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ORIGINAL ARTICLE

A role for recency of response conflict in producing 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 affects all trials that follow bivalent stimuli, including those trials that do not share any features with bivalent stimuli. However, the specific stimulus and response properties that trigger the bivalency effect are not well understood. In typical bivalency effect experiments, bivalent stimuli can be congruent or incongruent with respect to the response afforded by the irrelevant stimulus feature, and this distinction has never been examined. In the present study, we show that cognitive load defined by the response incongruence on bivalent trials plays a critical role in producing the subsequent response slowing observed in the bivalency effect, as well as maintaining the magnitude of the bivalency effect across practice. We propose that the bivalency effect reflects a process involved in predicting future cognitive load based on recent cognitive load experience. This is in line with a recent proposal for a role of the ACC in monitoring ongoing changes in the environment to optimize future performance (Sheth et al., in Nature 488:218–221, 2012).

Introduction

Imagine driving through the city, stopping at a number of red stop signs, changing lanes, and staying vigilant to pedestrian encounters. If along the way you encounter a red sign indicating directions to a nearby hotel, the red colour may trigger retrieval of cognitive processes that were active in response to the recently encountered 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., 2013; Meier, Woodward, Rey-Mermet, & Graf, 2009; Rey-Mermet & Meier, 2012a, b; 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 may 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). After sufficient practice with univalent stimuli (stimuli that cue a single task), participants are presented with a block of trials which contain occasional bivalent stimuli (e.g. the colour on a case judgment trial is red or blue). 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. Responses to all subsequent univalent trials within this bivalent block are delayed relative to trials in purely univalent blocks. This block-wise response slowing is known as *the bivalency effect* (Woodward et al., 2003). The bivalency effect is a robust and long lasting effect (Meier et al., 2009; Rey-Mermet & Meier, 2012b) believed to involve a change in response

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strategy signalled by the dorsal anterior cingulate cortex (dACC; Grundy et al., 2013; Woodward et al., 2008), an area believed to be involved in conflict detection (Kerns et al., 2004; Kerns, 2006; Liu, Banich, Jacobson, & Tanabe, 2004; Milham et al., 2001; van Veen, Cohen, Botvinick, Stenger, & Carter, 2001) outcome evaluation (Bush et al., 2002; Nieuwenhuis, Yeung, Holroyd, Schurger, & Cohen, 2004), and predictions of future cognitive load (Sheth et al., 2012).

The bivalency effect is problematic for current theories of cognitive control that rely on overlapping stimulus and response properties, including negative priming (Allport, Style, & Hsieh, 1994; Allport & Wylie, 2000; Koch & Allport, 2006), task-decision process (Braverman & Meiran, 2010; Meiran & Kessler, 2008; 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 et al., 2001) accounts. Specifically, existing 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 example, an episodic retrieval account for negative priming (e.g. D'Angelo & Milliken, 2012) 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 subsequent univalent case judgment trials and this leads to a response slowing. These arguments do not work as well to explain the slowing observed on parity decisions, because these trials do not share any features with the other trials. The conflict monitoring theory (Botvinick et al., 2001; Botvinick, 2007; Botvinick et al., 2004; van Veen et al., 2001) suggests that 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 so that future conflict is more easily resolved. This post-conflict focus on task-relevant features can explain why 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 example, to focus on the task-relevant feature (case) to facilitate selection on bivalent trials, the irrelevant feature (colour) might be inhibited. When subsequent colour judgment trials are presented, the associated inhibition is retrieved and performance suffers. It is not as clear how task-relevant focusing (i.e. focusing on case features) after encountering bivalent stimuli would lead to a performance cost on univalent case judgment trials; there is no task-relevant conflict on these trials and the focus on case features should actually facilitate processing. It is also not clear how performance is hindered on parity decision trials on which 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).

This paper argues that a large part of the magnitude and robustness of the bivalency effect is driven by an increase in cognitive load on bivalent trials and that this leads to a prediction that future cognitive load will be increased. To test this hypothesis, we examine the effect of response congruency of bivalent trials on subsequent univalent responses; this variable has not been studied in previous work on the bivalency effect. A bivalent stimulus always cues two different tasks, and is either congruent or incongruent with respect to the response[1]. 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). Response times (RTs) to incongruent bivalent stimuli are typically longer compared to RTs to congruent bivalent stimuli (see Meiran & Kessler, 2008 for a review; Sudevan & Taylor, 1987), suggesting that more cognitive resources are required to disentangle the conflicting responses.

We expect that the additional resources allocated to this response conflict may hinder performance on subsequent univalent stimuli for a couple of reasons. After encountering a number of univalent trials, participants develop a fluency of processing; this fluency is interrupted (*breaking of inertia;* Paus, 2001; Woodward et al., 2008) when bivalent stimuli appear, triggering a reconfiguration of response style (Woodward et al., 2003, 2008). We suggest that the reconfiguration may be greater following an incongruent compared to a congruent bivalent stimulus because in addition to dealing with cues to two tasks, the response mapping must also be re-evaluated. This may lead to a slower build-up of subsequent momentum following an incongruent bivalent trial.

A slightly different interpretation of the bivalency effect is based on episodic context retrieval (Meier et al., 2009; Rey-Mermet & Meier, 2012a, b). For instance, when a parity decision trial is encountered within a bivalent block,

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[1] Response congruency can be examined for experiments that involve manual responses for all tasks, but not for experiments in which a verbal response is required (e.g. Woodward et al., 2003).

the confusing block context (i.e. due to occasional bivalent stimuli) is retrieved along with the parity decision task-set, leading to response slowing. Rey-Mermet and Meier (2012a) suggested that the presence of conflict in the retrieved context leads to an adjustment of cognitive control, but that the response slowing is not sensitive to the amount or source of the conflict. However, this view does not yet incorporate the distinction between response congruent vs. incongruent bivalent trials.

Here we wished to explore the idea that congruent and incongruent bivalent stimuli in bivalency effect experiments lead to different behavioural adaptations. We suspect that the bivalency effect reflects a process by which future demand for cognitive resources is predicted. By this view, additional conflict on bivalent stimuli (e.g. response conflict) might signal larger future cognitive demand. This is in line with a recent study that implicated the dACC in maintaining a continuously updated account of current and recent cognitive demands (Sheth et al., 2012). The modulation that occurred at the dACC based on recent cognitive demands was associated with a behavioural adaptation known as the Gratton effect (Gratton, Coles, & Donchin, 1992), in which tasks of similar difficulty to previous tasks are facilitated, and tasks of dissimilar difficulty to previous tasks are hindered. Because incongruent (vs. congruent) bivalent stimuli have an additional source of conflict (i.e. response conflict), they are more dissimilar to the univalent trials that follow. As a consequence, responses to these univalent trials should be prolonged relative to trials that follow congruent bivalent stimuli.

In the present study, we predicted a larger bivalency effect on univalent trials following incongruent compared to congruent bivalent trials. Experiment 1A tested the congruency hypothesis in a traditional bivalency effect design by examining the influence of congruent vs. incongruent bivalent trials mixed within a bivalent block. Experiment 1B re-examined behavioural data from a previous study (Grundy et al., 2013) to demonstrate the influence of congruency in extant data. Experiment 2 presented congruent and incongruent bivalent stimuli in different blocks to disambiguate the influence of overlapping processes that may occur when congruency is mixed within the same block.

Experiment 1A

Participants

Twenty-eight undergraduate students (5 males; mean age 19) 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. In this experiment, and in the following experiments, all procedures complied with the Canadian tri-council policy on ethics and were approved by the McMaster Research Ethics Board.

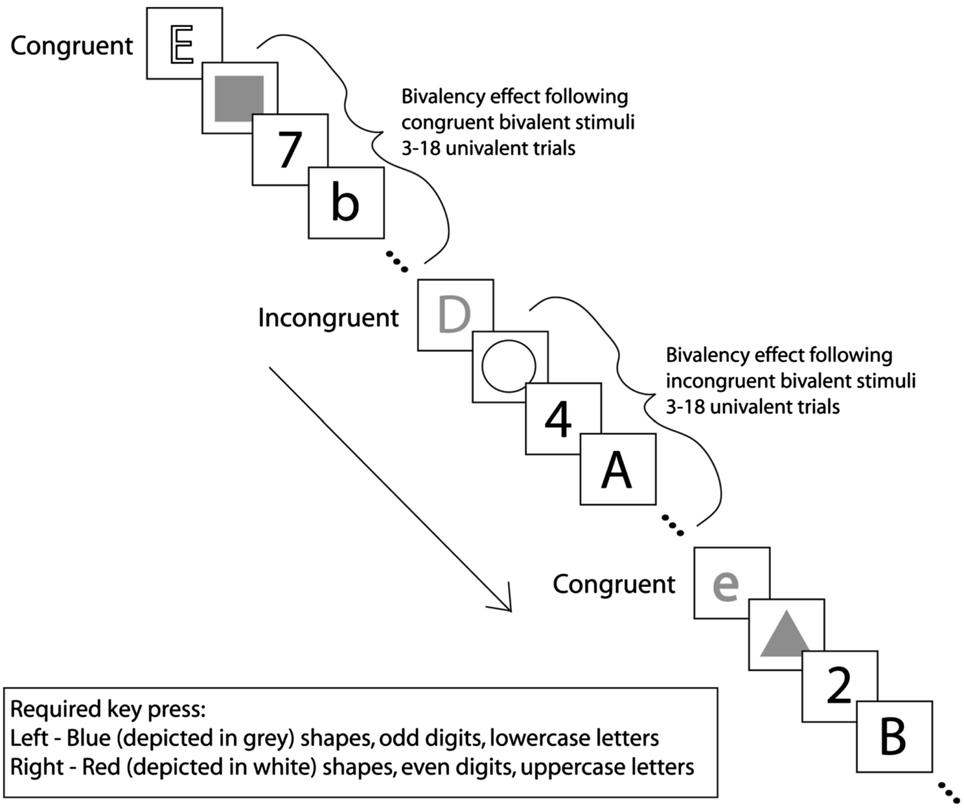
Materials and apparatus

All stimuli were presented on a black background on a 17-in. 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, with trial defined as a single task presentation (i.e. case, colour, or parity judgment). 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; this produced 48 trial triplets. 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 Fig. 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 33 % of case judgment trials (11 % of the 144 trials). Within each block, participants were given accuracy feedback after every 12 trials. This helped participants remain focused and accurate. Stimuli remained on the



Required key press:
Left - Blue (depicted in grey) shapes, odd digits, lowercase letters
Right - Red (depicted in white) shapes, even digits, uppercase letters

Fig. 1 Illustration of the trial sequence and type of stimuli used during the experiment. This particular illustration is an example of a bivalent block. 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

screen until response or until 1,500 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 and 900 ms throughout the experiment.

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.

To compare the influence of congruent vs. incongruent trials within the *same* block, we averaged all the univalent trials that followed congruent bivalent trials separately from the univalent trials that followed incongruent bivalent trials. Due to pseudo-random presentation of bivalent trials, the number of univalent trials that followed each congruent and incongruent bivalent trial ranged from 3 to 18, producing approximately 64 univalent trials that follow each type of bivalent trial in each bivalent block.

In Experiment 1A, we performed a 2 (preceding bivalent stimulus: congruent vs. incongruent) × 3 (task: colour, parity, case) × 3 (block pair: block 2–1, block 4–3, block 6–5) repeated-measures ANOVA to examine RT difference scores. The difference scores were calculated by subtracting RTs to univalent trials in pure blocks from RTs to univalent trials in bivalent blocks (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; 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[2].

A significant main effect of preceding bivalent stimulus type revealed that the bivalency effect was much larger for

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[2] We also analyzed our data after removing the first 3 trials following bivalent stimuli to reduce the contribution of an orienting response (cf. Rey-Mermet et al., 2013) to our congruency results. There was a significant effect of congruency ($p < 0.001$) with no effect of block pair ($p > 0.05$) or interaction ($p > 0.05$). Furthermore, the congruent bivalency effect was no longer present for any of the block pairs (all $ps > 0.05$), strengthening support for our congruency hypothesis. The incongruent bivalency effect was present throughout the entire experiment (all $ps < 0.05$).

Table 1 Bivalency effect and standard error (ms) as a function of task, block pair comparison, and response congruency of the bivalent trial

	Congruent			Incongruent		
	Block 2–1	Block 4–3	Block 6–5	Block 2–1	Block 4–3	Block 6–5
Experiment 1A						
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						
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						
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)

Blocks 1, 3, and 5 consist purely of univalent trials; blocks 2, 4, and 6 contain occasional bivalent trials followed by univalent trials. The congruent and incongruent bivalent trials are randomly mixed within the bivalent blocks (Experiments 1A and 1B), or blocked as a between-subjects variable (Experiment 2). Congruent: bivalency effect calculated as the mean RT difference between univalent trials that follow congruent bivalent trials in bivalent blocks vs. univalent trials in purely univalent blocks. Incongruent: bivalency effect calculated as the mean RT difference between univalent trials that follow incongruent bivalent trials in bivalent blocks vs. univalent trials in purely univalent blocks

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, $F(2,54) = 7.50$, $p = 0.001$, $\eta^2 = 0.217$, $\varepsilon = 0.79$ 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, $F(2,54) = 4.20$, $p = 0.003$, $\eta^2 = 0.134$, $\varepsilon = 0.78$. 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.

The interaction between preceding bivalent stimulus type and block pair did not reach significance, $F(2,54) = 1.10$, $p = 0.342$, $\eta^2 = 0.039$, $\varepsilon = 0.92$. This reflects a similarity in the change in the bivalency effect from the first block pair to the following block pairs; in both congruent and incongruent conditions, the size of the bivalency effect in the first block pair is larger than in the following block pairs. However, this does not tell us whether the presence of the bivalency effect differed across the block pairs for each congruency condition (i.e. whether the magnitude of the bivalency effect was significantly different from 0 across the block pairs). We tested this directly by performing separate t tests for each block pair for trials that followed congruent and incongruent bivalent stimuli. For trials following *congruent* bivalent stimuli, the response slowing was significantly different from 0 in the first block pair comparison only (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 Table 1; Fig. 2a).

Discussion

We suspected that the bivalency effect reflected predictions of upcoming cognitive load based on a recent past. To explore this, we ran a typical bivalency effect study in which data were analysed based on the prediction that the type of conflict defined by response congruency on bivalent trials

Table 2 RTs and standard errors (ms) for univalent trials as a function of task, block, and response congruency of the bivalent trial

	Univalent blocks			Bivalent blocks		
	Block 1	Block 3	Block 5	Block 2	Block 4	Block 6
	Pure			Congruent (mixed)		
Experiment 1A						
Colour	593 (19)	591 (21)	591 (22)	606 (21)	590 (18)	597 (19)
Parity	645 (20)	634 (20)	618 (21)	673 (21)	627 (22)	616 (20)
Case	632 (21)	593 (19)	597 (22)	650 (23)	600 (25)	606 (23)
				Incongruent (mixed)		
Colour				634 (21)	634 (20)	637 (25)
Parity				704 (23)	653 (24)	635 (22)
Case				656 (18)	632 (24)	611 (24)
Experiment 1B						
	Pure			Congruent (mixed)		
Colour	617 (21)	618 (20)	597 (17)	643 (19)	624 (21)	598 (18)
Parity	644 (19)	642 (20)	621 (16)	667 (22)	634 (22)	617 (15)
Case	600 (16)	599 (ms)	578 (15)	615 (15)	595 (18)	567 (12)
				Incongruent (mixed)		
Colour				683 (24)	647 (20)	639 (19)
Parity				679 (20)	644 (21)	625 (17)
Case				631 (16)	605 (16)	588 (15)
Experiment 2						
	Pure			Congruent (blocked)		
Colour	581 (23)	606 (25)	598 (27)	603 (19)	607 (22)	591 (23)
Parity	626 (25)	622 (24)	616 (25)	642 (22)	628 (24)	601 (22)
Case	576 (22)	576 (20)	580 (22)	586 (18)	587 (21)	575 (22)
				Incongruent (blocked)		
Colour	606 (18)	613 (16)	607 (15)	671 (23)	645 (15)	631 (19)
Parity	634 (19)	626 (17)	632 (16)	685 (21)	654 (19)	645 (20)
Case	615 (19)	609 (17)	600 (16)	654 (22)	618 (17)	619 (19)

The congruent and incongruent bivalent trials are randomly mixed within the bivalent blocks (Experiments 1A and 1B), or blocked as a between-subjects variable (Experiment 2). Pure: the mean RTs for univalent trials in purely univalent blocks. Congruent: the mean RTs for univalent trials that follow congruent bivalent trials in bivalent blocks. Incongruent: the mean RTs for univalent trials that follow incongruent bivalent trials in bivalent blocks

would play a critical role in producing the subsequent 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. Moreover, there were differential practice effects. In the first bivalent block, the presence of congruent and incongruent bivalent stimuli resulted in similar adaptations (i.e. response slowing). With practice, however, participants learned to discriminate between the two types of bivalent stimuli and adapted to them in different ways: response slowing was present in later block comparisons only when univalent trials followed incongruent bivalent stimuli.

We suggest that the magnitude and robustness of the bivalency effect are sensitive to predictions of change in cognitive demand. Because bivalent stimuli are more complex than univalent stimuli, an encounter with a bivalent stimulus creates a signal for increased upcoming cognitive load. Processing of subsequent univalent trials reflects this information and a behavioural adaptation (i.e. response slowing) is observed. Because incongruent bivalent stimuli are more complex than congruent bivalent stimuli, a larger disruption occurs, which leads to larger cognitive load estimation and consequently a larger and more robust bivalency effect.

Experiment 1A provides strong support for the notion that congruency contributes to cognitive load, which is a major factor contributing to the magnitude of the bivalency effect, and to the ability to adapt to conflict over extended practice. It is important to show that our previous datasets are consistent with this hypothesis, thus Experiment 1B

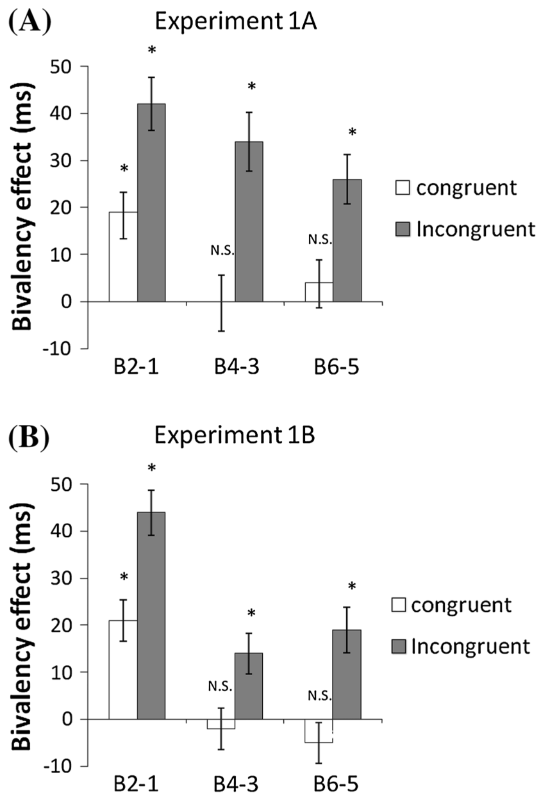

Fig. 2 The bivalency effect across Experiment 1A (**a**) and Experiment 1B (**b**) as a function of whether univalent trials in the bivalent block followed congruent or incongruent bivalent stimuli. *B2–1* bivalency effect for the first block comparison (block 2–block 1 RTs), *B4–3* bivalency effect 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. Bonferroni adjustments were applied to correct for multiple comparisons

further tested these claims by re-examining the data collected from Grundy et al. (2013). For this analysis, these data were re-sorted according to response congruency of the bivalent stimuli.

Experiment 1B

Participants

Twenty-five participants (8 males; mean age 19) 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.

Materials, apparatus and procedure

In Experiment 1B, each block contained 168 trials, with each trial consisting of a single task (i.e. case, colour, or parity judgment). In bivalent blocks, bivalent stimuli appeared on 16 of the 56 case judgment trials (29 % of case judgment trials; 10 % of 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; RT means and standard errors are presented in Table 2. Figure 2b provides a graphical depiction of the bivalency effect across the experiment for stimuli that followed congruent vs. incongruent bivalent stimuli.[3]

A significant main effect of preceding bivalent stimulus type revealed that the bivalency effect was 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, $F(2,48) = 6.23$, $p = 0.004$, $\eta^2 = 0.206$, $\varepsilon = 0.96$; 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, $F(2,48) = 18.08$, $p < 0.001$, $\eta^2 = 0.206$, $\varepsilon = 0.98$, and $F(2,48) = 6.61$, $p = 0.003$, $\eta^2 = 0.216$, $\varepsilon = 0.97$, 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 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 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

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[3] Like experiment 1A, we reanalyzed our data after removing the first three trials following bivalent stimuli to remove orienting responses. There was again a significant effect of congruency ($p < 0.001$), and an effect of block pair ($p < 0.01$). The congruent bivalency effect was present for the first block pair ($p < 0.01$) but not later block pairs (both $ps > 0.05$), consistent with the results presented herein. The incongruent bivalency effect was more resistant to practice; it was present across all blocks pair comparisons (all $ps < 0.05$).

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: $t(24) = 0.10$, $p = 0.925$]. The finding that colour judgment trials showed a greater and more robust slowing than parity and case judgment trials following incongruent bivalent stimuli is not surprising because colour is always the feature whose response needs to be inhibited on bivalent trials. Retrieval of this response inhibition upon presentation of colour judgment trials (e.g. via negative priming) might contribute to the greater response slowing. A similar trend for the robustness of response slowing on post-incongruent colour trials was also observed in Experiment 1A.

The interaction between preceding bivalent stimulus type and block pair did not reach significance, $F(2, 48) = 0.366$, $p = 0.694$, $\eta^2 = 0.008$, $\varepsilon = 0.95$. This reflects a similarity in the change in the bivalency effect from the first block pair to the following block pairs. To examine whether the presence of the bivalency effect differed across the block pairs for each congruency condition (i.e. whether the magnitude of the bivalency effect was significantly different from 0 across the block pairs), we performed separate t tests on bivalency effect scores for each block pair. For trials following *congruent* bivalent stimuli, response slowing was 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, 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 Fig. 2b).

Discussion

Experiment 1B replicated the results of Experiment 1A, providing additional support for the hypothesis that the bivalency effect reflects cognitive load estimation based on recent experience. The additional conflict produced by response incongruence is important in producing the response slowing observed in the bivalency effect. Univalent trials that followed incongruent bivalent stimuli showed a larger and more robust response slowing compared to univalent trials that followed congruent bivalent stimuli. Participants adapted quickly to the congruent bivalent stimuli, so that the bivalency effect was no longer evident after the first block pair. In contrast, the bivalency effect following incongruent bivalent stimuli was maintained across all three block pairs. These findings support the hypothesis that the bivalency effect is sensitive to manipulations of conflict. The greater the conflict produced by the bivalent trial, the greater the slowing on the following univalent trials. We suggest that slowing of responses observed as the bivalency effect is part of a process of cognitive adjustment that prepares for cognitive load based on recent experience.

In both Experiments 1A and 1B, congruent and incongruent bivalent stimuli were mixed within the same block. We know that the bivalency effect is long lasting and it is possible that our observations are sensitive to overlapping processes; we do not know if the difference in the size of the bivalency effect following congruent vs. incongruent bivalent trials is purely due to the difference in congruency. Congruent bivalent stimuli might produce an advantage when processing the following univalent trials due to the fluency generated because both relevant and irrelevant features cue the correct response, but this subsequent performance enhancement might be masked by interference that remains from previous incongruent bivalent stimuli in the same block. Congruent bivalent stimuli might enhance the costs associated with incongruent bivalent stimuli by providing more uncertainty about the nature of upcoming trials; it might be easier to adapt to incongruent bivalent stimuli if there were no congruent bivalent stimuli in the block. To shed light on these possibilities, we blocked the congruency variable in Experiment 2 so that one group of participants saw only incongruent bivalent stimuli and another group saw only congruent.

Experiment 2

Experiment 2 was designed to examine the influence of congruent vs. incongruent bivalent stimuli in producing the bivalency effect using a between-subjects blocked-design. Participants were randomly assigned to one of the two groups. In one group, the occasional bivalent stimuli (in bivalent blocks) were always incongruent (e.g. the relevant and irrelevant stimulus features were associated with incompatible responses); in the other group, the occasional bivalent stimuli (in bivalent blocks) were always congruent (e.g. the relevant and irrelevant stimulus features were associated with the same response). All other materials, apparatus, and procedures were the same as described in Experiment 1A.

Participants

Forty-four participants recruited from McMaster University's Introductory Psychology and Cognition subject pool participated in exchange for course credit. There were (coincidentally) 14 females (and 8 males) per congruency group. The average age for the congruent group was 19.6 and the average age for the incongruent group was 18.9.

These groups did not differ significantly ($p > 0.5$). All participants had normal or corrected to normal vision.

Data analysis

A 2 × 3 × 3 mixed-measures ANOVA used group (incongruent vs. congruent) as a between-subjects variable, and task (colour, parity, case) and block pair (block 2–1, block 4–3, block 6–5) as within-subjects variables. As in Experiments 1A and 1B, the bivalency effect difference (RTs to univalent trials in pure blocks subtracted from RTs to univalent trials in bivalent blocks) was used as the dependant variable.

Results

Baseline reaction times from the practice block were first examined to ensure that the two groups did not differ before the congruency manipulation. Indeed, RTs during the practice block did not differ between the groups, $t(42) = 0.79$, $p = 0.43$. Figure 3 provides a graphical depiction of the bivalency effect across the experiment for stimuli that followed congruent vs. incongruent bivalent stimuli; bivalency effect mean differences and standard errors for each condition and each block pair are presented in Table 1; RTs and standard errors are presented in Table 2[4].

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 on univalent trials that followed congruent bivalent stimuli, as expected. A significant effect of block pair was also revealed, $F(2,84) = 6.66$, $p = 0.002$, $\eta^2 = 0.137$, $\varepsilon = 0.91$, 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, $t(21) = 1.47$, $p = 0.155$.

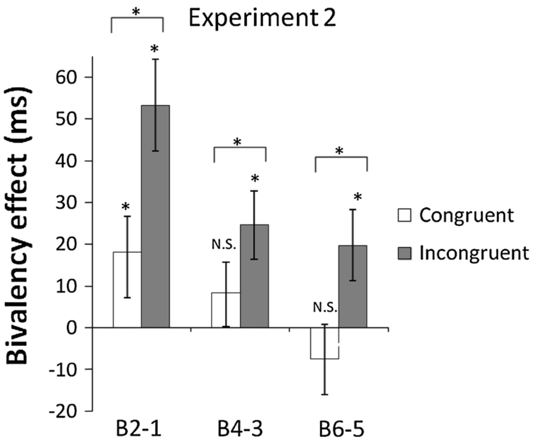

Fig. 3 The bivalency effect between two groups (congruent vs. incongruent) in Experiment 2. In the congruent group, the correct response on bivalent trials was always congruent with respect to the irrelevant feature. In the incongruent group, the correct response on bivalent stimuli was always incongruent 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. Bonferroni corrections were applied to correct for multiple comparisons

The interaction between preceding bivalent stimulus type and block pair did not reach significance, $F(2, 86) = 0.661$, $p = 0.519$, $\eta^2 = 0.011$, $\varepsilon = 0.95$. This reflects a similarity in the change in the bivalency effect from the first block pair to the following block pairs. To examine whether the presence of the bivalency effect differed across the block pairs for each congruency condition (i.e. whether the magnitude of the bivalency effect was significantly different from 0 across the block pairs), we performed separate t tests on each block pair for the congruent and incongruent groups. The bivalency effect following *congruent* bivalent stimuli was 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 following *incongruent* bivalent stimuli was significantly greater than 0 for all three block pair comparisons, $t(21) = 4.58$, $p < 0.001$ (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).

To illustrate the longevity of the congruency results, we plotted the congruency effects across the first 12 trials for Experiments 1A, 1B, and 2. These trials were grouped into triplets: each triplet contains a case decision, a parity decision, and a colour decision trial (see Fig. 4).

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[4] Like experiments 1A and 1B, we reanalyzed our data after removing the first three trials following bivalent stimuli to remove orienting responses. There was again a significant effect of congruency ($p < 0.001$), and an effect of block pair ($p < 0.01$). The congruent bivalency effect was present for the first block pair ($p < 0.01$) but not later block pairs (both $ps > 0.05$), consistent with the results presented herein. The incongruent bivalency effect was present throughout the entire experiment (all $ps < 0.05$).

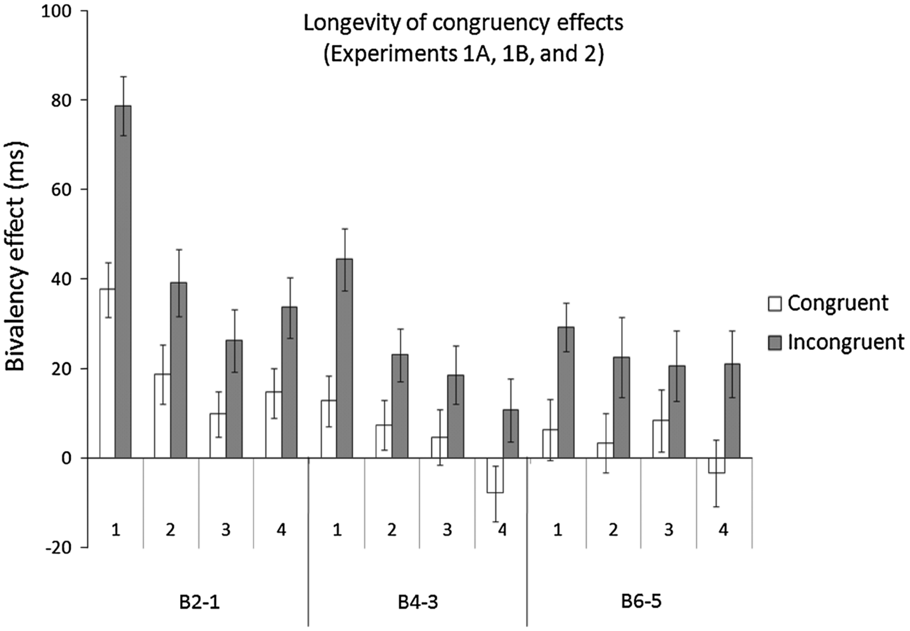

Fig. 4 The bivalency effect was calculated for 4 trial triplets across 12 trials following congruent vs. incongruent bivalent stimuli, illustrating the longevity of the congruency effects. 1 = trials 1–3, 2 = trials 4–6; 3 = trials 7–9; 4 = trials 10–12. Each triplet contains a colour judgment trial, a case judgment trial, and a parity judgment trial. *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). The data represent averages across Experiments 1A, 1B, and 2 (*error bars* are standard errors)

Discussion

Experiment 2 was designed to examine the possibility that overlapping processes between congruent and incongruent bivalent trials contributed to the congruency effects observed in Experiments 1A and 1B. We looked at the influence of response congruency as a between-subjects variable, rather than having congruent and incongruent trials mixed within the same block. Participants who encountered incongruent bivalent stimuli in bivalent blocks showed a large response slowing that remained throughout the experiment. On the other hand, participants who received congruent bivalent stimuli in bivalent blocks showed a response slowing that was smaller than those who received incongruent bivalent stimuli, and this effect was only present in the first bivalent block.

The results from Experiment 2 support the claim that the response congruency observations are not influenced by an overlap of processes due to mixing congruent and incongruent bivalent stimuli within the same block. Together with Experiments 1A and 1B, our results support the hypothesis that the bivalency effect reflects a process in predicting future cognitive demands based on recent cognitive load experience.

General discussion

The bivalency effect in task-switching refers to a response slowing on univalent trials that follow occasional bivalent stimuli (e.g. consisting of features that cue two different tasks). More specifically in the current experiment, a bivalent stimulus consisted of a task-relevant feature (e.g. an upper or lowercase letter) and a feature that was irrelevant for the current task but relevant for one of the other tasks in the sequence (e.g. font colour is irrelevant for the case judgment task). Importantly, the response slowing occurs even for stimuli that do not share the same stimulus features as the bivalent stimulus (e.g. digits), suggesting that the bivalency effect reflects a generalized adjustment in cognitive control. This control involves activation of the anterior cingulate cortex (ACC; Grundy et al., 2013; Woodward et al., 2008), a center thought to play a critical role in conflict detection (Botvinick et al., 2001; Botvinick, 2007; Botvinick et al., 2004; Cohen, Botvinick, & Carter, 2000; Egner, 2008; Veen & Carter, 2002; van Veen et al., 2001), outcome evaluation (Bush et al., 2002; Nieuwenhuis et al., 2004) and predictions of future cognitive load (Sheth et al., 2012).

In the current paper, we examined the influence of cognitive load on the bivalency effect by comparing response congruent vs. incongruent bivalent stimuli. A bivalent stimulus is congruent if the irrelevant feature is associated with the same response as the relevant feature and incongruent if the two features are associated with different responses. We show that the bivalency effect is substantially larger and less sensitive to practice when bivalent stimuli are incongruent. We suggest that response congruency of the bivalent stimulus determines the magnitude of the bivalency effect that is reported in most studies, possibly due to the increase in cognitive load that incongruent bivalent stimuli produce.

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 et al., 2008; Monsell et al., 2000; Rubinstein et al., 2001; Sohn & Anderson, 2001; van Veen et al., 2001). These models 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) can explain the slowing of responses on colour and case judgment trials within bivalent blocks by means of association with the more difficult bivalent trials. A bivalent trial shares task-relevant features (e.g. letters) with the case judgment task and task-irrelevant features (e.g. colour) with the colour judgment task. On the case and colour judgment trials that follow, this association with the bivalent trials is retrieved and leads to a response slowing. In contrast, the slowing observed on parity decision trials is problematic for a negative priming account because they do not share any features or task cues with bivalent stimuli.

One way to think about the slowing in the bivalency effect is to examine the *breaking of inertia* account (Paus, 2001; Woodward et al., 2008). With enough practice switching among different tasks, a fluency of processing develops. The occurrence of a bivalent stimulus triggers a reconfiguration of response style which interrupts this fluency. A larger magnitude bivalency effect following incongruent vs. congruent bivalent stimuli may indicate greater disruption to fluency due to additional conflict at the response stage. It may also take longer to regain the fluency, producing the difference in the time course of the bivalency effect following incongruent and congruent bivalent trials. The breaking of inertia account is consistent with the idea that conflict or uncertainty on the current trial triggers a more careful responding on following trials due to prediction and preparation for an increase in cognitive load.

The episodic context account for the bivalency effect proposes that the confusing context produced by the bivalent stimuli is retrieved upon presentation of the univalent trials that follow, and this leads to the response slowing (Meier & Rey-Mermet, 2012; Meier et al., 2009; Rey-Mermet & Meier, 2012a, b). Recent evidence supports a hypothesis that response conflict is not a critical part of the confusing context because the bivalency effect is observed even when responses are not shared across features (e.g. each task-relevant stimulus feature is mapped to a different response key; Rey-Mermet & Meier, 2012b). The authors argue that an association based on shared responses between univalent and bivalent trials does not account for the bivalency effect. Although it appears that these results are inconsistent with ours, it may be possible to reconcile the discrepant findings. In Rey-Mermet and Meier (2012b), each response was mapped to a different finger, but the pairs of responses for each task were split across left and right hands so that bivalent trials could be sorted into response congruent (e.g. features mapped to the same hand) or response incongruent (e.g. features mapped to different hands) trials. It is possible that differences in the magnitude of the bivalency effect might be observed by examining differences in cognitive load due to response congruency across left and right hands.

Rey-Mermet and Meier (2012a) also show that although the bivalency effect is sensitive to conflict, the amount and source of conflict do not play a role in modulating the bivalency effect. They introduced task-repetition trials to contrast the influence of conflict due to task-switching with conflict due to shared stimulus features. The bivalency effect was reduced for repetition trials only when they did not share any features with bivalent stimuli (i.e. on parity decision tasks); no difference between switch and repetition trials was observed for the other two tasks. Moreover, the magnitude of the bivalency effect was the same whether the conflict came from task-switching alone, stimulus feature conflict alone, or both together. These results suggest that the bivalency effect is equally affected by conflict of different types and from different sources. These findings challenge the prominent cognitive control notion that cognitive control is always modulated by the amount and source of conflict (Botvinick et al., 2001, 2004; Egner, 2008).

Our observation of the influence of response congruity on the magnitude of the bivalency effect suggests that the amount and/or source of conflict do matter. Even when we remove the first task triplet from the analyses to avoid possible contamination from orienting responses to the rare bivalent trials (cf. Rey-Mermet, Koenig, & Meier, 2013), response congruity on bivalent trials explains most of the variance in the bivalency effect. One way to reconcile the differences between our study and that of Rey-Mermet and Meier (2012a) is to consider that they collapsed RTs on univalent trials that followed congruent and incongruent bivalent trials, masking effects that would reveal the influence of the amount and/or source of conflict associated with response congruency.

Although response congruency of the bivalent stimulus contributed to most of the variance in the bivalency effect, interactions with other variables should be mentioned. For instance, there was a larger response slowing on colour trials compared to parity or case decision trials when these trials followed incongruent (but not congruent) bivalent stimuli. Colour is always the response feature that must be inhibited on bivalent stimuli and this inhibition might be retrieved upon subsequent presentations of colour trials, leading to additional slowing. This additional slowing on colour trials is in line with the idea that predictions of upcoming cognitive load on a particular trial are based on a recent history with conflict.

We propose that the bivalency effect reflects a process involved in predicting future cognitive load based on recent cognitive load experience. A promising behavioural adaptation hypothesis for dACC function is that it provides a continuous update on predicted cognitive demand that is sensitive to the changing details of the recent history of cognitive load (Sheth et al., 2012). This function of dACC works toward efficient processing, speeding responses when cognitive demands do not change and slowing responses to maintain accuracy when demands do change (Sheth et al., 2012). This view is in line with behavioural observations of conflict adaptation (Gratton et al., 1992). Conflict adaptation refers to a benefit in processing when cognitive load is repeated; that is, when high cognitive load trials follow high cognitive load and when low cognitive load trials follow low cognitive load. In terms of the bivalency effect, the behavioural adaptation hypothesis does not require that the source of conflict is due to any overlap of stimulus or response features, just that there is a change in cognitive demand. Bivalent stimuli create such a change in demand, resulting in slowed responses over the next few trials, including trials that do not share features with the bivalent stimulus (e.g. parity trials). Incongruent bivalent stimuli are more dissimilar from univalent stimuli than are congruent bivalent stimuli because they contain additional conflict and this larger mismatch in cognitive load leads to a larger bivalency effect for univalent trials that follow. The similarities between the behavioural responses in the Gratton effect and the bivalency effect are striking and suggest that at least some of the mechanisms producing the two effects overlap; future studies should examine this relationship further.

We also claim that the magnitude and robustness of the bivalency effect are sensitive to the magnitude of the signal predicting the change in cognitive demand. A bivalent stimulus creates a signal for increased future cognitive demand, and processing of subsequent univalent trials reflects this information. An incongruent bivalent stimulus produces more complexity and a larger disruption than a congruent bivalent stimulus, resulting in a larger prediction for future cognitive demand and a larger bivalency effect that does not return to baseline levels of responding after practice. Likewise in the Rey-Mermet and Meier (2012a) findings, the first of a pair of parity task-repeat trials does not share features with the bivalent stimulus or with any of the previous bivalent stimuli, and there is some history that it may be followed by an exact repetition; the prediction of upcoming cognitive demand would be low and the probability high that the second parity task repeat trial would not show the same slowed response as the other trials.

We know from ERP and fMRI studies that the bivalency effect is associated with dACC activity (Grundy et al., 2013; Woodward et al., 2008). Future studies can test the prediction that the magnitude of change in cognitive load (e.g. response congruency) can be detected electrophysiologically.

Conclusion

The present study is the first to examine the direct influence of response congruency on the bivalency effect. The bivalency effect is a robust task-switching phenomenon defined by the slowing of responses to univalent stimuli when they follow occasional bivalent stimuli (Grundy et al., 2013; Meier & Rey-Mermet, 2012; Meier et al., 2009; Rey-Mermet et al., 2013; Rey-Mermet & Meier, 2012a, b; Woodward et al., 2003, 2008). We demonstrate that response congruency mediates the magnitude and robustness of the bivalency effect, with a larger effect that does not return to baseline levels of responding after practice when bivalent stimuli are response incongruent. We support a hypothesis in line with recent proposals for a role of the dACC in providing ongoing predictions regarding future cognitive demands based on recent history to optimize performance (Sheth et al., 2012).

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