice in the letter classification block preceding a critical digit classification block. Specifically, one new vowel and one new consonant were introduced (presented alone twice each) in Blocks 4 and 6 to avoid novelty/surprise effects in the ERPs when they were subsequently presented alongside digits in the following digit classification block. Two four-letter sets (a, i, r, v and e, u, c, n) were assigned the old and new status, respectively, for half of the participants, while for the other half of the participants this assignment was reversed.

Block 3 (144 trials) was a practice block for the odd/even classification with compound stimuli. As in Blocks 5 and 7, two thirds of its bivalent stimuli contained old and one third contained new letters (in this block, the new letters were consonants d and f for all participants). In all digit classification blocks with compound stimuli (i.e., Blocks 3, 5, and 7), half of the stimuli were bivalent and half univalent. Every letter and every symbol was paired equally often with each digit, and the two orders of the characters in the compound (e.g., 2d and d2) were equally repre-
sented for every pair of characters. The structure of a trial was the same on Day 2 as on Day 1 (see Figure 1).

**EEG/ERP s.** The EEG was sampled continuously at 500 Hz with a band-pass of 0.016–100 Hz, the reference at Cz, and the ground at AFz. There were 61 electrodes on the scalp in an extended 10–20 configuration, one below the right eye, and one on each earlobe. Electrode locations were adjusted using a CMS ultrasound digitizer (Zebris Medical, Isny, Germany), and their impedances kept below 10 kΩ. Following offline filtering with a 20-Hz low-pass filter (24 dB/oct) and rereferencing to the linked ears, the EEG was segmented into stimulus-locked epochs, consisting of a –100 to 0 ms prestimulus baseline and a 500 ms poststimulus segment.

Following baseline correction, segments associated with errors, as well as those containing ocular, muscle, and other artifacts, were discarded by means of visual inspection. The remaining EEG segments were averaged for every participant and experimental condition.

To limit the number of statistical tests and improve the signal-to-noise ratio, differences between experimental conditions were assessed by comparing the amplitude of the ERPs averaged within temporal ranges (time windows). The identification of time windows was based on the scalp distribution (topography) of the difference between conditions. Data-driven temporal segmentation of ERPs, as in the current procedure and in other methods (such as temporal principal component analysis, e.g., Weber & Lavric, 2008), ensures more optimal and less biased “windowing” of the waveform. A time window was defined as the interval of relative topographic stability between abrupt topographic changes. The changes in topography were identified with topographic analysis of variance (TANOVA, Pasqual-Marquï, Michel, & Lehmann 1994), a method that treats the differences between two scalp maps as a vector over the scalp electrodes. The magnitude of the difference between the maps (the topographic dissimilarity) can be expressed as the vector length: the square root of the sum of squares of all its components (difference at each electrode), resulting in a value that expresses the topographic dissimilarity. For every experimental contrast (e.g., univalent vs. bivalent conditions), we computed the difference wave and used TANOVA to assess the topographic dissimilarity of adjacent time points in the difference wave. To ensure sensitivity to changes in topography that are more graded, we ran TANOVs with a lag of 2, 10, and 20 ms (i.e., computed the dissimilarity between time point and the time point 2, 10, or 20 ms back). The resulting dissimilarity time courses were then used to identify the intervals of relative topographic stability, which were subsequently used as time windows in the statistical analysis.

ERP amplitudes in these time windows were averaged and submitted to repeated measures ANOVAs. To assess potential interactions with scalp regions in the ANOVAs, ERPs were averaged for seven groups of electrodes in each hemisphere, ignoring the midline electrodes, to yield average scores for seven regions on the left: anterior frontal (FP1, AF1, AF7, F5), lateral frontal (F7, F9, FT7), medial frontal (F1, F3, FC1, FC3), posterior frontal (FC5, C1, C3, C5), temporal (T7, TP7, CP5), parietal (CP1, CP3, P1, P3, PO1), occipital (P5, P7, PO7, O1), and the corresponding regions on the right. The grouping of electrodes has several useful features: it improves the signal-to-noise ratio by spatial smoothing, has some anatomical validity, and enables one to simultaneously apply straightforward tests of anterior versus posterior and laterazilation effects, while using > 86% of electrodes. Region and hemisphere were factors in the ANOVA along with the factors bi-/univalent, old/new, and congruent/incongruent. Significance levels were adjusted using the Huynh-Feldt correction for violations of sphericity (but unadjusted degrees of freedom are reported). Significant interactions of switch/repeat with region were followed by two-tailed t tests by region, which were Bonferroni-corrected to control for the inflation of Type I error in multiple comparisons.

**Results**

**Behavioral results.** Planned contrasts by means of t tests showed that RTs were longer for bivalent (digit-letter) stimuli (603 ms) than for univalent (digit-symbol) stimuli (579 ms), a mean difference (± standard error) of 25 ± 5 ms, t(23) = 5.37; p < .001, suggesting greater interference in the digit classification task from the letter than from the symbol. This was true even when comparing bivalent congruent stimuli (601 ms) to univalent stimuli, a difference of 23 ± 5 ms, t(23) = 4.80; p < .001. An ANOVA on the bivalent stimuli with factors letter type (old vs. new) and congruency found digit classification RTs to be insensitive to whether digits were paired with letters that had well-practiced response mappings in the irrelevant (letter) task (old letters, 604 ms), or with letters seen only twice in the immediately preceding letter-task block (new letters, 603 ms), p > .1. Response congruency, that is whether the digit and letter in the compound stimulus were mapped to the same (congruent) or different (incongruent) response keys, had only a small and nonsignificant effect on RTs (congruent = 601 ms; incongruent = 606 ms), p > .1, which did not interact with the old/new letter manipulations, p > .1.

There were no significant differences in error rates between bivalent (5.1%) and univalent (5.3%) stimuli, or bivalent congruent (5.4%) and univalent (5.3%) stimuli. The ANOVA on bivalent stimuli with factors letter type (old vs. new) and congruency did not reveal any significant differences between old (4.8%) and new (5.2%) or congruent (5.4%) and incongruent (4.7%) stimuli, nor was the interaction between these manipulations reliable.

**ERP results**

**Bivalent versus univalent.** For the bivalent versus univalent contrast, the following time windows were defined: 130–150 ms, 170–200 ms, 210–270 ms, 350–430 ms, and 460–480 ms. Between 130 and 150 ms, amplitudes in the occipital region of the left hemisphere were more negative for bivalent than for univalent trials; however, this effect did not reach significance when corrected (Valence × Hemisphere, F(1,23) = 4.13, p = .054; Valence × Region in the left hemisphere F(6,138) = 3.67, p < .05; t test in the left occipital region, t(23) = −2.18, p = .28, corrected; .04, uncorrected).

The 170–200 ms time window, which seems to capture the peak of the N1 (see Figure 2, left plot), showed a reliably more negative
amplitude in response to univalent stimuli: main effect of valence, $F(1,23) = 6.1, \ p < .05$; Region $\times$ Valence interaction, $F(6,138) = 3.87, \ p < .05$.

In the time window from 210 to 270 ms, valence interacted reliably with region, $F(6,138) = 53.23, \ p < .001$. In the left, $t(23) = -7.85, \ p < .001$, and right, $t(23) = -5.75, \ p < .001$, occipital regions, amplitudes were more negative in the bivalent condition than in the univalent condition, possibly reflecting a posterior selection negativity, whose amplitude was larger following bivalent stimuli, or a delayed/more variable N1 in the bivalent condition (Figure 2, left). While for univalent trials the N1 showed a sharp peak, which largely recovered to baseline by 210–270 ms, for bivalent trials the N1 seemed broader, possibly due to greater variability in its latency. Concurrent with this negativity, frontocentral positivity amplitudes were more positive for the bivalent condition than the univalent condition (see Figure 2, right): anterior frontal left, $t(23) = 5.37, \ p < .001$, and right, $t(23) = 4.59, \ p < .01$; lateral frontal left, $t(23) = 5.38, \ p < .001$, and right, $t(23) = 3.78, \ p < .05$; medial frontal left, $t(23) = 5.36, \ p < .001$, and right, $t(23) = 5.31, \ p < .001$; posterior frontal left, $t(23) = 4.02, \ p < .01$.

The 350–430 ms time window contained a robust negativity for the bivalent condition relative to the univalent condition: main effect of valence (see Figure 3A), $F(1,23) = 16.08, \ p < .01$; an effect that was maximal in the posterior scalp regions, indicated by the valence by region interaction, $F(6,138) = 11.66, \ p < .01$. There were no statistically significant effects involving valence in the 460–480 ms time window.

For the contrast on digit task trials containing old versus new letters, the following time windows were defined: 110–130 ms, 160–180 ms, 220–280 ms, 330–390 ms, and 420–480 ms. Only the last time window between 420–480 ms showed reliable differences (main effect of old/new, $F(1,23) = 5.63, \ p < .05$) with amplitudes for old letters being more positive compared to new over the posterior scalp. Old/New $\times$ Region interaction, $F(6,138) = 3.0, \ p < .05$, possibly suggesting a larger P3b for the old condition (see Figure 3B).

**Response conflict: Congruent versus incongruent.** Although there were no reliable effects of congruency in the behavioral data, we examined the possibility that the ERP effects of valence might reflect response-level conflict by analyzing the effects of congruency in the three time windows associated with robust effects of valence (170–200 ms, 210–270 ms, 350–430 ms). There were insufficient trials to examine the congruence by old/new interaction in the ERPs. Because there were twice as many old than new trials and because one would expect congruency effects to be more pronounced for the more practiced stimuli, congruency analyses were run for bivalent stimuli containing old letters. No statistically reliable effects of congruency were found in these analyses in any of the three time windows under scrutiny.

**Set conflict: Congruent versus univalent.** To determine whether the valence effects may instead reflect set-level conflict, which yielded a robust effect in the RT data, we contrasted the bivalent congruent condition with the univalent condition for the three time windows associated with effects of valence (170–200 ms, 210–270 ms, 350–430 ms). Robust effects were also found in the ERPs—in all three time windows—very similar to the differences between all bivalent trials and the univalent trials (see Figure 3C). Relative to univalent ERPs, congruent ERPs showed a reduced amplitude of N1 (170–200 ms), $F(1,23) = 5.86, \ p < .05$, greater posterior selection negativity, accompanied by anterior positivity (Condition $\times$ Region interaction at 210–270 ms, $F(6,138) = 32.63, \ p < .001$) and more negative ERPs over posterior regions at longer latencies (350–430 ms), as indicated by the Condition $\times$ Region, $F(6,138) = 10.01, \ p < .001$, and Condition $\times$ Region $\times$ Hemisphere interactions, $F(6,138) = 4.44, \ p < .01$, and the (marginally) significant follow-up t tests in the posterior regions (left occipital, $t(23) = 2.71; \ p < .05$; left and right parietal, $t(23) = 2.58; \ p = .068$, $t(23) = 2.55; \ p = .072$).

**Discussion**

We found effects of valence on performance on the digit task: RTs were longer for bivalent (digit-letter) stimuli than for univalent (digit-symbol) stimuli. Moreover, RTs for congruent stimuli were reliably longer than for univalent stimuli, and there was little difference between congruent and incongruent stimuli. This pattern suggests set-level rather than response-level conflict. In the ERPs, bivalence elicited some early effects in waveform components
associated with visual attention—a diminished N1 and an enhanced selection negativity (or, alternatively, these two differences could both reflect a delayed and more variable N1 in the bivalent condition, see Figure 2). Bivalency also elicited a later effect—a negativity over the parietal scalp in the ~300–500 ms range, whose polarity, timing, and scalp distribution are reminiscent of the poststimulus switch-repeat negativity previously documented in task-switching paradigms (see introduction). The earlier effects (on N1 and, possibly, the selection negativity) may suggest that the locus of conflict may at least in part be in selective attention.

There was no discernable effect of response congruence, suggesting that the above effects reflect set-level rather than response-level conflict. There was also no evidence of a contribution from stimulus-specific associations or bindings between stimulus and task or response, as old and new letters appeared to slow responses to bivalent stimuli to an equivalent extent. Hence, the task conflict seen here appears to result from the training having created an association with the whole class of letters (rather than specific stimuli) to attentional settings or to the goal of classifying the letter.

There are, however, alternative interpretations of the above findings. First, letters are arguably more familiar both individually and as a class than the alphanumeric symbols. Hence, what we have interpreted as task conflict due to training on the letters could instead reflect greater attention-pulling by the more familiar letters. Second, the task may have an element of visual search: the participant may need to “find” the digit in the pair. Perhaps the digit is easier to find next to a symbol than next to a letter, because it is easier to discriminate from a symbol. Indeed, the early ERP components modulated by stimulus valence have been implicated (Hillyard & Anllo-Vento, 1998) in spatial selection (N1) and feature selection (selection negativity) and hence their modulation might reflect differences in ease of attentional selection of the relevant category or character. To examine the possible contribution of such intrinsic differences between the letter and symbol characters, we ran a second experiment.

Experiment 2

Experiment 2 was designed as a control for the valence manipulation in Experiment 1. The critical blocks (containing the digit classification task and compound stimuli) were constructed in the same way in the two experiments. The critical difference was that in Experiment 2 there was no exposure to the letter classification task at any point. Thus, one could examine behavioral and electrophysiological differences between digit-letter (bivalent in Experiment 1) and digit-symbol (univalent in Experiment 1) stimuli, which in Experiment 2 did not stem from an association of the distractor element of the stimulus to another task performed earlier in the experiment; indeed, both digit-letter and digit-symbol stimuli were univalent in Experiment 2. The procedural equivalence of the critical phase of the two experiments makes direct comparisons between the two straightforward.

Method

Sixteen right-handed University of Exeter students, 12 female, 4 male, aged 18–45 (M = 23, SD = 6.6), were paid £10 for their participation following informed written consent (see Experiment 1). The apparatus and EEG set-up and analysis procedures were as in Experiment 1. There was now a single session (see Figure 4) just like the second session in Experiment 1, with one exception: in Blocks 2, 4, and 6, the letter (vowel/consonant classification) task was replaced with a “filler” classification task whose role was to maintain the same overall demands and duration of the testing session as Experiment 1. Stimuli for the filler task were black and white pictures of an animal (horse, mouse, duck) or an object (comb, ladder, key), which participants classified as living/nonliving using the same keys as those used in the digit task.

Results

Behavioral results. Planned contrasts by means of t tests found that responses to digit-letter stimuli (554 ms) were slower than those to digit-symbol stimuli (542 ms), t(15) = -2.32; p < .05 (see Figure 5). However, a t test comparing the digit-letter versus digit-symbol difference in the two experiments found this difference to be significantly reduced in Experiment 2, t(15) = -1.74; p < .05, one-tailed, to about half of that in Experiment 1 (13 vs. 25 ms). As in Experiment 1, no reliable difference was found in error rates between digit-letter (5.3%) and digit-symbol (4.5%) stimuli, nor was this difference (0.8 ± 0.6%) reliably different from that in Experiment 1 (~0.2 ± 0.6%).

Figure 5. RTs and error rates for the two experiments.

1. We assume that only two presentations of the new letters did not result in strong stimulus-task associations.
ERP results. Four time bins were extracted with the method described above (150–190 ms, 230–270 ms, 300–360 ms, 460–500 ms), and amplitudes averaged within these submitted to repeated measures ANOVAs with the factors stimulus type (digit-letter/digit-symbol), region, and hemisphere. In the time window between 150–190 ms, stimulus type interacted reliably with region, \( F(6,90) = 11.79, p < .001 \) (see Figures 6 and 7). Follow-up region-wise \( t \) tests showed more negative amplitudes, that is, a larger N1 for digit-symbol than digit-letter stimuli in the occipital region of the left hemisphere, \( t(15) = 4.05; p < .05 \). Between 230–270 ms, stimulus type interacted with region, \( F(6,90) = 6.73, p < .05 \); this time, amplitudes were more negative for digit-letter, again in the left occipital region of the scalp, \( t(15) = -4.18; p < .05 \). Between 300–360 ms, a main effect of stimulus type was found, \( F(1,23) = 9.02, p < .01 \), with more negative amplitudes for digit-letter than digit-symbol trials in frontocentral areas of the scalp (Stimulus Type \( \times \) Region interaction, \( F(6,90) = 3.45, p = .054 \)). In the 460–500 ms time window, there was a reliable interaction

Figure 6. ERPs for digit-letter and digit-symbol stimuli for both experiments in a subset of electrodes.
between region and stimulus type, $F(6,90) = 4.36; p < .05$, but no scalp regions showed reliable effects of stimulus type.

**Comparison of ERPs in Experiments 1 and 2.** Sample digit-letter and digit-symbol ERPs from both experiments are shown in Figure 6. Because letters were not associated in Experiment 2 with any explicit task or set of responses, the terms bivalent and univalent are not appropriate for referring to digit-letter and digit-symbol stimuli in this experiment. We do, however, use them for the ease of exposition of the comparison between the two experiments. For the cross-study statistical comparison only time windows that showed reliable bivalent versus univalent differences in either experiment were considered. The resulting time bins were 150–200 ms (including 150–190 ms from Experiment 2 and 170–200 ms from Experiment 1), 210–270 ms (including 210–270 ms from Experiment 1 and 230–270 ms from Experiment 2), 300–360 ms (reliable differences in Experiment 2), and 350–430 ms (reliable differences in Experiment 1). The amplitudes of the ERPs from both experiments were averaged in these time bins and submitted to an ANOVA with Experiment as between-subjects factor. The amplitudes of the ERPs from both experiments are shown in Figure 7.

Finally, in the 350–430 ms time window, the reliable Valence $\times$ Experiment interaction, $F(6,228) = 4.48$, $p < .018$, reflected the presence of a robust and widespread bivalence-induced negativity in Experiment 1 with a central-posterior maximum reliably bilaterally in the frontal posterior, $t_{left}(23) = -3.54$, $p < .05$; $t_{right}(23) = -3.81$, $p < 0.05$, parietal, $t_{left}(23) = -4.97$, $p < .05$; $t_{right}(23) = -5.94$, $p < 0.05$, temporal, $t_{left}(23) = -3.13$, $p < .07$; $t_{right}(23) = -4.74$, $p < 0.05$, and occipital, $t_{left}(23) = -4.82$, $p < .05$; $t_{right}(23) = -4.94$, $p < 0.05$, scalp regions and its absence in Experiment 2, for which no scalp region showed reliable effects of valence (see Figure 7).

**Discussion**

Experiment 2 showed that, even in the absence of any requirement to respond to letters throughout the experiment, pairing the digit with a letter slowed the odd versus even classification of a digit relative to pairing the digit with a nonalphanumeric character (symbol). However, this difference was reduced substantially in Experiment 2 compared to Experiment 1. We therefore conclude that about half of the effect of the character presented alongside the digit in Experiment 1 depended on its association with a competing task and hence indexed task-level conflict.

The two earliest electrophysiological effects of the character paired with the digit that were observed in Experiment 1 (the reduction/delay of the N1 component and larger selection negativity for digit-letter trials) were also found in Experiment 2 (see Figure 7). Hence, these perceptual/attentional effects are unlikely to reflect task conflict, but instead reflect attention-pulling by letters relative to symbols and/or perceptual differences between digit-letter and digit-symbol stimuli. However, the longer-latency ERP effect of valence (posterior negativity at ~300–500 ms poststimulus onset) was confined to Experiment 1—indeed there was no sign of this effect in Experiment 2 (see Figures 6 and 7). Instead, in Experiment 2 the presence of a letter alongside a digit elicited an
earlier and more short-lived (~300–360 ms poststimulus onset) negativity with a frontal scalp distribution (see Figure 6).

General Discussion
Electrophysiological Signature of Task Conflict

The present investigation aimed to identify the brain-potential correlate(s) of conflict/competition between task-sets. Previous research into the electrophysiology of task switching has suggested a likely candidate: the switch-induced negative deflection consistently observed following stimulus onset over posterior scalp (Elchlepp et al., 2012; Lavric et al., 2008; Nicholson et al., 2005).

However, the poststimulus switch versus repeat negativity could also be interpreted as a reflection of poststimulus TSR within the framework of theories/models that distinguish between pre- and poststimulus TSR (Meiran, 2000; Meiran et al., 2008; Rogers & Monsell, 1995; Rubinstein et al., 2001). To isolate task-set competition as the only cause of ERP modulations, we sought to rule out effects of TSR and manipulated stimulus valence in a design in which the task changed on a block-by-block rather than trial-by-trial basis. In this paradigm, conflict/competition between tasks could arise from relatively long-term associations between stimuli (or classes) of stimuli and task-sets, rather than from (the more transient) TSR.

Experiment 1 revealed two kinds of effect of stimulus valence on ERPs. The first was a modulation of early brain potentials (up to ~270 ms following stimulus onset) previously associated with visual selective attention: the posterior N1 component had larger amplitude for univalent stimuli, followed by a larger SN for bivalent stimuli (though the latter could also reflect a delayed and more variable N1 in the bivalent condition). The second kind of effect was a longer-latency bivalency-related negativity over the posterior scalp from ~350 ms onwards. Experiment 2, which controlled for perceptual, familiarity, and other possible differences between the digit-letter and digit-symbol stimuli used in Experiment 1 but used only univalent stimuli (there was no letter task in Experiment 2), showed that the differences in N1 and the SN were present in the absence of task conflict. In contrast, the longer-latency posterior negativity in response to digit-letter versus digit-symbol stimuli identified in Experiment 1 was not found in Experiment 2 (see Figure 7), indicating that perceptual and familiarity differences between digit-letter and digit-symbol stimuli are not sufficient to elicit this brain potential. This negativity can therefore be considered a marker of task conflict. We note that the biophysical characteristics of this ERP modulation (its polarity, onset latency, duration, and scalp distribution) are reminiscent of those of the switch versus repeat negativity observed in poststimulus ERPs in task-switching studies (see above and introduction). Although this may be seen as further supporting the interpretation of the latter in terms of task conflict, this parallel can only be tentative, given it is based on mere qualitative similarity.

Deconstructing Task Conflict

A further aim of our study was to examine the possible sources of task conflict and the level of processing at which conflict/competition might arise, by including a further experimental manipulation in our design—associative history of individual stimuli—and by exploiting the high temporal resolution of brain potentials.

With regard to sources of task conflict, as already mentioned, it is very unlikely that the behavioral and electrophysiological differences between univalent and bivalent stimuli were due to TSI—there is persuasive evidence from task switching that TSI is transient (see introduction). The likely source of conflict in Experiment 1 is the association between letters and the vowel-consonant task. Intriguingly, conflict (as indexed by the valence effect in Experiment 1) was not greater for the old letters that were extensively trained in the context of the letter task (on the day of ERP testing and on the previous day) than for the new letters. This indicates that the relevant associations were not those between individual letters and the vowel/consonant task but between the class of letter stimuli (“letterness”) and the vowel/consonant task. Thus, conflict can arise from the binding of classes of stimuli (or the common features across those stimuli) to task-sets, not only from the binding of specific stimuli to task-sets (e.g., Waszak et al., 2003).

With regard to the level of conflict, Experiment 1 found little or no evidence of response conflict, as indicated by the absence of an effect of congruency. Longer RTs for congruent stimuli than for univalent stimuli point to conflict at set level. What might be the processing locus of the observed set-level conflict? At least two possibilities suggest themselves. First, there may be some carryover of the attentional settings of the irrelevant task-set, for example, tuning to letter features persisting from the preceding letter classification block, and/or reactivated by the presence of such features. This could lead to letters in digit-letter stimuli capturing attention more than symbols in the digit-symbol stimuli, thus delaying the selection and subsequent processing of the digit. Another potential source of conflict is competition between task goals. This assumption implies that even incomplete perceptual analysis of the dimension of the stimulus that is no longer relevant (e.g., letter in digit-letter compounds) may (re)activate the irrelevant classification criterion (vowel vs. consonant) whose activation may thus compete with that of the relevant criterion (odd vs. even). One aspect of the ERP results speaks against the attentional locus of set-level conflict in Experiment 1. One would expect competition between the attentional settings of the irrelevant and relevant tasks to be manifest in the early part of the ERP—in components associated to attentional selection—N1 and SN. Yet, although the presence of letters alongside digits did result in modulation of these ERP components, it did so irrespective of the association of letters with another task-set—indeed these modulations were equally prominent in Experiment 2 in the absence of any exposure to the vowel/consonant task (see Figure 7). We therefore conclude that the locus of task-set level conflict observed in Experiment 1 was postattentional. This conclusion is consistent with recent ERP evidence that attentional set established over multiple trials results in effective attentional filtering of distractors in a visual search task (Eimer, Kiss, & Nicholas, 2011). This does not, of course, imply the absence of attentional task-set conflict in task-switching experiments, in which the task changes on a trial-by-trial basis and the persistence of the irrelevant attentional settings is likely to be greater than in the present paradigm. Indeed, ongoing investigations in our laboratory have documented such “attentional inertia” and its relation to performance (Longman, Lavric, & Monsell, in press).

To conclude, the present investigation has shown that: (a) task conflict results in a protracted negativity over the posterior scalp from ~350 ms following stimulus onset; (b) task conflict and its electrophysiological correlate can arise in the absence of conflict at
between a task and a class of stimuli, not only from the association at the response level; (c) task conflict can arise from the association between a task and a specific stimulus; and (d) given the timing of the negativity and its insensitivity to response congruence, the conflict it reflects arises on the processing continuum after attentional selection but before response selection.

References


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