THE BIVALENCY EFFECT IN TASK-SWITCHING

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ABSTRACT

During task-switching, if we occasionally encounter stimuli that cue more than one task (i.e. bivalent stimuli), response slowing is observed on all univalent trials within that block, even when no features overlap with the bivalent stimuli. This observation is known as the *bivalency effect*. Here, I show that the bivalency effect reflects a form of top-down cognitive control that is not easily explained by most current models of control in the literature. The research presented within my thesis reveals that the bivalency effect reflects an adjustment in cognitive control that is highly dependent on past experience with response conflict (chapters 4 and 5), violations of expectancy (chapter 3 and 5), and recent inhibition (chapters 3, 4, and 5). Furthermore, the processes in response to these factors are likely captured by the dorsal anterior cingulate cortex (dACC) and the temporal parietal junction (TPJ) (chapters 2 and 5), reflecting responses to inhibitory demands, and extra visual feature extraction after encountering bivalent stimuli, respectively. These findings provide support for a recent cognitive control model that suggests that the role of the ACC is to track current and recent changes in the environment in order to optimize future performance by predicting changes in cognitive demand (Sheth et al., 2012).

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DECLARATION OF ACADEMIC ACHIEVEMENT

In all of the chapters that follow, I was undoubtedly the lead author responsible for the development of hypotheses, design of experiments, and data analyses. I was also the lead writer for all the papers presented within my thesis. With that said, a number of important collaborators include Judith M. Shedden, Miriam F.F. Benarroch, and Sandra Monteiro from McMaster University. Additional collaborators for chapter 2 were Todd S. Woodward, Paul D. Metzak, and Jennifer C. Whitman from University of British Columbia.

CHAPTER 1 – INTRODUCTION

We are constantly switching between tasks, attending to novel objects, and dividing our cognitive resources to adapt to our environments. As such, it is not surprising that, in the past couple of decades, the endogenous and exogenous properties that influence task-switching behaviour have been under scrutiny (for a review, see Hsieh, 2012). To understand how we are able to move seemingly fluently through our environments despite the multitude of obstacles and distractions, we must first understand what influences and modulates our actions. Generally speaking, my dissertation focuses on the cognitive processes involved in modulating behavioural actions during task-switching and moves the field forward by scrutinizing and explaining a phenomenon that current theories of cognitive control and task-switching cannot fully explain.

My thesis is based primarily on a task-switching phenomenon known as the bivalency effect. The bivalency effect refers to the finding that the occasional presence of bivalent stimuli (stimuli that cue two tasks) within a task-switching paradigm is enough to elicit a block-wise response slowing on all trials within that block compared to a block in which only univalent stimuli appear (Grundy et al., 2011; Meier, Woodward, Rey-Mermet, & Graf, 2009; Rey-Mermet & Meier, 2012a, 2012b; Woodward, Meier, Tipper, & Graf, 2003; Woodward, Metzak, Meier, & Holroyd, 2008). A major point to note here is that this slowing is seen on *all* univalent trials, including those that do not share any features with bivalent stimuli, which points to the involvement of a top-down cognitive control process that is beyond the influence of and dissociated from the individual stimulus and response properties associated with a particular task.

In typical bivalency effect studies, participants alternate predictably between case judgments of letters (uppercase vs. lowercase), parity judgments of numbers (odd vs. even) and colour judgments of shapes (blue shape vs. red shape). Occasionally in bivalent blocks, some of the case judgment letters appear in red or blue, making these stimuli bivalent. The bivalency effect is calculated as the difference in response times to univalent stimuli within bivalent blocks compared to univalent stimuli in purely univalent blocks.

A number of important cognitive control models, including negative priming accounts (Allport & Wylie, 2000; DeSchepper & Treisman, 1996; D'Angelo & Milliken, 2012; Mayr & Buchner, 2006; Milliken, Thomson, Bleile, MacLellan, & Giammarco, 2012; Tipper, 1985, 2001; Tipper & Baylis, 1987), task-decision process accounts (Braverman & Meiran, 2010; Nachshon Meiran & Kessler, 2008; Nachshon Meiran, Kessler, & Adi-Japha, 2008; Monsell, Yeung, & Azuma, 2000; Rubinstein, Meyer, & Evans, 2001; Sohn & Anderson, 2001), and conflict monitoring (Botvinick, Braver, Barch, Carter, & Cohen, 2001; Botvinick, 2007; Botvinick, Cohen, & Carter, 2004; van Veen, Cohen, Botvinick, Stenger, & Carter, 2001) have shown promise in explaining some of the behavioural adjustments observed in the bivalency effect. These theories explore distinctions between task-switch versus task-repeat trials, univalent versus bivalent trials, congruent versus incongruent trials, and conflict versus no-conflict trials.

Collectively however, these distinctions often involve trials that share stimulus and task properties with other trials within the paradigm. For instance, we know that univalent stimuli are processed more quickly than bivalent stimuli and that this processing difference is reflected behaviourally by slower response times to bivalent compared to univalent trials (Allport & Wylie, 2000; Mueller, Swainson, & Jackson, 2007; Poulsen, Luu, Davey, & Tucker, 2005; Rogers & Monsell, 1995). However, the univalent trials in these studies usually contain a feature that is shared with bivalent stimuli, and thus performance on univalent trials might suffer as a result of interference. This can be explained by a negative priming account (Allport, Style, & Hsieh, 1994; Allport & Wylie, 2000; Koch & Allport, 2006) in which the previously irrelevant dimension on the bivalent stimulus becomes the relevant dimension on the univalent stimulus, or by a task-decision process account (Braverman & Meiran, 2010; Nachshon Meiran & Kessler, 2008; Nachshon Meiran et al., 2008; Monsell et al., 2000; Rubinstein et al., 2001; Sohn & Anderson, 2001), in which the univalent stimulus cues the now irrelevant bivalent stimulus, thus slowing down a task-decision process. However, as you will see, none of these theories can sufficiently explain this block-wise adjustment in behaviour because they can explain slowing on tasks that share features with bivalent stimuli, but not for those tasks in which there is no overlap.

In what follows, I provide a brief overview of some important cognitive control and process literatures, and then explain how each one can/cannot explain the bivalency effect observations.

Task switching and task-decision process

Response slowing is often seen when switching between two tasks compared to repeating the same task in sequence (Allport et al., 1994; Hsieh, 2012; Jersild, 1927; Mayr & Kliegl, 2000; Meiran, 2000; Meiran, 1996; Monsell, 2003; Rogers & Monsell, 1995; Spector & Biederman, 1976), and this has received widespread attention over the past couple of decades (Hsieh, 2012). Here, I consider some of the most influential models of switch costs and discuss how these theories fit with the bivalency effect observations.

Beginning in the early 1990's, two very influential models of switch costs drove a significant portion of important advances: 1) The task-set inertia hypothesis (TSI; Allport, Styles, & Hseih, 1994; Allport & Wylie, 2000), and 2) the task-set reconfiguration hypothesis (TSR; Rogers & Monsell, 1995).

The task-set inertia hypothesis first proposed that switch costs are the result of proactive interference persisting from the activation of a previous task-set and slowing response times when switching to the second task. This hypothesis was supported by a task-switching paradigm using Stroop stimuli (Stroop, 1935), in which asymmetric switch costs were observed (Allport et al., 1994). Because word reading is a practiced and relatively automatic process (LaBerge & Samuals, 1974), reading a word (e.g. "blue") is performed with ease, regardless of the colour of the ink (e.g. red). On the other hand, naming the ink colour of a word that is incongruent with the ink colour (e.g. correctly saying "red" to the ink colour when the word reads "blue") is more difficult and results in performance slowing. Interestingly, Allport et al. (1994) showed that when these two tasks were performed in alternation, larger switch costs were observed when switching to the easy task (word reading) compared to switching to the difficult task (colour naming). The authors suggested that this could be explained by proactive interference from the previous trial because more cognitive resources are necessary to inhibit the dominant task-set; this inhibition carries over to the next trial, consequently leading to performance slowing.

The task-set reconfiguration hypothesis on the other hand suggested that switching costs result from the time required to reconfigure a task-set for the upcoming task. In support of task-set reconfiguration, lengthening the response-stimulus interval reduces the observed switch costs (Mayr & Kleigl, 2000; Meiran, 1996; Meiran et al., 2000; Monsell, 2003; Rogers & Monsell, 1995); theoretically this is because one is allowed more time to fully reconfigure the task set and be prepared for the upcoming stimulus. Furthermore, in an explicit task-cuing paradigm (Sudevan & Taylor, 1987), preparation benefits can be found when the response-stimulus interval is held constant, but the cue-stimulus interval (potential preparation time) is lengthened (Meiran, 1996; Meiran et al., 2000). Task-set reconfiguration, but not task-set inertia, can account for these findings. Task-set inertia would predict no reaction time benefit with increased cue-stimulus interval because the available time for decay was held constant. Moreover, when multiple repeat trials follow a switch trial, a sharp reduction in response time is observed on the first repeat trial, but no additional reduction in reaction time is seen on subsequent repeat trials. This is again consistent with task-set reconfiguration, but not with task-set inertia. Task-set inertia would predict that the repeat trials show a gradual decrease in reaction time (RT) as the inhibition decays over time.

It must be noted that task-set reconfiguration and task-set inertia both predict that switch costs should be eliminated given ample time between the presentation of the two competing task sets. The task-set inertia theory predicts that the previous task set should decay with enough time, therefore switching from one task to another with sufficient time delay should eliminate the switch cost. Task-set reconfiguration postulates that with an increased time delay between tasks, task-sets can be appropriately reconfigured, and therefore switching costs should not be observed. However, even with long delays and sufficient time to reconfigure, residual switch costs often remain (De Jong, 2000; Meiran, 1996; Meiran et al., 2000; Rogers & Monsell, 1995). The task-set inertia theory cannot account for this effect in terms of decay, but the task-set reconfiguration theory attributed these residual switch costs to "completing" reconfiguration once the stimulus appears (Rogers & Monsell, 1995). With the latter explanation however, it remains unclear what is carried-out by advance reconfiguration and what processes are being completed by the stimulus-driven (exogenous) component.

Mayr and Kliegl (2000) as well as Waszak et al. (2003) helped shed some light on the endogenous and exogenous components of task-switching. Mayr and Kliegl (2000) suggested that the endogenous reconfiguration component was consistent with retrieving relevant action rules for the upcoming task from long-term memory, and Waszak and colleagues (2003) attributed the residual switch cost to a mismatch between stimulus and response histories associated with the presentation of the target. For instance, if two conflicting responses are cued upon presentation of the target (e.g., “do not respond” and “respond”), a response slowing is observed due to interference. It should be noted that the latter theory was driven by a re-formulated version of the task-set interia hypothesis (Allport & Wylie, 2000; Wylie & Allport, 2000), in which inhibition or activation associated with previous trials can be retrieved from memory upon presentation of the stimulus.

It should be clear from the aforementioned theories that task-set reconfiguration, task-set inertia, and associative retrieval models are not mutually exclusive and that a combination of the processes within these models likely contributes to switch costs. Consistent with this idea, comprehensive reviews of the literature adopt this perspective (Hsieh, 2012; Kiesel et al., 2010; Monsell, 2003; Vandierendonck, Liefooghe, & Verbruggen, 2010). However, it is also clear from these models that they rely heavily on processes engaged by stimulus features or responses. This is problematic in explaining the bivalency effect because the block-wise response slowing observed occurs even on trials that share no features or associations with conflicting or intervening information (i.e., on parity decision trials – remember that bivalent stimuli are coloured letters). Furthermore, in most bivalency effect studies, all trials are switch trials and thus switch cost explanations are not equipped to explain the block-wise response slowing.

A task-decision process account (e.g. Braverman & Meiran, 2010) can explain the slowing that is observed in bivalent compared to univalent blocks, but only for case and colour trials. According to this account, high task-conflict on a particular trial will lead to slower performance because of the need to disambiguate competing tasks (i.e. the relevant and irrelevant tasks). For colour trials, it is possible that its association with the case task leads to a performance decrement because of the need to separate the relevant (colour) from the irrelevant (case) task. This same logic can be applied for the presentation of univalent case trials, in which the relevant and irrelevant tasks must be dissociated before a response can be made. Again however, the task-decision process account cannot explain why a performance cost is observed on univalent trials that share no features with bivalent stimuli (i.e., on parity decision trials) because there is no ambiguity to be resolved.

From the various task-switching models described thus far, it is clear that at least part of the behavioural adjustments observed in the bivalency effect reflect a form of endogenous cognitive control that is not easily explained by current task-switching models.

Negative priming

Another line of research that might shed light on bivalency effect processes deals with a phenomenon known as negative priming: When a recently ignored stimulus becomes a target, a performance cost is observed in the response to the target (Allport & Wylie, 2000; DeSchepper & Treisman, 1996; D’Angelo & Milliken, 2012; Milliken et al., 2012; S. Tipper, 1985, 2001; S. P. Tipper & Baylis, 1987). In typical negative priming studies, two trials are presented in rapid succession, of which the first trial is termed the *prime* and the second trial is termed the *probe*.

Some of the earlier reports of negative priming suggested that reaction time slowing to recently ignored items depended on an abstract inhibitory process carried over from the prime distractor to the probe target (Neill, 1977; Tipper, 1985; Tipper, Weaver, Cameron, Brehaut, & Bastedo, 1991). By this view, one of the ways in which we are able to select the correct response when distracting information is competing for selection, is by means of a mechanism that suppresses the distractor’s internal activation levels; when this distractor then becomes the target, the below-average activation levels for its representation interfere with performance. One line of evidence for this view comes from studies that show that individuals who are more prone to distracting information show smaller negative priming effects (Beech et al., 1989; Tipper, 1991; Tipper & Baylis, 1987); this suggests that inhibiting distracting information may be a critical process by which actions are selected. Another line of evidence for the inhibitory account includes the finding that negative priming effects increase when the target is more difficult to select (Fox, 1994; Milliken et al., 1994), which suggests again that inhibiting distracting information in order to focus on the target may be an important process in action selection. Furthermore, single-cell recordings in monkeys have shown that visual neurons that normally respond strongly to a particular stimulus when the stimulus appears within the monkey’s receptive field, show significantly reduced activity if they appear as distractors (Chelazzi, Miller, Duncan, & Desimone, 1993). This again supports the notion that inhibition is a critical process in negative priming.

Alternative negative priming models however, favour a perspective by which previously ignored information is retrieved upon presentation of the probe (Neill, Valdes, Terry, and Gorfein, 1992; Mayr & Buchner, 2006). For instance, presentation of the previously ignored items cues retrieval of incompatible response tags (e.g. “do not respond” tag; Neill, Valdes, Terry, and Gorfein, 1992) or incompatible perceptual information (Mayr & Buchner, 2006). Support for this view comes from studies that show very long lasting (e.g. up to a month) negative priming effects (DeSchepper & Treisman, 1996). An active inhibition account of negative priming cannot explain this finding because it would predict that the internal activation level of a particular stimulus would return to baseline levels after sufficient delays. In other words, the inhibition of the prime distractor would decay over time. An episodic retrieval account on the other hand can readily explain the long-lasting negative priming effects because presentation of the probe target retrieves past episodes with inhibition.

More recent negative priming models that focus on episodic retrieval also suggest that context-specific control processes are engaged upon presentation of the target stimulus (D’Angelo & Milliken, 2012; Milliken et al., 2012). Here, negative priming effects depend to a large extent on the transfer appropriate processing principle (Morris, Bransford, & Franks, 1977), in which the probe target context conflicts (i.e. is inappropriate) with information retrieved from the prime trial.

From the negative priming models described above it should be clear that despite their differences, they all depend on a repetition of stimulus features between prime and probe. These accounts cannot (nor were they designed to) explain bivalency effect behavioural adjustments because the block-wise response slowing is seen even on probe trials that share no features with the ignored-feature trials (i.e., bivalent trials). We can however clearly see that a negative priming account can explain why performance slowing is seen on the case and colour judgment trials in the bivalency effect. Because the bivalent stimuli (coloured letters) contain features from both the colour task and the case task, they become bound together and this association may be retrieved upon subsequent presentation of the case or colour tasks. Thus, when colour trials are encountered in bivalent blocks, performance may suffer because the task set associated with colour trials had to be suppressed on bivalent stimuli; response times to colour trials would therefore suffer as a result of negative priming. On the other hand, when the case task is encountered, its association with colour trials may retrieve the inhibition linked to colour trials and slow performance accordingly. Notice however, that the parity judgment task does not have any feature overlap with bivalent stimuli, yet a performance cost is still observed when this task appears within a block of trials that contain occasional bivalent stimuli. This suggests that a negative priming account cannot fully explain the response slowing observed in the bivalency effect.

Conflict Monitoring

Arguably the most influential cognitive control model proposed to date is the conflict monitoring theory (Botvinick et al., 1999; Carter et al., 2000; Cohen et al., 2000;

MacDonald et al., 2000; Botvinick, Braver, Barch, Carter, & Cohen, 2001; Botvinick, 2007; Botvinick, Cohen, & Carter, 2004; van Veen, Cohen, Botvinick, Stenger, & Carter, 2001), and it would be cursory to discuss the cognitive control observed in the bivalency effect without first exploring conflict monitoring as an explanation.

The conflict monitoring theory proposes that the anterior cingulate cortex (ACC) is activated in response to conflict in information processing, which then recruits other control centers to implement adjustments that serve to prevent the occurrence of future conflict. In this context, conflict is defined as the simultaneous activation of two or more cognitive processes that interact with each other. Behaviourally, encountering conflict results in a subsequent increase of attention to task-relevant stimulus properties (Botvinick, Braver, Barch, Carter, & Cohen, 2001).

The conflict monitoring theory has received a plethora of empirical support implicating the ACC in conflict detection (e.g. Botvinick et al., 2001; Botvinick, Cohen, & Carter, 2004; Cohen, Botvinick, & Carter, 2000; van Veen, Cohen, Botvinick, Stenger, & Carter, 2001). For instance, the ACC is consistently found to produce stronger signals during presentation of incongruent compared to congruent Stroop stimuli (e.g. Barch et al., 2001; MacLeod & MacDonald, 2000), when multiple response paths are possible (Palmer et al. 2001, Thompson-Schill, 1997; Barch et al., 2000; Frith et al. 1991), and during error commission (Falkenstein, 2000; Gehring, 1993; Kiehl, 2000; Menon, 2001), the latter of which has also been associated with response conflict (Botvinick et al., 2004; Yeung et al., 2004).

Behavioural adaptations supporting the conflict monitoring hypothesis include a highly cited phenomenon known as the Gratton effect (Gratton et al., 1992). The Gratton effect reflects a behavioural adjustment in response to conflicting information. For instance, in a flanker task, interference on the current incongruent trial will be reduced if the previous trial was also incongruent (e.g. Durston et al., 2003; Gratton et al., 1992). Conflict monitoring accounts for this by suggesting that in response to conflict, a focus on task-relevant features helps reduce the influence of distracting information on the current trial.

Although the conflict monitoring theory has received an abundance of empirical support, it does not satisfactorily explain the bivalency effect. For instance, in an fMRI study of the bivalency effect (Woodward et al., 2008), the dorsal ACC was found to be more active for bivalent compared to univalent trials, but also for *univalent* trials that appeared within bivalent compared to univalent blocks. The first finding is consistent with the view that simultaneous activation of conflicting processing pathways is detected by the ACC, but activation of the ACC on trials that contain no conflicting information is problematic. This result suggests that the ACC remains active following conflict, and possibly even plays a role in implementing control in addition to acting as a relay center. However, it is also possible that because of the lack of temporal resolution, the BOLD responses measured in the fMRI study are reflecting lingering blood flow activity from the presentation of bivalent stimuli, rather than activity on univalent trials per se. As we will see in chapter 2 however, I rule out this possibility by using high temporal resolution event-related potentials.

Explaining the bivalency effect with current models of cognitive control

Many cognitive control and task-switching models focus on bottom-up processes (Allport et al., 1994; Allport & Wylie, 2000; Koch & Allport, 2006; Waszak, Hommel, & Allport, 2003), whereas others have focused on the influence of top-down cognitive control (Arrington, Altmann, & Carr, 2003; Arrington & Logan, 2004; Logan & Gordon, 2001; U. Mayr & Kliegl, 2000; Nachshon Meiran, 1996; Rogers & Monsell, 1995; Rubinstein et al., 2001); still others have incorporated both top-down and bottom-up processes (Hsieh, 2012; Kiesel et al., 2010; Monsell, 2003; Vandierendonck et al., 2010). Most of these models however, rely on stimulus and response properties that overlap to some extent with respect their current and previous representations. This is problematic in explaining the control observed for the bivalency effect because adjustments in response to previous presentations of bivalent stimuli are observed even on trials that share no stimulus or response representations with bivalent stimuli.

From the evidence accrued thus far, it should be clear that the bivalency effect reflects an adjustment of cognitive control that is not easily explained by the current task switching and cognitive control literatures, and thus a new model or revision of a current model would provide an important contribution to these literatures.

So far, only six studies have been published on the bivalency effect (Grundy et al., 2011; Meier et al., 2009; Rey-Mermet & Meier, 2012a, 2012b; Woodward et al., 2003, 2008). Following the first bivalency effect study (Woodward et al., 2003), efforts were put forth to uncover the mechanisms involved in this block-wise adjustment in cognitive control. As mentioned above, Woodward et al. (2008) used functional magnetic resonance imaging (fMRI) and demonstrated that the dorsal anterior cingulate cortex (dACC) clearly played a role in modulating this effect.

Meier et al. (2009) then demonstrated that the bivalency effect was robust across a number of different stimulus types and across multiple modalities. The fourth bivalency effect study sought to rule out an alternative negative priming account for the bivalency effect (Rey-Mermet & Meier, 2012b). Because univalent and bivalent stimuli always shared the same response keys in previous studies, it remained possible that the univalent stimuli within bivalent blocks were being negatively primed via response set. However, these authors showed that even when each task had its own set of response keys, a block-wise performance cost (i.e., the bivalency effect) was observed on all trials.

Despite these advances, there are still many questions about the stimulus and response properties that trigger and modulate the bivalency effect, and about the role of the dACC and its interaction with other mechanisms and processes involved in this block-wise adjustment in cognitive control. A primary goal of my dissertation is to advance our understanding of the stimulus properties and processes involved in eliciting, maintaining, and modulating the bivalency effect. The following is a brief overview of the empirical chapters within my thesis. I then preface each empirical chapter by providing a more elaborate description of the particular motivations.

Brief overview of empirical and concluding chapters

In chapter 2, I sought to examine the time course associated with dACC activity by using high temporal resolution electroencephalography (EEG). This gave us insight into the cognitive processes and neural networks involved in the block-wise response slowing by providing electrophysiological correspondence with the behavioural responses inherent in the bivalency effect. I was also able to provide insight for the effects of extended practice on responses associated with the bivalency effect.

Chapter 3 explored the stimulus properties that influence the bivalency effect. Because bivalent stimuli in bivalency effect studies are not predictable, they are by definition unexpected. Thus, it remained possible that the bivalency effect was driven at least in part by a violation of expectancy rather than being constrained to the influence of stimulus or response cueing. I further explored the role of previously inhibited tasks in producing a larger and more robust bivalency effect. More specifically, because colour was always the feature that had to be suppressed on bivalent stimuli, colour trials might be selectively targeted in the bivalency effect via a process similar to negative priming.

Directly motivated by the questions regarding inhibition in chapter 3, chapter 4 scrutinizes the role of inhibition in modulating the bivalency effect. Specifically, because bivalent stimuli always cue two responses (one relevant to the task, the other irrelevant), and because there are always two response keys associated with each task, some bivalent stimuli are response incongruent (the relevant and irrelevant features cue two conflicting responses) whereas others are response congruent (the relevant and irrelevant features afford the same response). I hypothesized that trials following these two different types of stimuli would be affected in qualitatively different ways. Because incongruent bivalent stimuli typically produce a larger response slowing than congruent bivalent stimuli (Meiran, 2005; Meiran, Hsieh, & Dimov, 2010; Meiran & Kessler, 2008; Sudevan & Taylor, 1987), I predicted that trials following incongruent bivalent stimuli would show a greater response slowing as a result of a carry-over of response inhibition.

Chapter 5 was motivated by a desire to incorporate the themes and conclusions from chapters 2-4 into a coherent theoretical framework for the bivalency effect. I studied the electrophysiological correlates for the roles of violation of expectancy, task-cueing, and response inhibition in producing and maintaining the block-wise response slowing observed in the bivalency effect.

I conclude my thesis with a summary and discussion of the general findings for each empirical chapter and how these findings extend current theories of cognitive control. I then highlight the limitations of the present research and provide helpful suggestions for future studies. Taken together, my thesis provides valuable insight into the cognitive processes involved in a controlled response style that affects an entire block of tasks, and provides four new contributions to a total of only five published studies on the bivalency effect by authors other than myself.

I take this opportunity to note that the introductions within each of my chapters contain a significant amount of repetition because they are all either submitted or published manuscripts.

CHAPTER 2

The following chapter is a published manuscript in the journal Human Brain Mapping. Permission to use the article in my thesis has been approved by the copyright holder (Wiley Periodicals, Inc.).

Reference

Grundy, J. G., Benarroch, M. F. F., Woodward, T. S., Metzak, P. D., Whitman, J. C., & Shedden, J. M. (2011). The Bivalency effect in task switching: Event-related potentials. Human brain mapping, 000. doi:10.1002/hbm.21488

Preamble

The motivation for this chapter was two-fold: 1) to provide the first high temporal resolution account for the bivalency effect, and 2) to examine the effects of extended practice on the bivalency effect, both behaviourally and electrophysiologically.

Previous functional magnetic resonance imaging (fMRI) work on the bivalency effect clearly suggested a role for the dorsal anterior cingulate cortex (dACC; Woodward et al., 2008), but the particular processes engaged after stimulus onset remained elusive because of the lack of temporal resolution inherent in fMRI blood-oxygen-level-dependent (BOLD) responses. Thus, I used a 128-electrode electroencephalographic system to examine stimulus-locked event-related potentials capturing the processes engaged following univalent trials presented within bivalent vs. univalent blocks. I further extended the number of encounters with bivalent blocks to examine practice effects. Previous work has shown that the bivalency effect is reduced when participants know to expect bivalent stimuli (Woodward, Meier, Metzak, & Graf, submitted), thus I expected that this would result in a decreased need for processing adjustments on univalent trials within bivalent blocks.

The bivalency effect in task switching: Event-related potentials

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ABSTRACT

During task-switching, if we occasionally encounter stimuli that cue more than one task (i.e. bivalent stimuli), response slowing is observed on all univalent trials within that block, even when no features overlap with the bivalent stimuli. This observation is known as the *bivalency effect*. Previous fMRI work (Woodward et al., 2008) clearly suggests a role for the dorsal anterior cingulate cortex (dACC) in the bivalency effect, but the time course still remains uncertain. Here, we present the first high-temporal resolution account for the bivalency effect using stimulus-locked event-related potentials (ERPs). Participants alternated between three simple tasks in six experimental blocks, with bivalent stimuli appearing occasionally in bivalent blocks (blocks 2, 4, and 6). The increased reaction times for univalent stimuli in bivalent blocks demonstrate that these stimuli are being processed differently from univalent stimuli in purely univalent blocks. Frontal electrode sites captured significant amplitude differences associated with the bivalency effect within time windows 100-120 ms, 375-450ms, and 500-550ms, which may reflect additional extraction of visual features present in bivalent stimuli (100-120 ms) and suppression of processing carried over from irrelevant cues (375-450 ms and 500-550 ms). Our results support the fMRI findings and provide additional evidence for involvement of the dACC. Furthermore, the bivalency effect dissipated with extended practice both behaviourally and electrophysiologically. These findings are discussed in relation to the differential processing involved in a controlled response style.

INTRODUCTION

The *bivalency effect* refers to a blockwise slowing of responses that occurs when occasional task stimuli contain cues from two ongoing tasks (bivalent stimuli). The appearance of even a few bivalent stimuli causes response slowing on all other trials within the block. Consider for instance, an experiment involving three tasks: a colour task which requires classification of shapes as red or blue, a case task which requires classification of letters as uppercase or lowercase, and a parity task which requires classification of digits as odd or even. Now consider encountering a red letter. The coloured letter is a bivalent stimulus because it contains features from both the letter task and the colour task; the letter cues the participant to perform the case judgment task while its coloured appearance cues the participant to perform the colour judgment task. Participants must ignore the colour judgment cue in order to make the correct case judgment response, and performance on the bivalent trials suffers. The *bivalency effect* refers to the observation that, during practiced performance of different tasks in alternation, the occasional presence of a bivalent trial affects performance on univalent trials within the same block, even when the features of the univalent stimuli do not overlap with the bivalent features (Woodward et al., 2003). A few bivalent stimuli within a block may be enough to elicit a block-wise response strategy requiring adjustment in control, and this adjustment in control appears to involve the anterior cingulate cortex (ACC; Woodward et al., 2008).

Activation of the ACC has consistently been reported in studies that compare task switching versus task repetition (e.g. Slagter et al., 2006; Yeung et al., 2006), as well as studies that use bivalent stimuli to stimulate processing conflict (Kerns et al., 2004; Liu et al., 2004; Milham et al., 2001, van Veen et al., 2001). Experiments that examine the bivalency effect, including the experiment described in this paper, alternate between different tasks on each trial, so there is no contrast between switching and repeat trials. However the involvement of the ACC in the bivalency effect can still be evaluated. The frontal ACC is more strongly activated for univalent trials within blocks that included a few bivalent stimuli compared to univalent trials in purely univalent blocks (Woodward et al., 2008). This suggests that the frontal ACC is recruited when adjustment in control is triggered by the presence of a few bivalent stimuli. The authors characterized this as a change in response style that requires breaking the inertia that has built up during the presentation of purely univalent stimuli in the previous block (Woodward et al., 2008).

The fMRI results clearly point to a role for the ACC in the bivalency effect; however, due to the temporal limitations of fMRI, the time course of ACC involvement immediately after stimulus onset remains uncertain. This time course can be illuminated with event-related potentials (ERPs), which provide millisecond temporal resolution. We do not know whether the fMRI activity difference between univalent stimuli in bivalent blocks (hereafter referred to as uni-biv stimuli) and univalent stimuli in purely univalent blocks (hereafter referred to as uni-uni stimuli) is a result of ACC response differences at early or late stages within the time course following the stimulus. Higher resolution temporal measurements from ERP will help to answer this question and clarify the role of the ACC in the bivalency effect.

As far as we know, the current paper is the first ERP work examining the *bivalency effect*, per se. However, even though the three tasks alternate on every trial in bivalency effect studies (i.e., there are no task repeat trials), it is expected that important processing might be reflected in similar ERP components reported in other task switching studies which compare switching trials to repeat trials. The task switch versus repeat contrast within an ERP study typically reveals a negative-going waveform for switch trials relative to repeat trials over parietal electrode Pz that begins between 300-400 ms after stimulus onset (e.g. Karayanidis et al., 2003, Hsieh & Liu, 2008). Studies comparing switch to repeat trials have also found ERP differences in frontal areas that may reflect ACC involvement in task switching (Slagter et al., 2006; Wylie , et al., 2003; Yeung et al., 2006). For example, Wylie, Javitt, and Foxe (2003) found a more negative deflection for switch trials relative to repeat trials at frontal electrode sites (F3 and F4) approximately 470 ms after stimulus onset. Other studies have found task switch related negativity at frontal electrode sites between 350-600 ms (Lorist, et al., 2000), 300-600 ms (Hsieh & Liu, 2009), and 400-700 ms (Hsieh & Chen, 2006).

When comparing task switching to task repetition, there is some reconfiguration required to adjust stimulus evaluation and responses to the new task, and this is often associated with ACC involvement (e.g., Wylie et al., 2009). In the bivalency effect, all the trials are switching trials and participants are well trained on the alternating task sequence so that the additional control associated with the ACC may be lessened. When a bivalent stimulus is suddenly encountered, even though the tasks and the task sequence have not changed, the ACC may reengage on all trials to sort out the general conflict generated by the occasional irrelevant stimulus feature. If the ACC is influencing these same task switching processes to produce the bivalency effect, then we might expect to distinguish univalent stimuli in bivalent blocks relative to univalent stimuli in univalent blocks over frontal electrodes within the same time windows reported by the task switching ERP studies mentioned above. Although the slowing of responses in bivalent blocks does not exactly parallel the difference between task switch and repeat trials, the ACC may influence the same critical task switching processes in order to bring about the bivalency effect. We would also predict that with enough practice with the bivalent stimuli, the ACC involvement would once again be lessened; therefore the frontal activity that we predict will distinguish between univalent stimuli in univalent versus bivalent blocks should lessen with extended practice.

Task switching studies that deal with stimulus conflict and/or response conflict may also help predict the time course of ERP differences associated with the bivalency effect. For example, modulation of the N2 ERP component is associated with task stimuli that contain some form of conflict (Yang & Wang, 2002; Kong et al. 2000, Wang et al., 2002). The N2 typically occurs between 200-350ms after stimulus onset, is recorded at frontal electrode sites and has been indexed to the ACC (van Veen & Carter, 2002) which neuroimaging studies also link to the bivalency effect. ERP studies that directly compare univalent trials to bivalent trials within a task switching paradigm have reported frontopolar ERP differences between 300-600 ms (Poulsen et al., 2005; Hsieh & Liu, 2008). The contrast in the bivalency effect is between univalent stimuli that occur in univalent blocks versus bivalent blocks and does not compare univalent to bivalent trial responses directly (less than 7% of the trials in the bivalent blocks are bivalent trials), however the ACC activity associated with the need to adjust control in the bivalent blocks may be similar.

We recorded stimulus-locked ERPs while participants alternated between a colour judgment of a shape (red vs. blue), a parity judgment of a digit (odd vs. even), and a case judgment of a letter (uppercase vs. lowercase). The trials were grouped into univalent blocks in which no bivalent stimuli appeared (i.e. purely univalent blocks), and bivalent blocks in which bivalent stimuli appeared on 20% of the case judgment trials (uppercase or lowercase letters in red or blue). Our focus of interest is on ERP activity that corresponds with the ACC activity reported in the fMRI experiments (Woodward et al., 2008), and the change in the ACC activity with extended practice. Past studies on the bivalency effect have analyzed three alternating experimental blocks (Woodward et al., 2003; 2006; 2008). These blocks consisted of a bivalent block flanked by 2 univalent blocks; the experimental blocks were preceded by univalent practice blocks. The present study added 3 additional alternating experimental blocks to assess the effects of extensive practice on the bivalency effect. We expected to see a decrease in the bivalency effect over time as participants learned to process the bivalent stimuli more efficiently, and a corresponding decrease in ACC-related ERP responses. Previous work has shown that the bivalency effect is reduced when participants know to expect bivalent stimuli

(Woodward, Meier, Metzak, & Graf, submitted for publication). Furthermore, Meier et al. (2009) demonstrated a decrease in the bivalency effect on subsequent trials following bivalent stimuli. This suggests that extending the number of experimental blocks may also result in a reduction of the bivalency effect.

METHODS

Participants

Twenty-five undergraduate volunteers (8 males and 17 females) from McMaster University's Introductory Psychology and Cognition subject pool participated for course credit. All participants had normal or corrected-to-normal vision. All procedures complied with the Canadian tri-council policy on ethics and were approved by the McMaster Ethics Research Board.

Materials and Apparatus

Stimuli were presented on a black background on a 17" CRT monitor (resolution 1024x768; refresh rate 85 Hz). The experiment was controlled by Presentation® software (Neuro Behavioral Systems; version 11). The stimulus set was adapted from Woodward and colleagues (2008). For the colour decision task, the stimuli were one of four shapes (circle, triangle, square, or pentagon), displayed in either red or blue. The parity decision task consisted of numerals 1 through 8, displayed in white (60-point Times New Roman font). The case decision task consisted of letters a, b, d, e, displayed in upper or lower case (white, 60-point Times New Roman). For the bivalent stimuli, the case letters were displayed in either red or blue (e.g. lowercase "a" displayed in blue). The colour of the bivalent stimuli was randomly varied between red and blue. This resulted in some bivalent stimuli in which the case judgment response was congruent with the colour response and other bivalent stimuli in which the case judgment response was incongruent with the colour response. Participants were seated in a dimly lit room at a distance of 90 cm from the monitor, with the height of each stimulus subtending a visual angle of 1.26º. A chinrest was used to ensure that each participant was viewing the screen from the same distance, and to minimize movement artefacts during ERP recordings. See Figure 1 for an example of the stimuli and experimental procedure.

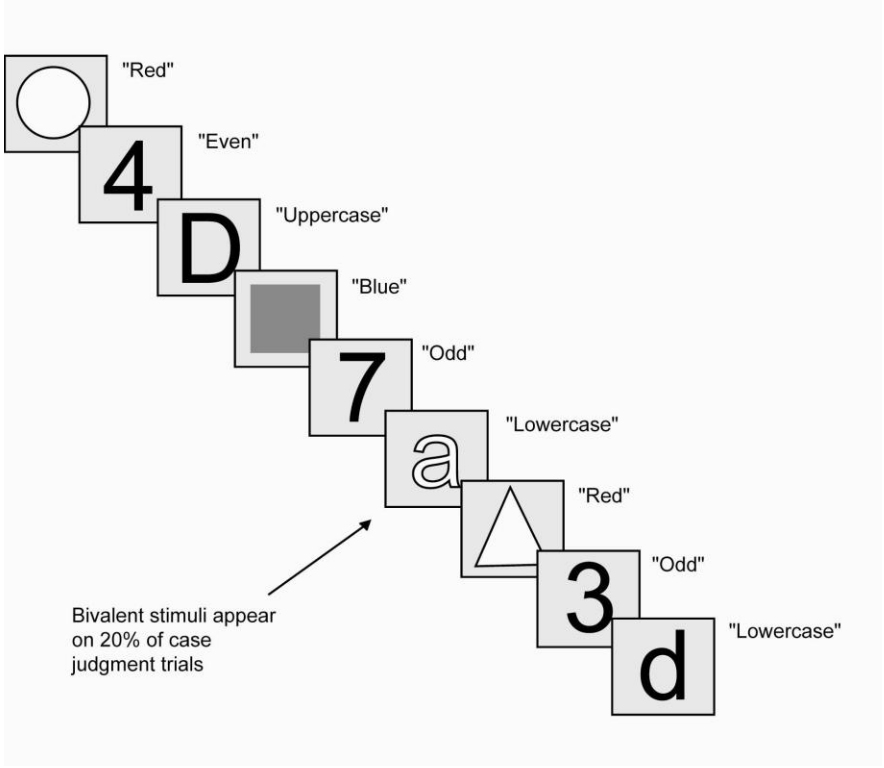

Figure 1 – Illustration of the trial sequence and type of stimuli used during the experiment. The words appearing beside the stimuli represent correct responses. During bivalent blocks (blocks 2, 4, and 6), bivalent stimuli appear on 20% of all case judgment

trials. Bivalent stimuli do not appear at all during the univalent blocks (blocks 1, 3, and 5). In the grey-scale diagram we use white to represent the red stimuli and grey to represent the blue stimuli.

Procedure

Prior to participation, written informed consent was obtained from all participants. Each experimental session was approximately 2 hours in duration, including electrode application. Participants were informed that they would be completing three tasks in alternation and that they should indicate with a key press whether the shape was red or blue (colour judgment task), whether the number was odd or even (parity judgment task), and whether the letter was uppercase or lowercase (case judgment task). Participants were instructed to make a left key press (the "<" key using index finger of right hand) for blue shapes, odd digits, and lowercase letters, and to make a right key press (the ">" key using middle finger of right hand) for red shapes, even digits, and uppercase letters. Left and right key mappings were counter-balanced across participants. The sequence of trials always proceeded from colour to parity to case. Participants were not informed that bivalent stimuli would appear.

Accuracy on the three tasks within past experiments is typically quite high (Woodward et al., 2003; 2006; 2008) and so we imposed a time limit of 1500 ms in order to encourage the participants to respond quickly as well as accurately. This time restriction is also in line with the procedure used by Woodward et al. (2008) in their fMRI study of the bivalency effect. On each trial a stimulus (shape, digit, or letter) was presented in the centre of the computer screen (Figure 1) and remained visible until the participant responded or for 1500ms, at which point the message “Too slow!” appeared on the screen. The inter-trial interval was randomized between 400ms and 900ms throughout the experiment. The varying inter-trial interval was used in order to reduce distortion of ERP components due to averaging of event epochs that overlap in time (Woldorff, 1993). To reduce blinking and general movement that might interfere with our ability to observe task-relevant event-related potentials, a message appeared after every 12 trials indicating that participants could take a “blink break”. To maintain motivation, accuracy over the previous 12 trials was provided during the blink break. Breaks were also provided between blocks. Participants resumed the experiment by pressing one of the response keys to start the next trial.

There were 8 blocks, each consisting of 168 trials (2 practice blocks followed by 6 experimental blocks). There were two types of blocks. The two practice blocks and experimental blocks 1, 3, and 5 were univalent blocks consisting of purely univalent stimuli. The 168 univalent stimuli in each of the univalent blocks, consisted of 56 colour judgment stimuli, 56 parity judgment stimuli, and 56 case judgment stimuli (presented in predictable order of colour, parity, case). Experimental blocks 2, 4, and 6 were bivalent blocks, which were similar to the univalent blocks except that on a random 16 of the 56 case judgment trials the stimulus letters were presented in red or blue (bivalent trials). The colour of the letters was irrelevant to the case judgment response.

Analyses examining the bivalency effect were restricted to univalent trials. The 16 bivalent trials in the bivalent blocks were not included in these analyses. We will use "uni-uni" to refer to univalent trials in univalent blocks and "uni-biv" to refer to univalent trials in bivalent blocks. Two types of RT analyses were performed to examine task type (colour, parity, case) and block type (univalent vs. bivalent). One analysis compared uni-uni trials from experimental blocks 1 and 3 to uni-biv trials from experimental block 2 across the three tasks, consistent with fMRI analyses (Woodward et al., 2008), under the hypothesis that uni-biv trials would show slower response times than uni-uni trials. The other RT analyses compared uni-uni trials to uni-biv trials across all 6 experimental blocks. We hypothesized that the magnitude of the bivalency effect would be reduced with practice, therefore we compared uni-uni and uni-biv differences across block pairs. Block 1 mean RTs were subtracted from block 2 means (blocks 2-1), block 3 means were subtracted from block 4 means (blocks 4-3), and block 5 means were subtracted from block 6 means (blocks 6-5). If the bivalency effect is reduced with practice, then the RT mean differences for blocks 2-1 should be larger than the mean differences for blocks 4-3 and blocks 6-5. The second analysis asked whether the bivalency effect dissipated more slowly for the colour task compared to the case and parity task. We used a polynomial contrast with 5 levels to measure performance across the 6 block sequence to look for an interaction between task and the bivalency effect over time. Following a significant interaction, we then compared the tasks more directly with pairwise comparisons.

Electrophysiological Recordings and Analyses

The ActiveTwo Biosemi electrophysiology system (www.biosemi.com) was used to record continuous electroencephalographic (EEG) activity from 128 Ag/AgCl scalp electrodes plus 4 additional electrodes placed at the outer canthi and just below each eye for recording of horizontal and vertical eye movements. Two additional electrodes, common mode sense (CMS) active electrode and driven right leg (DRL) passive electrode were also used. These electrodes replace the "ground" electrodes used in conventional systems (www.biosemi.com/faq/cms&drl.htm). The continuous signal was acquired with an open pass-band from DC to 150 Hz and digitized at 512 Hz. The signal was bandpass filtered off-line at 0.3 to 30 Hz and rereferenced to a common average reference. Offline signal processing and averaging were done using EEProbe (www.ant-nero.com). Voltage maps were created using Brain Electrical Source Analysis (BESA; version 5.1.8; www.besa.de) by MEGIS Software GmbH. Eye blinks and movement artifacts were automatically identified and manually verified. EEProbe signal processing software was used to apply a correction procedure; eye movement prototypes were estimated for each individual and movement artifacts were subtracted across the electrode array based on calculated VEOG propagation factors via a regression algorithm. Each corrected waveform was verified manually; epochs containing eye-blinks or movements that could not be adequately corrected were rejected from the analyses.

EEG analysis allows for a vast number of possible comparisons between locations, times, and conditions. To reduce the search space we used a multivariate statistical tool, partial least squares (PLS; Lobaugh et al., 2001; McIntosh et al., 1996), which does not require any a priori bias with respect to time course or location of effects.

PLS is similar to a principle components analysis (PCA) in that it uses singular value decomposition to extract information from the dataset, but different in that it constrains the analysis to variance that can be explained by experimental conditions. Singular value decomposition yields a set of *latent variables* (LVs; similar to eigenvalues in PCA) that represent particular contrasts, which account for a percentage of the cross-block covariance explained by the experimental conditions. Each *singular value* explains how much of the covariance was explained by a particular latent variable. One thousand permutations were computed and provided an estimate of obtaining a singular value by chance (similar to a *p*-value). The *electrode saliences* represent the relation between the experimental design contrasts (as represented by the LV) and the spatiotemporal pattern of ERP amplitude changes. Two hundred bootstrap re-samplings were performed to assess the reliability of electrode saliences at each time point by providing a standard error for each salience. The bootstrap procedure uses random sampling with replacement so that even though each sample will have the same number of elements as the original data, slightly different samples will be produced and reliability of the saliences can be measured. Since the ratio of the salience to the standard error is approximately equal to a z-score, data points where the ratio was more than 1.7 ($p < 0.05$) were considered reliable. For a nice example of how PLS can be applied to EEG data, see Düzel et al. (2003).

The PLS analyses allowed us to narrow the time windows and locations of experimental effects in order to perform conventional statistics. Our primary area of interest remains the frontal areas as we aim to address the role of the ACC in the bivalency effect. As such we will be primarily restricting our analysis to electrophysiological differences observed within frontal electrodes. Repeated measures analyses of variance (ANOVAs) and paired samples t-tests were performed on specific time points and locations of interest.

Dipole source analysis was performed on the ERP difference scores between uni-uni trials and uni-biv trials to spatially localize where the bivalency effect was being captured for all time windows of interest. Using BESA software (version 5.1.8), a four-shell spherical head model (head, scalp, bone, and cerebrospinal fluid) was used as an approximation of dipole fitting. The scalp thickness was set to 6 mm and the bone thickness was set to 7 mm.

Principle components analysis was used to determine the number of dipoles to be fitted for each model (e.g., each time window). Dipoles explaining less than 2% of the variance were not considered. Locations and orientations of the dipoles were calculated to account for the maximum amount of variance that could be explained within a particular time window. The residual variance (RV) expresses the percentage of the ERP power not explained by the fitted dipoles.

RESULTS

Behavioural Results: Accuracy

Although reaction time data is our main focus behaviourally, we will first present accuracy data to rule out speed-accuracy trade-offs.

Accuracy was tested in two different ways. The first set of analyses was performed on the first 3 experimental blocks, consistent with the fMRI analyses in Woodward et al. (2008). A 2X3 omnibus repeated measures ANOVA crossed block (average of uni-uni trials in blocks 1 and 3 vs. uni-biv trials in block 2) and task (colour, parity, case) to examine accuracy within the first three blocks. There was a significant main effect of block, $F(1, 24) = 7.50$, $p = 0.011$, $\eta^2 = 0.238$, and a significant main effect of task, $F(2, 48) = 12.69$, $p < 0.0001$, $\eta^2 = 0.346$, but no interaction, $F(2, 48) = 0.795$, $p = 0.458$, $\eta^2 = 0.032$. Pairwise tests indicate that a higher proportion of errors were made during the first bivalent block than in the average of blocks 1 and 3, $t(24) = 3.376$, $p = 0.002$, and that the case task had fewer errors than the parity and colour tasks, $t(24) = 4.15$, $p < 0.001$ and $t(24) = 4.25$, $p < 0.001$, respectively; parity and colour did not differ from each other $t(24) = 0.114$, $p = 0.910$.

Behavioural Results: Accuracy and extended practice

Extended practice effects on the proportion of errors were analyzed by examining the difference scores of blocks 1 and 2, blocks 3 and 4, and blocks 5 and 6, using task as an additional within-subject factor. A 3X3 (task X block difference scores) repeated-measures ANOVA was performed and revealed a significant main effect of block differences, $F(2, 48) = 6.38$, $p = 0.003$, $\eta^2 = 0.210$. There was no main effect of task, $F(2, 48) = 1.91$, $p = 0.159$, $\eta^2 = 0.074$, and no interaction, $F(4, 96) = 0.896$, $p = 0.470$, $\eta^2 = 0.036$. The significant main effect of block differences can be explained by pairwise comparisons indicating that block 2-1 and block 4-3 showed larger block differences for proportion of errors than block 6-5, $t(24) = 2.92$, $p = 0.008$, $t(24) = 2.67$, $p = 0.013$, respectively, but block 2-1 and block 4-3 did not differ from each other, $t(24) = -1.12$, $p = 0.272$. This is consistent with a dissipating error rate given extended practice.

Behavioural Results: The bivalency effect (RTs to uni-biv tials vs uni-uni trials)

All mean reaction times (RTs) for task type and block are illustrated in Figure 1; all error trials were excluded from RT analyses. For repeated measures analyses of factors involving more than two levels the Greenhouse-Geisser correction was applied when necessary, in which case epsilon and the adjusted p-values are reported along with the original degrees of freedom.

Like the accuracy data, the bivalency effect on RTs was tested in two different ways. The first set of analyses was performed on the first 3 experimental blocks, consistent with the fMRI analyses in Woodward et al. (2008). A 2X3 omnibus repeated measures ANOVA crossed block (average of uni-uni trials in blocks 1 and 3 vs. uni-biv trials in block 2) and task (colour, parity, case) to examine the bivalency effect within the first three blocks. The analysis revealed a significant main effect of task, $F(2, 48) = 6.54$, $p = 0.006$, $\eta^2 = 0.214$, a significant main effect of block, $F(1,24) = 29.21$, $p < 0.0001$, η^2

= 0.549, and a significant interaction, $F(2,48) = 6.68$, $p = 0.003$, $\eta^2 = 0.218$. The significant block effect shows that uni-biv trials were slower than uni-uni trials, as predicted. Pairwise comparisons for the tasks revealed that participants were faster at responding to the case task compared to both the colour task, $t(24) = 2.619$, $p = 0.015$, and the parity task, $t(24) = 5.568$, $p < 0.001$, but that there were no response time differences between the colour and parity tasks, $t(24) = 1.149$, $p = 0.262$. Follow-up analyses comparing uni-uni trials in blocks 1 and 3 to uni-biv trials in block 2 for each task confirmed that the bivalency effect was present in the colour task, $F(1,24) = 47.56$, $p < 0.0001$, $\eta^2 = 0.665$, the parity task, $F(1,24) = 22.2$, $p < 0.0001$, $\eta^2 = .488$ and the case task, $F(1,24) = 10.37$, $p = 0.004$, $\eta^2 = 0.302$. To clarify the interaction, pairwise comparisons on the difference scores (uni-biv trials in block 2 minus uni-uni trials in blocks 1 and 3) for each task revealed that the magnitude of the bivalency effect was greatest for the colour task compared to the case task, $t(24) = 4.32$, $p < 0.001$, and the parity task, $t(24) = 2.91$, $p = 0.008$, but did not differ between the case and parity tasks, $t(24) = 1.39$, $p = 0.193$.

Behaviour: Extended practice and the bivalency effect (RTs to uni-biv tials vs uni-uni trials)

The second set of analyses included all 6 experimental blocks to examine questions about practice effects. An analysis of RT differences between pairs of univalent and bivalent blocks (univalent trials only) was performed to assess whether the magnitude of the bivalency effect changes with practice. Extensive practice effects were analyzed by examining the difference scores of blocks 1 and 2, blocks 3 and 4, and blocks 5 and 6. Task was included as a factor to assess possible differences of practice on the bivalency effect across task. The difference scores (blocks 2-1, 4-3, and 6-5) were analyzed by means of a 3X3 repeated measures ANOVA (block differences X task). Significant main effects of task type and block differences were revealed, $F(2, 48)= 19.87$, $p<.0001$, $\eta^2 = 0.453$, $F(2, 48)= 6.30$, $p = 0.004$, $\eta^2 = 0.208$, respectively. Task did not interact with block differences, $F(4, 96) = 0.21$, $p = 0.932$, $\eta^2 = 0.208$ indicating that the effect of practice on the bivalency effect did not differ across task. The main effect of task type can be explained by pairwise comparisons indicating that the difference scores were larger for the colour task compared to the case task, $t(24) = 5.27$, $p < 0.001$, and the parity task, $t(24) = 5.69$, $p < 0.001$, but did not differ between the case and the parity task, $t(24) = 1.01$, $p = 0.324$. Pairwise comparisons for the block differences (bivalency effect) revealed that RT differences between blocks 2-1 were larger than the differences in blocks 4-3, $t(24) = 3.19$, $p = 0.004$, and 6-5, $t(24) = 5.69$, $p < 0.001$, but that the difference scores for blocks 4-3 and 6-5 were not significantly different from each other, $t(24) = 0.475$, $p = 0.639$. These results are consistent with a dissipating bivalency effect across the experiment.

Although the interaction between block pair differences and task was not significant, it is interesting that there was a larger bivalency effect for the colour task compared to case and parity tasks in the previous analyses. The irrelevant feature in the bivalent stimulus was colour, leading to a question of whether there might be a trend for the dissipation of the bivalency effect to occur more slowly for the colour task. One way to ask this question is to use a polynomial trend analysis with 5 levels (order 5 contrast) to look at the pattern of RTs sequentially across all 6 blocks. This model defines the hypothesis that the mean response time will change on each sequential block: slower responses on block 2 compared to block 1, faster responses on block 3 compared to block 2, and continuing in this pattern as blocks alternate between univalent and bivalent, producing 5 changes in direction. This analysis can be run as a 6x3 repeated measures ANOVA with block (1, 2, 3, 4, 5, 6) crossed with task (colour, parity, case), and should produce a significant interaction if the RT trend across the 6 blocks differs between the tasks. The ANOVA analysis revealed a significant main effect of block, $F(5, 120) = 10.98$, $e = 0.58$, $p < 0.001$, $\eta^2 = 0.314$, a significant main effect of task, $F(2, 48) = 7.99$, $e = 0.76$, $p = 0.003$, $\eta^2 = 0.250$, and a significant interaction, $F(10, 240) = 2.87$, $e = 0.62$, $p = 0.01$, $\eta^2 = 0.107$. The within-subject contrasts produced a significant order 5 contrast for block, $F(1,24) = 18.7$, $p < 0.001$, $\eta^2 = 0.437$, and a significant order 5 contrast for the interaction between block and task, $F(1,24) = 15.7$, $p = 0.001$, $\eta^2 = 0.395$, suggesting that the trend differed between the tasks. To test the hypothesis that the colour task differed from the other two tasks in terms of the dissipation of the bivalency effect with practice, pairwise comparisons between the colour task and the average of the parity and case tasks were conducted on the block pair differences. The RT difference between uni-uni and uni-biv trials was larger for the colour task compared to the parity and case tasks for the block 2-1 difference (46.1 vs. 30.0, respectively; $t(24) = 2.86$, $p = 0.009$), for the block 4-3 difference (17.0 vs. 0.9, respectively; $t(24) = 2.21$, $p = 0.037$), and for the block 6-5 difference (23.7 vs. 3.3, respectively; $t(24) = 4.00$, $p = 0.001$), supporting the hypothesis that the bivalency effect dissipates more slowly for the colour task compared to the parity and case tasks.

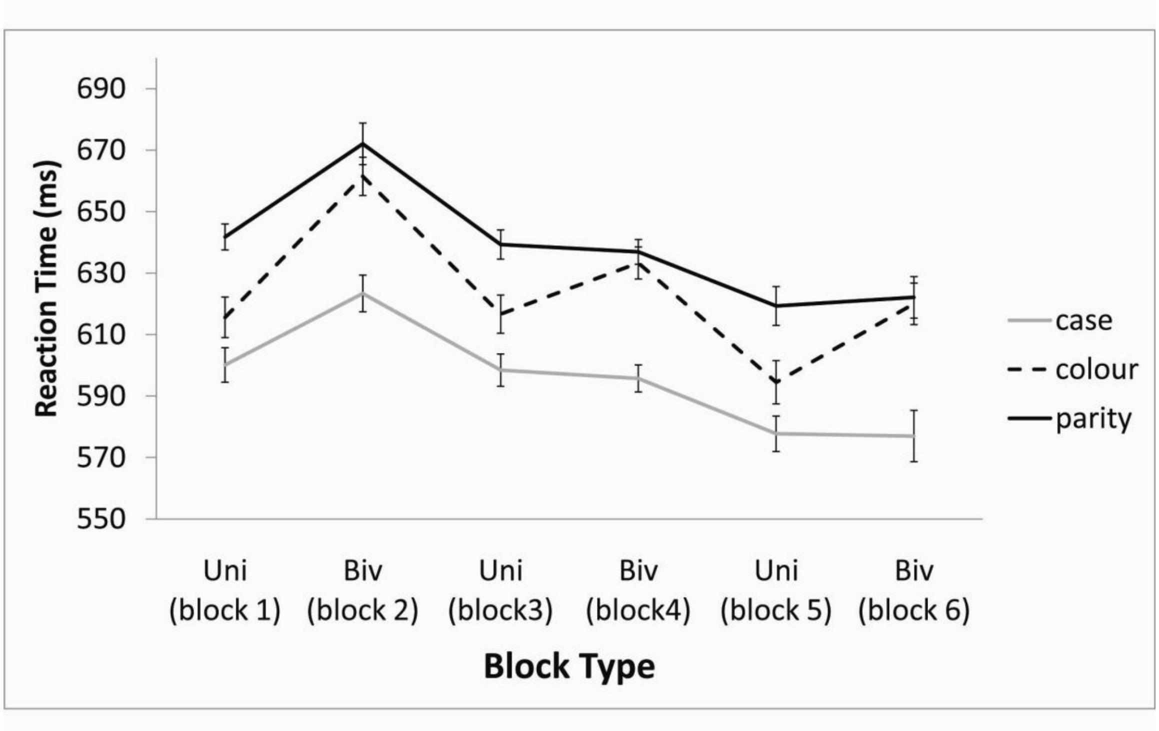

Figure 2 – Mean reaction times for univalent trials in all six experimental blocks for the three tasks: case, colour, and parity. Error bars represent standard errors.

Electrophysiological Results

The average reaction time across all blocks was approximately 650 ms, therefore a -200 to 600 ms time window was used to capture stimulus-locked ERPs for all analyses. We first examine the bivalency effect (uni-uni trials compared to uni-biv trials) via whole-brain PLS analysis followed by a classic statistical analysis of ERP amplitudes across the first three experimental blocks. We then discuss the effect of extended practice on the bivalency effect across all six experimental blocks. Only significant latent variables identified by PLS are discussed.

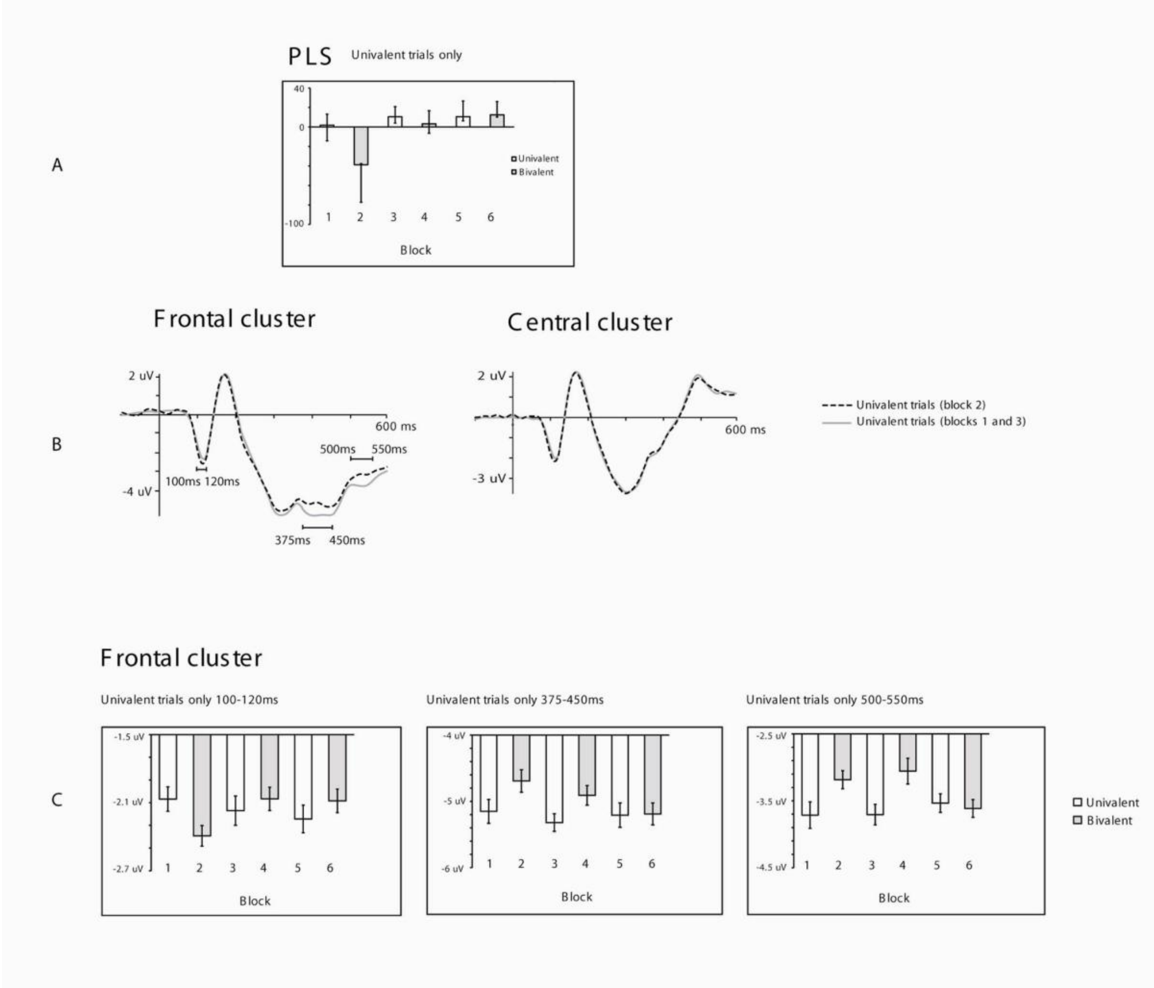

Figure 3 – Representation of whole brain analysis and electrode clusters capturing the bivalency effect. (A) Partial least squares (PLS) analyses produced Latent variable 1 (LV1) which captures the contrast between the first bivalent block compared to the other blocks. LV1 accounts for 35% of the cross-block covariance explained by the experimental conditions (p = 0.006). (B) Frontal and central waveforms depicting electrophysiological responses during the bivalency effect (uni-biv trials in block 2 compared to the average uni-uni trials in blocks 1 and 3). (C) Block by block comparison illustrating the bivalency effect over time.

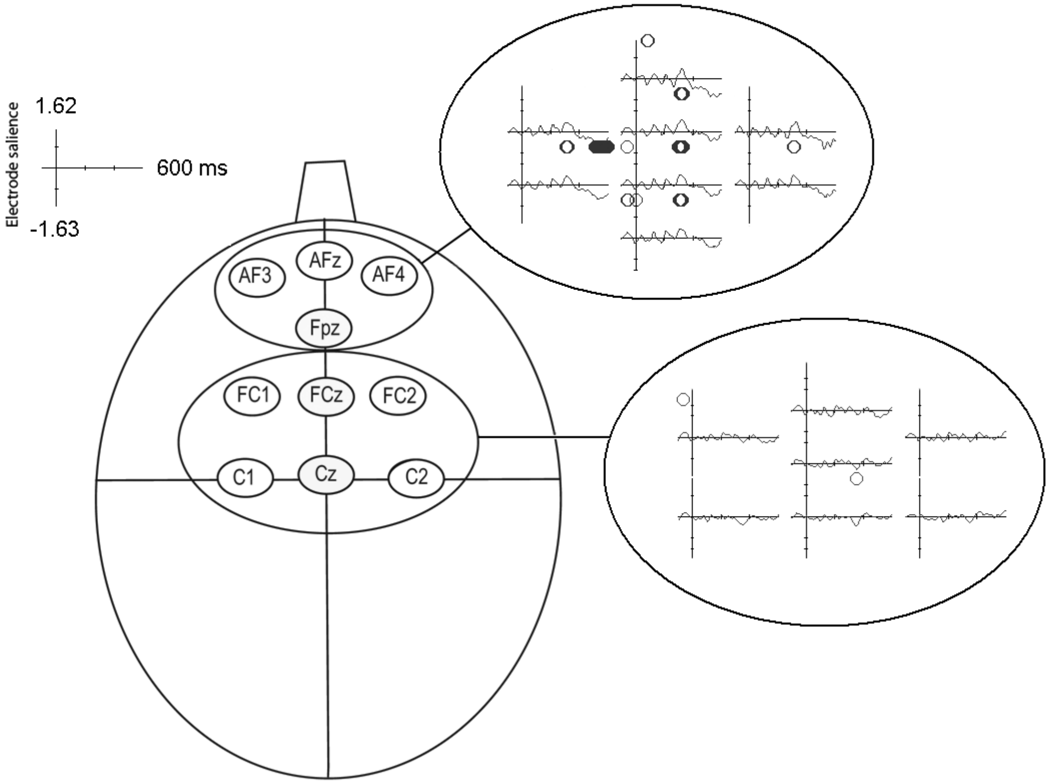

Figure 4 – Illustrates the location of electrodes chosen for the central and frontal clusters according to the standard 10/20 system. The frontal cluster consisted of areas Fpz, AFz, AF4, and AF3, while the central cluster consisted of areas Cz, C1, C2, FCz, FC1, FC2. The electrode salience maps for the partial least squares analysis (see results section) for these clusters are also illustrated.

Electrophysiology: Bivalency effect (uni-uni vs.uni-biv trials)

The PLS analysis was conducted to examine the bivalency effect. An examination of latent variable 1 (LV1) suggested that univalent trials in the first bivalent block (block 2) were processed differently from univalent trials in other blocks (see Figure 3A) and accounted for 35% of the variance, *p* = 0.006. The bootstrap analysis of electrode salience, which provides confidence intervals for salience across time points and electrodes, revealed that this effect was most reliable in frontal electrodes (Fpz, AFz, AF4, and AF3; hereafter referred to as the frontal cluster; see Figure 4) within time windows 115-135ms, 300-340ms, and 500-580ms. These results are consistent with fMRI results (Woodward et al., 2008) for which univalent trials in the first bivalent block (block 2) showed differential activation from that of univalent trials in the first two univalent blocks (blocks 1 and 3) in the frontal ACC. Even though this difference was not captured by central sites (Cz, C1, C2, FCz, FC1, FC2; hereafter referred to as the central cluster; see Figure 4) as might be expected from ERP studies that discuss ACC activity (e.g. Stemmer et al., 2003; Ullsperger & von Cramon, 2001; van Veen & Carter, 2002), the fMRI results (Woodward et al., 2008) showed a very frontal ACC BOLD response that is consistent with our frontal cluster (see Figure 5 for topographies and Figure 6 for source models). Examination of LV1 also suggested that ERP responses to univalent trials in the later bivalent blocks did not differ from responses in the univalent blocks, which supports the behavioural results showing that the bivalency effect dissipates over the course of the experiment. To examine these results further, classic componential statistical tests were performed on the bivalency effect at the frontal cluster, and for comparison at the central cluster. Components were selected based on visual inspection and correspondence with the PLS results.

The frontal electrode cluster captured the bivalency effect (mean of blocks 1 and 3 compared to block 2) within time windows 100-120ms, 375-450ms, and 500-550ms (see Figure 3B). Paired-samples t-tests revealed that uni-uni trials showed more negative amplitudes than uni-biv trials at 100-120ms (-2.39 μV vs. -2.12 μV, respectively; t(1, 24) = -2.76, p = 0.011, η^2 = 0.241), and less negative amplitudes at 375-450ms (-4.69 μV vs. -5.24 μV, respectively; t(1, 24) = -2.639, p = 0.014 , η^2 =0.225) and 500-550ms (-3.19 μV vs. -3.71 μV, respectively; t(1, 24) = 3.518, p = 0.002 , η^2 = 0.340). No significant electrophysiological differences were found over the central cluster (see Figure 3B). The voltage maps (Figure 5) illustrate the frontal extent of the bivalency effect contrast, consistent with the frontal ACC activity shown by the fMRI results (Woodward et al., 2008).

To provide further confidence in our claim that these results are consistent with fMRI results, we performed source dipole analysis (BESA) on the amplitude differences between uni-biv and uni-uni trials. We used PCA to determine the number of dipoles needed for each time window; the software then automatically calculated the locations and orientations of each dipole. All coordinates are reported in Talairach – Tournoux coordinates.

For the 100-120 ms time window, two principle components were needed to account for 99.8% of the variance (95.4% + 4.4% separately) in the ERP difference scores. The first dipole (accounting for 95.4% of the variance) was located at x, y, z = -27.5, -53.5, 11.2, orientation (ori): -0.5, -0.4, -0.7. The second dipole was located at x, y, z = 44.3, -31, 7.2, ori: 0.4, -0.8, -0.4. This model is the best fit for the data, and corresponds to a residual variance (RV) of 5.5% at the peak activity of these dipoles (100 ms; see Figure 6A). We will focus on the first dipole which is located in the left temporal region. Our hypothesis is that this dipole is explaining variance due to both posterior and anterior activity, and it is possible that the 100-120ms effect we have measured at the frontal cluster is reflecting simultaneous activity in more posterior sites. Examination of a cluster of electrodes (P5, P7, and PO7) over the left temporal parietal scalp area supports this hypothesis. Statistical analysis of this posterior cluster confirmed a significantly larger positive deflection to uni-uni trials than to uni-biv trials at 100-120 ms after stimulus onset, $t(24) = 2.30$, $p = 0.03$, $\eta^2 = 0.181$. This effect was also significant at the corresponding right posterior cluster (P6, P8, and PO8), $t(24) = 2.34$, $p = 0.028$, $\eta^2 = 0.186$.

For the 375-450 ms time window, two principle components were needed to account for 98.4% of the variance (96% + 2.4% separately) in the ERP difference scores. The first dipole (accounting for 96% of the variance) was located at x, y, z = 4.2, 20.8, 33.1, ori: -0.3, 0.8, -0.6. This corresponds to the dorsal anterior cingulate cortex (dACC), consistent with the fMRI BOLD responses obtained from the Woodward et al. (2008) bivalency effect study. The second dipole was located at x, y, z = 11.1, -51.3, 15.8, ori: 0.7, 0.7, 0.2, near the posterior cingulate cortex. This model is the best fit for the data, and corresponds to a residual variance (RV) of 5.2% at the peak activity of these dipoles (418 ms; see Figure 6B).

For the 500-550 ms time window, two principle components were needed to account for 98.7% of the variance (86.4% + 12.3 % separately) in the ERP difference scores. The first dipole (accounting for 86.4% of the variance) was located at x, y, z = -

13, 25.2, 36.8, ori: -0.2, 0.9, -0.5. This corresponds to the dACC, consistent with the fMRI BOLD responses obtained from the Woodward et al. (2008) bivalency effect study. The second dipole was located at x, y, z = 5.2, -30.9, -3.9, ori: 0.3, 0.4, 0.9, in the midbrain area. This model is the best fit for the data, and corresponds to a residual variance (RV) of 7.7% at the peak activity of these dipoles (523 ms; see Figure 6C).

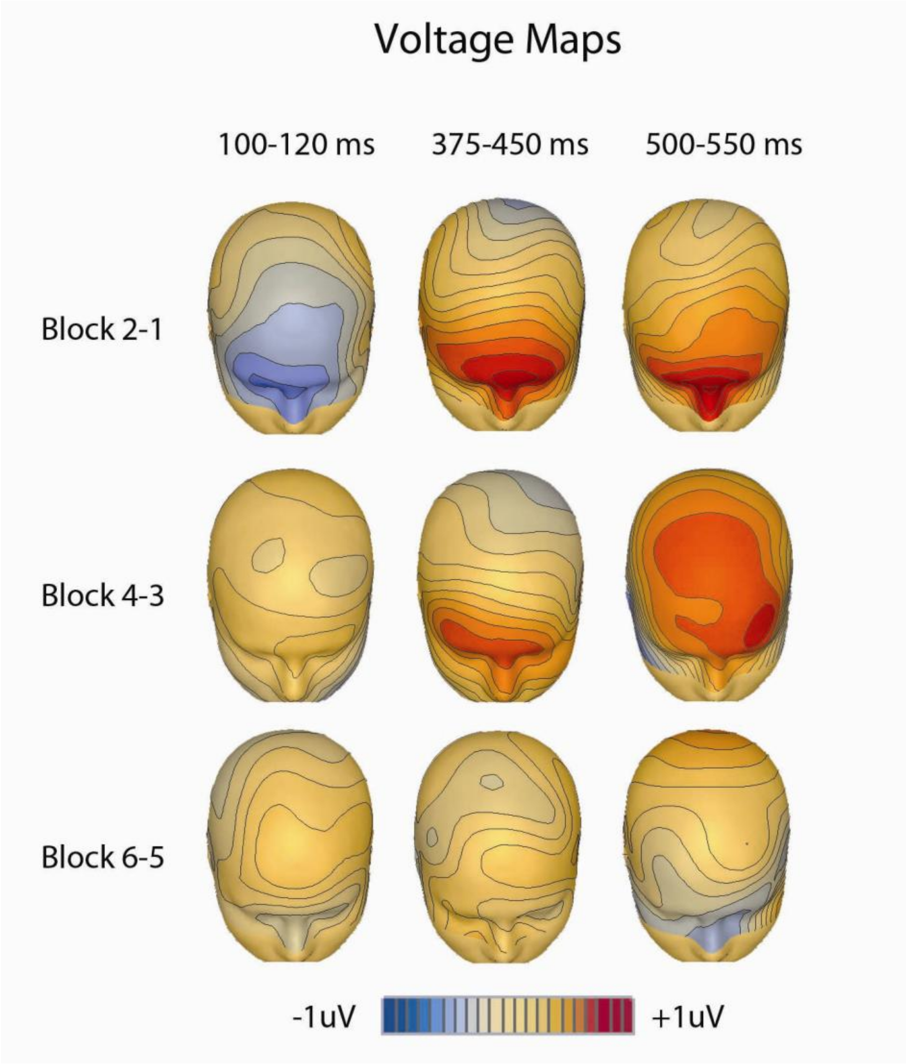

Figure 5 – Voltage topographies showing a change in electrophysiological responses for univalent trials across the experiment. Topographies are displayed for each time window of interest: 100-120 ms, 375-450 ms, and 500-550 ms. The bivalency effect was captured

in three block sets, in which block 1 amplitudes were subtracted from block 2, block 3 amplitudes were subtracted from block 4, and block 5 amplitudes were subtracted from block 6. These block sets represent changes in the bivalency effect at three stages across the experiment.

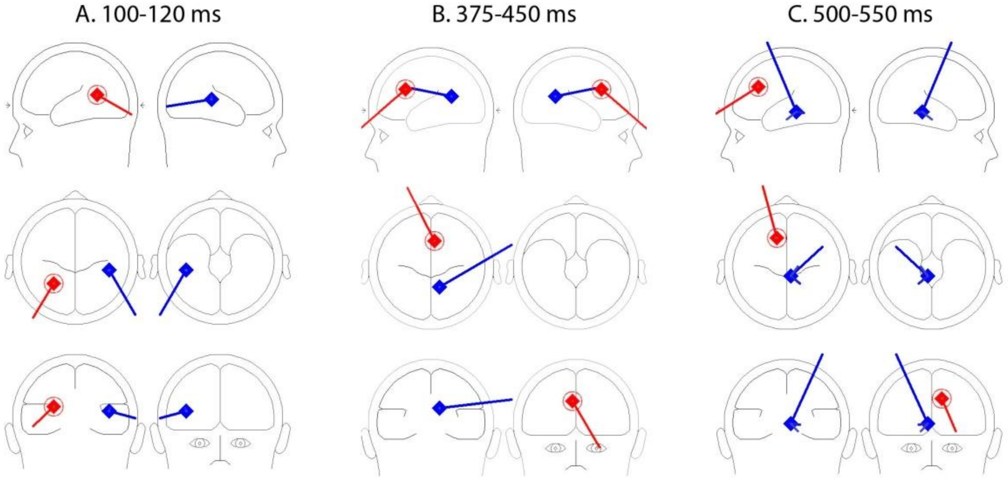

Figure 6 – Source dipole models used to explain the maximum amount of variance for the bivalency effect in each time window of interest: A) 100-120 ms, B) 375-450 ms, C) 500- 550 ms. For each component, the first dipole accounting for most of the variance is shown in black, and the second dipole is shown in grey. The first dipole for the 100-120 ms window explains 95.4% of the variance and is located in the temporal-parietal area; the first dipole for the 375-450 ms window explains 96% of the variance and is located in the ACC, and the first dipole for the 500-550 ms window explains 86.4% of the variance and is located in the ACC.

Electrophysiology: Extended practice and the bivalency effect

To examine extended practice on the bivalency effect we return to our PLS analysis (Figure 3A). LV1 shows a pattern across the 6 blocks that suggests a reduction in the size of the bivalency effect with practice, consistent with the behavioural results. To further examine this possibility, ERP amplitude difference scores at the frontal cluster were calculated to represent the difference between responses to uni-uni stimuli and uni-biv stimuli (bivalency effect). Block 1 was subtracted from block 2 (blocks 2-1), block 3 was subtracted from block 4 (blocks 4-3), and block 5 was subtracted from block 6 (blocks 6-5). If the bivalency effect is reduced with practice, then it should be largest for the first two blocks and smallest for the last two blocks, leading to a significant linear contrast over time. The difference scores (blocks 2-1, 4-3, and 6-5) were analyzed by means of repeated measures ANOVAs. Within the time windows 100-120 ms, and 500-550 ms, these ANOVAs revealed significant within-subject linear contrasts at the frontal cluster, $F(1, 24) = 6.955$, $p = 0.014$, $\eta^2 = 0.225$, and $F(1, 24) = 6.403$, $p = 0.018$., $\eta^2 = 0.211$, respectively. At 375-450ms, the linear contrast for this comparison was non-significant, $F(1, 24) = 2.063$, $p = 0.164$, $\eta^2 = 0.079$, but in the predicted direction (i.e. the difference scores became smaller over time). Figure 5 illustrates the voltage maps that capture the bivalency effect at each time window and stage of the experiment. The voltage maps provide an illustration of the amplitude differences between univalent trials within univalent and bivalent blocks. Across time windows, the voltage maps show that the activity seen at the beginning of the experiment (block 2 – 1) disappears by the end of the experiment (block 6-5), as would be expected from a practice effect. These maps in concert with the aforementioned results further support that the electrophysiological responses to the bivalency effect dissipate over the course of the experiment (see Figure 3 and 5).

DISCUSSION

When alternating between multiple tasks, if we occasionally encounter stimuli that cue two ongoing tasks (i.e. bivalent stimuli), response slowing is observed on *all* trials (bivalency effect). The occasional presence of bivalent stimuli within a block may be enough to elicit an alternative block-wise response strategy (Woodward et al., 2003; 2008). There is a crucial role for the ACC in the bivalency effect as evidenced by fMRI studies (Woodward et al., 2008) although the role of the ACC has been unclear. Significantly greater ACC activation was observed on univalent trials when they occurred in a block with occasional bivalent trials, and the authors concluded that the ACC may be responsible for breaking task inertia in order to implement an alternative response strategy. This hypothesis is supported by other neuroimaging studies, mathematical modelling, and animal studies which have suggested that changing response strategies may be signalled by the ACC (Behrens et al., 2007; Gehring & Taylor, 2004; Hayden & Platt, 2006; Luks et al., 2002; Paus, 2001; Ridderinkhof et al., 2004; Rushworth et al., 2004; Volz et al. 2003; Williams et al., 2004).

Using a paradigm similar to that of Woodward et al. (2008), we measured ERPs to extend the fMRI findings and suggest a time course for ACC activity as it relates to the bivalency effect. This allowed us to identify components that captured the differential processing of uni-biv and uni-uni stimuli, which aids in our understanding of how we implement and maintain a new response style after encountering bivalent stimuli. In addition, we looked at how brain and behavioural responses associated with the bivalency effect changed over extended practice. Past studies have examined the bivalency effect using two univalent blocks and one bivalent block; the present paradigm examined the effects of practice by doubling the number of blocks (3 univalent blocks alternating with 3 bivalent blocks) and increasing the number of trials per block (an additional 48 trials or 16 triplets). We present two main findings: 1) The contrast between univalent trials in bivalent compared to univalent blocks (the bivalency effect) is reflected by amplitude differences at frontal electrodes between 100-120 ms, 375-450 ms, and 500-550 ms (Figure 3B), with sources in the ACC for the two later components (Figure 6). 2) The bivalency effect dissipates with practice, both behaviourally and electrophysiologically (Figures 2 and 3C).

We replicated previous behavioural results (Woodward et al., 2003; 2008), showing slower responses to univalent trials when they occurred in blocks in which occasional bivalent stimuli were presented. Furthermore, a practice effect was observed across all three tasks (colour judgment, parity judgment, and case judgment) showing a decrease in the magnitude of the bivalency effect across the experimental session. These behavioural data fit nicely with the ERP results showing that the bivalency effect dissipates with extended practice.

Interestingly, the behavioural bivalency effect appeared most pronounced for colour judgment trials and did not dissipate with practice to the same extent as did the case and parity judgments (see Figure 2). A possible explanation for this effect can be attributed to the predictable trial sequence. Past work has shown that, in a predictable trial sequence, trials immediately following bivalent stimuli have longer reaction times than subsequent stimuli (Meier et al., 2009). Because bivalent stimuli were always followed by colour trials, it is reasonable to predict that these trials would have the longest average reaction times. Thus, when comparing all colour trials within bivalent blocks to all colour trials within univalent blocks, we should not be surprised that we observed a more pronounced bivalency effect than for case or parity judgments across the experiment. Another possible explanation for colour showing a more robust bivalency effect is that the colour judgments share a feature (colour) with the bivalent stimuli, a feature that is irrelevant and must be ignored or suppressed on bivalent trials. Consistent with this idea, Rey-Mermet and Meier (in press) conducted a bivalency effect study in which the colour task occurred before the case task and after the parity task; the colour task appeared to produce the largest bivalency effect regardless of sequence position[1]. It may be that the whole task set for the colour trials is suppressed in response to the bivalent stimuli, and that this suppression has a longer lasting effect than the reconfiguration signalled by the ACC. The idea of task set suppression is supported by an ERP study comparing univalent stimuli to congruent and incongruent bivalent stimuli (Hsieh & Liu, 2008). ERPs for congruent and incongruent bivalent stimuli did not differ from one another although both differed from the univalent stimulus. The authors

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[1] When the sequence of tasks proceeded from colour to parity to case the bivalency effect was 100 ms, 48 ms, and 38 ms, respectively. When the sequence proceeded from parity to colour to case the bivalency effect was 62 ms, 83 ms, and 51 ms, respectively. While the colour task appeared to produce the largest bivalency effect in both sequences, pairwise tests were not performed to confirm this observation.

proposed that the irrelevant feature on a bivalent trial leads to the suppression of the task set rather than suppression at the response level. In the case of our experiment, colour was always the irrelevant feature on the bivalent trials, possibly leading to a more robust bivalency effect for the colour task.

The main purpose of this paper is to expand on the existing behavioural and fMRI work by providing high temporal resolution time course analyses. The ERP measurements captured the bivalency effect at the frontal cluster and revealed three relevant time windows: 100-120 ms, 375-450 ms, and 500-550 ms. At 100-120 ms the electrophysiological response was sensitive to the bivalency manipulation in the first set of univalent versus bivalent blocks (blocks 2-1), and this response was not apparent at the later block comparisons. Source analysis revealed that this component may be a reflection of activity from an area near the left temporal-parietal junction (TPJ). At the 375-450 ms and 500-550 ms time windows, the bivalency effect was observed for the first two block-set comparisons (blocks 2-1 and blocks 4-3), but not for the last comparison (blocks 6-5). Source analysis revealed that dACC activity is likely responsible for modulating the bivalency effect behavioural changes during these time windows.

It is interesting that the bivalency effect contrast at the early component appears to dissipate earlier with practice than do the later components. The 100-120 ms time window may reflect additional early visual-perceptual processing needed during bivalent blocks. Source modeling identified a possible source for this time window near the area of the TPJ, which has been known to be involved in early visual extraction of object components. For instance, in a global/local task involving the identification of the smaller (local) letters that make up a larger (global) letter, the left TPJ plays a role in early visual processing (Evans et al., 2000). When bivalent stimuli are first detected within the first bivalent block of our experiment, they are unexpected and it may not be clear that bivalent features will be present only on case judgement trials. In the first bivalent block, it may be necessary to analyze stimuli at a more featural (local) level in order to determine which features are relevant to the task. This analysis of stimuli at a featural level extends to all trials within bivalent blocks, including parity decisions, which do not share any features with bivalent stimuli. For example, given the surprising coloured letter on the case task, the system cannot rule out the possibility of an equivalent surprise on the parity task. This uncertainty triggers a more in-depth analysis at the featural level. This change in visual processing may disrupt the fluency of early visual processing, and require additional TPJ activity to help extract critical visual information. In later bivalent blocks, when participants have clearer expectations about where to expect bivalent stimuli (i.e. on occasional case judgment trials), it is possible that the TPJ receives feedback from higher order centers (such as the dACC), and additional visual extraction is no longer necessary. The latency of this early component (100-120 ms) is consistent with the posterior P1, an early visual component associated with extrastriate cortex, however, our source modeling does not put the source in that area and moreover, the P1 has not been shown to be sensitive to task-switching manipulations (Wylie et al., 2003). Given that this is a block-wise effect, such an early response on individual trials is not entirely surprising because previous bivalent stimuli set the system into a more cautious state, which could affect very early processes on subsequent trials.

Studies examining switch versus repeat trials and studies comparing univalent and bivalent stimuli share some similarities with our later components (375-450 ms, 500-550 ms). For example, the comparison between univalent and bivalent trials noted by Poulsen et al. (2005) is similar to the differences we found between uni-uni and uni-biv stimuli. Those authors found a more positive deflection for bivalent relative to univalent trials between 300-600 ms and our ERP results show that uni-biv stimuli are more positive relative to uni-uni stimuli during these time frames. Remember that in the Poulsen et al. (2005) study, the ERP waveforms contrasted responses to univalent versus bivalent stimuli. Our ERP waveforms did not include the bivalent trials; rather, our contrast was between univalent trials in univalent blocks versus bivalent blocks. Thus, the similarities in the ERP components may suggest an overlap in processes related to the bivalency effect and conflict generated by the bivalent stimuli. In the bivalency effect, this conflict may carry over to the univalent trials. Detection of conflict may signal the dACC to implement an alternative response strategy, and this response strategy may include suppression of irrelevant features as well as more careful perceptual processing on the other tasks. After sufficient practice with bivalent stimuli it becomes easier to extract the relevant and ignore the irrelevant information, and this more efficient processing leads to the dissipation of processing differences across the univalent trials, consistent with our behavioural and ERP results. By that time, the ACC signals are no longer necessary to trigger additional control. The broad time windows of these later components make them good candidates as representing the generators that produce the BOLD response in dACC that is associated with the bivalency effect (Woodward et al., 2008). This hypothesis is further supported by the source modeling that we performed suggesting dACC sources for these components.

There are also similarities between our later components at 375-450 ms and 500-550 ms and ERP components revealed in task-switching experiments that compare task repeat versus switch trials; those components are also located at frontal electrodes within a similar time window of 300-700 ms (Lorist et al., 2000; Hsieh & Liu, 2009; Wylie et al., 2003; Hsieh & Chen, 2006). It is possible that these similarities across these task switching experiments, the bivalent vs. univalent contrast (Poulsen et al., 2005), and our bivalency effect results indicate that the frontal components are all accessing processes related to the task-switching demands inherent in all three types of experiments.

Interestingly, we did not observe an ERP distinction between uni-biv and uni-uni stimuli within the time window of the N2 (200-350 ms). The N2 has been identified in a number of ERP studies as dissociating between conflict and non-conflict trials (Yang & Wang, 2002; Kong et al. 2000, Wang et al., 2002) and has a hypothesized generator localized in the ACC (van Veen & Carter, 2002). Studies comparing univalent to bivalent stimuli also do not find ERP differences at the N2 (Poulsen et al. 2005, Hsieh & Liu, 2008) suggesting that bivalency and the bivalency effect present a special case of conflict that influences later task switching processes.

The dorsal ACC (Brodmann's area 32) fits well with our data and was the primary area of interest in the fMRI work on the bivalency effect. Woodward et al. (2008) also noted peak activation associated with the bivalency effect at Brodmann's area 9, which is part of the pre-frontal cortex (PFC). The PFC is often associated with higher-order mental processes including top-down attentional control (Liston et al., 2006) and task preparation (Sohn et al., 2000; MacDonald et al., 2000; Yeung et al., 2006). While our source modeling analysis places the source of our frontal effects in the dACC, we cannot rule out that the PFC may be contributing to our frontal effects.

Another consideration when interpreting the current results is the relation between the initial univalent blocks and the effect of bivalent stimuli. Participants performed three univalent blocks before encountering bivalent stimuli in the fourth block (following two practice univalent blocks and one experimental univalent block). If participants had encountered bivalent stimuli in the first experimental block, immediately after the two univalent practice blocks, the bivalency effect may have dissipated more quickly over the course of the remaining experimental blocks. This counterbalancing was not done in the present experiment and could be addressed in future work interested in the relation between initial practice and the bivalency effect.

CONCLUSIONS

Using an unbiased whole-brain statistical approach (PLS; Lobaugh et al., 2001; McIntosh et al., 1996) coupled with conventional componential analyses, we provide the first ERP account for the bivalency effect and identify three significant components at a frontal electrode cluster within time windows 100-120 ms, 375-450 ms, and 500-550 ms. We believe the bivalency effect is captured by two processes: additional extraction of visual features on all trials that is triggered by irrelevant cues in bivalent stimuli (100-120 ms) and suppression of processing carried over from irrelevant cues (375-450 ms & 500-550 ms). We showed a correspondence between behavioural and ERP responses that provide additional temporal information related to the dissipation of the bivalency effect with practice. Our results extend the fMRI findings on the bivalency effect (Woodward et al., 2008) in that the activity reflected by the frontal electrode cluster is consistent with dACC activity contrasting univalent trials in bivalent blocks to univalent trials in univalent blocks within time windows 375-450 ms and 500-550 ms.

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CHAPTER 3

The following chapter is a submitted manuscript. Permission to use the article in my thesis will be sought upon acceptance for publication.

Reference

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Preamble

Chapter two provided insight into the cognitive processes involved in the bivalency effect, but the underlying stimulus and response properties responsible for eliciting and maintaining these processes were still largely unknown. Specifically, I was interested in determining whether the bivalency effect reflected the engagement of processes in response to conflicting-task-cueing, or if a violation of expectancy could explain part of this block-wise response slowing. Thus, I ran a number of experiments in which bivalent trials (that cue conflicting tasks) were removed from bivalent blocks and replaced with unexpected univalent trials. This allowed me to evaluate the role of expectancy violation in producing the block-wise response slowing observed in the bivalency effect.

Scrutinizing the bivalency effect: Factors influencing a block-wise response slowing

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ABSTRACT

During execution of a sequence of well-learned task switching, performance is affected by the occurrence of occasional bivalent stimuli that cue two different tasks in the sequence. A block-wise response slowing is observed, affecting all the trials that follow bivalent stimuli, including those trials that do not share any features with the bivalent stimuli or the two tasks that are cued by the bivalent stimuli. This may be due to an adjustment in response style and has been called the bivalency effect. The bivalency effect is thought to involve top-down cognitive control that is engaged when a possibility for stimulus or response conflict is detected. This paper explores specific stimulus and response properties that trigger block-wise response slowing in a bivalency effect paradigm but using non-bivalent stimuli. We show that unexpected non-bivalent stimuli produce a block-wise response slowing, suggesting that a portion of the bivalency effect may be due to an initial uncertainty about upcoming trials. We also note that colour appears to have a special status in the bivalency effect when trial order is predictable, colour is the irrelevant bivalent feature, and colour judgment trials immediately follow bivalent stimuli. We show that task order is not the critical factor to elicit the greater magnitude of the bivalency effect on colour trials, supporting the hypothesis that response conflict is more important for this effect.

INTRODUCTION

The bivalency effect is a phenomenon observed during task-switching in which the occasional presence of bivalent stimuli (stimuli that cue two tasks) elicits a block-wise response slowing compared to a block in which only univalent stimuli appear (Grundy et al., 2011; Meier, Woodward, Rey-Mermet, & Graf, 2009; Rey-Mermet & Meier, 2011, 2012; Woodward, Meier, Tipper, & Graf, 2003; Woodward, Metzak, Meier, & Holroyd, 2008). This response slowing is observed even on trials that do not share any features with bivalent stimuli, suggesting that some top-down cognitive control must be engaged. While there is some evidence that this control is modulated by the dorsal anterior cingulate cortex (dACC; Grundy et al., 2011; Woodward et al., 2008), that the bivalency effect is a very robust phenomenon (Grundy et al., 2011; Meier et al., 2009), and that the bivalency effect has a time course that likely involves very early visual processing as well as feedback from higher order centers (Grundy et al., 2011), less is known about the specific stimulus properties that modulate the effect.

The bivalency effect is calculated by looking at response times (RTs) to univalent stimuli that appear in purely univalent blocks and comparing this to RTs for univalent stimuli that appear in blocks in which occasional bivalent stimuli appear. For instance, participants might alternate predictably between a colour judgment task (green shapes vs. red shapes), a parity judgment task (odd digits vs. even digits), and a case judgment task (lowercase letters vs. uppercase letters) by making a left or a right key press. In bivalent blocks, occasional case judgment trials appear in green or red, making these stimuli bivalent. These rare bivalent stimuli are enough to elicit a block-wise response slowing.

A number of hypotheses have been suggested for processes involved in the bivalency effect. Woodward et al. (2008) first suggested that the bivalency effect might be explained by a "breaking of inertia" account (Behrens, Woolrich, Walton, & Rushworth, 2007; Paus, 2001). This account suggests that when switching predictably between multiple tasks without interruption, we develop a fluency of response. When bivalent stimuli appear, this triggers a break in inertia that requires an adjustment in cognitive control; this adjustment in control is implemented by the dACC, a known conflict-detection center (Kerns et al., 2004; Liu, Banich, Jacobson, & Tanabe, 2004; Milham et al., 2001; van Veen, Cohen, Botvinick, Stenger, & Carter, 2001). Subsequently, Meier et al. (2009) demonstrated that the bivalency effect is a robust phenomenon lasting up to 20 seconds after the presentation of a bivalent stimulus. They suggested an "episodic context binding" account to explain the long-lasting nature of the effect, extending the breaking of inertia explanation. The episodic context binding theory is based on the notion that stimuli acquire a history over the course of the experiment, and that these stimuli become associated with the task in which they occur (Waszak, Hommel, & Allport, 2003). The episodic context binding account proposes that in addition to the task-set, the "tricky" context of a bivalent block (i.e. having both univalent and occasional bivalent stimuli appear within the same block) is also retrieved upon presentation of each trial within that block. This retrieval then interferes with task performance, resulting in a slowing of performance on all tasks, regardless of feature overlap with bivalent stimuli.

While these theories provide us with a conceptualization of the processes involved in the bivalency effect, they do not shed light on the specific stimulus properties that elicit these processes. Because bivalent stimuli are always unexpected, it is possible that unexpectedness, beyond the influence of task-cueing (i.e. bivalence), contributes to the engagement of processes leading to the bivalency effect. In fact, both of the aforementioned hypotheses would predict that unexpected, but *non-bivalent* stimuli might also show a response slowing. Namely, the introduction of unexpected stimuli, regardless of whether or not they cue two tasks, should cause a break in task inertia because they interrupt the flow of the environment. This break in inertia should lead to an adjustment in cognitive control over the course of the block in response to dACC activity. Similarly, if unexpected stimuli become associated with the context of a block, then a tricky context (i.e. having both univalent and occasional unexpected univalent stimuli appear within the same block) will be retrieved upon presentation of univalent stimuli within that block. This should lead to a block-wise response slowing because of the more demanding context retrieval. Thus, both hypotheses can account for why we might expect to see a block-wise response slowing similar to the bivalency effect simply by presenting participants with unexpected stimuli, regardless of whether or not they cue two tasks.

In the present study, we removed the potential influence of bivalence by replacing bivalent stimuli with unexpected, but non-bivalent stimuli. If bivalence is required to elicit the block-wise response slowing observed in the bivalency effect, then introducing unexpected but non-bivalent stimuli should not affect the response times of subsequent univalent stimuli. On the other hand, if response slowing is still observed following these stimuli, then this suggests that the response to unexpected stimuli may contribute to the size of the RT difference observed in bivalency effect experiments and may be part of the process influencing the block-wise adjustment in cognitive control.

EXPERIMENT 1

In Experiment 1, we followed exactly the structure of the bivalency effect paradigm that has been used in past studies (e.g., Grundy et al., 2011; Woodward et al., 2008), except that we replaced the occasional bivalent stimuli with occasional irrelevant-colour letters. In a regular bivalency effect design, the coloured letters on bivalent case judgment trials are presented in the same colours that require responses in the colour judgment task (e.g., red and green). Here, the unexpected stimuli are presented in colours that do not require responses on any of the trials (e.g., blue and yellow), and are therefore irrelevant in terms of the tasks.

Participants

Thirty-one undergraduate students from McMaster University's psychology participant pool took part in the experiment in exchange for course credit. In this and all of the following experiments, all participants had normal or corrected-to-normal vision. All procedures complied with the Canadian tri-council policy on ethics and were approved by the McMaster Research Ethics Board.

Materials and apparatus

Stimuli were presented on a black background on a 17-inch CRT monitor at a refresh rate of 85 Hz. For the colour decision task, stimuli consisted of one of four shapes (circle, square, pentagon, triangle) presented in either red or green. The case decision task stimuli consisted of one of four letters (a, b, d, e) presented in either uppercase or lowercase (white, 60-point Times New Roman font). The parity decision task consisted of numerals 1-8 (white, 60-point Times New Roman font). For unexpected trials, occasional case judgment letters appeared in yellow or blue (e.g. uppercase "A" appeared in yellow). Participants were seated individually in a dimly lit room 90 cm from the computer monitor. Stimuli were presented in the centre of the screen; the height of each stimulus subtended a visual angle of 1.26 degrees.

Procedure

After obtaining informed consent, participants were seated at a computer and instructed that they would be making case decisions about letters (uppercase vs. lowercase), parity decisions about digits (even vs. odd), and colour decisions about shapes (red vs. green). In one counterbalancing condition, participants were instructed to use the left arrow key (<) for lowercase letters, odd digits, and green shapes, and to make a right key press (>) for uppercase letters, even digits, and red shapes. The left and right key mappings used for these decisions were counterbalanced across participants. Participants were instructed to respond as quickly and as accurately as possible. Each stimulus remained on the screen until the participant responded, or until 1500 ms, after which point the text "Too Slow!" appeared on the screen. This encouraged participants to respond in a timely manner. Accuracy feedback was provided after every 12 trials to encourage accuracy. The inter-trial interval varied randomly between 400-900 ms.

Each block contained 168 trials. Two practice blocks were introduced at the beginning of the experiment. Three experimental blocks were then presented. Experimental blocks 1 and 3 were pure blocks, within which all trials were normal case, colour, and parity judgments. Experimental block 2 was an unexpected block, within which 16 of the case judgment trials appeared in yellow or blue, making these stimuli unexpected, but still univalent with respect to the experimental design. Trial sequence always proceeded predictably from colour judgments to parity judgments to case judgments (see Figure 1 for an example of a trial sequence).

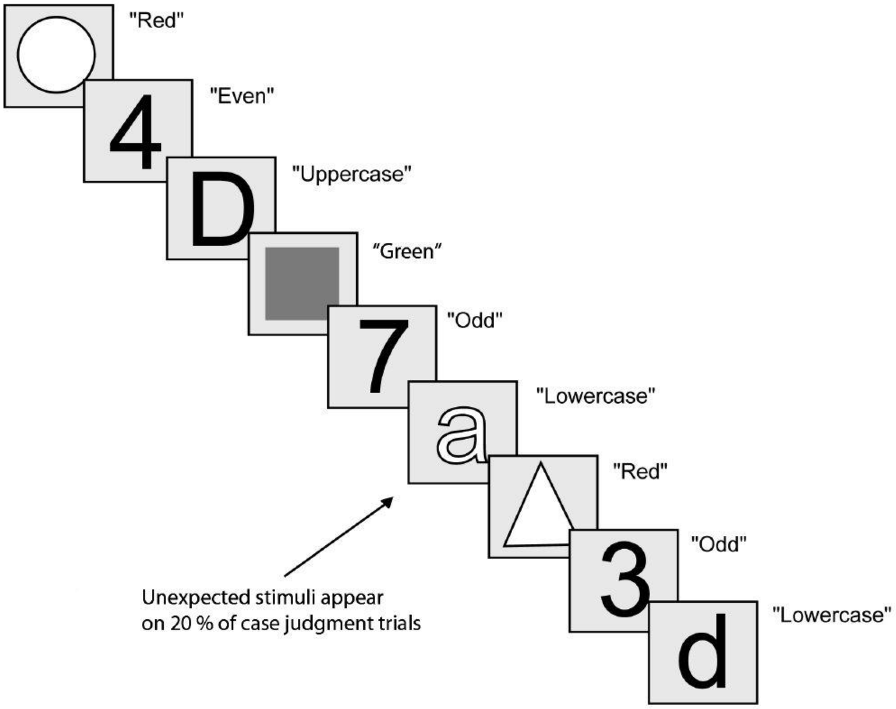

Figure 1 - Illustration of the trial sequence and type of stimuli used in Experiments 1 through 4. This particular illustration is an example from an unexpected block. The words appearing beside the stimuli represent correct responses. During the unexpected block (block 2), unexpected stimuli appear on 20% of all case judgment trials. Unexpected stimuli do not appear at all during the pure blocks (blocks 1 and 3). In the grey-scale diagram we use white to represent the red stimulus and grey to represent the green stimulus. The white letter represents the unexpected stimulus (e.g., blue or yellow in Experiment 1; patterned in Experiment 2; font change in Experiment 3, unexpected background in Experiment 4).

Data analyses

To examine the influence of unexpected stimulus features on a block-wise response slowing, we performed a 2 (Block: average of block 1 & 3 vs. block 2) X 3 (Task: Colour, Parity, Case) repeated-measures ANOVA for accuracy and response time. In all the experiments, the accuracy and RT means do not include responses to the unexpected stimuli. RTs were analyzed for correct responses only. We predicted that slower response times would be observed for univalent stimuli in unexpected blocks than univalent stimuli in pure blocks.

Results

Outliers were defined as RTs greater than three standard deviations above or below the mean and were eliminated from all further analyses (experiments 1-5). Participants performed with high accuracy in all the experiments and conditions (4% errors; see Table 1). There was a trend toward higher accuracy in the pure blocks compared to the unexpected block, $F(1,30) = 3.80$, $p = 0.060$, $\eta^2 = 0.113$; none of the other comparisons were significant ($F < 1$).

Table 1 – Accuracy (percent correct) and standard errors for Experiments 1-4. Occasional unexpected stimuli appeared in block 2. Responses to unexpected stimuli were not included in the accuracy analyses.

	Experiment 1			**Experiment 2**		
	Block 1	**Block 2**	**Block 3**	**Block 1**	**Block 2**	**Block 3**
Colour	96 (0.8)	95 (0.9)	95 (0.8)	96 (0.9)	95 (0.9)	96 (0.7)
Parity	96 (0.4)	95 (0.7)	96 (0.6)	95 (0.8)	95 (0.9)	95 (1.1)
Case	98 (0.7)	96 (1.0)	97 (0.5)	98 (0.6)	98 (0.4)	97 (0.6)

	Experiment 3			**Experiment 4**		
	Block 1	**Block 2**	**Block 3**	**Block 1**	**Block 2**	**Block 3**
Colour	95 (0.7)	94 (1.0)	94 (0.9)	96 (0.7)	96 (0.6)	96 (0.8)
Parity	94 (1.1)	95 (1.1)	95 (0.8)	95 (1.0)	96 (0.6)	94 (0.9)
Case	98 (0.6)	99 (0.4)	98 (0.6)	98 (0.4)	99 (0.4)	97 (0.7)

In the response time (RT) analyses, a significant effect of Task, $F(2, 60) = 7.00$, $p = 0.002$, $\eta^2 = 0.189$, can be explained by pairwise t-tests showing that RTs to case judgment trials were faster than to the colour and parity judgment trials, $t(30) = 2.75$, $p = 0.010$, $t(30) = 4.22$, $p < 0.001$, but that the colour and parity judgment RTs did not differ from each other, $t(30) = 0.48$, $p = 0.630$. Participants were 23 ms slower to respond in block 2 than in the average of blocks 1 and 3, leading to a significant effect of Block, $F(1, 30) = 22.14$, $p < 0.001$, $\eta^2 = 0.425$. A significant interaction, $F(2, 60) = 3.45$, $p = 0.041$, $\eta^2 = 0.103$ reflects a larger unexpectedness effect for the colour (28 ms; $t(30) = 2.27$, $p = 0.032$) and parity (27 ms; $t(30) = 2.30$, $p = 0.031$) judgment trials compared to the case judgment trials (15 ms); the response slowing did not differ between the colour and parity judgment trials, $t(30) = 0.13$, $p = 0.902$ (see Table 2).

Table 2 – Reactions times (RTs) and standard errors for Experiments 1-4. Occasional unexpected stimuli appeared in block 2. Responses to unexpected stimuli were not included in the RT analyses.

	Experiment 1			**Experiment 2**		
	Block 1	**Block 2**	**Block 3**	**Block 1**	**Block 2**	**Block 3**
Colour	609 (4.5)	640 (4.0)	615 (4.4)	576 (4.2)	587 (3.6)	577 (3.9)
Parity	623 (4.2)	644 (4.4)	610 (3.5)	612 (4.3)	616 (3.4)	604 (3.7)
Case	594 (4.3)	610 (3.4)	595 (4.4)	562 (3.7)	565 (4.0)	559 (3.6)

	Experiment 3			**Experiment 4**		
	Block 1	**Block 2**	**Block 3**	**Block 1**	**Block 2**	**Block 3**
Colour	579 (4.4)	607 (4.5)	598 (4.4)	611 (4.9)	638 (4.6)	613 (5.8)
Parity	614 (4.4)	615 (3.7)	609 (4.3)	649 (4.6)	656 (4.4)	640 (4.8)
Case	572 (4.5)	580 (3.8)	568 (4.1)	615 (4.5)	618 (4.5)	606 (4.3)

Discussion

Using unexpected but non-bivalent stimuli, we were able to show a block-wise response slowing across all tasks, which suggests a top-down adjustment in cognitive control was being implemented. Participants were 23 ms slower in a block in which occasional coloured letters appeared. The unexpected irrelevant-colour letters did not share any features with any other tasks, effectively making these stimuli univalent with respect to the experimental design, yet, we elicited an effect that looks similar in form to the bivalency effect (Grundy et al., 2011; Meier et al., 2009; Rey-Mermet & Meier, 2011, 2012; Woodward et al., 2003, 2008). This suggests that unexpectedness is likely engaging some of the same processes that are engaged for the adjustment in cognitive control seen in the bivalency effect.

However, an alternative explanation for observing this block-wise response slowing exists. The use of colour (yellow and blue) as the irrelevant feature on unexpected trials may have been enough to retrieve the colour task-set even though the relevant colours in the colour judgment task differed (i.e. red and green). In this sense, the unexpected stimuli would be functionally bivalent, and not simply unexpected. To rule out this possibility, we removed colour from the unexpected stimuli altogether.

EXPERIMENT 2

Experiment 2 was identical to Experiment 1 except that occasional black and white patterned letters replaced the occasional coloured letters (see Figure 2). Twenty-seven undergraduates from McMaster University's undergraduate participant pool took part in the experiment in exchange for course credit.

Results

Accuracy was high in all conditions (4% errors; see Table 1). A main effect of Task, $F(2, 52) = 8.56$, $p = 0.001$, $\eta^2 = 0.248$ reflected higher accuracy on case judgment trials compared to colour and parity judgments (both $p < 0.01$), while colour and parity did not differ ($p = 1$).

A significant effect of Task, $F(2, 52) = 8.82$, $p = 0.001$, $\eta^2 = 0.253$, showed that RTs were slower for the parity task than the case and colour tasks, $t(26) = 5.71$, $p <$

0.001, $t(26) = 2.19$, $p = 0.043$, but that RTs did not differ between the case and colour tasks, $t(30) = 1.48$, $p = 0.151$. A significant effect of Block, $F(1, 26) = 3.76$, $p = 0.033$, $\eta^2 = 0.126$, revealed that participants were 8 ms slower to respond to univalent trials in block 2 than to univalent trials in blocks 1 and 3 (see Table 2). The interaction was not significant, $F(2, 52) = 0.456$, $p = 0.641$, $\eta^2 = 0.017$.

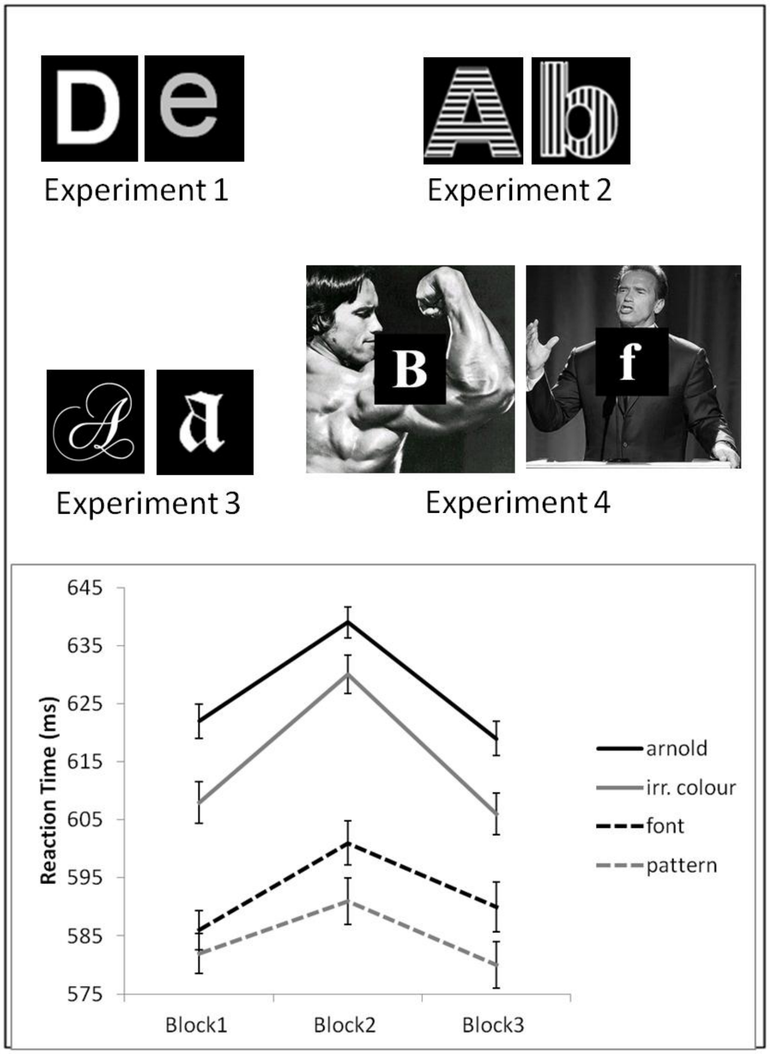

Figure 2 – Response times are compared across Experiments 1 through 4 (error bars represent standard errors). Blocks 1 and 3 consist of purely expected trials; Block 2 presents occasional unexpected trials. Responses to unexpected stimuli were not included in the RT analyses.

Discussion

Similar to Experiment 1, unexpected but non-bivalent stimuli on occasional case judgment trials in block 2 elicited a block-wise response slowing that looks similar in form to the bivalency effect, even when we removed colour as a contributing factor in producing the unexpectedness. Participants were 8 ms slower to respond to univalent stimuli when occasional black and white patterned letters appeared within a block compared to a block in which none of these unexpected stimuli appeared. This result supports the notion that unexpectedness may be engaging some of the same processes that are involved in the adjustment of cognitive control seen in the bivalency effect. However, because of the small size of the effect, we wondered if the magnitude of this effect could be increased by making the unexpected stimuli more salient in Experiment 3.

EXPERIMENT 3

Experiment 3 was identical to Experiment 2 except that instead of using patterned black and white letters, occasional case judgment trials appeared in *chopin* and *old english* script (see Figure 2), which we believed would be more salient and cause more disturbance. Thirty-three undergraduates from McMaster University's undergraduate participant pool took part in the experiment in exchange for course credit.

Results

Once again, accuracy was high in all conditions (4% errors). A main effect of Task, $F(2,64) = 14.85$, $p < 0.001$, $\eta2 = 0.317$, reflected higher accuracy for case judgment trials than colour and parity judgments ($p < 0.001$); no difference obtained between colour and parity ($p = 1$). As in all the experiments, the accuracy and RT means do not include responses to the unexpected stimuli.

RT analysis revealed a significant effect of Block, $F(1, 32) = 4.61$, $p = 0.022$, $\eta^2 = 0.126$, confirming the presence of an unexpectedness effect; participants responded 12 ms slower to expected stimuli in block 2 compared to expected stimuli in pure blocks 1 and 3. The main effect of Task was also significant, $F(2, 64) = 9.00$, $p < 0.001$, $\eta^2 = 0.220$, reflecting faster responses for case judgments than for colour, t(32) = 2.35, p = 0.025, and parity, t(32) = 7.13, p < 0.001; colour and parity judgments did not differ, t(32) = 1.60, p = 0.119, The significant interaction, $F(2, 64) = 3.13$, $p = 0.050$, $\eta^2 = 0.089$, can be explained by the finding that a larger unexpectedness effect was found for colour judgment trials than for parity judgment trials, $t(32) = 2.25$, $p = 0.031$, but that there were no unexpectedness effect differences between the colour and case judgments, $t(32) = 1.43$, $p = 0.164$, or between the parity and case judgments, $t(32) = 1.23$, $p = 0.234$ (see Table 2).

Discussion

Experiment 3 replicated the results from Experiments 1 and 2, showing a block-wise response slowing in response to occasional unexpected stimuli. Experiments 1 through 3 provide converging evidence for the notion that unexpectedness plays an important role in the engagement of a block-wise adjustment in cognitive control, beyond the influence of bivalence.

Our manipulations thus far have constrained unexpectedness to the stimuli. However, it is possible that surprising environmental events beyond the stimuli themselves will also elicit a block-wise response slowing. To examine this directly, we replaced the unexpected stimulus features with unexpected scenes in the background.

EXPERIMENT 4

Experiment 4 was identical to Experiment 3, except that on occasional case judgment trials in block 2, the case judgment letters were superimposed over a picture of Arnold Schwarzenegger (see Figure 2). Thirty-one undergraduates from McMaster University's undergraduate participant pool took part in the experiment in exchange for course credit.

Results

Accuracy was high in all conditions (4% errors). A significant main effect of Block, $F(1,30) = 8.38$, $p = 0.007$, $\eta^2 = 0.218$, was consistent with greater accuracy in block 2 compared to the average of blocks 1 and 3 (1% difference).

Examining RTs, a significant effect of Block, $F(1, 30) = 6.50$, $p = 0.021$, $\eta^2 = 0.178$, confirms the presence of the unexpectedness effect with RTs 17 ms slower for expected stimuli in block 2 compared to expected stimuli in blocks 1 and 3. Following a significant effect of Task, $F(2, 60) = 7.75$, $p = 0.001$, $\eta^2 = 0.205$, pairwise comparisons showed that case and colour judgments were faster than parity judgments, $t(30) = 5.22$, $p < 0.001$, and $t(30) = 2.70$, $p = 0.012$, respectively. Case and colour did not differ from each other, $t(30)= 0.80$, $p = 0.431$. The significant interaction, $F(2, 60) = 4.67$, $p = 0.013$, $\eta^2 = 0.135$, can be explained by the finding that the unexpectedness effect was greater for the colour task than for the parity or case tasks, $t(30) = 2.88$, $p = 0.011$, and $t(30) = 2.63$, $p = 0.014$, respectively, but that the unexpectedness effect did not differ between the parity and case judgment tasks, $t(32) = 0.57$, $p = 0.581$ (see Table 2).

Discussion

Experiment 4 demonstrated that a block-wise response slowing could be elicited when occasional stimuli within a block were presented on an unexpected background, even though the stimuli themselves were not altered. This result suggests not only that a bivalency-effect-like response strategy can be elicited by unexpected stimulus features, but that this expectancy violation can be generalized to the surrounding environment. This finding in conjunction with the results from Experiments 1 through 3 suggests that some of the processes engaged in response to unexpected univalent stimuli may be shared with the processes engaged in the cognitive control seen for the bivalency effect.

EXPERIMENT 5

It is interesting to note that three of our four experiments showed that colour judgment trials were more affected by the occasional unexpected stimuli and contributed more to the block-wise response slowing than parity and case judgments. To summarize, colour judgments showed a larger unexpectedness effect compared to case judgments in Experiment 1 (occasional letters presented in unexpected task-irrelevant blue or yellow), compared to parity in Experiment 3 (occasional letters presented in unexpected task-irrelevant fonts), and compared to case and parity judgments in Experiment 4 (occasional letters presented over unexpected background photos). Past studies have shown that trials immediately following bivalent stimuli show the largest bivalency effect (Meier et al., 2009), thus our findings here are not entirely surprising given that the task sequence was predictable and unexpected stimuli were always followed by a colour judgment trial. It is also possible that colour is more sensitive for other reasons. In Experiment 1, colour was the irrelevant unexpected feature, and the colour task-set may have been subject to suppression and response inhibition. In Experiments 3 and 4, colour was not the irrelevant unexpected feature, yet still showed greater sensitivity in unexpected blocks. In all cases, colour judgment trials occurred immediately following the unexpected stimulus.

Our previous bivalency effect work also found that colour judgment trials were more sensitive than the other tasks to the occasional presence of bivalent stimuli (Grundy et al., 2011). We suggested that this might be due to the fact that colour was always the feature whose response had to be inhibited on bivalent trials, and that this inhibition was retrieved upon presentation of colour trials within bivalent blocks. However, because colour trials in the present experiments showed the largest bivalency effect even when bivalence was removed, it leaves open the possibility that colour trials in our previous bivalency effect experiments were showing the largest effect because they always immediately followed bivalent stimuli. The question then becomes one of dissociating the roles of trial order from that of additional response conflict on colour trials.

In Experiment 5 we examined the importance of trial order in producing the larger effect for colour judgments by comparing conditions in which colour trials followed bivalent trials immediately versus appeared later in the sequence. We hypothesized that because colour is the response that is inhibited on bivalent stimuli, colour judgment trials would produce a larger bivalency effect compared to the parity and case decisions even when the colour trials did not immediately follow bivalent stimuli.

Participants

Twenty-six undergraduate students from McMaster University's psychology participant pool took part in the experiment in exchange for course credit. All participants had normal or corrected-to-normal vision. All procedures complied with the Canadian tri-council policy on ethics and were approved by the McMaster Research Ethics Board.

Materials and apparatus

Materials and apparatus were the same as Experiments 1 through 4, except that on occasional case judgment trials in bivalent blocks, letters were coloured in red or green, making these stimuli bivalent.

Procedure

Each block contained 144 trials. One practice block was introduced at the beginning of the experiment. Six experimental blocks were then presented, alternating between univalent and bivalent blocks, starting with a univalent block. Thus, experimental blocks 1, 3, and 5 consisted of purely univalent trials, and experimental blocks 2, 4, and 6 consisted of univalent trials and occasional bivalent trials. Within bivalent blocks, 16 of the case judgment trials appeared in red or green, making these stimuli bivalent. The trial sequence proceeded pseudo-randomly between colour judgments, parity judgments, and case judgments, such that there were no task repetition trials. All other procedures were identical to Experiments 1-4.

Data analyses

The bivalency effect is calculated as the difference in RT between univalent trials in purely univalent blocks versus univalent trials in bivalent blocks. Responses to bivalent stimuli themselves are not included in accuracy or RT analyses. We further divided the responses from the bivalent blocks into five bins to directly compare trials that immediately followed bivalent stimuli to trials that did not immediately follow bivalent stimuli. Because we do not include task repeat trials in our design, only parity and colour judgment trials immediately followed the bivalent case judgment trials. Consequently, our data set does not include case judgment trials that immediately follow bivalent trials and we could not fully cross the task factor (colour, parity, case) with sequence position (immediate vs. later). Thus, we compared five sets of means within the Task Order factor: colour and parity trials that immediately followed bivalent stimuli, and colour, parity, and case trials that did not immediately follow bivalent stimuli. We performed a 2 (Bivalency Effect: univalent vs. bivalent blocks) x 5 (Task Order: colour-immediate, colour-later, parity-immediate, parity-later, case-later) repeated-measures ANOVA. RT analyses included correct responses only.

Results

Accuracy was high in all conditions (5% errors; see Table 3). The main effect of Task Order was significant, $F(4,100) = 3.66$, $p = 0.008$, $\eta^2 = 0.142$. Pairwise comparisons showed only one significant comparison in which case-later judgments were more accurate than colour-immediate judgments, $t(25) = 3.22$, $p = 0.004$. The Bivalency Effect was significant, $F(1,25) = 5.35$, $p = 0.029$, $\eta^2 = 0.141$, with better accuracy in univalent compared to bivalent blocks. The interaction was not significant.

In the RT analysis, there was a significant main effect of Task Order, $F(4, 100) = 4.97$, $p = 0.001$, $\eta^2 = 0.166$. Both colour-immediate and colour-later responses were faster than parity-immediate and parity-later responses, $t(25) = 2.15$, $p = 0.044$, $t(25) = 2.11$, $p = 0.049$, $t(25) = 2.33$, $p = 0.034$, and $t(25) = 2.29$, $p = 0.032$, respectively. The case-later responses were faster than parity-immediate and parity-later responses, $t(25) = 4.21$, $p < 0.001$ and $t(25) = 4.08$, $p < 0.001$, respectively.

The Bivalency Effect was significant, $F(1, 25) = 11.64$, $p = 0.002$, $\eta^2 = 0.318$, with slower responses to univalent trials in bivalent blocks compared to univalent blocks, as expected. A significant interaction between Task Order and Bivalency Effect, $F(4, 100) = 4.18$, $p = 0.004$, $\eta^2 = 0.143$ revealed the most interesting differences (see Figure 3). The bivalency effect for colour-immediate and colour-later did not differ ($p > .05$). However colour-immediate and colour-later conditions both produced a larger bivalency effect compared to parity-later and case-later: $t(25) = 2.87$, $p = 0.004$, $t(25) = 2.26$, $p =$

0.016, $t(25) = 2.75$, $p = 0.005$, and $t(25) = 2.30$, $p = 0.015$, respectively. The parity-immediate bivalency effect was larger than parity-later and case, $t(25) = 1.97$, $p = 0.034$ and $t(25) = 1.76$, $p = 0.045$, respectively. Parity-later and case-later did not differ, $p > .05$.

Table 3 – Accuracy (average percent correct), response times (average ms), and standard errors for Experiment 5. There were 3 blocks with purely univalent trials (blocks 1, 3, and 5); occasional bivalent stimuli appeared in blocks 2, 4, and 6. Responses to bivalent stimuli were not included in the accuracy or RT analyses.

Experiment 5: Accuracy (percent correct)

	Univalent blocks	**Bivalent blocks**
Colour immediate	94 (0.9)	93 (1.2)
Colour later	96 (1.0)	94 (1.1)
Parity immediate	96 (1.0)	94 (1.1)
Parity later	94 (1.0)	95 (1.0)
Case later	97 (0.8)	96 (0.9)

Experiment 5: Response Time (ms)

	Univalent blocks	**Bivalent blocks**	**Bivalency Effect**
Colour immediate	642 (4.1)	674 (5.2)	32
Colour later	640 (4.5)	672 (5.0)	32
Parity immediate	672 (3.7)	695 (4.8)	23
Parity later	679 (3.8)	690 (4.3)	11
Case later	641 (3.9)	656 (4.5)	15

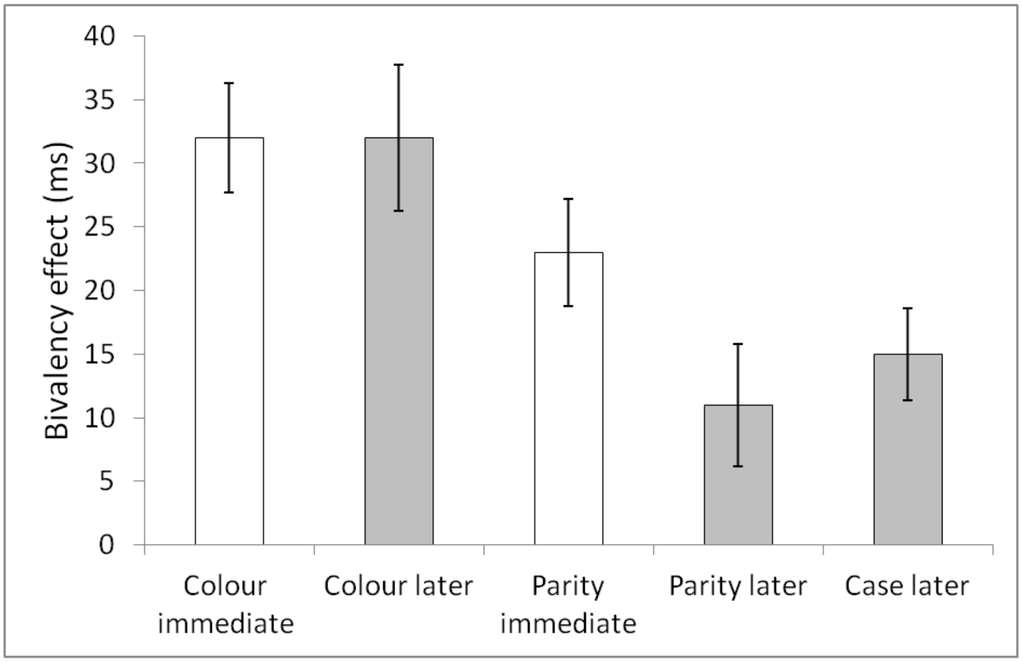

Figure 3 – The bivalency effect (RTs to univalent trials that followed incongruent bivalent trials in bivalent blocks 2, 4, and 6, minus RTs to univalent trials in bivalent blocks 1, 3, and 5) as a function of whether the tasks immediately followed or did not immediately follow bivalent stimuli. Bivalent stimuli appeared on case judgment trials only and there are no univalent case judgment trials that follow immediately a bivalent trial. Responses to bivalent stimuli were not included in the RT analyses.

Discussion

In Experiment 5 we tested the effect of task order following bivalent stimuli on the size of the bivalency effect. We were especially interested in the result from Experiments 1 through 4 in the current paper suggesting that colour judgments are more sensitive than parity and case judgments to the unexpectedness effect. We have noted in our previous work (Grundy et al., 2011) that colour produces the largest bivalency effect, and our hypothesis has been that this is due to response inhibition for colour because colour is the irrelevant feature in the bivalent stimulus. This makes the unexpectedness effect observation in the current paper more interesting, because one would not expect that the colour response would be suppressed in Experiments 3 and 4, in which the unexpected trial did not involve colour. In previous experiments, trial sequence has been shown to be important; trials that immediately follow bivalent stimuli produce a larger bivalency effect than trials that do not (Meier et al., 2009). In Experiments 1 through 4 in this paper, and in the majority of work reported on the bivalency effect (e.g., Grundy et al., 2011; Meier et al., 2009; Woodward et al., 2008), colour judgments immediately followed the unexpected (or bivalent) trial, therefore it is possible that the greater effect on colour is simply due to trial sequence.

In Experiment 5, we asked whether trial sequence alone explains the greater effect on colour judgments, or whether there is an additional influence from response conflict that produces a larger bivalency effect for colour judgments regardless of trial sequence. We replicated the trial sequence effect in Experiment 5, showing a larger bivalency effect for colour and parity judgments that immediately followed the bivalent case judgment trials compared to parity and case judgments that occurred later in the sequence. However, we also found that colour judgment trials showed a different pattern; the bivalency effect for colour trials that appeared later in the sequence did not differ significantly from the colour or parity trials that immediately followed bivalent stimuli. These findings provide additional support for the notion that colour judgment trials are more sensitive and show a larger bivalency effect compared to the other tasks when colour is the source of response conflict on bivalent stimuli.

GENERAL DISCUSSION

In the present study, we sought to examine factors that modulate the bivalency effect – a block-wise response slowing that occurs when we occasionally encounter bivalent stimuli during task-switching. This response slowing is seen even on trials that do not share features with bivalent stimuli, suggesting that there must be at least some top-down cognitive control being implemented. While much effort has been put forth to understand the mechanisms involved in this control (Grundy et al., 2011; Woodward et al., 2008), and to examine the robustness of the effect (Meier et al., 2009; Rey-Mermet & Meier, 2011), less is known about the stimulus properties that elicit the effect. Here we attempt to unravel some of these contributing factors. We provide converging evidence for the notion that unexpectedness, beyond the influence of bivalence, plays a pivotal role in the processes involved in eliciting a block-wise response slowing, and thus possibly contributes to an adjustment in top-down cognitive control. Introducing unexpected events is enough to elicit a block-wise response slowing that is similar in form to the bivalency effect.

In Experiment 1, we introduced irrelevant-colour letters (i.e. yellow and blue) on occasional case judgment trials in block 2 in place of task-relevant coloured letters (i.e. red and green) as is done in typical bivalency effect studies. A block-wise response slowing was observed for all trials that appeared in this block compared to blocks in which none of these surprising stimuli appeared. Given the possibility that the unexpected colours triggered retrieval of the colour task, even though they were task-irrelevant, we removed colour from the unexpected stimuli in Experiments 2 and 3. The unexpectedness effect was replicated, eliciting a block-wise response slowing on all trials in response to the occasional presence of unexpectedly patterned letters or unexpected fonts. In Experiment 4, we superimposed occasional case judgment trials over background pictures of Arnold Schwarzenegger, and once again demonstrated a block-wise response slowing. Even though bivalent stimuli were not used, we were able to elicit an unexpectedness effect that looks strikingly similar to the bivalency effect and suggests the involvement of overlapping processes.

We suggest that the unexpectedness effect presented here can be explained by the episodic context retrieval hypothesis proposed by Meier et al. (2009). This idea is based on the notion that stimuli develop a history over the course of the experiment (Waszak et al., 2003), and that upon presentation of a stimulus, the context of the block in which it occurs is retrieved along with the task demands specific to that particular stimulus. Thus, in a block in which occasional unexpected stimuli appear, this confusing block context is retrieved upon presentation of each stimulus, and this leads to response slowing on all trials, including those that share no features with the unexpected stimuli. At the beginning of the bivalent (or unexpected) block, participants may be unsure of when bivalent (or unexpected) stimuli will appear, and this may trigger a re-evaluation of task demands. For instance, participants cannot be certain after encountering the first few unexpected letters whether an equally surprising unexpected digit will appear within an unexpected block. We suggest that this re-evaluation of task demands may be part of the driving force behind the unexpected context associated with the block, and that the stimulus causing this re-evaluation need not be bivalent.

In summary, across the first four experiments in the present study, we revealed a block-wise response slowing without using bivalent stimuli. Participants were on average 15 ms slower to respond to expected univalent stimuli in a block in which occasional unexpected univalent stimuli appeared than in a block in which only univalent stimuli appeared (as illustrated in Figure 2). These findings suggest that a key factor in engaging the processes that lead to the bivalency effect is a violation of expectancy.

We must note however that the magnitude of the block-wise response slowing across Experiments 1 through 4 appears to be smaller than what is typically reported in bivalency effect studies (Grundy et al., 2011; Meier et al., 2009; Rey-Mermet & Meier, 2011, 2012; Woodward et al., 2003, 2008). If this is the case, then it suggests that there are additional processes involved in the bivalency effect that are not present in the effect elicited by unexpectedness alone.

A possible limitation of the present study is that we did not directly compare the influence of non-bivalent unexpected stimuli to that of bivalent stimuli in a within-subject design. Thus, it is still possible that the magnitude of the unexpectedness effect is not smaller than the bivalency effect. However, we note that the average unexpectedness effect reported here is 15 ms, whereas bivalency effect experiments have never reported a block-wise response slowing below 25 ms (Grundy et al., 2011; Meier et al., 2009; Rey-Mermet & Meier, 2011, 2012; Woodward et al., 2003, 2008). Furthermore, preliminary work in our lab suggests that bivalent stimuli elicit a larger block-wise response slowing than non-bivalent unexpected stimuli when a within-subjects design is used, consistent with the between-study comparisons. Despite these differences, we provide evidence for the similarities of processes elicited by the two stimulus types, and suggest that unexpectedness likely plays a pivotal role in both.

While experiments 1 through 4 were designed to shed light on the stimulus properties beyond the influence of bivalence that contribute to the processes involved in the bivalency effect, Experiment 5 was designed to examine the role of colour. Of particular interest was the consistent finding from our past experiments that colour trials showed the largest and most robust bivalency effect compared to the other tasks (Grundy et al., 2011). An initial hypothesis claimed that colour was showing the largest effect because colour was always the feature whose response had to be inhibited on bivalent trials, and that this inhibition was retrieved upon presentation of colour trials within bivalent blocks leading to additional response slowing. The results from Experiments 3 and 4 were surprising in this regard because colour judgments showed the largest unexpectedness effect compared to parity and case judgments even though there was no expectation that the colour response would be inhibited. However, in all of our previous experiments (Experiments 1 through 4; Grundy et al., 2011), and in the majority of published bivalency effect studies (e.g., Woodward et al., 2008), colour judgment trials were always the trials that immediately followed bivalent stimuli. There is evidence that trials that immediately follow bivalent stimuli typically show a larger bivalency effect (Meier et al., 2009). To rule out the possibility that trial order entirely explains the larger bivalency effect observed for colour judgment trials we compared conditions in which colour judgment trials sometimes did and sometimes did not immediately follow bivalent stimuli. Even for trials that appeared later in the trial sequence, colour judgment trials showed the largest bivalency effect. We conclude that response inhibition drives the larger bivalency effect on colour trials. This conclusion leads to the consideration that colour may have greater perceptual salience compared to other features, and that the nature of the feature used as the bivalent cue on bivalent trials may directly affect the magnitude of the bivalency effect.

CONCLUSION

Unexpected stimuli that are not bivalent with respect to the tasks in a task switching experiment elicit a block-wise response slowing similar to the bivalency effect. We suggest that unexpectedness, beyond the influence of task-cueing (i.e. bivalence), contributes to the engagement of processes leading to the bivalency effect. However, it is possible that the unexpectedness effect taps into separate processes than the ones triggered by the bivalency effect; future brain-imaging studies will tease apart these possibilities. These findings extend our understanding of how cognitive control is implemented under demanding conditions in a continually changing environment.

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CHAPTER 4

The following chapter is a submitted manuscript. Permission to use the article in my thesis will be sought upon acceptance for publication.

Reference

Grundy, J. G., & Shedden, J. M. (submitted). Carry-over of response interference in task-switching: A study of the bivalency effect.

Preamble

It was clear from experiment 5 in chapter three that inhibition likely plays a pivotal role in producing the bivalency effect behavioural adjustments. Bivalent stimuli appear to produce a larger block-wise response slowing than unexpected univalent stimuli, and it seemed likely that inhibition would be a strong contributor to this finding. Thus, in chapter 4, I scrutinized the role of inhibition in modulating the bivalency effect. Specifically, bivalent stimuli can be either congruent or incongruent with respect to the response afforded by the irrelevant stimulus feature, and this distinction might have important implications for the bivalency effect. I hypothesized that trials following these two different types of stimuli would be affected in qualitatively different ways. Because incongruent bivalent stimuli typically produce a larger response slowing than congruent bivalent stimuli (Meiran, 2005; Meiran, Hsieh, & Dimov, 2010; Meiran & Kessler, 2008; Sudevan & Taylor, 1987), I predicted that trials following incongruent bivalent stimuli would show a greater response slowing as a result of a carry-over of response inhibition.

Carry-over of response interference in task-switching: A study of the bivalency effect

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ABSTRACT

The bivalency effect is a block-wise response slowing that is observed during task switching when rare stimuli that cue two tasks (bivalent stimuli) are encountered. This adjustment in response style is believed to involve top-down cognitive control because it affects all trials that follow bivalent stimuli, including those trials that do not share any features with bivalent stimuli. The specific stimulus and response properties that trigger the bivalency effect are not well understood. Bivalent stimuli can be either congruent or incongruent with respect to the response afforded by the irrelevant stimulus feature, and in the present study, we show that response incongruence is a major contributing factor in producing the subsequent response slowing observed in the bivalency effect. Further, we show that after sufficient practice, the bivalency effect is present *only* for trials that follow incongruent bivalent stimuli. We suggest that a carry-over of response interference after encountering incongruent bivalent stimuli plays a critical role in maintaining the magnitude and robustness of the bivalency effect. Implications for current models of response congruency effects and future directions for bivalency effect research are discussed.

INTRODUCTION

Imagine driving through the city, stopping at a number of red stop signs, changing lanes, and staying vigilant to any pedestrian encounters. Along the way you encounter a *red* sign indicating directions to a nearby hotel. While this sign is meant to evoke a different response, the red colour may cue the currently irrelevant red stop sign. The hotel sign acts as a bivalent stimulus because it cues two tasks. In response to bivalent stimuli, people change their response strategies such that *all* subsequent tasks are slowed, even when these tasks do not share features with bivalent stimuli (Grundy et al., 2011; Meier, Woodward, Rey-Mermet, & Graf, 2009; Rey-Mermet & Meier, 2012a, 2012b; Woodward, Meier, Tipper, & Graf, 2003; Woodward, Metzak, Meier, & Holroyd, 2008). Extending the above analogy, for a period of time following the red hotel sign, responses would be slower to change lanes, stop at stop signs, and modify behaviour in response to pedestrian activity.

To observe this behaviour in the laboratory, participants typically alternate predictably between three simple classification tasks such as a case task (lowercase vs. uppercase letters), a parity task (odd vs. even digits), and a colour task (blue shapes vs. red shapes) by pressing a left or a right response key (e.g. left = lowercase letters, odd digits, and blue shapes; right = uppercase letters, even digits, and red shapes). In the first and third experimental blocks, participants encounter only univalent stimuli (stimuli that cue a single task). In the second (bivalent) block, occasional case judgment trials consist of red or blue letters, making these stimuli bivalent. The colour of the letter is irrelevant to the case judgment task; however, it is difficult to ignore and has a significant effect on behaviour. Response times to all subsequent univalent trials within this bivalent block are increased relative to the response times for univalent trials within the first and third experimental blocks. This block-wise response slowing is known as *the bivalency effect* (Woodward, Meier, Tipper, & Graf, 2003).

The bivalency effect is problematic for current theories of cognitive control that rely on overlapping stimulus and response properties, including negative priming (Allport et al., 1994; Allport & Wylie, 2000; Koch & Allport, 2006), task-decision process (Braverman & Meiran, 2010; Meiran & Kessler, 2008; Meiran, Kessler, & Adi-Japha, 2008; Monsell et al., 2000; Rubinstein et al., 2001; Sohn & Anderson, 2001), and conflict monitoring (Botvinick, Braver, Barch, Carter, & Cohen, 2001; Botvinick, 2007; Botvinick, Cohen, & Carter, 2004; van Veen, Cohen, Botvinick, Stenger, & Carter, 2001) accounts. Specifically, all models can explain the slowing observed on trials that share properties with bivalent stimuli, but not for trials that have no overlapping properties with bivalent stimuli (i.e. parity decision trials). For instance, an episodic retrieval account for negative priming can explain the slowing on univalent colour judgment trials by suggesting that because colour is always the feature that must be suppressed on bivalent trials, its association with suppression is retrieved upon presentation of colour judgment trials, and this leads to a response slowing. A similar argument can be made for case judgment trials because of their association with bivalent stimuli; bivalent stimulus properties (including colour suppression) are retrieved upon presentation of case judgment trials and this leads to a response slowing. Problems arise in explaining the bivalency effect with negative priming when attempting to explain the slowing observed on parity decisions, because these trials do not share any features with the other trials.

A task-decision process account (e.g. Braverman & Meiran, 2010), in which differing levels of task-conflict on a particular trial determine the speed at which the trial is processed, suffers from a similar problem in explaining the slowing observed on parity decision trials. By this account, the associations that colour and case trials have with bivalent stimuli might be retrieved upon presentation of these trials, and performance in bivalent blocks suffers because of the need to dissociate the relevant from irrelevant information retrieved. Because parity trials have no feature overlap with bivalent stimuli, this account cannot explain the response slowing on these trials; parity decision trials in bivalent blocks should be no slower than parity decisions in pure blocks because they have no conflict to resolve.

As a final example of why the bivalency effect is problematic for current theories of cognitive control, consider the conflict monitoring theory (Botvinick et al., 2001; Botvinick, 2007; Botvinick et al., 2004; van Veen et al., 2001), which is one of the most influential models of cognitive control. By this theory, the dACC is engaged in response to the simultaneous activation of competing stimulus and/or response properties and this leads to a subsequent focus on task-relevant features. This post-conflict focus on task-relevant features is beneficial when subsequent conflict needs to be resolved, but the issue becomes muddled when univalent trials are encountered. Conflict monitoring can explain why a response slowing might be observed on univalent colour trials, but it is unclear how it might predict the slowing observed on univalent case and parity trials. For instance, in order to focus on the task-relevant feature (case) and facilitate selection on bivalent trials, the irrelevant feature (colour) is inhibited. When subsequent colour judgment trials are presented, task-irrelevant inhibition is retrieved and performance suffers. On the other hand, it is unclear how task-relevant focusing (i.e. focusing on case features) would lead to a performance cost on case judgment trials, especially because no conflict exists on these trials. There is also no clear reason why parity decision trials would be hindered by a subsequent increase of attention on case features because there is no ambiguity to be resolved (i.e. parity decision trials are univalent, and share no overlapping features with any of the other trials). Furthermore, it has been shown that the dACC is engaged on *univalent* trials (trials that contain no conflict) when occasional bivalent stimuli appear within the same block (Grundy et al., 2011; Woodward et al., 2008). Together, these findings suggest that conflict monitoring is not sufficient to explain the block-wise response slowing inherent in the bivalency effect.

In light of the aforementioned problems in explaining the bivalency effect with current models, it is important to scrutinize the bivalency effect in order to more completely understand how we are able to adapt to our continually changing environments. The bivalency effect is a robust and long-lasting effect (Meier et al., 2009; Rey-Mermet & Meier, 2012a) believed to involve a change in response strategy signalled by the dorsal anterior cingulate cortex (dACC; Grundy et al., 2011; Woodward et al., 2008), an area believed to be involved in conflict-detection (Kerns et al., 2004; Kerns, 2006; Liu et al., 2004; Milham et al., 2001; van Veen et al., 2001). A time course for the bivalency effect has also been proposed that involves a network of very early visual processing of stimulus features as well as higher-order cognitive control from the dACC (Grundy et al., 2011). However, while these studies provide insight into the robustness of the effect and the cognitive processing involved, very little is known about the actual stimulus and response properties that produce the bivalency effect. For instance, the irrelevant feature on bivalent stimuli can either be congruent or incongruent with respect to the required key press for a correct response. Thus, it is unknown whether the bivalency effect is elicited by the additional response conflict present on incongruent bivalent stimuli, or whether the activation of the irrelevant task on congruent bivalent stimuli is sufficient to elicit this block-wise response slowing.

A bivalent stimulus always cues two different tasks, but can be either congruent or incongruent with respect to the response. For example, a bivalent stimulus might be a lowercase or uppercase letter in red or blue. A bivalent stimulus is congruent when the response mapping for the case and the colour is the same (e.g., both are associated with a left key response). A bivalent stimulus is incongruent when the response mapping for the case and the colour differs (e.g., they are associated with different response keys). Reaction times (RTs) to incongruent bivalent stimuli are typically delayed compared to RTs to congruent bivalent stimuli (Sudevan & Taylor, 1987; see Meiran & Kessler, 2008 for a review), which suggests more cognitive resources are required to disentangle these conflicting responses. We might expect that the additional resources allocated to this response conflict may also hinder performance on subsequent univalent stimuli for a couple of reasons.

After encountering a number of univalent trials, participants develop a fluency of processing, and this fluency is interrupted when bivalent stimuli appear and trigger a reconfiguration of response style (Grundy et al., 2011; Meier et al., 2009; Woodward et al., 2003; 2008). This *breaking of inertia* account (Paus, 2001; Woodward, Meier, Tipper, & Graf, 2003) may require more reconfiguration after encountering incongruent (vs. congruent) bivalent stimuli because the response mapping must also be re-evaluated, and this may lead to a slower build-up of subsequent momentum. Alternatively, it is possible that a generic response interference from incongruent bivalent trials carries over to univalent trials and causes interference, producing additional delays in response time on all subsequent univalent trials. In either case, a larger bivalency effect is predicted for trials that follow incongruent (vs. congruent) bivalent stimuli as a result of response interference affecting subsequent trials. We hereafter refer to this idea as *carry-over of response interference*.

The most recent model of the bivalency effect attributes the block-wise response slowing to an episodic context retrieval of a block upon presentation of the stimulus (Meier et al., 2009; Rey-Mermet & Meier, 2012a, 2012b). For instance, when a parity decision trial is encountered within a bivalent block, the confusing block context (i.e. occasional bivalent stimuli will appear) is retrieved along with the task-set, and this leads to a response slowing. By this account, there should be no difference in response times between univalent trials that follow congruent vs. incongruent bivalent trials because the context of the block is the same for all trials within that block. Furthermore, Rey-Mermet and Meier (2012b) suggest that "the bivalency effect reflects an adjustment of cognitive control, which is sensitive to the presence of conflict but neither to its amount nor to its source" (p. 219). On the other hand, a carry-over of response interference would predict that trials following incongruent bivalent stimuli would show a larger response slowing. This is an important potential influence to consider in conceptualizing a theory for the cognitive control observed in the bivalency effect, but to our knowledge, we are the first to examine the influence of response incongruence in the context of the bivalency effect.

Past bivalency effect studies have examined the block-wise slowing of responses irrespective of whether the bivalent stimulus was response congruent or incongruent. In the present set of experiments, we examined the contributions made by response incongruence versus that of irrelevant feature activation in producing the bivalency effect. To do this, we ran a number of bivalency effect studies and sorted these data so that RTs to univalent trials that followed congruent vs. incongruent bivalent stimuli were compared. If there are no differences in RTs for trials that follow these two types of stimuli, then we can assume that the activation of irrelevant stimulus features is sufficient to produce the bivalency effect and that an episodic context retrieval account may be sufficient to explain the bivalency effect. On the other hand, we may find that activation of conflicting responses on bivalent stimuli is a major contributing factor in producing this block-wise response slowing. Experiment 1A directly tests the congruency hypothesis, Experiment 1B solidifies these findings by presenting the results of reanalysis of Grundy et al. (2011) in terms of congruency, and Experiment 2 compares the influence of *only* congruent or *only* incongruent occasional bivalent stimuli appearing throughout the experiment (in bivalent blocks) to disambiguate any overlapping processes that these two types of stimuli may have as a result of appearing within the same block.

EXPERIMENT 1A

Participants

Twenty-eight undergraduate students were recruited from McMaster University's Introductory Psychology and Cognition subject pool and participated in exchange for course credit. All participants had normal or corrected to normal vision. All procedures complied with the Canadian tri-council policy on ethics and were approved by the McMaster Ethics Research Board.

Materials and apparatus

All stimuli were presented on a black background on a 17-inch CRT monitor at a distance of 80 cm from participants. A chinrest was used to maintain consistent viewing distance between participants. Presentation® experimental control software (Neuro Behavioural Systems; version 11) was used to present the stimuli and the refresh rate on the monitor was set to 85 Hz. Stimuli were presented in the center of the screen with the height of each stimulus subtending a visual angle of 1.26˚. For colour decisions, shapes (square, triangle, circle, pentagon) were presented in either red or blue. For parity decisions, numbers 1-8 were displayed in white (60-point, Times New Roman). Case decisions were presented as uppercase or lowercase letters (a, b, d, e) in white (60-point, Times New Roman). To create bivalent stimuli, case judgment trials were presented randomly in red or blue, making some of these stimuli congruent, and some incongruent. All participants completed the experiment individually in a dimly lit room.

Procedure

Each block contained 144 trials. Within bivalent blocks, 16 of the case judgment trials appeared in red or blue, making these stimuli bivalent. Trial sequence always proceeded predictably from colour judgments to parity judgments to case judgments. In each block, participants alternated between making a case decision (lowercase vs. uppercase), making a parity decision (odd vs. even), and making a colour decision (red shape vs. blue shape) by pressing one of two response keys (see Figure 1 for an example of the trial sequence). Using the index and middle fingers of the right hand, participants pressed a left key in response to lowercase letters, odd digits, and blue shapes, and a right key in response to uppercase letters, even digits, and red shapes (counterbalanced across response finger).

A practice block was presented at the beginning of the experiment in which only univalent stimuli for the three tasks appeared. This was followed by 6 experimental blocks which alternated between univalent and bivalent blocks. In bivalent blocks (experimental blocks 2, 4, and 6), bivalent stimuli appeared on 20% of case judgment trials. Within each block, participants were given accuracy feedback after every 12 trials. This helped participants remain focused and accurate. Stimuli remained on the screen until response or until 1500 ms elapsed, after which point the message “too slow” appeared on the screen, encouraging participants to maintain speed as well as accuracy.

The inter-trial interval was randomly varied between 400-900 ms throughout the experiment.

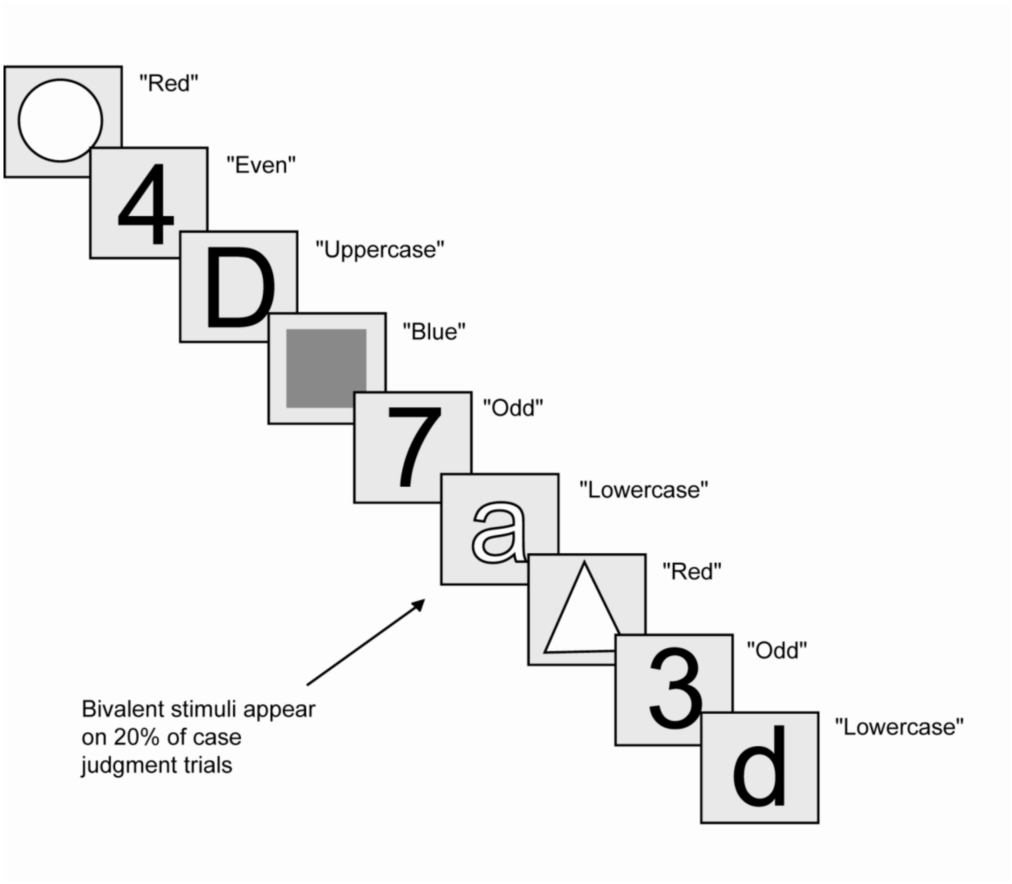


Figure 1 - Illustration of the trial sequence and type of stimuli used during the experiment. This particular illustration is an example of a bivalent block. The words appearing beside the stimuli represent correct responses. During bivalent blocks (blocks 2, 4, and 6), bivalent stimuli appear on 20% of all case judgment trials. Bivalent stimuli do not appear at all during the univalent blocks (blocks 1, 3, and 5). In the grey-scale diagram we use white to represent the red stimuli and grey to represent the blue stimuli.

Data analyses

The bivalency effect is calculated as the RT difference between univalent trials presented in purely univalent blocks and univalent trials presented in blocks that contain the occasional bivalent stimuli. Note that RTs to the bivalent stimuli are not included in the means.

Because we were interested in examining the influence of congruent vs. incongruent trials within the *same* block, we examined trials that followed one particular stimulus type until presentation of the next bivalent stimulus. For example, we might examine the slowing of performance following a congruent bivalent stimulus until presentation of another bivalent stimulus 9 trials later. Because bivalent stimuli appeared randomly on 20% of case judgment trials, the number of univalent trials that followed a particular bivalent stimulus (congruent vs. incongruent) varied between 3-18 trials.

In Experiment 1A, we performed a 2 (preceding bivalent stimulus: congruent vs. incongruent) x 3 (task: colour, parity, case) x 3 (block pair: block 2-1, block 4-3, block 6-5) repeated-measures ANOVA to examine RT difference scores for univalent trials in bivalent vs. univalent blocks (uni-biv vs. uni-uni trials, respectively). Thus, difference scores were calculated by subtracting RTs to uni-uni trials from RTs to uni-biv trials (bivalency effect).

For repeated-measures analysis of factors involving more than two levels, the Greenhouse-Geisser correction was used, in which case epsilon and the adjusted *p* and epsilon values are reported along with the original degrees of freedom. Bonferroni adjustment was also used for multiple comparisons.

Results

Bivalency effect mean differences and standard errors for each condition and each block pair are presented in Table 1, whereas raw RTs and corresponding standard errors are presented in Table 2. Figure 2 provides a graphical depiction of the bivalency effect across the experiment for stimuli that followed congruent vs. incongruent bivalent stimuli.

A significant main effect of preceding bivalent stimulus type revealed that the bivalency effect was much larger for trials that followed incongruent than congruent bivalent stimuli, $F(1,27) = 22.33$, $p < 0.001$, $\eta^2 = 0.453$.

A significant effect of preceding bivalent stimulus type by task interaction was also revealed, $F(2,54) = 7.50$, $p = 0.001$, $\eta^2 = 0.217$, which can be explained by the finding that the bivalency effect was larger for parity trials than for case trials when they followed *congruent* bivalent stimuli, $t(27) = 2.21$, $p = 0.035$, but that the bivalency effect was larger for colour trials than case trials when they followed *incongruent* bivalent stimuli, $t(27) = 2.32$, $p = 0.028$. The bivalency effects for colour and parity did not differ significantly following congruent bivalent stimuli, $t(27) = 0.074$, $p = 0.942$, or following incongruent bivalent stimuli, $t(27) = 1.18$, $p = 0.249$; however, numerically, the bivalency effect was 11 ms larger for colour trials than for parity trials when they followed incongruent bivalent stimuli, and differed by only 0.5 ms following congruent bivalent stimuli.

A significant interaction between block pair and task was also revealed, $F(2,54) = 4.20$, $p = 0.003$, $\eta^2 = 0.134$. This can be explained by the finding that the bivalency effect was larger for parity trials than for case trials in the first and second block pairs (block 2-1: $t(27) = 2.94$, $p = 0.007$; block 4-3: $t(27) = 3.70$, $p = 0.001$), and marginally larger for parity than for colour trials in the first block pair (block 2-1), $t(27) = 2.00$, $p = 0.056$. No other differences reached significance.

To examine whether the response slowings were significantly different from 0 across the experiment, we performed t-tests for each block pair for trials that followed congruent and incongruent bivalent stimuli separately. For trials following *congruent* bivalent stimuli, the response slowing was only significantly different from 0 in the first block pair comparison (block 2 vs. 1: 19 ms), $t(27) = 2.66$, $p = 0.013$, but not for the later block pairs (block 4 vs. 3: 0 ms; block 6 vs. 5: 4 ms), $t(27) = 0.52$, $p = 0.609$, and $t(27) = 1.21$, $p = 0.238$. For trials that followed *incongruent* bivalent stimuli, a response slowing was observed for all three block pairs (block 2 vs. 1: 42 ms; block 4 vs. 3: 34 ms; block 6 vs. 5: 26 ms), $t(27) = 4.84$, $p < 0.001$, $t(27) = 3.01$, $p = 0.006$, $t(27) = 3.60$, $p = 0.001$, respectively (see Figure 2A).

Table 1 – Bivalency effect and standard error (ms) as a function of task, block pair comparison, and whether RTs used for the difference scores were performed on trials that followed congruent or incongruent bivalent stimuli. Note: All analysis were performed on *univalent* trials only.

Experiment 1A

	Congruent			**Incongruent**		
	Block 2-1	**Block 4-3**	**Block 6-5**	**Block 2-1**	**Block 4-3**	**Block 6-5**
Colour	12 (3.9)	-1 (4.6)	6 (4.9)	41 (5.2)	43 (5.9)	46 (6.1)
Parity	28 (3.9)	-7 (5.4)	-2 (5.1)	59 (6.2)	19 (7.0)	17 (5.5)
Case	18 (4.9)	7 (6.8)	9 (4.6)	24 (5.4)	39 (6.1)	14 (4.2)

Experiment 1B

	Congruent			**Incongruent**		
	Block 2-1	**Block 4-3**	**Block 6-5**	**Block 2-1**	**Block 4-3**	**Block 6-5**
Colour	26 (5.4)	6 (4.1)	1 (3.6)	67 (5.2)	30 (4.9)	42 (4.7)
Parity	23 (4.0)	-8 (3.6)	-4 (4.7)	35 (4.2)	16 (3.8)	4 (4.9)
Case	15 (3.9)	-4 (5.4)	-12 (4.5)	31 (5.0)	6 (4.3)	10 (4.9)

Experiment 2

	Congruent			**Incongruent**		
	Block 2-1	**Block 4-3**	**Block 6-5**	**Block 2-1**	**Block 4-3**	**Block 6-5**
Colour	21 (13.2)	2 (9.5)	-10 (10.6)	64 (13.2)	32 (9.5)	23 (10.6)
Parity	15 (11.1)	7 (8.8)	-14 (10.6)	51 (11.1)	28 (8.8)	8 (10.6)
Case	9 (10.0)	12 (8.4)	-6 (9.4)	39 (10.0)	10 (8.4)	14 (9.4)

Table 2 – RTs and standard errors (ms) as a function of task, block, and whether trials followed congruent or incongruent bivalent stimuli. Note: All analysis were performed on *univalent* trials.

Experiment 1A

Congruent

	Block 1	Block 2	Block 3	Block 4	Block 5	Block 6
Colour	593 (19)	606 (21)	591 (21)	590 (18)	591 (22)	597 (19)
Parity	645 (20)	673 (21)	634 (20)	627 (22)	618 (21)	616 (20)
Case	632 (21)	650 (23)	593 (19)	600 (25)	597 (22)	606 (23)

Incongruent

	Block 1	Block 2	Block 3	Block 4	Block 5	Block 6
Colour	593 (19)	634 (21)	591 (21)	634 (20)	591 (22)	637 (25)
Parity	645 (20)	704 (23)	634 (20)	653 (24)	618 (21)	635 (22)
Case	632 (21)	656 (18)	593 (19)	632 (24)	597 (22)	611 (24)

Experiment 1B

Congruent

	Block 1	Block 2	Block 3	Block 4	Block 5	Block 6
Colour	617 (21)	643 (19)	618 (20)	624 (21)	597 (17)	598 (18)
Parity	644 (19)	667 (22)	642 (20)	634 (22)	621 (16)	617 (15)
Case	600 (16)	615 (15)	599 (ms)	595 (18)	578 (15)	567 (12)

Incongruent

	Block 1	Block 2	Block 3	Block 4	Block 5	Block 6
Colour	617 (21)	683 (24)	618 (20)	647 (20)	597 (17)	639 (19)
Parity	644 (19)	679 (20)	642 (20)	644 (21)	621 (16)	625 (17)
Case	600 (16)	631 (16)	599 (ms)	605 (16)	578 (15)	588 (15)

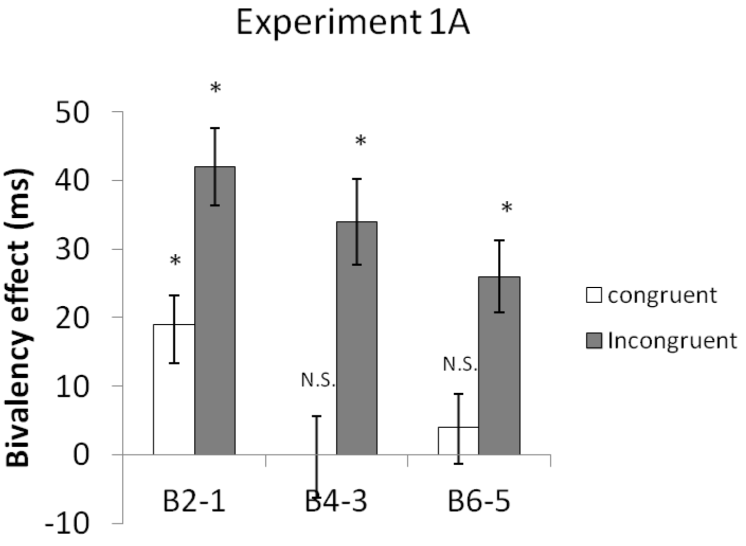
Experiment 2

Congruent

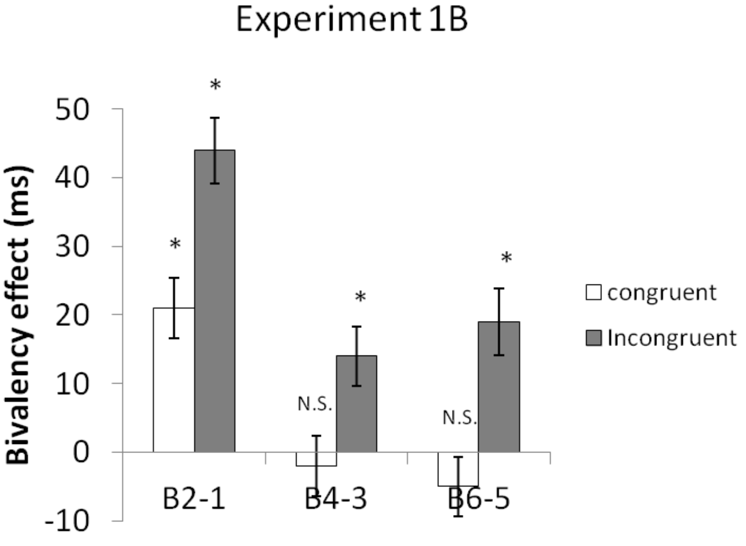
	Block 1	Block 2	Block 3	Block 4	Block 5	Block 6
Colour	581 (23)	603 (19)	606 (25)	607 (22)	598 (27)	591 (23)
Parity	626 (25)	642 (22)	622 (24)	628 (24)	616 (25)	601 (22)
Case	576 (22)	586 (18)	576 (20)	587 (21)	580 (22)	575 (22)

Incongruent

	Block 1	Block 2	Block 3	Block 4	Block 5	Block 6
Colour	606 (18)	671 (23)	613 (16)	645 (15)	607 (15)	631 (19)
Parity	634 (19)	685 (21)	626 (17)	654 (19)	632 (16)	645 (20)
Case	615 (19)	654 (22)	609 (17)	618 (17)	600 (16)	619 (19)



A)



B)

Figure 2 – The bivalency effect across Experiment 1A (A) and Experiment 1B (B) as a function of whether univalent trials in the bivalent block followed congruent or incongruent bivalent stimuli. B2-1 = bivalency effect for the first block comparison (Block 2 – Block 1 RTs), B4-3 = bivalency effect for the second block comparison (Block 4 – Block 3 RTs), B6-5 = bivalency effect for the last block comparison (Block 6 – Block 5 RTs). *: bivalency effect significant at $p < 0.05$, N.S.: non-significant bivalency effect.

Discussion

We ran a typical bivalency effect study and analyzed the data based on the prediction that response incongruence on bivalent stimuli would play a critical role in producing a block-wise adjustment in cognitive control. Consistent with this hypothesis, we found that participants were slower to respond to univalent stimuli when they followed incongruent bivalent stimuli than when they followed congruent bivalent stimuli, despite these stimuli appearing within the same block. Furthermore, a response slowing was present in later block comparisons only when univalent trials followed incongruent bivalent stimuli. Thus, the bivalency effect does not reflect a simple block-wise response slowing, as previously thought (Grundy et al., 2011; Meier & Rey-Mermet, 2012; Meier et al., 2009; Rey-Mermet & Meier, 2012a, 2012b; Woodward et al., 2003, 2008). It appears that the bivalency effect is not only elicited by cueing irrelevant stimulus features on bivalent trials (e.g. blue colour), but rather that the addition of response conflict is critical in producing the bivalency effect, especially after practice. This response conflict is present on bivalent trials only, thus performance on subsequent univalent trials is likely affected by the incongruence due to some form of response interference carry-over effect.

It is interesting that the colour trials showed the largest and most robust bivalency effect when they followed incongruent bivalent stimuli, but not when they followed congruent bivalent stimuli. This suggests that there is something special about colour that makes it more susceptible to response incongruence carry-over effects. One possibility is that colour is always the irrelevant feature on bivalent trials, and that suppression of the colour response is triggered upon the presentation of colour judgment tasks. Another possibility is that the carry-over of response interference has both generic as well as targeted carry-over properties, in the sense that all responses are slowed but there is additional slowing for the colour task. In any case, it appears that additional conflict on colour judgment tasks modulates the bivalency effect.

EXPERIMENT 1B

Experiment 1A provides strong support for the notion that congruency is a major factor contributing to the magnitude of the bivalency effect, and to the maintenance of the effect over extended practice. Experiment 1B was designed to solidify these claims by examining the data collected from Grundy et al. (2011); a replication of Experiment 1A would help to illustrate the robustness of the congruency findings.

Participants

Twenty-five participants were recruited from McMaster University's Introductory Psychology and Cognition subject pool and participated in exchange for course credit. All participants had normal or corrected to normal vision. All procedures complied with the Canadian tri-council policy on ethics and were approved by the McMaster Ethics Research Board.

Materials, Apparatus & Procedure

In Experiment 1B, each block contained 168 trials. Two practice blocks were presented at the beginning of the experiment. All other materials and procedures were the same as those described in Experiment 1A.

Results

Bivalency effect mean differences and standard errors for each condition and each block pair are presented in Table 1. Figure 2B provides a graphical depiction of the bivalency effect across the experiment for stimuli that followed congruent vs. incongruent bivalent stimuli.

A significant main effect of preceding bivalent stimulus type revealed that the bivalency effect was again much larger for trials that followed incongruent than congruent bivalent stimuli, $F(1,24) = 22.74$, $p < 0.001$, $\eta^2 = 0.487$. A significant effect of block pair was also revealed, $F(2,48) = 6.23$, $p = 0.004$, $\eta^2 = 0.206$; this can be explained by the finding that the bivalency effect was larger in the first block pair than in the second and third block pairs, $t(24) = 3.14$, $p = 0.004$, and $t(24) = 2.69$, $p = 0.013$, respectively, but that the latter block pairs did not differ from each other, $t(24) = 0.39$, $p = 0.699$.

A significant effect of task and a significant interaction between task and preceding bivalent stimulus type were revealed, $F(2,48) = 18.08$, $p < 0.001$, $\eta^2 = 0.206$, and $F(2,48) = 6.61$, $p = 0.003$, $\eta^2 = 0.216$, respectively. The significant task effect can be explained by the finding that colour judgment trials showed a larger bivalency effect than case and parity decision trials, $t(24) = 5.30$, $p < 0.001$, and $t(24) = 4.75$, $p < 0.001$, respectively, but that the bivalency effects for the case and parity decision trials did not differ, $t(24) = 0.62$, $p = 0.542$. The significant interaction can be explained by the finding that for trials following *incongruent* bivalent stimuli, the response slowing was much larger for colour trials than for case and for parity trials, $t(24) = 5.58$, $p < 0.001$, and $t(24) = 5.23$, $p < 0.001$, but that for trials following *congruent* bivalent stimuli, colour trials only showed a slightly larger response slowing over case judgment trials, $t(24) = 2.37$, $p = 0.026$, but not over parity judgment trials, $t(24) = 1.57$, $p = 0.130$. The response slowing observed between case and parity judgment trials did not differ as a function of preceding bivalent stimulus type (congruent: $t(24) = 0.87$, $p = 0.389$, incongruent: $t(24) = 0.10$, $p = 0.925$).

To examine the existence of a significant bivalency effect across the experiment as a function of congruency, separate t-tests were performed on bivalency effect scores for each block pair. For trials following *congruent* bivalent stimuli, response slowing was only significantly different from 0 in the first block pair comparison (block 2 vs. 1: 21 ms), $t(27) = 3.23$, $p = 0.004$, but not for the later block pairs (block 4 vs. 3: -2 ms; block 6 vs. 5: -5 ms), $t(27) = 0.29$, $p = 0.774$, and $t(27) = 0.67$, $p = 0.512$. For trials following *incongruent* bivalent stimuli on the other hand, response slowing was observed for all three block pair comparisons, (block 2 vs. 1: 44 ms, $t(27) = 5.52$, $p < 0.001$; block 4 vs. 3: 15 ms, $t(27) = 2.53$, $p = 0.018$; block 6 vs. 5: 19 ms, $t(27) = 2.55$, $p = 0.017$) (see Figure 2B).

Discussion

Experiment 1B clearly replicated the results of Experiment 1A and highlighted the importance of the additional conflict produced by response incongruence in producing a block-wise response slowing. Univalent trials that followed incongruent bivalent stimuli showed a much larger and more robust response slowing than when univalent trials followed congruent bivalent stimuli, despite appearing within the same block. Thus, these findings again suggest that the bivalency effect cannot be attributed to a simple *block-wise* response slowing, as previously assumed. Furthermore, colour judgment trials showed a more robust bivalency effect over the course of the experiment than did the parity and case judgment trials when they followed incongruent (but not congruent) bivalent stimuli, consistent with Experiment 1.

A possible limitation of Experiments 1A and 1B is that because congruent and incongruent bivalent stimuli appear within the same block, there is a possibility of carry over between processes involved in the congruent and incongruent bivalency effects. For example, congruent bivalent stimuli might aid in processing the following univalent trials because the coloured appearance always cues the correct response, but the subsequent performance enhancement might be masked by the carry-over of response interference from previous incongruent bivalent stimuli in the same block. We might also expect to see that the processes following congruent bivalent stimuli are masking the costs associated with incongruent bivalent stimuli. Alternatively, it might be easier to learn to deal with incongruent bivalent stimuli if there are no congruent bivalent stimuli in the block. To shed light on these possibilities, we wished to run a blocked-design in which only incongruent bivalent stimuli appear in bivalent blocks for one group and only congruent bivalent stimuli appear in bivalent blocks for another group.

EXPERIMENT 2

Experiment two was designed to examine the influence of congruent vs. incongruent bivalent stimuli in producing the bivalency effect using a between-subjects blocked-design. Half of the subjects were assigned to a group in which the occasional bivalent stimuli (in bivalent blocks) were always incongruent, whereas the other half of participants were assigned to a group in which the occasional bivalent stimuli (in bivalent blocks) were always congruent. All other materials, apparatus, and procedures were identical to Experiments 1A.

Participants

Forty-four participants were recruited from McMaster University's Introductory Psychology and Cognition subject pool and participated in exchange for course credit. All participants had normal or corrected to normal vision.

Data analysis

A 2 X 3 X 3 mixed-measures ANOVA used group (incongruent vs. congruent) as a between-subjects variable, whereas task (colour, parity, case) and block pair (block 2-1, block 4-3, block 6-5) were used as within-subjects variables. As in experiments 1A and

1B, the bivalency effect difference score (RTs to univalent trials in pure blocks subtracted from RTs to univalent trials in bivalent blocks) was used as the dependant variable.

Results

Figure 4 provides a graphical depiction of the bivalency effect across the experiment for stimuli that followed congruent vs. incongruent bivalent stimuli, whereas bivalency effect mean differences and standard errors for each condition and each block pair are presented in Table 1.

A significant effect of group was revealed, $F(1,42) = 19.49$, $p < 0.001$, $\eta^2 = 0.317$, which can be explained by the finding that response slowing was much larger on univalent trials that followed incongruent bivalent stimuli than trials that followed congruent bivalent stimuli, as expected. A significant effect of block pair was also revealed, $F(2,84) = 6.66$, $p = 0.002$, $\eta^2 = 0.137$,which reflects the finding that a larger bivalency effect was observed for the first block pair than the last block pair, $t(21) = 4.53$, $p < 0.001$, and marginally larger for the first than the second block pair, $t(21) = 1.89$, $p = 0.073$.

A significant interaction between group and task, $F(2,84) = 3.34$, $p = 0.038$, $\eta^2 = 0.075$, indicates that the colour judgment trials show the largest response slowing when following incongruent bivalent stimuli, $t(21) = 2.69$, $p = 0.014$ (vs. parity), and $t(21) = 3.00$, $p = 0.007$ (vs. case). No differences exist between tasks that follow congruent bivalent stimuli (all $t < 0.68$, $p > 0.51$) or between case and parity trials following incongruent bivalent stimuli, $t(21) = 1.47$, $p = 0.155$.

Once again, t-tests were performed on each block pair for the congruent and incongruent groups to see if the bivalency effect was significantly greater than 0 across the experiment. The bivalency effect following *congruent* bivalent stimuli was only significantly greater than 0 for the first block pair comparison, $t(21) = 1.78$, $p = 0.045$, but not for the later block pairs, $t(21) = 0.94$, $p = 0.358$, and $t(21) = -1.16$, $p = 0.257$, whereas the bivalency effect was significantly greater than 0 for all three block pair comparisons when univalent trials followed *incongruent* bivalent stimuli, $t(21) = 4.58$, $p < 0.001$ (block 2 vs. 1), $t(21) = 2.94$, $p = 0.008$ (block 4 vs. 3), and $t(21) = 1.73$, $p = 0.049$ (block 6 vs. 5).

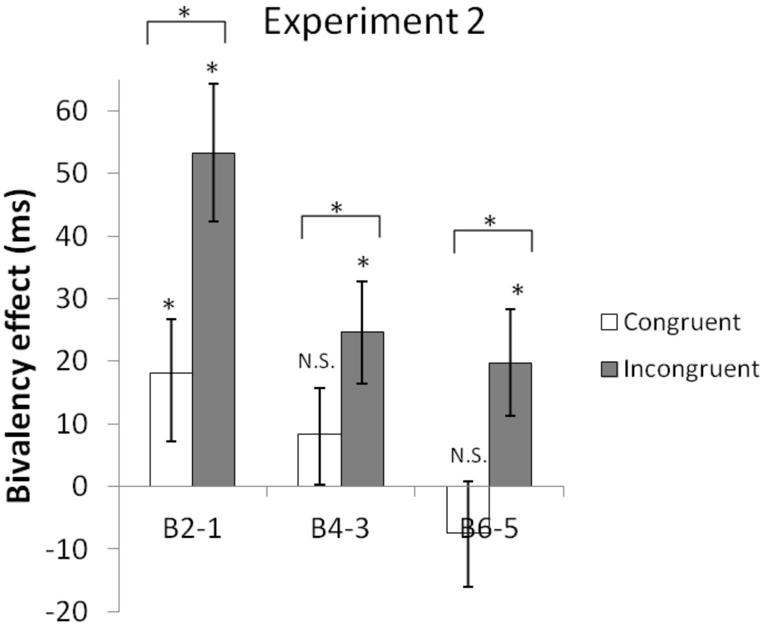


Figure 4 – The bivalency effect between two groups (congruent vs. incongruent) in Experiment 2. In the congruent group, the correct response on bivalent trials was always congruent with respect to the irrelevant feature. In the incongruent group, the correct response on bivalent stimuli was always incongruent with respect to the irrelevant feature. B2-1 = bivalency effect for the first block comparison (Block 2 – Block 1 RTs),

B4-3 = bivalency effect for the second block comparison (Block 4 – Block 3 RTs), B6-5 = bivalency effect for the last block comparison (Block 6 – Block 5 RTs). *: bivalency effect significant at $p < 0.05$, N.S.: non-significant bivalency effect. Brackets with an asterisk represent a between-groups significant effect at the $p < 0.05$ level.

GENERAL DISCUSSION

In the present study, we examined the bivalency effect – a response slowing that is triggered by the occurrence of occasional bivalent stimuli (stimuli that cue two tasks). Specifically, we examined the influence of congruent vs. incongruent bivalent stimuli on subsequent response times to univalent trials, an examination that has not yet been explored. We found that the bivalency effect was larger and more robust when trials followed incongruent bivalent stimuli than when trials followed congruent bivalent stimuli. In fact, the bivalency effect was present following congruent bivalent stimuli only at the beginning of the experiment, but not after sufficient practice. On the other hand, the bivalency effect remained throughout the entirety of the experiment when trials followed incongruent bivalent stimuli. This suggests that the bivalency effect is not merely a response to bivalence, but rather, depends to a large extent on response incongruence. We suggest that one of the major processes involved in producing the bivalency effect involves a generic response suppression that interferes with all trials following incongruent responses, a process that we call *carry-over of response interference*. These results have important implications for current theories of cognitive control as well as current bivalency effect models.

The bivalency effect has been problematic for theories of task-switching and cognitive control that rely on overlapping stimulus and/or response properties (Allport et al., 1994; Allport & Wylie, 2000; Botvinick et al., 2001; Botvinick, 2007; Botvinick et al., 2004; Braverman & Meiran, 2010; Koch & Allport, 2006; Meiran & Kessler, 2008; Meiran, Kessler, & Adi-Japha, 2008; Monsell et al., 2000; Rubinstein et al., 2001; Sohn & Anderson, 2001; van Veen et al., 2001) because they can account for the slowing observed on trials that share features with bivalent stimuli, but not for those that do not (i.e. parity decision trials). For instance, a negative priming account (D'Angelo & Milliken, 2012; Milliken, Thomson, Bleile, MacLellan, & Giammarco, 2012; Tipper, 2001; Tipper, Weaver, Cameron, Brehaut, & Bastedo, 1991) might explain the slowing of responses on colour and case judgment trials within bivalent blocks by means of association with bivalent trials, in which responses to irrelevant features must be ignored. Thus, upon presentation of case or colour judgment trials, this association with bivalent trials is retrieved and leads to a response slowing. The slowing observed on parity decision trials, on the other hand, is problematic for this account because the parity decision trials do not share any features with bivalent stimuli. Recently, Rey-Mermet & Meier (2012a) provided evidence for the idea that the bivalency effect was also independent of response set priming because the bivalency effect was still present even when each task had its own set of response keys. In other words, an association built from shared responses between univalent and bivalent trials could not account for the bivalency effect. However, in their study, each task still had a left or a right key press. In fact, each task was mapped to both the left and to the right hand. Thus, bivalent stimuli could still either be congruent or incongruent with respect to the key presses required for the relevant and irrelevant dimensions, by means of affording responses mapped to the left or right sides of space. In other words, the influence of response congruency could not be ruled out. Here, we show that response incongruence on bivalent trials is critical in producing a large and robust bivalency effect.

The most recent explanation for the bivalency effect is one of episodic context binding (Meier & Rey-Mermet, 2012; Meier et al., 2009; Rey-Mermet & Meier, 2012a, 2012b), in which the confusing block context is retrieved along with presentation of any trials within this bivalent block. However, such an account is not sufficient because we show that the slowing observed on univalent trials changes within the same block depending on the bivalent stimulus type (congruent vs. incongruent) that precedes it; in other words, the bivalency effect is not simply a block-wise effect, and block-context retrieval is not sufficient to explain the slowing observed on all univalent trials within these blocks. Rather, it appears that a carry-over of response interference plays a major role in producing the bivalency effect, especially after practice.

It is interesting that the colour judgment trials in our experiments showed the largest bivalency effect following *incongruent* bivalent stimuli, but not congruent bivalent stimuli. Because colour is always the feature that needs to be ignored on bivalent stimuli, it may be possible that the carry-over of response interference has both generic as well as specific carry-over properties. Specifically, it may be that the response suppression targets colour trials because the dimension relevant to make a correct response was inhibited earlier.

The target specific sub-component of this carry-over effect supports the notion that the bivalency effect is sensitive to conflict on a particular univalent trial, an idea recently proposed by Rey-Mermet and Meier (2012b). Interestingly however, Rey-Mermet and Meier also found evidence for the idea that the amount and source of conflict do not play a role in modulating the bivalency effect. In their bivalency effect study, the authors introduced repetition trials and found that the bivalency effect was reduced significantly for repetition trials compared to switch trials when the repetition trials did not share any features with bivalent stimuli (i.e. on parity decision tasks), but that no difference between switch and repetition trials was observed for the other two tasks. They argued that because switch trials produce a form of conflict (disengage current task and engage the next), their results provided evidence that the bivalency effect was sensitive to conflict, but neither to its amount nor to its source. This is a very interesting finding in light of our results which showed that additional conflict present on incongruent bivalent stimuli *did* modulate the bivalency effect. In fact, after sufficient practice, the bivalency effect was present following incongruent bivalent stimuli only, stimuli that provided additional conflict. We also found that the bivalency effect was sensitive to additional conflict on univalent trials (i.e. colour trials). However, there are a couple of reasons that might explain the seemingly discrepant findings between the two studies. The additional conflict produced by a task-switch versus a task-repetition may be a qualitatively different form of conflict from the conflict produced by response-set or stimulus-set retrieval. The additional conflict that we examined in the present study relies on retrieval of stimulus and response properties upon presentation of the stimulus, whereas the additional conflict on predictable task switching trials results, at least in part, on endogenous preparation before the onset of the stimulus. Thus, the bivalency effect might be sensitive to both endogenous and stimulus-driven processes, but to produce additive effects on the magnitude of the bivalency effect, both forms of conflict must be stimulus-driven. Another possibility is simply that the bivalency effect on switch trials is a qualitatively different measure from the bivalency effect on repetition trials.

From the present results, we cannot attribute the entirety of the bivalency effect to a carry-over of response interference because response slowing was also observed on trials that followed *congruent* bivalent stimuli at the beginning of the experiment (block pair 2 vs. 1). We suggest that top-down cognitive control is implemented in this case to adjust the response strategy on all trials, including those that do not share any features with congruent bivalent stimuli (i.e. on parity decisions). Such an account can be explained by the idea that an episodic context binding (Meier et al., 2009; Rey-Mermet & Meier, 2012a, 2012b) leads to an additional block-wise response slowing when it is unclear where bivalent stimuli will appear. For example, in the first bivalent block, participants cannot rule out the possibility of occasional coloured digits appearing on parity judgment trials. Upon presentation of univalent stimuli, the confusing context of the block is retrieved at the same time that the stimulus and response rules are retrieved, and this leads to a block-wise response slowing. After sufficient practice over the course of the experiment, participants become aware that bivalent stimuli will only appear on case judgment trials, and the context of bivalent blocks becomes less confusing. Hence, the retrieval of this context no longer causes interference and the influence of congruent bivalent stimuli on subsequent univalent stimuli no longer produces a response slowing. On the other hand, carry-over of response interference is present throughout the entire experiment, and appears to be resistant to practice. We suggest that episodic context retrieval explains why a bivalency effect is present at the beginning of the experiment (block 2-1) for trials that follow congruent bivalent stimuli, and why trials that follow incongruent bivalent stimuli in the beginning show a larger bivalency effect than in the later block comparisons (block 4-3, block 6-5). The carry-over of response interference appears to be more resilient to practice effects, as the bivalency effect following incongruent bivalent stimuli did not differ significantly between the later two block comparisons in all three of our experiments.

To support the aforementioned claims, we note that the bivalency effect following congruent bivalent stimuli in the *first* block comparison across all three experiments was on average 19 ms, an effect that we attribute solely to confusing context retrieval (present before sufficient practice); the bivalency effect following incongruent bivalent stimuli in the *last* block comparison was on average 20 ms, an effect that we attribute solely to a carry-over of response interference (more resilient to practice effects). If confusing context retrieval and response interference carry-over are both present in the first bivalent block, then the magnitude of the bivalency effect for the first block comparison should roughly reflect a sum of these two processes. Indeed, the magnitude of the bivalency effect in the first block comparison for trials that follow incongruent bivalent stimuli is 46 ms.

Our findings have implications for theories of incongruence as well. Current theories of response incongruence cannot explain the bivalency effect findings reported herein, mainly because most theories center around the influence of response incongruence on the trial containing the interference (e.g. *task rule congruency effect*; Koch & Allport, 2006; Meiran, 2005; Meiran & Kessler, 2008, Sudevan & Taylor, 1987) rather than trials following interference. Recently, the competitor response suppression (CRS) theory of incongruence was introduced (Meiran, Hsieh, & Dimov, 2010). This theory proposes that if response incongruence is observed on trial n-1, response suppression will be observed on trial n. However, they also stipulate that the irrelevant dimension (causing the response conflict) on trial n-1 must be the same dimension as the required response on trial n. Our data do not support this stipulation. CRS may explain the additional slowing on colour judgment trials relative to the other trials following incongruent bivalent stimuli in the present experiments; but we also found a response slowing on *all* decision trials following incongruent bivalent stimuli, including trials whose relevant dimension was not the dimension causing conflict on bivalent stimuli (i.e. on case and parity tasks), and on trials that do not share any features at all with bivalent stimuli (i.e. on the parity task). A possible explanation for the discrepancy between our study and that of Meiran et al. (2010) can be understood in light of the fact that all of their trials were bivalent trials, whereas we measured our effect of incongruence on univalent trials only. Thus, from the start, an additional source of conflict was present on all trials that followed their incongruent bivalent stimuli. The additional conflict present on these trials may have masked the contribution of a response interference carry-over. Consistent with this idea, a recent study showed that post-conflict slowing is masked when bivalent compared to univalent stimuli are the trials being measured (Verguts, Notebaert, Kunde, & Wühr, 2011). The fact that we showed a significant response slowing on all trials following incongruent bivalent stimuli (relative to congruent bivalent stimuli) suggests the existence of a non-specific carry-over of response interference after encountering incongruent bivalent stimuli. We suggest that future models of response incongruence incorporate the role of target general (i.e. target does not have to be a dimension previously suppressed) carry-over of response interference as well as the target-specific (e.g. CRS) carry-over of response interference.

It is important to understand how these findings might fit with current models of anterior cingulate cortex (ACC), a center that we know to be highly involved in the control observed in the bivalency effect (Grundy et al., 2011; Woodward et al., 2008). A prominent ACC control theory, conflict monitoring (Botvinick et al., 2001; Botvinick, 2007; Botvinick et al., 2004; Cohen, Botvinick, & Carter, 2000; van Veen & Carter, 2002; van Veen et al., 2001), suggests that the role of the ACC is to detect simultaneous activation of conflicting processing pathways, which then recruits other centers (e.g. dorsolateral prefrontal cortex; DLPFC) to implement subsequent changes in response strategy. This theory cannot explain a number of bivalency effect findings, including both behavioural and neurophysiological observations. For instance, increased ACC activation on univalent trials within a bivalent block (relative to univalent trials in univalent blocks) is problematic for conflict monitoring because there is no conflict on univalent trials (Grundy et al., 2011; Woodward et al., 2008). Furthermore, conflict monitoring suggests that conflict on a particular trial leads to a subsequent focus on task-relevant features, and this aids in performance when a similar conflict trial appears (Botvinick et al., 2001; Compton, Huber, Levinson, & Zheutlin, 2012; Mayr, Awh, & Laurey, 2003; Ullsperger, Bylsma, & Botvinick, 2005). It is unclear why a post-conflict response slowing should be observed on univalent trials, especially when these trials contain no conflict and have no features in common with bivalent trials. In other words, conflict monitoring does not obviously predict why an increase of attention on case features should lead to performance slowing on parity decision trials, because these trials have no ambiguity to be resolved. An alternative influential perspective for ACC activity is one of outcome evaluation (Bush et al., 2002; Nieuwenhuis, Yeung, Holroyd, Schurger, & Cohen, 2004), in which the ACC is particularly active in response to negative outcomes in order to motivate decision making. Again however, increased ACC activity on univalent trials in bivalent compared to univalent blocks is problematic because these trials are exactly the same other than the fact that they do or do not appear within a block containing occasional bivalent stimuli.

A couple of very recent ACC models stipulate that rather than the ACC being responsible for the minutia of conflict detection and motivation of single tasks, the ACC has a larger role in motivating extended behaviours over time (Holroyd & Yeung, 2012) and predicting future cognitive load based on current and recent demands (Sheth et al., 2012). By these views, it is clear why one might expect to see more ACC activity on univalent trials within bivalent (compared to univalent) blocks. For instance, when a bivalent stimulus, which by definition contains conflict, appears within a block, the ACC records this conflicting information and future predicted cognitive load is increased. Thus, on univalent trials within bivalent blocks, the predicted future cognitive load should be larger than when trials appear within purely univalent blocks, and more ACC activity should be observed; this is indeed what is found (Grundy et al., 2011; Woodward et al., 2008). In light of the present results, we expect that more ACC activity would be observed on univalent trials that follow incongruent than trials that follow congruent bivalent stimuli because future predicted cognitive load should be increased following the encoding of additional (response) conflict on incongruent bivalent stimuli. Future fMRI and electroencephalography studies should be conducted to examine these predictions.

CONCLUSION

The present study examined factors that influence the bivalency effect – a block-wise response slowing observed during task-switching in response to the occasional presence of bivalent stimuli. Whereas past research has focused on the robustness of the effect and the neural mechanisms involved, we present data that bring to light the stimulus and response properties that elicit the effect. We suggest that there are two important components contributing to the bivalency effect: 1) Episodic context retrieval of confusing task demands in bivalent blocks (Meier et al., 2009; Rey-Mermet & Meier, 2012a, 2012b), and 2) Carry-over of response interference. These findings clearly demonstrate that the bivalency effect is not simply a block-wise response slowing, as previously believed (Grundy et al., 2011; Meier & Rey-Mermet, 2012; Meier et al., 2009; Rey-Mermet & Meier, 2012a, 2012b; Woodward et al., 2003, 2008)

The response slowing as a result of confusing context retrieval appears to be short lived and is only present at the beginning of the experiment when participants are unsure of where bivalent stimuli will appear. On the other hand, carry-over of response interference reflects a process by which a non-specific response suppression is carried over to univalent trials in response to incongruent bivalent stimuli, and appears to be more resilient to practice effects. These findings have important implications for future directions in bivalency effect research because response incongruence clearly plays an imperative role and has not been examined until now. Furthermore, our results suggest that future models of response congruency effects should take into account non-specific as well as feature-targeted influences of response incongruence.

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CHAPTER 5

The following chapter is a submitted manuscript. Permission to use the article in my thesis will be sought upon acceptance for publication.

Reference

Grundy, J. G., & Shedden, J. M. (submitted). Electrophysiological correlates of expectancy, response conflict and task-cueing in the bivalency effect.

Preamble

I designed chapter five in an attempt to tie all of the other chapters together, and to come up with a coherent theoretical framework for the bivalency effect. Specifically, I designed an event-related potential study in which I could examine the processes engaged in response to a violation of expectancy (using unexpected univalent stimuli), feature-cueing (using congruent bivalent stimuli), and response-cueing (using incongruent bivalent stimuli). The electrophysiological recordings allowed me to compare and contrast the processes engaged by all three stimulus types with millisecond temporal resolution, and helped provide additional information about hypothesized brain regions and processing that is not apparent from the behavioural data alone.

Electrophysiological correlates of expectancy, response conflict and task-cueing in the bivalency effect

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ABSTRACT

In the present study, we examine electrophysiological correlates of factors influencing a block-wise adjustment in cognitive control known as the bivalency effect. During task-switching, the occasional presence of bivalent stimuli amongst a block of univalent trials is enough to elicit a response slowing on all subsequent univalent trials. Recently, we showed that incongruent bivalent stimuli (in which the relevant and irrelevant dimensions cue conflicting responses) elicit a larger and more robust bivalency effect than congruent bivalent stimuli; we attributed this to a carry-over of response inhibition (Grundy & Shedden, submitted). In contrast, congruent bivalent stimuli appear to produce a response slowing that is similar in magnitude to a block-wise response slowing that can be elicited by non-bivalent unexpected stimuli. Here we show that the incongruent bivalency effect is distinguished from both the congruent bivalency and unexpectedness effects at a frontal component (350-390 ms) associated with dACC activity, and that the unexpectedness effect is distinguished from both congruent and incongruent bivalency effects at an earlier component (100-120 ms) in temporal parietal scalp regions. We suggest that the frontal component reflects an inhibitory process, whereas the posterior component may index early visual feature extraction in response to the occasional presence of bivalent (but not unexpected univalent) stimuli; dACC activity may trigger the temporal parietal activity only when specific task cueing is involved. Implications for bivalency effect research, congruency theories, and electrophysiological correspondence are discussed.

INTRODUCTION

The bivalency effect refers to a block-wise adjustment in cognitive control in response to the occasional presence of bivalent stimuli (Grundy et al., 2011; Meier, Woodward, Rey-Mermet, & Graf, 2009; Rey-Mermet & Meier, 2011, 2012; Woodward, Meier, Tipper, & Graf, 2003; Woodward, Metzak, Meier, & Holroyd, 2008). This adjustment is characterized by a slowing of response to all trials within the block, even when these trials contain no features that overlap with the bivalent stimuli. This effect is robust (Meier et al., 2009) and recent neuroimaging and electrophysiological studies have suggested a role for the anterior cingulate cortex in modulating the top-down control (Grundy et al., 2011; Woodward et al., 2008).

More recently, we identified some of the stimulus and response properties that contribute to the magnitude of the bivalency effect. For one, unexpected but non-bivalent stimuli can elicit a block-wise response slowing (Grundy et al., submitted), suggesting that violations of expectancy may contribute to the engagement of processes leading to the bivalency effect. However, this effect appears to be smaller in magnitude than the response slowing typical of bivalency effect studies, suggesting that bivalent stimuli engage additional processes leading to the bivalency effect. Consistent with this idea, we have also shown a strong influence of response congruency. When incongruent response mappings were cued on bivalent stimuli a larger response slowing was observed on subsequent univalent trials compared to when the irrelevant feature on bivalent stimuli cued the correct response (i.e. when the bivalent stimuli were congruent) (Grundy &

Shedden, submitted). We further showed that the response slowing following incongruent bivalent stimuli was resistant to practice, whereas the response slowing following congruent bivalent stimuli was eliminated after the first bivalent block.

There is a similarity in the behavioural response to non-bivalent unexpected stimuli and the response to congruent bivalent stimuli, both of which are distinct from the response to incongruent bivalent stimuli. It is possible that non-bivalent unexpected stimuli and congruent bivalent stimuli lead to an adjustment in response style that is modulated in a similar fashion by the dACC. Both stimulus types of stimuli are likely to be unexpected when initially encountered, and this may trigger a re-evaluation of task demands when there is uncertainty about when the surprising stimuli will appear. After sufficient practice however, participants may learn that occasional surprising stimuli will only appear on one of the tasks and re-evaluation of all task demands is no longer necessary; this effectively eliminates the continuing need for more careful processing on all trials. Alternatively, it is possible that the response slowing triggered by congruent bivalent stimuli taps into separate processes than the ones engaged by non-bivalent unexpected stimuli. For example, the cueing of two task-sets, beyond the influence of response conflict, may engage separate processes from those engaged by non-bivalent unexpected stimuli.

In the present study, we directly examined the influence of congruent bivalent, incongruent bivalent and non-bivalent unexpected stimuli on a block-wise adjustment in response style using event-related potentials (ERPs). The electrophysiological recordings allow us to compare and contrast the processes engaged by all three stimulus types with millisecond temporal resolution, and may provide additional information about hypothesized brain regions and processing that is not apparent from the behavioural data alone.

In a previous ERP study of the bivalency effect (Grundy et al., 2011), two frontal components were identified that captured the processing differences due to the bivalency effect between 375-550 ms after stimulus onset; this difference was reflected by a smaller amplitude negativity for the univalent stimuli in bivalent blocks versus univalent blocks. Using source modeling, we localized this activity to the dACC (Grundy et al., 2011). The involvement of the dACC is consistent with an fMRI study of the bivalency effect (Woodward et al., 2008).

If non-bivalent unexpected stimuli and congruent bivalent stimuli engage the same processes, then we should see a similar pattern of responses both behaviourally and electrophysiologically. If this is the case, then it suggests that a key process engaged during the bivalency effect is a response to unexpectedness, beyond the influence of cueing two tasks. On the other hand, responses to univalent stimuli that follow incongruent bivalent stimuli should show a different pattern of responses because of the additional processes engaged by response incongruence. We suspect that the response slowing observed after encountering incongruent bivalent stimuli will be greatest, that it will not be eliminated after practice with unexpected stimuli, and that this will be reflected by dACC activity captured by frontal electrode sites between 375-550 ms after stimulus onset.

In the present study, participants were presented with six experimental blocks consisting of one block in which occasional bivalent stimuli appeared on case judgment trials and one block in which occasional non-bivalent unexpected stimuli appeared on case judgment trials. Both surprising block types were flanked by pure blocks in which only expected univalent stimuli appeared, resulting in two types of block sets. This allowed us to examine practice effects. If congruent bivalent stimuli and non-bivalent unexpected stimuli engage the same processes, then practice with one surprising block-type (whether congruent or unexpected) should be sufficient to eliminate the response slowing because there is no longer a need to re-evaluate task demands. We hypothesized that this practice effect would be observed for the influence of non-bivalent unexpected stimuli and congruent bivalent stimuli, but that the additional response conflict present on incongruent bivalent stimuli would result in an adjustment of response style that is reduced, but not eliminated after practice. These differences should be reflected behaviourally in the RTs and electrophysiologically in the ERPs at frontal electrode sites between 375-550 ms after stimulus onset, consistent with the ERP results from Grundy et al. (2011).

METHODS

Participants

Eighteen undergraduate students were recruited from McMaster University's Introductory Psychology and Cognition subject pool and participated in exchange for course credit. All participants had normal or corrected to normal vision. All procedures complied with the Canadian tri-council policy on ethics and were approved by the McMaster Ethics Research Board.

Materials and apparatus

All stimuli were presented on a black background on a 17-inch CRT monitor at a distance of 80 cm from participants. A chinrest was used to maintain consistent viewing distance between participants. Presentation® experimental control software (Neuro Behavioural Systems; version 11) was used to present the stimuli and the refresh rate on the monitor was set to 85 Hz. Stimuli were presented in the center of the screen with the height of each stimulus subtending a visual angle of 1.26˚. For colour decisions, shapes (square, triangle, circle, pentagon) were presented in either red or blue. For parity decisions, numbers 1-8 were displayed in white (60-point, Times New Roman). Case decisions were presented as uppercase or lowercase letters (a, b, d, e) in white (60-point, Times New Roman).

In the bivalent block, occasional case judgment trials were presented randomly in red or blue. Some of these stimuli were response congruent (matching responses between case and colour), and some response incongruent bivalent stimuli. In the unexpected block, occasional case judgment trials were presented randomly in Chopin or Old English font, making these stimuli non-bivalent unexpected stimuli with no response incongruency. All participants completed the experiment individually in a dimly lit room.

Procedure

Each block contained 168 trials. Within bivalent (or unexpected) blocks, 16 of the case judgment trials appeared in red or blue (or Chopin or Old English), making these stimuli bivalent (or non-bivalent unexpected stimuli). Trial sequence always proceeded predictably from colour judgments (red shape vs. blue shape) to parity judgments (odd vs. even) to case judgments (lowercase vs. uppercase); participants responded by pressing one of two response keys (see Figure 1 for an example of the trial sequence). Using the index and middle fingers of the right hand, participants pressed a left key in response to lowercase letters, odd digits, and blue shapes, and a right key in response to uppercase letters, even digits, and red shapes (response mapping counterbalanced across participants).

Two practice blocks were presented at the beginning of the experiment in which only univalent expected stimuli for the three tasks appeared. Six experimental blocks followed this, consisting of one bivalent and one unexpected block, each flanked by pure blocks in which only expected univalent stimuli appeared, resulting in two types of block sets: the bivalency block set (pure, bivalent, pure) and the unexpected block set (pure, unexpected, pure). Participants were randomly assigned so that the bivalent block set or the unexpected block set was encountered first; thus block set order was manipulated as a between-subjects variable. We refer to the first three experimental blocks encountered in the design (pure, bivalent or unexpected, pure) as the *first block set*, and the last three experimental blocks (pure, bivalent or unexpected, pure) as the *second block set*. Within each block, participants were given accuracy feedback after every 12 trials. This helped participants remain focused and accurate and provided a blink break, critical to obtaining clean event-related potentials (ERPs) during the trials. Stimuli remained on the screen until response or until 1500 ms elapsed, after which point the message “too slow” appeared on the screen, encouraging participants to maintain speed as well as accuracy. The inter-trial interval was randomly varied between 400-900 ms, which allowed us to reduce distortion of ERP components due to averaging of epochs that overlap in time (Woldorff, 1993).

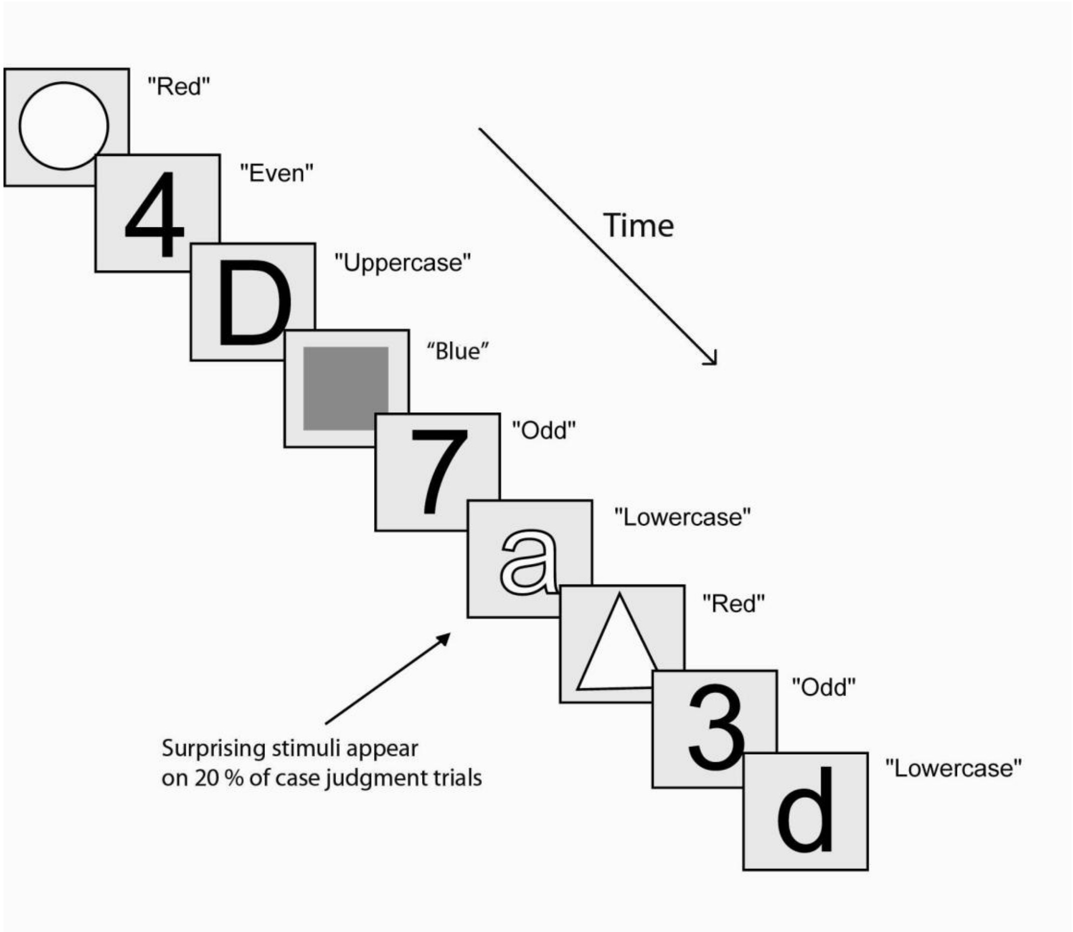

Figure 1 - Illustration of the trial sequence and type of stimuli used in the present study. This particular illustration is an example from a surprising block. The words appearing beside the stimuli represent correct responses. During the surprising block (bivalent or unexpected), surprising stimuli appear on 20% of all case judgment trials. Surprising stimuli do not appear at all during the pure blocks (blocks 1 and 3, and blocks 4 and 6). In the grey-scale diagram we use white to represent the red stimulus and grey to represent the blue stimulus. The white letter represents the surprising stimulus (e.g., blue or red for bivalent blocks; Chopin or Old English font for unexpected blocks)

Electrophysiological Recordings

The ActiveTwo Biosemi electrophysiology system (www.biosemi.com) was used to record continuous electroencephalographic (EEG) activity from 128 Ag/AgCl scalp electrodes plus 4 additional electrodes placed at the outer canthi and just below each eye for recording of horizontal and vertical eye movements. Two additional electrodes, common mode sense (CMS) active electrode and driven right leg (DRL) passive electrode were also used. These electrodes replace the "ground" electrodes used in conventional systems (www.biosemi.com/faq/cms&drl.htm). The continuous signal was acquired with an open pass-band from DC to 150 Hz and digitized at 512 Hz. The signal was bandpass filtered off-line at 0.3 to 30 Hz and rereferenced to a common average reference. Offline signal processing and averaging were done using EEProbe (www.ant-nero.com). Voltage maps were created using Brain Electrical Source Analysis (BESA; version 5.1.8; www.besa.de) by MEGIS Software GmbH. Eye blinks and movement artifacts were automatically identified and manually verified. EEProbe signal processing software was used to apply a correction procedure; eye movement prototypes were estimated for each individual and movement artifacts were subtracted across the electrode array based on calculated VEOG propagation factors via a regression algorithm. Each corrected waveform was verified manually; epochs containing eye-blinks or movements that could not be adequately corrected were rejected from the analyses. Paired-samples t-tests were then performed on the time windows of interest based on visual inspection and correspondence with our previous ERP results (Grundy et al., 2011) and present hypotheses. Of particular interest was a medial frontopolar electrode cluster (Fpz, AFz, AF4, and AF3), and electrodes near temporal-parietal scalp regions (left hemisphere: P5, P7, PO7; right hemisphere: P6, P8, and PO8). We previously noted that these electrode clusters are associated with dACC and temporal parietal junction (TPJ) activity that capture bivalency effect processes (Grundy et al., 2011). Our focus on these regions is based on electrophysiological studies on task-switching and conflict (e.g. Grundy et al., 2011; Meiran, Hsieh, & Chang, 2011; Poulsen, Luu, Davey, & Tucker, 2005) as well as correspondence with fMRI work on the bivalency effect (Woodward et al., 2003).

RESULTS

The bivalency effect is calculated as the RT difference between univalent trials presented in purely univalent blocks and univalent trials presented in blocks that contain occasional bivalent stimuli. A similar calculation is done for the unexpectedness effect (Grundy et al., submitted), which is the RT difference between univalent trials in pure blocks in which only expected univalent trials appear and univalent trials that appear in blocks in which occasional unexpected univalent stimuli are encountered. Responses to the bivalent stimuli and to the non-bivalent unexpected stimuli are not included in the RT means, the accuracy analyses, or the ERP analyses; therefore all behavioural and ERP analyses involve responses to univalent, expected stimuli only. The important contrasts are based on the context in which those trials occur.

To simplify the discussion in the results section, we will distinguish between the critical conditions as follows. Trials and responses that occur in the univalent blocks contain only univalent, expected trials (pure blocks that flank the bivalent and unexpected blocks). Uni-biv-congruent and uni-biv-incongruent refer to the univalent trials and responses that follow the occasional congruent or incongruent bivalent stimuli, respectively, in bivalent blocks. Uni-unexpected refers to the univalent trials and responses that follow the occasional unexpected, univalent stimuli in the unexpected blocks. Thus, the congruent bivalency effect and the incongruent bivalency effect are calculated as a block-wise slowing in response times calculated as the uni-biv-congruent or the uni-biv-incongruent responses, respectively, in bivalent block 2 (or bivalent block 5, depending on block set order) minus the average of the responses in the pure univalent blocks 1 and 3 (or blocks 4 and 6, depending on block order). Similarly, the unexpectedness effect represents a block-wise slowing in response times calculated as the uni-unexpected responses in unexpected block 5 (or unexpected block 2, depending on block order) minus the average of univalent responses in the pure univalent blocks 4 and 6 (or blocks 1 and 3, depending on block order).

Two separate mixed-measures ANOVAs were performed on accuracy and response time to directly compare the congruent and incongruent bivalency effect scores to the unexpectedness effect scores, using block-set order as a between-subjects variable. We performed two separate ANOVAs for the congruent and incongruent bivalency effects because the univalent trials (in univalent blocks) used for calculating these effects were shared; remember that the bivalency effect is calculated as the response time difference between uni-biv (congruent or incongruent) and univalent trials in pure blocks. The first ANOVA examined the block-wise response slowing for uni-biv-congruent compared to uni-unexpected responses: 2 (block-set order: congruent first vs. unexpected first) x 3 (task: colour, parity, case) x 2 (block-set type: congruent vs. unexpected). The second ANOVA examined the block-wise response slowing for uni-biv-incongruent compared to uni-unexpected responses: 2 (block-set order: incongruent first vs.

unexpected first) x 3 (task: colour, parity, case) x 2 (block-set type: incongruent vs. unexpected). To assess whether the bivalency and unexpectedness effects were significantly different from 0, we performed t-tests for each condition.

For repeated-measures analysis of factors involving more than two levels, the Greenhouse-Geisser correction was used, in which case epsilon and the adjusted *p* and epsilon values are reported along with the original degrees of freedom. Bonferroni adjustment was applied for multiple comparisons. Furthermore, outliers were defined as being greater than three standard deviations above or below the mean and were eliminated from all further analyses.

Behavioural (Accuracy)

Accuracy did not differ across conditions (< 9 % error). The first ANOVA examined block-set order by task by block-set type, where block-set type contrasted the congruent bivalency effect with the unexpected effect. The second ANOVA consisted of the same factors but contrasted the incongruent bivalency effect with the unexpected effect. No effects reached significance for either ANOVA (all $p > 0.100$).

Behavioural (RTs)

We first assessed the statistical significance of the congruent bivalency effect, the incongruent bivalency effect, and the unexpectedness effect (Figure 2). These difference scores were subjected to one-sample t-tests to determine whether they were significantly different from 0. The congruent bivalency effect and the unexpectedness effect were significantly different from 0 in the first block set, $t(8) = 2.48$, $p = 0.019$, and $t(8) = 3.87$, $p = 0.003$, respectively, but not in the second block set, $t(8) = 1.07$, $p = 0.151$, and $t(8) = 1.32$, $p = 0.110$, respectively. In contrast, the incongruent bivalency effect was significant in both the first and second block sets, $t(8) = 5.52$, $p < 0.001$ and $t(8) = 2.52$, $p = 0.018$, respectively.

The first ANOVA examined block-set order by task by block-set type, where block-set type contrasted the congruent bivalency effect with the unexpectedness effect. Block-set type interacted with block-set order, $F(1, 16) = 10.21$, $p = 0.003$, $\eta^2 = 0.390$, as well as with task, $F(2, 32) = 5.66$, $\varepsilon = 0.881$, $p = 0.004$, $\eta^2 = 0.261$. No other main effects or interactions were significant ($p > 0.1$). As expected, pairwise comparisons for the block-set type by block-set order interaction showed practice effects across the first and second block sets. Response slowing was greater for uni-biv-congruent trials compared to trials in univalent blocks that appeared in the first block set (20 ms) versus the slowing observed for uni-biv-congruent trials (-16 ms), $t(8) = 1.77$, $p = 0.059$ (marginal effect), or uni-unexpected trials (- 6 ms), $t(8) = 2.49$, $p = 0.019$, that appeared in the second block set. There was also a greater response slowing for uni-unexpected trials that appeared in the first block set (32 ms) compared to uni-biv-congruent trials, $t(8) = 2.76$, $p = 0.013$, or uni-unexpected trials, $t(8) = 4.44$, $p = 0.001$, in the second block set.

Pairwise comparisons for the block-set type by task interaction revealed three observations. The colour task showed a larger unexpectedness effect compared to the unexpectedness effect for the parity task, $t(8) = 3.08$, $p = 0.015$, and compared to the congruent bivalency effect for the case task, $t(8) = 3.57$, $p = 0.007$. Within the case task, the unexpectedness effect was larger than the congruent bivalency effect, $t(8) = 3.00$, $p = 0.017$. None of the other comparisons were significant.

The second ANOVA examined block-set order by task by block-set type, where block-set type compared the incongruent bivalency effect with the unexpectedness effect. This analysis revealed a significant main effect of block-set type, $F(1, 16) = 10.29$, $p = 0.005$, $\eta^2 = 0.391$, in which the incongruent bivalency effect was larger than the unexpectedness effect (40 ms vs. 13 ms), $t(8) = 3.39$, $p = 0.005$.

A significant main effect of task, $F(2, 32) = 4.62$, $\varepsilon = 0.901$, $p = 0.017$, $\eta^2 = 0.224$, can be explained by a greater response slowing for the colour task (39 ms) than the parity task (17 ms), $t(8) = 2.41$, $p = 0.021$, and a slightly larger (albeit non-significant) response slowing for colour compared to case judgment trials (24 ms), $t(8) = 1.46$, $p = 0.091$.

There was also a significant block-set type by block-set order interaction, $F(1, 16) = 20.56$, $p < 0.001$, $\eta^2 = 0.562$. Pairwise comparisons showed an effect of practice across the first and second block sets: both the incongruent bivalency effect and the unexpectedness effect were larger in the first block set than in the second block set (59 ms vs. 21 ms: $t(8) = 2.20$, $p = 0.032$, and 32 ms vs. -6 ms: $t(8) = 4.44$, $p = 0.001$, respectively). When the bivalent block is encountered before the unexpected block, the incongruent bivalency effect is larger than the unexpectedness effect (59 ms vs. -6 ms: $t(8) = 5.21$, $p < 0.001$), but the reverse is not true; when the unexpected block is encountered before the bivalent block, the unexpectedness effect is not larger than the incongruent bivalency effect (32 ms vs. 21 ms, $p > 0.05$). Moreover, the incongruent bivalency effect was larger than the unexpectedness effect when both are presented in the second block set (21 ms vs. -6 ms: $t(8) = 3.94$, $p = 0.002$), and marginally larger when both are presented in the first block set (59 ms vs. 32 ms: $t(8) = 1.56$, $p = 0.081$).

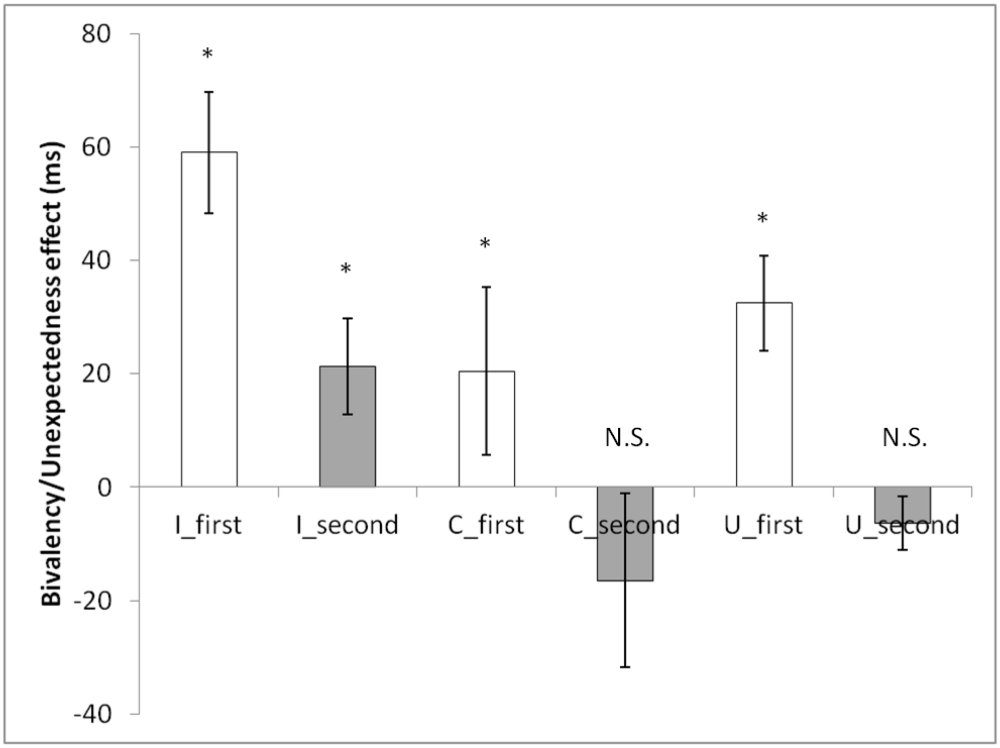

Figure 2 – Block-wise response slowing observed in response to congruent bivalent stimuli (C), incongruent bivalent stimuli (I), and non-bivalent unexpected stimuli (U) throughout the experiment. Block order was as follows: pure, surprising, pure, pure, surprising, pure. The bivalency/unexpectedness effect is calculated by subtracting the responses to univalent stimuli in the blocks flanking a surprising block to the expected univalent stimuli within that surprising block. First: these responses appeared in the first of the two surprising blocks. Second: these responses appeared in the second of the two surprising blocks (i.e. after practice with the first block set). * = bivalency/unexpectedness effect significantly different from zero. N.S. = non-significant.

Electrophysiological results (300-550 ms)

The bivalency/unexpectedness effects (differences in amplitudes between uni-biv trials and trials in purely univalent blocks) were captured by amplitude differences between 300-550 ms after stimulus onset at a frontal electrode cluster (Fpz, AFz, AF4, and AF3), consistent with our previous bivalency effect study (Grundy et al., 2011). Figure 3 provides an illustration of the waveforms for each stimulus type in the first and second block sets, and Figure 4 provides an illustration of the frontopolar topography of this late component between 350-390 ms.

Amplitude differences between trials that followed *congruent* bivalent stimuli compared to trials in purely univalent blocks appeared within the first block set between 350-400 ms. Responses to uni-biv-congruent trials showed a less negative amplitude than trials in pure blocks (-3.43 µV vs. -3.97 µV), *t*(8) = -2.10, *p* = 0.039. On the other hand, the amplitude differences between these trial types were not apparent within this time frame when the bivalent block appeared in the second block set (-4.36 µV vs. -3.60 µV), *t*(8) = 1.30, *p* = 0.232.

Amplitude differences between trials that followed *unexpected* univalent stimuli compared to trials in purely univalent blocks appeared within the first block set between 350-500 ms. Less negative amplitudes were revealed for uni-unexpected trials than univalent trials in pure blocks (-1.76 µV vs. -3.20 µV), *t*(8) = 2.28, *p* = 0.025. No differences within this time frame were found when uni-unexpected trials appeared in the second block set (-4.56 µV vs. -3.84 µV), *t*(8) = 0.82, *p* = 0.441.

The incongruent bivalency effect was captured following *incongruent* bivalent stimuli at frontal electrodes within a time window of 300-550 ms after stimulus onset when the first block set was bivalent. This component was the broadest of all the components and showed the largest difference of all the conditions. Uni-biv-incongruent trials showed a less negative amplitude than trials in pure blocks, (-2.17 µV vs. -3.97 µV), $t(8) = 2.72$, $p = 0.013$. Contra to uni-biv-congruent and uni-unexpected trials, uni-biv-incongruent trials in the second block set captured processing differences at 325-390 ms after stimulus onset. Less negative amplitude was observed for uni-biv-incongruent trials than trials in pure blocks, (-2.19 µV vs. -2.84 µV), $t(8) = 1.94$, $p = 0.040$ (see Figure 3).

Because all three stimulus types (uni-biv-congruent, uni-biv-incongruent, uni-unexpected) were associated with the block-wise response slowing in the first block set between 350-390 ms after stimulus onset, these amplitude difference scores (bivalency/unexpectedness effect) were subjected to a 2 (block-set order: bivalent first vs. unexpected first) x 2 (block-set type: bivalent vs. unexpected) mixed measures ANOVA for both the congruent vs. unexpected and the incongruent vs. unexpected comparisons.

For uni-biv-congruent vs. uni-unexpected, a significant interaction between block-set order and block-set type was revealed, $F(1, 16) = 3.68$, $p = 0.035$, $\eta^2 = 0.187$. No main effects reached significance ($F < 1$, $p > 0.7$). As expected, pairwise comparisons for the block-set type by block-set order interaction showed practice effects across the first and second block sets. Amplitude differences were greatest for uni-unexpected trials when they appeared within the first block set compared to uni-unexpected trials, $t(8) = 1.83$, $p = 0.050$, or uni-biv-congruent trials, $t(8) = 2.19$, $p = 0.031$, in the second block set. There were also greater amplitude differences for uni-biv-congruent trials when they appeared within the first block set compared to uni-biv-congruent trials, $t(8) = 3.43$, $p = 0.005$, or uni-unexpected trials, $t(8) = 2.06$, $p = 0.035$, in the second block set.

The same mixed-measures ANOVA was performed for amplitude differences between pure blocks and unexpected vs. incongruent blocks. A main effect of block-set type, $F(1, 16) = 3.65$, $p = 0.037$, $\eta^2 = 0.186$, and a block-set type by order interaction, $F(1, 16) = 3.43$, $p = 0.041$, $\eta^2 = 0.177$, was revealed. The block-set type effect can be explained by the finding that a larger amplitude difference was observed for uni-biv-incongruent than uni-unexpected trials, $t(8) = 2.06$, $p = 0.035$.

Pairwise comparisons for the interaction showed an effect of practice: both the incongruent bivalency effect and the unexpectedness effect were larger when encountered in the first compared to the second block set, $t(8) = 1.50$, $p = 0.080$ (marginal) and $t(8) = 2.55$, $p = 0.017$, respectively. When the bivalent block is encountered before the unexpected block, the incongruent bivalency effect is larger than the unexpectedness effect, $t(8) = 3.97$, $p = 0.002$, but the reverse is not true; when the unexpected block is encountered before the bivalent block, the unexpectedness effect is not larger than the incongruent bivalency effect ($p = 1$). Moreover, the incongruent bivalency effect was larger than the unexpectedness effect when both were presented in the second block set, *t*(8) = 2.14, *p* = 0.032, and marginally larger when both were presented in the first block set, *t*(8) = 1.61, *p* = 0.073.

Note that when we plot the amplitude difference scores for the three stimulus types within this time window (350-390 ms), we obtain an image that reflects a similar pattern of data to that of the behavioural responses (see Figure 5).

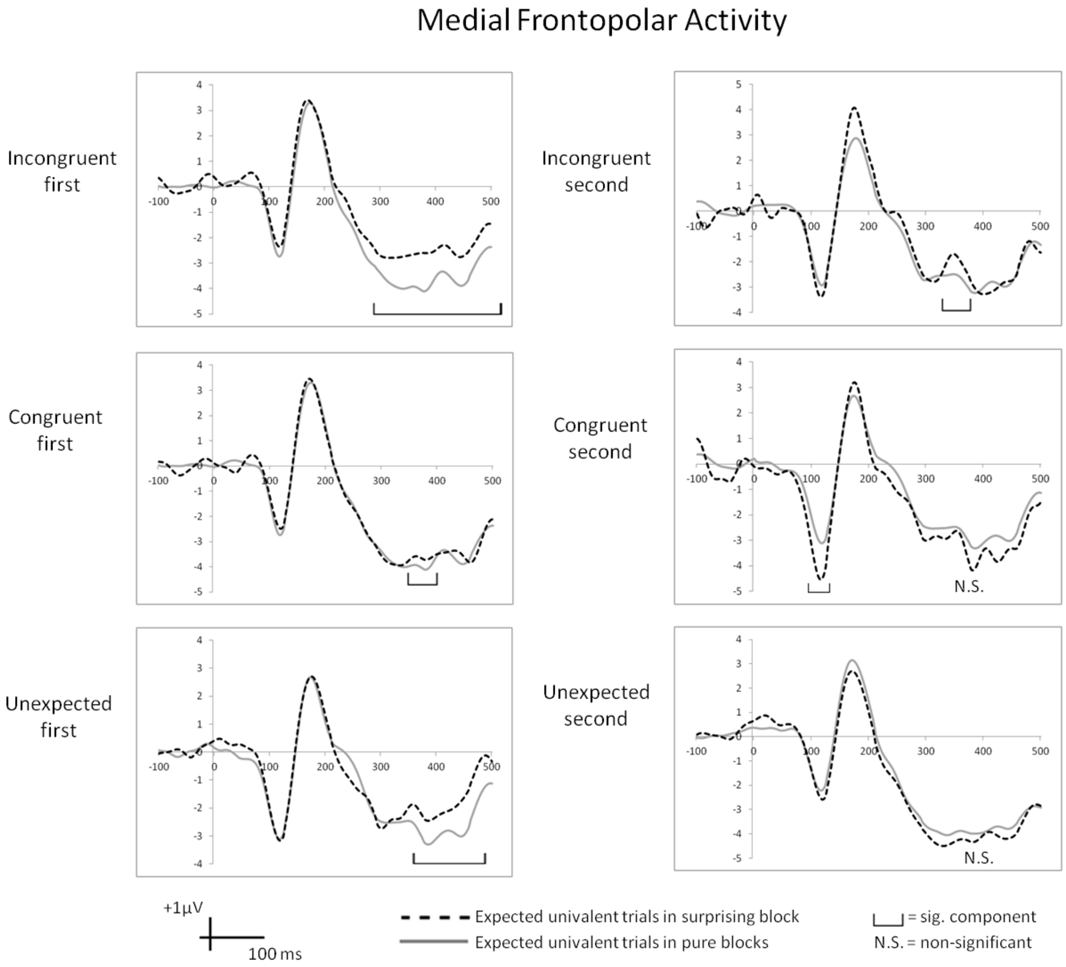

Figure 3 – Event-related potentials capturing processing differences between expected univalent stimuli that appear in pure vs. surprising blocks. The leftmost figures represent processing differences when the surprising stimulus type appears in the first block set, whereas the rightmost figures represent processing differences when the surprising stimuli appear in the second block set (i.e. after practice with the first block set).

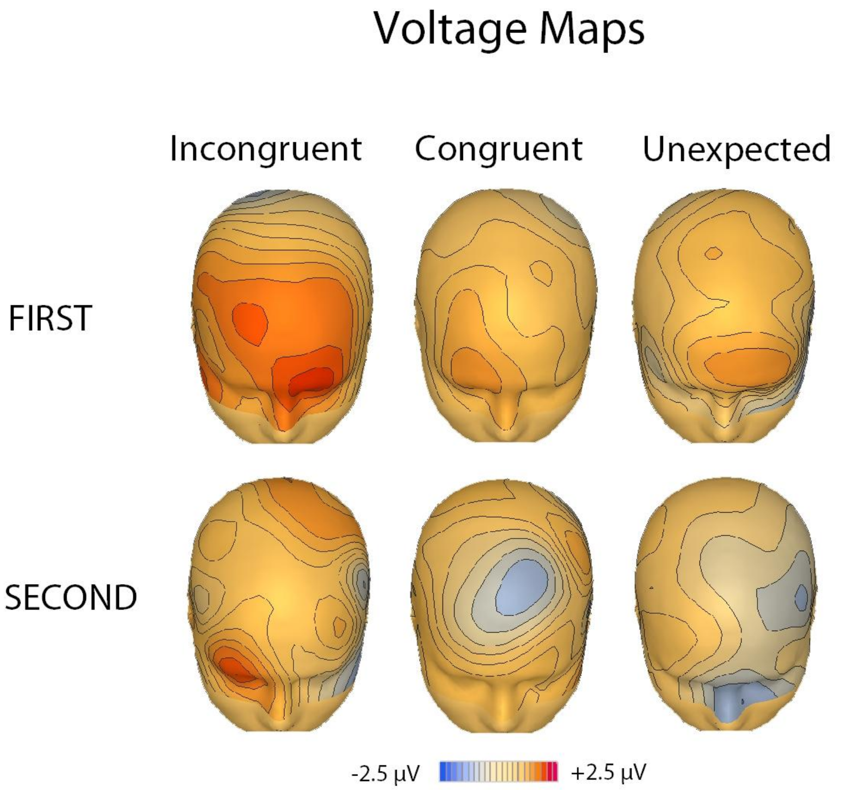

Figure 4 – Voltage topographies for amplitude differences capturing the bivalency/unexpectedness effect within 350-390 ms after stimulus onset for the univalent trials that followed incongruent, congruent, or unexpected trials. First: amplitude differences in the first block set. Second: amplitude differences in the second block set (i.e. after practice with the first block set).

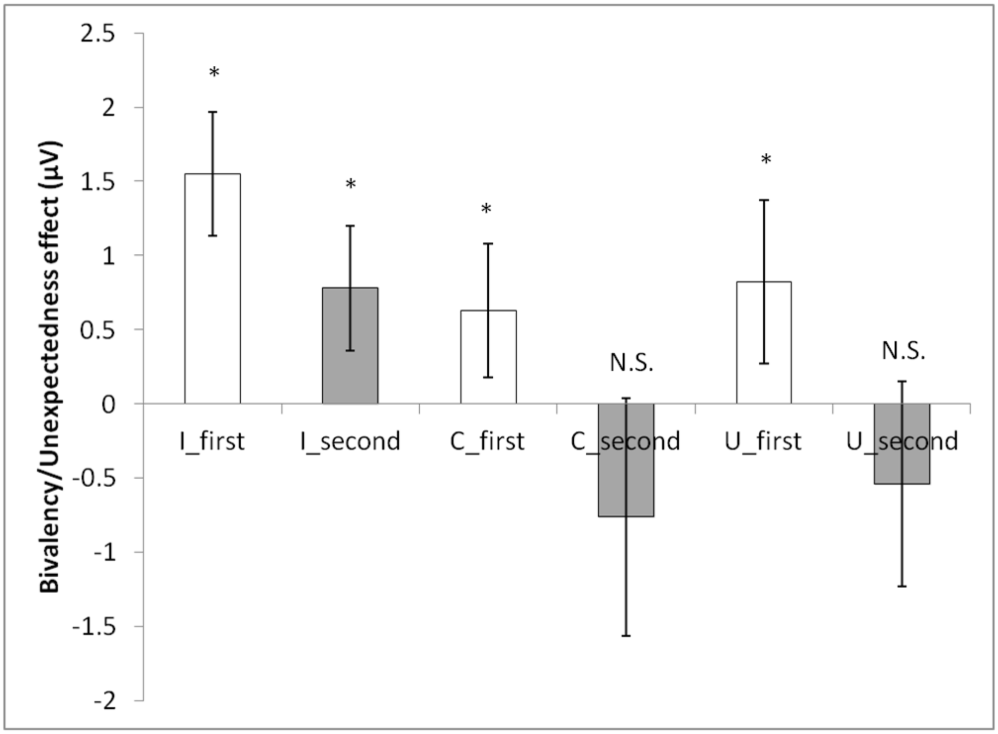

Figure 5 – Event-related potential values for the frontal cluster capturing the bivalency/unexpectedness effect at 350-390 ms after stimulus onset in response to congruent bivalent stimuli (C), incongruent bivalent stimuli (I), and non-bivalent unexpected stimuli (U) throughout the experiment. Block order was as follows: pure, surprising, pure, pure, surprising, pure. The bivalency/unexpectedness effect is calculated by subtracting the amplitudes to univalent stimuli in the blocks flanking a surprising block to the expected univalent stimuli within that surprising block. First = amplitude differences appeared in the first block set. Second = amplitude differences appeared in the second block set (i.e. after practice with another surprising block). * = amplitude difference scores significantly different from zero. N.S. = non-significant.

Electrophysiological results (100-120 ms)

A significant amplitude difference within 100-120 ms was found at the frontal cluster for uni-biv-congruent trials compared to univalent trials in pure blocks in the second block set, $t(8) = 3.62$, $p = 0.007$, but not for uni-biv-incongruent trials or uni-unexpected trials ($t(8) < 0.5$, $p > 0.1$). Because we previously reported that this component is likely a reflection of activity from electrodes near the temporal parietal scalp area (Grundy et al., 2011), we examined a cluster of electrodes in this region for each hemisphere (see Figure 6).

A 2 (block-set order: bivalent vs. unexpected) x 2 (block-set type: bivalent vs. unexpected) x 2 (laterality: left vs. right hemisphere) mixed-measures ANOVA within this time window (100-120 ms) for uni-biv-congruent trials revealed a significant main effect of block-set type, $F(1, 16) = 3.69$, $p = 0.036$, $\eta^2 = 0.188$, in which uni-biv-congruent trials showed a larger amplitude difference than uni-unexpected trials.

This same analysis comparing uni-biv-incongruent to uni-unexpected revealed a significant block-set type by order interaction, $F(1, 16) = 3.61$, $p = 0.038$, $\eta^2 = 0.184$. This interaction is explained by a practice effect for uni-biv-incongruent trials: a greater amplitude difference was revealed for trials that appeared in the second block set than in the first, $t(8) = 2.10$, $p = 0.035$, a greater amplitude difference was revealed for uni-biv-incongruent trials that appeared in the second block set than uni-unexpected trials in the first block set, $t(8) = 1.91$, $p = 0.046$, and a marginally larger difference for uni-biv-incongruent trials than uni-unexpected trials in the second block set, $t(8) = 1.46$, $p = 0.092$. No other effects reached significance.

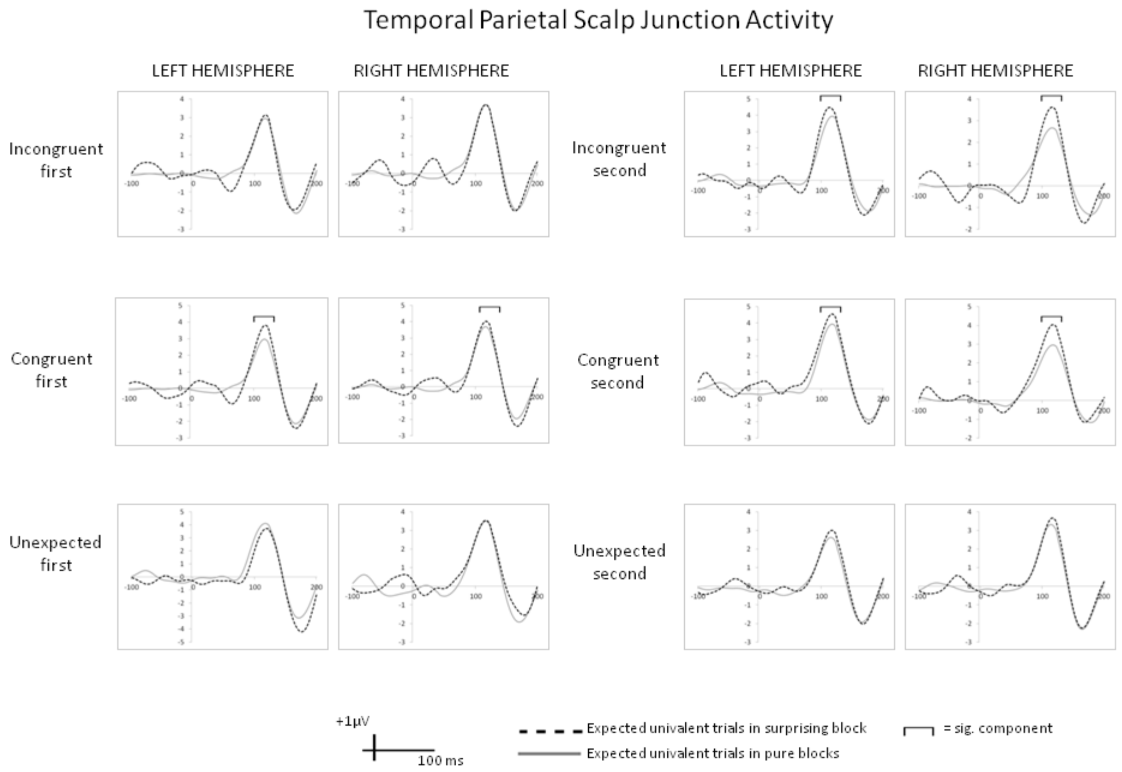

Figure 6 - Event-related potentials capturing processing differences between expected univalent stimuli that appear in pure vs. surprising blocks. The leftmost figures represent processing differences when the surprising stimulus type appears in the first block set, whereas the rightmost figures represent processing differences when the surprising stimuli appear in the second block set (i.e. after practice with surprising stimuli).

DISCUSSION

In the present study we examined influences of different surprising stimulus types in modulating behavioural and electrophysiological responses during a block-wise response slowing. The occasional presence of bivalent stimuli within a block of univalent trials is enough to elicit a block-wise response slowing on all trials within that block, including trials that do not share any features with bivalent stimuli; this is known as the bivalency effect (Woodward et al., 2003). The block-wise adjustment observed in the bivalency effect is believed to involve top-down cognitive control modulated by the dorsal anterior cingulate cortex (dACC; Grundy et al., 2011; Woodward et al., 2008), a known conflict detection center (Kerns et al., 2004; Kerns, 2006; Liu et al., 2004; Milham et al., 2001; van Veen et al., 2001). Recently, we found that non-bivalent unexpected stimuli can elicit a similar block-wise response slowing that appears to be smaller in magnitude than typical bivalency effect studies (Grundy et al., submitted). This suggests that at least part of the block-wise response slowing observed in the bivalency effect is engaged by a violation of expectancy, which is triggered by the bivalent (or unexpected) trials and slows processing on following trials.

A large contribution to the bivalency effect appears to be a carry-over of response inhibition from incongruent bivalent trials, in which the irrelevant feature cues the incorrect response and slows processing on following trials (Grundy & Shedden, submitted). Congruent bivalent stimuli (in which both relevant and irrelevant features cue the correct response), do not have the same kind of response conflict and appear to produce a response slowing that is similar in magnitude to that produced by non-bivalent unexpected stimuli (Grundy & Shedden, submitted). Based on the similarity of the behavioural responses, we suggested that non-bivalent unexpected stimuli and congruent bivalent stimuli may be engaging similar processes that differ from those engaged by incongruent bivalent stimuli. In each case there is an adjustment in cognitive control leading to a block-wise response slowing, but the adjustment driven by incongruent bivalent stimuli is larger and longer lasting over the course of the experiment.

In this paper we collected behavioural and electrophysiological evidence to further distinguish between these factors. Participants cycled through three tasks which required colour, parity, and case judgments; behavioural and ERP measures revealed differences in block-wise slowing of responses that followed incongruent bivalent stimuli (incongruent bivalency effect), congruent bivalent stimuli (congruent bivalency effect), and non-bivalent unexpected stimuli (unexpectedness effect). Each participant saw two surprising blocks containing occasional bivalent or unexpected stimuli, flanked by purely univalent blocks. The order in which participants encountered the surprising blocks was an important factor, illustrating the robustness of the incongruent bivalency effect compared to the other two effects (Figure 2). The congruent bivalency effect and the unexpectedness effect were observed in the first block set only, whereas the incongruent bivalency effect was observed in both the first and second block sets, even after practice with the non-bivalent unexpected trials. In contrast, practice with the bivalent trials or the unexpected trials in the first block set eliminated the unexpectedness effect and the congruent bivalency effect, respectively, in the second block set. Thus, behaviourally, there appears to be a similar adjustment in response style following non-bivalent unexpected and congruent bivalent trials that differs from the responses that follow incongruent bivalent trials.

Two ERP components, observed at a frontal electrode cluster (Fpz, AFz, AF4, and AF3), were sensitive to the bivalency and unexpectedness effects in revealing ways; an early component was observed between 100 – 120 ms, and a later component was observed between 350 – 390 ms. Both components are consistent with our previous ERP work, which used source modeling to suggest a temporal parietal source for the earlier activity, and localized the generators of the later component to the dorsal anterior cingulate cortex (dACC; Grundy et al., 2011), consistent with fMRI results (Woodward et al., 2008).

The ERP results provide further insight regarding the differential adjustment in response style across the bivalent and unexpected conditions. Amplitude differences reflecting the incongruent bivalency effect were greater than the congruent bivalency effect and the unexpectedness effect over the 350 – 390 ms window. Moreover, this difference was even greater after practice such that the incongruent bivalency effect amplitude difference was maintained over the second set of blocks, whereas the congruent and unexpectedness effects appeared to be eliminated by practice with the first set of blocks. One way to think about this is that practice with incongruent bivalent trials prepared participants to deal with unexpected trials, but the reverse was not true to the same extent. This additional conflict is likely due to carry-over of the suppression of the response to the irrelevant bivalent feature. Notably, the congruent bivalency effect was similar to the unexpectedness effect at this later component; the amplitude difference was significant for the first set of blocks only. This is consistent with the hypothesis that the response conflict on incongruent bivalent trials is responsible for the robust and long-lasting nature of the bivalency effect.

Similar frontopolar ERPs within these late time windows have been identified for task-switch vs. task-repeat comparisons (Hsieh & Chen, 2006; Hsieh & Liu, 2009; Lorist et al., 2000; Wylie, 2003) as well as univalent vs. bivalent stimulus comparisons (Poulsen et al., 2005), suggesting that there may be overlapping processes involved in the task-demands inherent in these different experiments. For instance, Poulsen et al. (2005) found less negative medial frontopolar activity for bivalent compared to univalent switch trials within 300-700 ms after stimulus onset, which is in the same direction and time window as the current experiment. However, the bivalency effect differences reflect the difference between univalent stimuli in pure blocks and the univalent stimuli that follow bivalent stimuli in the bivalent blocks, suggesting that the processes engaged by bivalent stimuli may be carried-over to subsequent univalent trials.

Reduced negative deflections in medial frontal areas have also been implicated in response to inhibitory processes (Poulsen et al., 2005; Schnider, Valenza, Morand, & Michel, 2002). For instance, distracter items that were once targets have been characterized by a reduced negative deflection in frontopolar sites compared to target and novel items (Schnider et al., 2002). In the Poulsen et al. study (2005), ERP amplitudes to both congruent and incongruent bivalent trials differed from univalent trials at frontopolar sites, but only incongruent bivalent stimuli maintained a large difference after practice; the authors hypothesized that this was due to greater inhibitory demands during processing of incongruent bivalent trials. Consistent with this idea, we also showed that incongruent bivalent stimuli led to a reduced negative deflection that was less susceptible to practice effects. Because our analyses were constrained to univalent trials, any inhibitory processes engaged on univalent stimuli must have been carried-over from incongruent bivalent stimuli.

Trials that followed congruent bivalent stimuli or non-bivalent unexpected stimuli in the present study initially elicited a similar reduction in negativity at these frontopolar sites. Because these trials do not have response conflict, this might reflect an inhibitory process, beyond response conflict, when task demands are uncertain. In that case, the automatically-cued response inherent in the task set associated with a particular trial might have to be suppressed in order to re-evaluate the demands. After sufficient practice this re-evaluation is no longer necessary as we learn to more efficiently process the occasional irrelevant feature that appears on case judgment trials, and the inhibitory process dissipates. In contrast, incongruent bivalent stimuli produce a larger and longer lasting response, both behaviourally and electrophysiologically, because there is both uncertainty about task demands and the influence of response conflict. The incongruent bivalency effect dissipates somewhat with practice due to reduction of task demand uncertainty but is not eliminated after practice because the carry-over effect of response conflict is maintained.

These findings have important implications for current theories of response incongruence. The evidence for a generic carry-over of response incongruence presented in this study and previous work (Grundy & Shedden, submitted) challenges a recent inhibitory theory known as competitor rule suppression (CRS; Meiran, Hsieh, & Dimov, 2010). This phenomenon is based on the idea that response incongruence on trial n-1 will cause interference on trial n only if the relevant dimension on trial n was the irrelevant dimension causing interference on trial n-1. All trials used in the CRS paradigm were bivalent stimuli, whereas we examined the influence of incongruence on subsequent *univalent* trials. Thus, we were able to show that incongruent bivalent stimuli cause interference on all subsequent trials regardless of feature overlap with the dimension causing response interference. In keeping with this idea, recent findings suggest that using only bivalent trials masks the effects of a post-conflict slowing (Verguts, Notebaert, Kunde, & Wühr, 2011). Specifically, encountering an incongruent stimulus leads to post-conflict focusing on task-relevant dimensions to avoid the response conflict. This produces post-conflict slowing but also facilitates response times if the next trial is also bivalent because of the additional attention toward the relevant dimension. This facilitation can effectively mask the post-conflict slowing, which may be why the slowing was not observed in the Meiran et al. (2010) results, in which all trials were bivalent. In the current experiment, the trials following the bivalent trial are always univalent, so this masking of post-conflict slowing does not occur. Our electrophysiological findings strengthen our claim for a more generic carry-over of response inhibition by showing strong frontopolar amplitude suppression for all tasks that follow incongruent bivalent stimuli compared to trials that appear in purely univalent blocks.

Another amplitude difference of interest was an early frontal component (100-120 ms). Using source modeling we previously localized this activity to the temporal-parietal junction (TPJ), and hypothesized that the activity measured at the frontal cluster may be a reflection of TPJ activity (Grundy et al., 2011). In the current study we replicated the ERP amplitude differences over the same set of electrodes, and focused analyses within this time window to these posterior electrode sites typically associated with TPJ activity. A positive component in the 100-120 ms time range was sensitive to the bivalency effect following both congruent and incongruent bivalent trials; it was greater in amplitude for univalent trials that followed bivalent stimuli compared to univalent trials that appeared in pure blocks (see Figure 5). Amplitude differences at TPJ electrode sites have been associated with visual extraction of stimulus features (Evans, Shedden, Hevenor, & Hahn, 2000), and Grundy et al. (2011) hypothesized that this early component might represent feature extraction triggered by task-set cueing on bivalent trials when task demands become uncertain. Critically, this distinction did not obtain for the unexpectedness effect, suggesting that this additional feature extraction at early stages distinguishes bivalent processes (which always cue two tasks whether or not there is response conflict) from more generic responses to unexpected features (which never cue two tasks). This is interesting in the sense that it does not require response conflict, but does appear to require bivalency. Thus, the incongruent bivalency effect is distinguished from both congruent bivalency and unexpectedness effects at the later ACC component in terms of response to practice, and the unexpectedness effect is distinguished from both congruent and incongruent bivalency effects at the earlier TPJ component. Thus, the

ACC activity may trigger the posterior activity only when specific task cueing is involved. The observation of a bivalency effect but not unexpectedness effect at the posterior sites supports this hypothesis.

We found that the TPJ distinction appeared for the congruent bivalency effect in both first and second block sets; curiously however, this early amplitude difference was not statistically significant for the incongruent bivalency effect in the first block set comparison. It is possible that the stronger inhibition due to response conflict masked the early TPJ differences in the first block set. However, given the lack of TPJ differences in the unexpectedness condition, we can assume that this early TPJ scalp component is reflecting a process that is specific to the influence of task-set cueing, so the difference between congruent and incongruent in the first block set might have something to do with differences in the way these conditions cue the task-set. Because congruent and incongruent bivalent trials always appeared within the same block in the present study, it is possible that the response strategies elicited by these stimuli overlap somewhat.

A blocked design might reveal interesting results. Consider for instance, the basic Stroop effect, in which responses to incongruent colour words are much slower than responses to congruent colour words (for review see MacLeod, 1991). When the proportion of incongruent colour words is increased within a block of trials, the Stroop effect is much reduced; responses to the frequent incongruent trials are facilitated while responses to the relatively infrequent congruent trials are slowed (Bugg & Chanani, 2011; Logan & Zbrodoff, 1979; West & Baylis, 1998). If instead the proportion of congruent colour trials is increased, the Stroop effect is enhanced; responses to the frequent congruent trials get much faster while incongruent trials result in even greater inhibition and response slowing. Recently, this pattern of facilitation and inhibition was shown to be modulated by both item-specific as well as block-wise adjustments in control (Bugg & Chanani, 2011; Bugg, Jacoby, & Chanani, 2011; Jacoby, Lindsay, & Hessels, 2003). An early positive posterior ERP component in the same time window as our early TPJ activity (100 ms) has also been implicated as an index of control processes when the proportion of congruent and incongruent stimuli is manipulated (Shedden et al., in preparation). This early amplitude difference may index the implementation of different types of control: a more careful response style in the incongruent context and a faster automatic response style in the congruent context. Manipulation of the proportion of congruent and incongruent bivalent stimuli might have an effect on the bivalency effect, providing some insight regarding the different response styles triggered by congruent and incongruent bivalent trials. One might expect an exaggeration of the difference between the congruent and the incongruent bivalency effects. The most straightforward prediction would be a smaller bivalency effect that is soon eliminated if the bivalent trials are all congruent because there is no need to inhibit responses. If the bivalent trials are all incongruent, the prediction is less obvious. Given that the incongruent bivalency effect is maintained even after practice, we might expect a larger bivalency effect due to the increased number of trials that carry response conflict, and a consequent increase in the amount of response conflict carried over to the following univalent trials. On the other hand, it might be easier to learn to deal with incongruent bivalent trials if there are no congruent bivalent trials in the block. Future studies examining the influence of proportion of congruent and incongruent bivalent stimuli in producing the bivalency effect will provide useful insight into the response strategies afforded by irrelevant task- vs. response-cueing processes.

CONCLUSION

Using high temporal resolution event-related potentials, we evaluated stimulus properties that lead to a block-wise adjustment in cognitive control known as the bivalency effect (Woodward et al., 2003). We showed that processes initiated by a violation of expectancy and carry-over of response inhibition are captured by an amplitude suppression at medial frontopolar electrode sites between 350-550 ms after stimulus onset. Both processes are likely a reflection of a controlled inhibitory response style modulated by higher-order cognitive control centers, such as the dorsal anterior cingulate cortex, which may then trigger posterior attentional processes for feature extraction and implementation of response style, observable at an early temporal parietal site between 100-120 ms when irrelevant task-cueing (inherent in bivalent stimuli) is involved. The influence of response inhibition is more resistant to practice, both behaviourally and electrophysiologically, compared to the influence of expectancy violation, which dissipates more quickly. These processes provide valuable insight into the cognitive control mechanisms inherent in the bivalency effect and suggest that future theories on congruency effects incorporate generic carry-over of response inhibition.

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CHAPTER 6 –DISCUSSION

A primary focus of my dissertation has been to advance our understanding of the stimulus and response properties and processes involved in eliciting, maintaining, and modulating a block-wise response slowing known as the bivalency effect. This phenomenon refers to the observation that if occasional bivalent stimuli are encountered within a block of univalent trials, response times are slowed on all trials within that block, even when these trials have no overlapping features with bivalent stimuli (Grundy et al., 2011; Meier, Woodward, Rey-Mermet, & Graf, 2009; Rey-Mermet & Meier, 2012a, 2012b; Woodward, Meier, Tipper, & Graf, 2003; Woodward, Metzak, Meier, & Holroyd, 2008). This is problematic for current theories of cognitive control and task-switching that rely on overlapping stimulus and response properties (Allport, Style, & Hsieh, 1994; Allport & Wylie, 2000; Braverman & Meiran, 2010; Koch & Allport, 2006; Meiran & Kessler, 2008; Meiran, Kessler, & Adi-Japha, 2008; Monsell, Yeung, & Azuma, 2000; Rubinstein, Meyer, & Evans, 2001; Sohn & Anderson, 2001) (see implications section below for expansion). As such, it is important to scrutinize the bivalency effect in order to more completely understand how we are able to adapt to our continually changing environments.

The importance of understanding such a phenomenon beyond the gap in the literature can be brought to light with an analogy. Imagine an air traffic controller trying to coordinate a number of incoming planes, communicating with multiple control stations, and staying vigilant to important information appearing on the control board. Now imagine that a red light flashes on the control screen that indicates an incoming call.

While this signal is designed to evoke a particular response (e.g. pick up or transfer the call), its red appearance cues a highly associated irrelevant “stop” signal, consequently slowing response time for this particular task. According to the bivalency effect, *all* subsequent responses to tasks will be slowed as a result of this stimulus, including tasks that share no associations with the flashing red light. Even a small delay in reactions to time-imperative signals, such as clearing the runway, can be catastrophic. Although this analogy is extreme and warrants real-world experimental validation, it illustrates the relevance of gaining a better understanding of the stimulus properties, factors, and processes that elicit and maintain such an umbrella response strategy.

In chapter 2, I provide the first high-temporal resolution account of the bivalency effect using stimulus-locked event-related potentials (ERPs). I show that the bivalency effect is captured by frontal ERP components between 350-550 ms after stimulus onset, and by an earlier component between 100-120 ms. The later components were localized using source modeling to the dorsal anterior cingulate cortex (dACC), and the earlier component to the temporal-parietal junction (TPJ). The broad time-windows and the results of the source modeling of the later components make them good candidates for the dACC activity visualized in the fMRI study of the bivalency effect (Woodward et al., 2008). I further suggested that these late components reflect suppression of processing carried-over from the irrelevant cues on bivalent trials. In addition, I proposed that the early TPJ activity likely reflects additional extraction of visual features present on bivalent stimuli under conditions of uncertainty.

While this provides us with insight into the cognitive processes and potential networks involved in the bivalency effect, the contributions of particular stimulus properties that elicit the bivalency effect remained elusive. Thus, in chapter 3 the stimulus properties responsible for eliciting the bivalency effect were explored. In a series of experiments, I demonstrated that the appearance of occasional unexpected univalent stimuli intermixed within a block of expected univalent stimuli was enough to elicit a block-wise response slowing that was similar in form, but smaller in magnitude to the bivalency effect. This provides evidence for the notion that unexpectedness, beyond the influence of bivalence, plays a pivotal role in the processes involved in eliciting a block-wise response slowing, and thus likely contributes to the adjustment in top-down cognitive control. It was clear from experiment 5 however that the inhibition of task-irrelevant stimulus features on bivalent trials selectively affected performance when those features became task-relevant. Thus, a violation of expectancy cannot explain the entirety of processes involved in the bivalency effect. This drove critical questions about why bivalent stimuli might produce larger adjustments in cognitive and behavioural control. One possibility is that the additional stimulus features being cued on bivalent stimuli leads to a greater adjustment in subsequent responding. However, it seemed equally plausible that response conflict, beyond the influence of feature-cueing, was affecting subsequent performance.

In chapter 4, I directly tested this prediction. In two experiments, I showed that the bivalency effect was much larger and more robust when univalent trials followed incongruent (affording two separate response keys) vs. congruent (affording the same response key) bivalent stimuli. I suggested from this that a non-task-specific carry-over of response inhibition must be at play. Previous studies of the bivalency effect have collapsed trials that follow these two different types of stimuli, and my results clearly show that this is an inappropriate procedure given the disparate effects that these stimuli have on performance. In fact, after sufficient practice, the bivalency effect was *only* present following incongruent bivalent stimuli, suggesting that the effects of response inhibition are pivotal in maintaining the block-wise response slowing observed in the bivalency effect.

The motive for my final empirical chapter was to examine the electrophysiological correlates of the previously defined stimulus and response properties responsible for eliciting and maintaining the bivalency effect. Specifically, I directly compared the influence of response conflict (incongruent bivalent stimuli), feature-conflict (congruent bivalent stimuli), and a violation of expectancy (unexpected univalent stimuli) using event-related potentials. Results indicated that all three factors were able to elicit a block-wise response slowing that could be captured by the same frontopolar electrode cluster as in chapter 2 between 350-390 ms after stimulus onset. This response was eliminated both behaviourally and electrophysiologically after practice with (bivalent or unexpected) surprising stimuli for the congruent bivalency and unexpectedness effects, but not for the incongruent bivalency effect. This suggests that the processes engaged are stronger following incongruent bivalent stimuli than both congruent and unexpected stimuli, and that this is likely a result of additional inhibitory demands triggered by response conflict. Furthermore, from my previous source modeling (chapter 2) and the fMRI study of the bivalency effect (Woodward et al., 2008), it is likely that these frontal components reflect ACC activity. The temporal parietal junction (TPJ) component was replicated from chapter 2, but interestingly, this component only appeared for the congruent and incongruent bivalency effects, and not the unexpectedness effect. This suggests that the TPJ component might involve processing that is specific to the influence of dual feature-cueing, which does not occur for unexpected univalent stimuli.

Implications for current theories of task-switching and cognitive control

As mentioned in chapter 1, negative priming (Allport et al., 1994; Allport & Wylie, 2000; Koch & Allport, 2006), task-decision process (Braverman & Meiran, 2010; Meiran & Kessler, 2008; Meiran, Kessler, & Adi-Japha, 2008; Monsell et al., 2000; Rubinstein et al., 2001; Sohn & Anderson, 2001), and conflict monitoring (Botvinick, Braver, Barch, Carter, & Cohen, 2001; Botvinick, 2007; Botvinick, Cohen, & Carter, 2004; van Veen, Cohen, Botvinick, Stenger, & Carter, 2001) accounts of cognitive control cannot adequately explain the block-wise response slowing observed in the bivalency effect. Specifically, all models predict that the overlapping properties shared by bivalent and univalent stimuli within a block can account for the slowing observed on univalent trials, but they cannot predict the slowing observed on univalent trials that share no features with bivalent trials (i.e. on parity decision trials).

Negative priming can explain the slowing on colour trials because colour is always the feature that must be inhibited on bivalent stimuli. This inhibition is retrieved upon presentation of colour judgment trials and interferes with performance. Because bivalent stimuli are coloured letters, case judgment trials might cue associations with colour (which had to be suppressed earlier), effectively leading to a performance decrement. However, the negative priming account cannot explain the slowing of performance on parity decisions, which share no features with any other trials.

The task-decision process account suffers from a similar gap in explaining the behaviour observed on parity decision trials. When either the case or the colour trials are encountered, their associations with one another (from overlapping representations on bivalent stimuli) may be retrieved, and an additional task-decision process must be engaged in order to disambiguate the relevant from the irrelevant task. Because parity trials share no features with bivalent or other univalent trials, there is no ambiguity to be resolved. Another important finding that the task-decision process account cannot explain is why a larger bivalency effect is seen following incongruent vs. congruent bivalent stimuli. Both congruent and incongruent bivalent stimuli lead to a task-decision process in order to tease apart the two stimulus features (relevant vs. irrelevant), but only incongruent stimuli require an additional process to disambiguate the conflicting responses. The task-decision process account is not equipped to explain response incongruence because response processing is believed to be a separate process from that of a task-decision (Braverman & Meiran, 2010). I support and extend this notion by showing that trials *following* response conflict suffer an additional performance cost, thereby suggesting that response processes engaged on a particular trial affect subsequent processing of unrelated trials. With that said, it is clear that the task-decision process account cannot explain the slowing observed on parity decisions, nor can it explain the effects of response conflict on the bivalency effect.

The conflict monitoring theory (Botvinick, Braver, Barch, Carter, & Cohen, 2001; Botvinick, 2007; Botvinick, Cohen, & Carter, 2004; van Veen, Cohen, Botvinick, Stenger, & Carter, 2001) stipulates that our cognitive systems implement adaptive control in response to conflict, yet this model cannot fully explain the bivalency effect either. The original theory (Botvinick et al., 2001) was based on the premise that when the ACC detects conflict, additional control centers are recruited in order to fine tune adjustments in behaviour by inducing a focus of visual attention on task-relevant features. A subsequent update of the theory proposed that conflict also serves as a learning signal for avoidance behaviour (Botvinick, 2007), which explains why the ACC has often been reported to be activated in a number of negative action outcomes (Eisenberger, Lieberman, & Williams, 2003; Gehring & Willoughby, 2002; Nieuwenhuis, Yeung, Holroyd, Schurger, & Cohen, 2004; Yeung & Sanfey, 2004). However, both the original and modified versions of the conflict monitoring theory cannot fully explain the bivalency effect because the ACC is also active on univalent trials following conflict (chapters 2 and 5; Woodward et al., 2008), a finding that is not predicted by conflict monitoring.

Recent single-cell recording and lesion studies of primate behaviour (Ito, Stuphorn, Brown, & Schall, 2003; Mansouri, Buckley, & Tanaka, 2007; Nakamura, Roesch, & Olson, 2005) have also cast doubt on the conflict monitoring account of cognitive control (Cole, Yeung, Freiwald, & Botvinick, 2009). For instance, Mansouri and colleagues (2007) trained monkeys and administered a modified version of the Wisconsin Card Sorting Task (WCST); behavioural and neurophysiological responses were recorded during this task for monkeys with ACC lesions, dorsolateral prefrontal cortex (dlPFC) lesions, and controls. In their WCST analog, monkeys were required to match a sample to one of three target items based on the currently relevant rule. In low-conflict trials, the sample matched one of the three target items in both colour and shape, and none of its features overlapped with the other two items. In high-conflict trials on the other hand, the sample matched one of the items in colour, and another one of the items in shape. Thus, monkeys had to resolve conflict between two task rules in order to correctly identify the relevant target. The authors found that lesions to the dlPFC rather than lesions to the ACC led to the abolition of conflict-induced behavioural adjustments. This finding cannot be explained by the conflict monitoring theory of cognitive control because it would predict that lesions to the ACC should abolish any behavioural adjustments to conflict. These authors thus proposed that the dlPFC, and not the ACC, was responsible for conflict detection.

A very recent model (Sheth et al., 2012) of anterior cingulate cortex control was proposed that might shed light on this discrepancy and also be able to account for the cognitive control observed during the bivalency effect. Sheth et al. (2012) demonstrated using single-cell recordings in humans that ACC neurons were activated in response to current conflict trials as well as trials *following* conflict. Furthermore, they showed that lesions in the ACC did not disrupt normal responses to conflict presented on the current trial (i.e. people showed slower RTs for conflict vs. no conflict trials), but instead, ACC lesions abolished the history-dependant behavioural adjustments (i.e. conflict adaptation or “Gratton” effects; Gratton et al., 1992). In other words, ACC lesions did not disrupt how people responded to conflict, but it did affect how they adjusted performance after conflict. However, because ACC activation was seen on both conflict trials and trials following conflict despite divergent behavioural adjustments, the authors proposed that the role of the ACC was to maintain a continuously updated account of predicted cognitive demand, rather than one of conflict detection per se. I support this notion and further suggest that this model may be capable of predicting the behavioural and neurophysiological responses that reflect the bivalency effect, and that the experiments reported within my thesis provide additional empirical support for this novel theory of cognitive control.

When bivalent stimuli (that by definition involve conflict) are encountered, the ACC is activated, and slower response times are observed on these trials (Woodward et al., 2008). In bivalency effect experiments, univalent trials that *follow* bivalent stimuli also show greater ACC activity than trials in purely univalent blocks (chapters 2 and 5; Woodward et al., 2008), and this can be explained by a model in which predicted cognitive load is being processed by the ACC (Sheth et al., 2012). After encountering a bivalent stimulus, the ACC encodes the conflicting information and this raises the internal activation of future predicted cognitive load; when subsequent univalent trials appear, this signal is more active and leads to slower behavioural responses than when one continually encodes univalent trials (i.e. in pure blocks).

If the ACC's role is to maintain a history and anticipate future cognitive load, it is also not surprising that trials following incongruent bivalent stimuli show greater behavioural (chapters 4 and 5) and electrophysiological (chapter 5) adjustments compared to congruent bivalent or unexpected univalent stimuli. When an incongruent bivalent stimulus is encountered, the ACC records the response conflict and predicted future cognitive demand is raised. This leads to both behavioural slowing and stronger ACC signals following the incongruent stimulus. If a congruent bivalent stimulus is encountered, a different prediction on cognitive load is made and a lesser degree (relative to incongruent bivalent stimuli) of response slowing and ACC activity is needed. Similarly, when unexpected univalent stimuli appear, the ACC encodes the information in a similar way to that of congruent bivalent stimuli because both types of stimuli are surprising, but neither have response conflict; in other words, increased cognitive load is predicted relative to no conflict (i.e. pure blocks), but decreased cognitive load is predicted relative to the influence of incongruent bivalent stimuli. Thus, trials following these stimuli have similar behavioural and electrophysiological responses that differ from trials following incongruent bivalent stimuli.

The history-dependent predictive model of the ACC also helps to explain the observation of a block-wise response slowing following any unexpected univalent stimulus (chapters 3 and 5), even when there is none of the task- or response- cueing forms of conflict found in congruent and incongruent bivalent stimuli. Unexpected univalent stimuli take longer to process because they are by definition unanticipated, and a response slowing is observed on subsequent trials in order to anticipate future encounters with these surprising types of trials. Notice also, that Sheth et al.'s (2012) ACC model is the only cognitive control model that can account for the response slowing observed on trials that share no features with bivalent stimuli (i.e. on parity decision trials). The model does not rely on an overlap of stimulus and response properties between trials to predict future behaviour; rather, it relies solely on current and recent cognitive demand. Because the bivalency effect studies reported in my thesis fit well with this model, I suggest that they provide additional support for this novel model of cognitive control.

Previous attempts to account for the bivalency effect adjustments in control have focused on a breaking of inertia (Woodward et al., 2008), whereas more recent attempts have focused on an episodic context retrieval account (Meier et al., 2009; Rey-Mermet & Meier, 2012a, 2012b), but neither accounts can explain the findings presented herein. For instance, according to the episodic retrieval account of cognitive control, the context of the bivalent block (i.e. "tricky block") is retrieved along with the presentation of trials within that block and this leads to a response slowing. However, this does not explain why trials following incongruent bivalent stimuli show a larger response slowing than trials following congruent bivalent stimuli, despite the fact that they appear within the same block (chapters 4 and 5). On the other hand, this finding is easily predicted by a model in which the ACC encodes information about predicted cognitive demand on a trial-by-trial basis (Sheth et al., 2012). When congruent bivalent stimuli appear, the ACC encodes information with one source of conflict (i.e. task-cueing), and this leads to the prediction that more of these stimuli will be encountered in the future, and a response slowing is observed on the following trials. When incongruent bivalent stimuli appear, the ACC encodes two forms of conflict (irrelevant task- and response- cueing), and this leads to even slower subsequent response times because of the prediction that more trials with two forms of conflict will appear.

In sum, I suggest that the bivalency effect studies presented herein support a novel model of cognitive control that encodes current information about required cognitive load in order to predict future outcomes (Sheth et al., 2012). This model challenges current models of cognitive control, including conflict monitoring (Botvinick et al., 2001; Botvinick, 2007; Botvinick et al., 2004; Cohen, Botvinick, & Carter, 2000; Kerns et al., 2004), which is perhaps the most highly cited and accepted model of control reported to date.

Limitations and future directions

In the bivalency effect experiment presented in chapter 3 (Experiment 5), I showed that colour judgment trials were most affected by the presence of occasional bivalent stimuli. Previous research has shown that trials immediately following bivalent stimuli show the largest bivalency effect (Meier et al., 2009), but I further showed that even when colour judgment trials did not appear immediately after bivalent trials, they produced the largest and most robust bivalency effect. I argued that this was likely because colour was always the feature that had to be suppressed on bivalent trials and that this inhibition was retrieved upon presentation of colour judgment trials. However, I also noted that colour judgment trials in three of the four unexpectedness experiments also showed a larger unexpectedness effect than the other trial types. Colour judgment trials in these experiments always appeared after unexpected stimuli, so it is highly plausible that the additional slowing on colour judgment trials was due to trial order. However, despite the fact that colour here is not a feature that must be inhibited, an alternative explanation beyond trial order exists for why colour judgment trials are most affected by occasional unexpected stimuli. It is possible that colour trials show the largest bivalency/unexpectedness effect because of another factor, such as task salience or an attribute specific to colour judgment trials. This could explain why a larger bivalency effect was seen for colour judgment trials in response to the occasional presence of unexpected univalent stimuli as well as bivalent stimuli, regardless of trial order. In order to rule out this possibility, it is necessary to show that colour judgment trials show a larger unexpectedness effect only when they immediately follow unexpected univalent trials. Recent pilot data support this notion by showing that colour trials no longer show the largest unexpectedness effect when the presentation of trial types following unexpected univalent stimuli is randomized. If this finding holds, it supports my previous suggestion that colour trials show the largest bivalency effect because colour is always the task that must be inhibited on bivalent stimuli.

In chapters four and five, I suggested that response conflict played a significant role in producing the bivalency effect. Specifically, I suggested that a larger and more robust bivalency effect was seen for trials that followed incongruent vs. congruent bivalent stimuli. Both types of stimuli produced a bivalency effect at the beginning of the experiment, but after practice, only incongruent bivalent stimuli led to a performance cost on subsequent univalent trials. However, it is also possible that the processes engaged by one stimulus type are interfering or enhancing the processes engaged by the other stimulus type because they appear within the same block. For example, congruent bivalent stimuli may in fact aid in processing because the coloured appearance always cues the correct response, but the subsequent performance enhancement is masked by the carry-over of response inhibition from incongruent bivalent stimuli. We might also expect to see that the processes following congruent bivalent stimuli are masking the costs associated with incongruent bivalent stimuli. Alternatively, it might be easier to learn to deal with incongruent bivalent trials if there are no congruent bivalent trials in the block. To shed light on these possibilities, a blocked-design should be used in which only incongruent bivalent stimuli appear in bivalent blocks for one group and only congruent bivalent stimuli appear in bivalent blocks for another group.

CONCLUSION

I have made a case for the idea that the bivalency effect reflects a form of top-down cognitive control that is not easily explained by most current models of control in the literature. We know from the research presented within my thesis that the bivalency effect reflects an adjustment in cognitive control that is highly dependent on past experience with response conflict (chapters 4 and 5), violations of expectancy (chapter 3 and 5), and recent inhibition (chapters 3, 4, and 5). Furthermore, the processes in response to these factors are likely captured by the dACC and the TPJ (chapters 2 and 5), reflecting responses to inhibitory demands, and extra visual feature extraction after encountering bivalent stimuli, respectively. These findings provide additional evidence for a very recent cognitive control model that suggests that the role of the ACC is to track current and recent changes in the environment in order to optimize future performance by predicting changes in cognitive demand (Sheth et al., 2012).

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