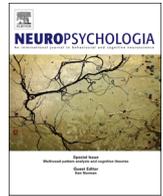




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Support for a history-dependent predictive model of dACC activity in producing the bivalency effect: An event-related potential study



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ABSTRACT

In the present study, we examine electrophysiological correlates of factors influencing an adjustment in cognitive control known as the bivalency effect. During task-switching, the occasional presence of bivalent stimuli in a block of univalent trials is enough to elicit a response slowing on all subsequent univalent trials. Bivalent stimuli can be congruent or incongruent with respect to the response afforded by the irrelevant stimulus feature. Here we show that the incongruent bivalency effect, the congruent bivalency effect, and an effect of a simple violation of expectancy are captured at a frontal ERP component (between 300 and 550 ms) associated with ACC activity, and that the unexpectedness effect is distinguished from both congruent and incongruent bivalency effects at an earlier component (100–120 ms) associated with the temporal parietal junction. We suggest that the frontal component reflects the dACC's role in predicting future cognitive load based on recent history. In contrast, the posterior component may index early visual feature extraction in response to bivalent stimuli that cue currently ongoing tasks; dACC activity may trigger the temporal parietal activity only when specific task cueing is involved and not for simple violations of expectancy.

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1. Introduction

When task demands change we are able to flexibly alter performance to meet the new demands. The cognitive control that allows this flexibility is not fully understood, but seems to be especially sensitive to changes in stimulus and response conflict. For example, traffic signals at intersections are, by necessity, consistent. An encounter with conflicting signals (e.g. both red and green lights flash simultaneously) will not only slow responses to the conflicting signals but also to any traffic signals that follow, until the norm is re-established. The bivalency effect refers to an adjustment in cognitive control in response to the occasional presence of a few bivalent stimuli amongst mostly univalent stimuli (Grundy et al., 2013; Grundy & Shedden, 2013; Meier, Woodward, Rey-Mermet, & Graf, 2009; Meier & Rey-Mermet, 2012a, 2012b; Meier, Rey-Mermet, Woodward, Müri, & Gutbrod, 2013; Rey-Mermet & Meier, 2012a, 2012b, 2013; Rey-Mermet, Koenig, & Meier, 2013; Woodward, Meier, Tipper, & Graf, 2003; Woodward, Metzak, Meier, & Holroyd, 2008). This adjustment is characterized by a slowing of response to all univalent 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 dorsal anterior cingulate cortex (dACC) in modulating the top-down control that is triggered by the bivalent stimuli (Grundy et al., 2013; Woodward et al., 2008).

In a typical bivalency effect experiment, trials alternate predictably between a parity decision task (odd vs. even digits), a colour decision task (blue vs. red shapes), and a case decision task (lowercase vs. uppercase letters). The stimulus itself cues the relevant task (digits cue the parity task, coloured shapes cue the colour task, letters cue the case task) and univalent trials contain no overlapping features that might trigger one of the irrelevant tasks. In bivalent blocks, about 10% of the trials (or 30% of the case judgment trials) are bivalent. For example, a case judgment trial may appear in blue or red, cueing both the relevant case judgment task, and the irrelevant colour judgment task. The irrelevant colour of these letters is difficult to ignore and this results in slower responses on these trials as well as all trials that follow for a significant period of time. The bivalency effect is calculated as the difference in response time on univalent trials that follow bivalent trials compared to univalent trials in blocks that do not contain any bivalent trials.

Critically, the slowing observed in the bivalency effect is present even on the trials that contain no overlapping features with the bivalent stimulus, an observation that is challenging to

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explain by models that incorporate overlapping stimulus and response properties (Allport, Style, & Hsieh, 1994; Allport & Wylie, 2000; Koch & Allport, 2006; Braverman & Meiran, 2010; Meiran & Kessler, 2008; Meiran, Kessler, & Adi-Japha, 2008; Monsell, Yeung, & Azuma, 2000; Rubinstein, Meyer, & Evans, 2001; Sohn & Anderson, 2001; Botvinick, Braver, Barch, Carter & Cohen, 2001a, 2001b; Botvinick, 2007; Botvinick, Cohen, & Carter, 2004; Van Veen, Cohen, Botvinick, Stenger, & Carter, 2001). Similarly, we know from fMRI (Woodward et al., 2008) and EEG (Grundy et al., 2013) studies of the bivalency effect that the dACC is involved, but the specific role of the dACC is unclear. Models of dACC function that involve activation of conflicting processing pathways (Botvinick et al., 2001a, 2001b, 2004; Botvinick, 2007; Compton, Huber, Levinson, & Zheutlin, 2012; Ullsperger, Bylsma, & Botvinick, 2005; Van Veen et al., 2001) or processes involved in outcome evaluation (Bartra, McGuire, & Kable, 2013; Bush et al., 2002; Eisenberger, Lieberman, & Williams, 2003; Gehring & Willoughby, 2002; Knutson, Taylor, Kaufman, Peterson, & Glover, 2005; Nieuwenhuis, Yeung, Holroyd, Schurger, & Cohen, 2004; Yeung & Sanfey, 2004) can explain the slowing on trials with overlapping features, but we need further explanation for the general response slowing.

A recent model of dACC function in regulation of cognitive control that might help explain the bivalency effect suggests a mechanism involved in predicting changes in upcoming cognitive load based on recent cognitive demands (Sheth et al., 2012). Using fMRI and single-cell recordings in humans, Sheth et al. (2012) demonstrated that dACC neurons were activated in response to conflict trials as well as trials that followed the conflict trials, showing that dACC neurons code for current and recent past. They also showed that dACC lesions did not disrupt processing on conflict trials which still produced slower responses compared to the no-conflict trials. However, dACC lesions did abolish the history-dependent behavioural adjustments (i.e. conflict adaptation effect; Gratton, Coles, & Donchin, 1992). The authors proposed that the dACC is involved in maintaining a continuously updated account of cognitive demand so that a change in cognitive control is implemented when demand increases or decreases.

In a bivalency effect experiment, we suggest that the conflict generated by the bivalent stimulus is detected by the dACC as an increase in demand for cognitive control. Thus, cognitive control is increased on the following univalent trials and a response slowing is observed. One might predict that a larger difference in cognitive load between bivalent and univalent trials would produce a larger bivalency effect; response congruency is one way to manipulate this difference (Grundy & Shedden, 2013; Rey-Mermet & Meier, 2014). Bivalent stimuli can be congruent or incongruent with respect to the associated responses of the relevant and irrelevant tasks. For example, consider that a left key press is required for blue shapes, odd digits and lowercase letters, and that a right key press is required for red shapes, even digits, and uppercase letters. A blue lowercase letter is a congruent bivalent stimulus (both features cue a left key press), whereas a red lowercase letter is an incongruent bivalent stimulus (the two features cue opposing key presses). Response slowing on univalent trials is substantially larger and less susceptible to adaptation when univalent trials follow incongruent compared to congruent bivalent trials (Grundy & Shedden, 2013). Thus, a larger disruption in the flow of ongoing processing produces a larger response, reflecting a mechanism by which required cognitive resources are predicted based on recent encounters with different amounts of conflict. This proposal is in line with the dACC's role in monitoring ongoing changes in the environment in order to optimize future performance (Sheth et al., 2012; see also Shenhav, Botvinick, & Cohen, 2013).

We can make further predictions about what to expect from electrophysiological measurements to link the response congruency

manipulation in the bivalency effect to known temporal and source components. In the first EEG study of the bivalency effect (Grundy et al., 2013), two main ERP processes corresponding to the bivalency effect were identified, reflecting differences in the response to univalent trials according to whether or not they followed bivalent trials. An early effect at 100–120 ms was localized to the temporal parietal junction (TPJ), and a later effect at 350–550 ms was localized to the dACC. We proposed that the TPJ component might reflect early additional visual-perceptual processing when task demands are uncertain. This was supported by the finding that this component was only present at the beginning of the experiment but not after extended practice. On the other hand, the later dACC component was present even after extended practice and appeared to accurately predict the behavioural responses. We proposed that this component reflects a disruption in the flow of cognitive processing as a result of encountering bivalent stimuli. We suspect that this component might also be sensitive to the amount of conflict encountered on bivalent trials, consistent with the behavioural findings (Grundy & Shedden, 2013). In other words, it might reflect predictions of upcoming cognitive load based on recent experiences with conflict. In the context of the current experiment, we expect that the response at the later dACC component will be larger and more robust for univalent trials that follow incongruent versus congruent bivalent stimuli.

A defining feature of the bivalency effect is that the bivalent trials are rare and unexpected, so that there is an element of surprise associated with processing the bivalent stimulus. A couple of recent studies (Metzak, Meier, Graf, & Woodward, 2013; Rey-Mermet & Meier, 2013) examined the extent to which surprise contributes to the bivalency effect, and showed that the response slowing observed in response to unexpected univalent stimuli is smaller than the bivalency effect. Despite the difference in magnitude of the response slowing, it is possible that unexpected univalent and unexpected bivalent stimuli lead to a similar adjustment in response style modulated by the dACC. There is a level of uncertainty about future cognitive demand in both conditions and we might expect that the dACC would respond to violations of expectancy in general. The current experiment compared responses to unexpected univalent trials with unexpected bivalent trials to determine whether the response slowing triggered by bivalent stimuli reflects similar and/or distinct processes from the ones engaged by unexpected univalent stimuli. Whereas we anticipated that the dACC component would reflect a similar process in response to bivalent and unexpected univalent stimuli, our prediction for the TPJ component was more uncertain. Because we previously proposed that the TPJ component reflects early additional feature extraction in the bivalency effect (Grundy & Shedden, 2013), we wondered whether or not it would obtain for a simple violation of expectancy effect in which simultaneous task-cueing is not present.

In summary, the purpose of the present bivalency effect study was two-fold: (1) To provide electrophysiological and source analysis support for the behavioural findings suggesting a role for the dACC in predicting future cognitive demand (Grundy & Shedden, 2013), and (2) to compare the influence of violations of expectancy versus bivalence on behavioural and electrophysiological responses.

Following previous bivalency effect designs, participants alternated between case, colour, and parity judgment tasks on each trial. Each participant encountered two sets of three blocks. In each block set, two univalent blocks (consisting of univalent stimuli only) flanked one bivalent/unexpected block. The bivalent/unexpected block included occasional surprising stimuli on the case judgment trials which were either bivalent (coloured letters) or unexpected univalent (letters with altered font). Block set order (bivalent vs. unexpected univalent) was counterbalanced; this allowed us to examine practice effects and thus

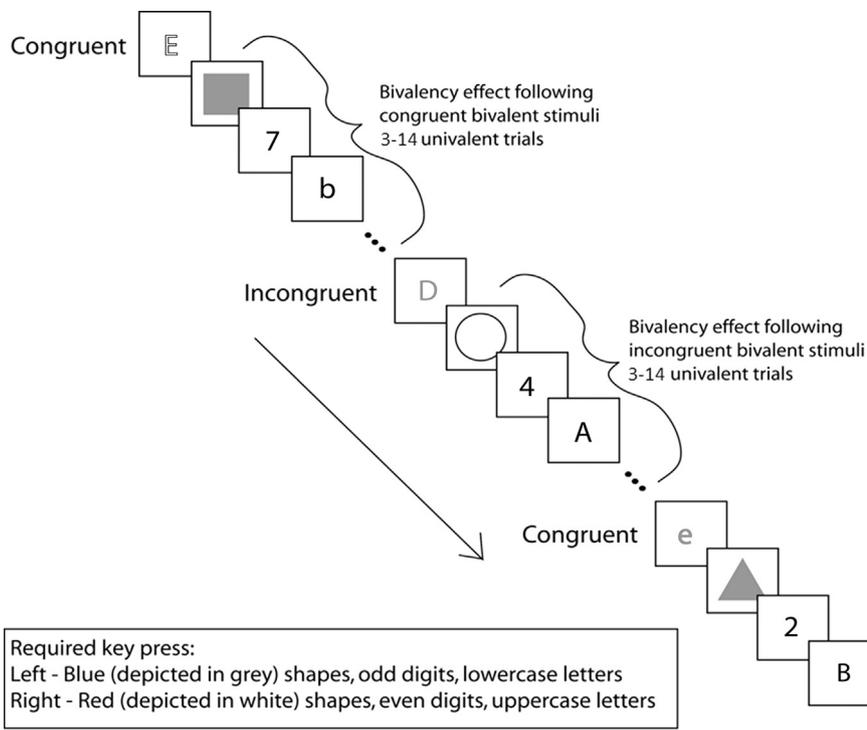


Fig. 1. Illustration of the trial sequence and type of stimuli used during the experiment. This particular illustration is an example of a *bivalent* block. During bivalent blocks, bivalent stimuli appear on 30% of all case judgment trials. Bivalent stimuli do not appear at all during the flanking pure univalent blocks. In the grey-scale diagram we use white to represent the red stimuli and grey to represent the blue stimuli. During *unexpected* blocks, unexpected univalent stimuli (i.e. change in font type) appear on 30% of all case judgment trials. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

the robustness of the influence of each type of surprising stimulus. EEG was recorded throughout the experiment.

2. Methods

2.1. Participants

Eighteen undergraduate students (mean age 19; 10 females, 8 males) 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.

2.2. 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–e) in white (60-point, Times New Roman).

In the bivalent block, occasional case judgment trials were presented randomly in red or blue. Bivalent stimuli were either response congruent (matching responses between case and colour), or response incongruent. In the unexpected block, occasional case judgment trials were presented randomly in Chopin or Old English font¹, resulting in univalent unexpected stimuli with no response incongruency. All participants completed the experiment individually in a dimly lit room.

¹ The unexpected stimulus could be constructed in various ways, for example, we could have used changes in texture, font, or colour. We did not want to use irrelevant colour because of the possibility that the unexpected trials would act as bivalent trials; even if the colours are task-irrelevant they may trigger retrieval of the colour task-set. For example, the magnitude of the unexpectedness effect in the

2.3. Procedure

Each block (including practice blocks) contained 168 trials, and subjects were provided with a brief break at the end of each block. Within bivalent (or unexpected) blocks, 16 of the case judgment trials (randomly selected) presented the letters in red or blue (or Chopin or Old English), making these stimuli bivalent (or unexpected univalent stimuli). There were 8 incongruent bivalent and 8 congruent bivalent stimuli within each bivalent block. These stimuli were pseudo-randomly mixed within the block, and the first encounter with a bivalent stimulus was counterbalanced between congruent and incongruent bivalent 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). Fig. 1 illustrates an example of the trial sequence. Participants responded by pressing one of two response keys using the index and middle fingers of the right hand: 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). 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

(footnote continued)

Rey-Mermet and Meier (2013) study with colour is larger than the Metzak et al. (2013) study with texture (30 ms vs. 10 ms, respectively). Unexpected differences in texture or font changes do not have this task-set problem and they produce similar effect sizes according to our pilot data. We chose to use font changes in the current experiment, although it should not matter whether the unexpected stimulus uses texture or font.

accuracy. The inter-trial interval was randomly varied between 400 and 900 ms, which allowed us to reduce distortion of ERP components due to averaging of epochs that overlap in time (Woldorff, 1993). All participants were told to ignore the modification to case judgments (on occasional bivalent or unexpected univalent trials), and to continue making the case decisions as usual.

The bivalency (or unexpectedness) 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 (or unexpected univalent) stimuli. Note that RTs to the bivalent (or unexpected univalent) stimuli are not included in the means. To remove the possibility of an orienting response contributing to the ERP waveforms (Rey-Mermet et al., 2013), we removed the first three trials (consisting of a colour trial, a parity trial, and a case trial) immediately following bivalent stimuli from the analyses. Due to pseudo-random presentation of bivalent (or unexpected) trials, the number of univalent trials included in the analyses that followed each bivalent or unexpected trial ranged from 5 to 14, resulting in approximately 100 univalent trials.

To compare the influence of congruent vs. incongruent bivalent trials within the same² block, we averaged all the univalent trials that followed congruent bivalent trials separately from the univalent trials that followed incongruent bivalent trials, resulting in approximately 50 univalent trials following each type of bivalent trial.

2.4. 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 EEPProbe (www.ant-nero.com). Eye blinks and movement artifacts were automatically identified and manually verified. EEPProbe 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.

Source analysis was performed using Brain Electrical Source Analysis (BESA; version 5.1.8; www.besa.de) by MEGIS Software GmbH. EEG data do not have high enough spatial resolution to make estimates as precise as Talairach coordinates, however, BESA provides Talairach coordinates as a guide for interpretation of source estimates. We used the Talairach Client (version 2.4.3; Lancaster et al., 1997, 2000) to estimate the closest grey matter to the source coordinates supplied by BESA, however, caution should be taken when interpreting results due to variability in the source localization.

2.5. Data analyses (behavioural)

The bivalency (or unexpected) 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 (or unexpected) stimuli. Responses to the bivalent stimuli and to the unexpected univalent 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 the univalent trials appear.

We first performed a 2 (block-set order: bivalent first vs. unexpected first) \times 3 (block-set type: congruent vs. incongruent vs. unexpected) \times 3 (task: colour, parity, case) mixed-measures ANOVA on accuracy and RT difference scores for the block-sets. To assess whether the congruent, incongruent, and unexpectedness effects were significantly different from 0, we performed t-tests for each type of difference score.

² The congruent bivalency effect and the incongruent bivalency effect were examined by looking at univalent trials that appeared immediately following congruent or immediately following incongruent bivalent stimuli until the presentation of the next bivalent stimulus. Because congruent and incongruent trials appeared within the same block, one might argue that overlapping processes between congruent and incongruent bivalent trials contribute to the congruency effects reported. However, we have previously shown that the contrast between congruent and incongruent bivalency effects is equivalent (incongruent > congruent) whether congruency is mixed within the same block or separated across blocks or participants (Grundy & Shedden, 2013).

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 adjustments were applied for multiple comparisons. Outliers were defined as being greater than three standard deviations above or below the mean and were eliminated from all further analyses. All analyses including reaction time and electrophysiological responses were performed on correct trials.

2.6. Data analyses (electrophysiological)

Because of the vast number of possible locations and time windows that our 128-electrode EEG system allows, we employed Partial Least Squares (PLS; Lobaugh, West, & McIntosh, 2001; McIntosh, Bookstein, Haxby, & Grady, 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).

We used the PLS analysis to validate our subsequent componential analyses based on predictions generated by our hypotheses in correspondence with our previous ERP results (Grundy et al., 2013). The PLS analysis was done across 108 of the 128 electrodes (edge electrodes excluded). Of particular interest was a medial frontopolar electrode cluster (Fpz, AFz, AF4, and AF3), and electrodes around 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., 2013). These regions are consistent with electrophysiological studies on task-switching and conflict (e.g. Grundy et al., 2013; Meiran, Hsieh, & Chang, 2011; Poulsen, Luu, Davey, & Tucker, 2005).

3. Results

3.1. Behavioural results for bivalent/unexpected stimuli

Even though we are mainly concerned with the *after-effects* of bivalent/unexpected stimuli, it is important to document performance on these surprising stimuli and to compare them to baseline performance on case judgment trials within their respective critical blocks. Thus, a 2 (block-set order: first vs. second) \times 4 (stimulus type: univalent, congruent, incongruent, unexpected) mixed-measures ANOVA was performed on accuracy and response times (RTs). For accuracy, a significant effect of stimulus type was revealed, $F(3,48)=3.94$, $p < 0.05$, $\eta^2=0.198$; accuracy was greater for expected univalent case judgment trials than incongruent bivalent trials ($p < 0.05$) and unexpected trials ($p < 0.05$), but not congruent bivalent trials (albeit in the same direction; $p=0.17$). No other effects reached significance for accuracy.

For RTs, this ANOVA revealed a significant main effect of block-set order, $F(1,16)=4.55$, $p < 0.05$, $\eta^2=0.221$, and a significant main effect of stimulus type, $F(3,48)=13.71$, $p < 0.001$, $\eta^2=0.462$. The order effect can be explained by practice, such that people were faster to respond to stimuli in the second block-set than the first ($p < 0.05$). The stimulus type effect can be explained by the finding that RTs were longer for incongruent bivalent stimuli than all other stimulus types (all $ps < 0.05$), that unexpected and congruent bivalent stimulus types did not differ from each other

Table 1

Accuracy (and standard error) for univalent trials within bivalent/unexpected blocks compared to the corresponding flanking univalent (i.e. pure) blocks. B=block.

| Accuracy (proportion correct) | | | | |
|-------------------------------|--------------------------|----------------------------|------------------------|-------------|
| Univalent blocks | | Bivalent/unexpected blocks | | |
| First block set (B 1&3) | Second block set (B 4&6) | First block set (B 2) | Second block set (B 5) | |
| Pure | | Congruent | | |
| Colour | 0.92 (0.02) | 0.92 (0.01) | 0.90 (0.03) | 0.92 (0.02) |
| Parity | 0.92 (0.02) | 0.95 (0.01) | 0.94 (0.02) | 0.96 (0.02) |
| Case | 0.96 (0.02) | 0.94 (0.02) | 0.93 (0.03) | 0.95 (0.02) |
| | | | Incongruent | |
| | | | 0.87 (0.03) | 0.90 (0.02) |
| | | | 0.93 (0.02) | 0.93 (0.02) |
| | | | 0.94 (0.03) | 0.90 (0.04) |
| | | | Unexpected | |
| | | | 0.95 (0.01) | 0.90 (0.02) |
| | | | 0.96 (0.02) | 0.91 (0.02) |
| | | | 0.97 (0.01) | 0.95 (0.02) |
| | | | Pure | |
| Colour | 0.94 (0.01) | 0.91 (0.03) | 0.95 (0.01) | 0.90 (0.02) |
| Parity | 0.96 (0.01) | 0.91 (0.03) | 0.96 (0.02) | 0.91 (0.02) |
| Case | 0.96 (0.03) | 0.95 (0.03) | 0.97 (0.01) | 0.95 (0.02) |

Table 2

Response times (and standard errors) for univalent trials within bivalent/unexpected blocks compared to the corresponding flanking univalent (i.e. pure) blocks. B=block.

| Response times (ms) | | | | |
|-------------------------|--------------------------|----------------------------|------------------------|----------|
| Univalent blocks | | Bivalent/unexpected blocks | | |
| First block set (B 1&3) | Second block set (B 4&6) | First block set (B 2) | Second block set (B 5) | |
| Pure | | Congruent | | |
| Colour | 581 (17) | 638 (42) | 589 (22) | 635 (35) |
| Parity | 585 (24) | 657 (33) | 623 (33) | 643 (30) |
| Case | 581 (26) | 637 (35) | 596 (36) | 604 (20) |
| | | | Incongruent | |
| | | | 654 (19) | 670 (34) |
| | | | 645 (30) | 668 (34) |
| | | | 627 (32) | 657 (38) |
| | | | Unexpected | |
| | | | 649 (36) | 605 (19) |
| | | | 643 (23) | 583 (25) |
| | | | 651 (29) | 571 (24) |
| | | | Pure | |
| Colour | 602 (28) | 600 (20) | 649 (36) | 605 (19) |
| Parity | 631 (26) | 596 (24) | 643 (23) | 583 (25) |
| Case | 612 (30) | 582 (26) | 651 (29) | 571 (24) |

($p > 0.05$), and that both congruent and unexpected stimulus types differed from expected univalent case judgments ($p < 0.001$ and $p < 0.02$, respectively). We note also that a significant linear trend was revealed, showing the slowest response times to incongruent bivalent stimuli (800 ms, $SE = 39$ ms) followed by unexpected stimuli (741 ms, $SE = 17$ ms), congruent bivalent stimuli (702 ms, $SE = 31$ ms), and then expected univalent case judgment stimuli (618 ms, $SE = 20$ ms), $F(1,16) = 34.48$, $p < 0.001$, $\eta^2 = 0.683$.

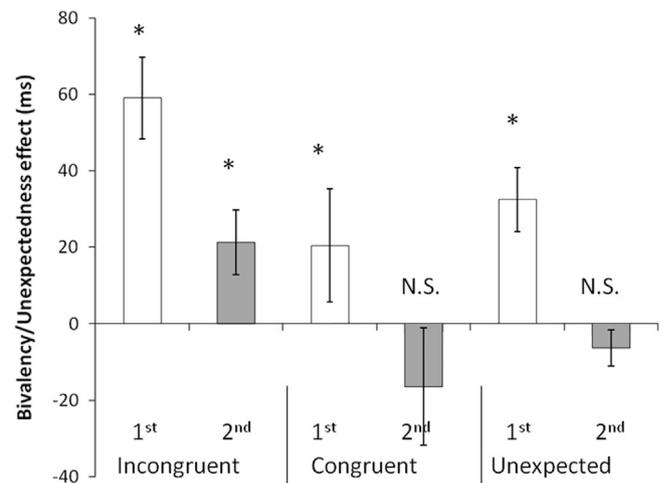
3.2. Behavioural results for univalent trials (accuracy)

Table 1 provides mean accuracy rates for all tasks. Accuracy did not differ across conditions ($< 9\%$ error overall). A $2 \times 3 \times 3$ mixed-measures ANOVA examined block-set order (first vs. second) by block-set type (congruent, incongruent, unexpected) by task (colour, parity, case). No effects reached significance (all $ps > 0.100$).

3.3. Behavioural results for univalent trials (RTs)

Table 2 provides mean reaction times (RTs) for all tasks. A significant main effect of block-set type was revealed, $F(2,32) = 8.56$,

Behavioural bivalency/unexpectedness effect



ERPs (ACC activity) at 350-390 ms

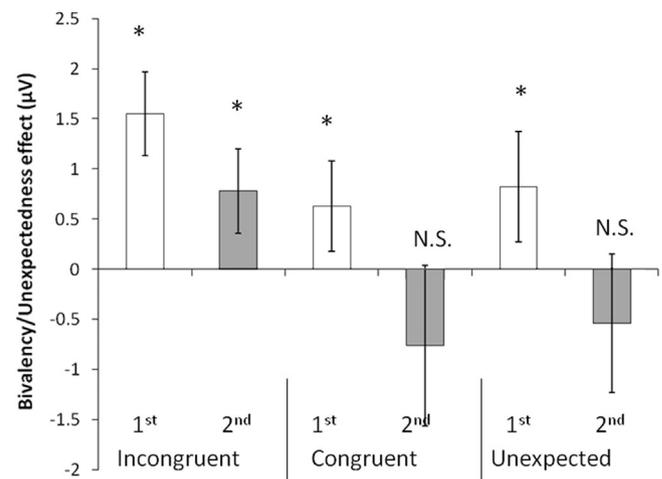


Fig. 2. Behavioural bivalency/unexpectedness effects and corresponding ERP amplitude differences (localized to the dACC) in response to congruent bivalent stimuli, incongruent bivalent stimuli, and non-bivalent unexpected stimuli. Block order was as follows: pure, bivalent/unexpected, pure, pure, bivalent/unexpected, pure. The bivalency/unexpectedness effect is calculated by subtracting the responses to univalent stimuli in the blocks flanking a bivalent/unexpected block to the expected univalent stimuli within that bivalent/unexpected block. 1st: these responses appeared in the first of the two bivalent/unexpected blocks. 2nd: these responses appeared in the second of the two bivalent/unexpected blocks (i.e. after practice with the first block set). * = Bivalency/unexpectedness effect significantly different from zero. N.S. = non-significant.

$p = 0.001$, $\eta^2 = 0.349$, $\epsilon = 0.76$. A significant interaction between block-set type and order was also revealed, $F(2,32) = 10.74$, $p < 0.001$, $\eta^2 = 0.402$, $\epsilon = 0.76$, supporting a hypothesis related to practice effects. All three of the block-set types (incongruent, congruent, and unexpected) showed smaller effects in the second block-set compared to the first block-set (Fig. 2); however, these practice effects differed across block-set type as follows. The congruent bivalency effect in the first block-set was greater than the congruent ($p = 0.05$) and unexpected ($p = 0.02$) effects but not the incongruent bivalency effect ($p = 0.72$) in the second block-set. Likewise, the unexpected effect in the first block-set was greater than the congruent ($p = 0.01$) and unexpected ($p = 0.001$) effects but not the incongruent bivalency effect ($p = 0.35$) in the second block-set. The incongruent bivalency effect was greater in the first block-set compared to all other conditions ($ps < 0.05$).

Our interpretation is that the incongruent bivalency effect is less susceptible to practice, consistent with other work (Grundy & Shedden, 2013).

To further assess the above interpretation and the statistical significance of the congruent bivalency effect, the incongruent bivalency effect, and the unexpectedness effect, the difference scores were subjected to one-sample *t*-tests to determine whether or not 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 significantly different from 0 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 main effect of task was not significant, $F(2,32)=2.91$, $p=0.08$, $\eta^2=0.154$, $\epsilon=0.87$, nor were any interactions with the factor task (all F s < 2.91).

We described in the methods that the first encounter with a bivalent stimulus was counterbalanced between congruent and incongruent bivalent stimuli. We did not include this contrast in our analyses due to the small number of participants in each group; we also did not have a priori predictions with respect to whether the incongruent or congruent bivalent stimulus occurred first in the bivalent block. We have shown previously that mixing congruent and incongruent bivalent trials does not change the differential effects of congruency on the bivalency effect (Grundy & Shedden, 2013). We were not as interested in the very first encounter with a bivalent stimulus because our model involves a faster adaptation of the cognitive system, such that prediction of upcoming cognitive load is updated based on the most recent conflict-loaded bivalent stimulus. If the very first bivalent stimulus has a strong effect on the rest of the block, we would not be able to detect that in the current design, but what we can say is that the effect is not large enough to negate the large difference between the effects of congruent versus incongruent bivalent stimuli mixed throughout the rest of the block. Future experiments may examine the influence of whether the very first bivalent stimulus in the bivalent block is congruent or incongruent.

3.4. Electrophysiological results

The PLS analysis revealed one reliable latent variable (LV) demonstrating that univalent trials following incongruent bivalent stimuli differed from univalent trials following congruent and unexpected univalent stimuli, which did not differ from each other; univalent trials in pure blocks differed from all three of these conditions. This latent variable accounted for 46.71% of the variance ($p=0.03$). The bootstrap analysis of electrode salience, which provides confidence intervals for salience across time points and electrodes, revealed that this latent variable was most reliable in frontal electrodes (Fpz, AFz, AF4, and AF3) at points between 225 and 550 ms after stimulus onset (see Fig. 3). To examine these results further, classic componential statistical tests were performed at the frontal cluster based on visual inspection within this time-frame.

The bivalency (and unexpectedness) effects were measured as differences in amplitudes between univalent trials in bivalent (or unexpected) blocks and univalent trials in purely univalent blocks. As was done for the behavioural results, amplitude differences reflecting the congruent and incongruent bivalency effects involved the univalent trials that followed congruent or incongruent bivalent trials, respectively. Amplitude differences were observed between 300 and 550 ms at a frontal electrode cluster (Fpz, AFz, AF4, and AF3), consistent with the PLS analysis and our previous bivalency effect study (Grundy et al., 2013).

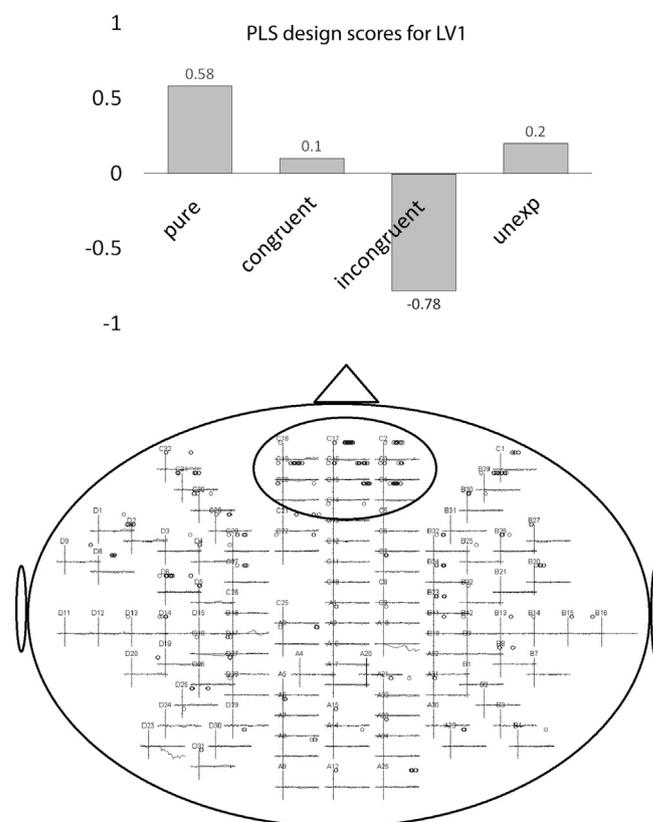


Fig. 3. PLS electrode salience map and design scores for latent variable 1. The PLS analysis revealed one reliable latent variable (LV) demonstrating that univalent trials following incongruent bivalent stimuli differed from univalent trials following congruent and unexpected univalent stimuli, which did not differ from each other; univalent trials in pure blocks differed from all three of these conditions. This latent variable accounted for 46.71% of the variance ($p=0.03$). The bootstrap analysis of electrode salience, which provides confidence intervals for salience across time points and electrodes, revealed that this latent variable was most reliable in frontal electrodes (Fpz, AFz, AF4, and AF3) at points between 225 and 550 ms after stimulus onset.

For statistical analyses involving block-set type comparisons, we focused on the time window 350–390 ms, which was the largest significant window shared across the incongruent, congruent, and unexpected effects that corresponded with the PLS analysis. Within this time window, amplitude difference scores reflected the behavioural responses (see Fig. 2), and dipole source analysis estimated ACC as a possible source associated with these amplitude differences (source analyses are described in more detail below). Amplitude difference scores within this window were subjected to a 2×3 mixed-measures ANOVA examining block-set order (first vs. second) by block-set type (congruent, incongruent, unexpected). The waveforms are presented in Fig. 4.

A significant main effect of block-set type, $F(2,32)=2.56$, $p=0.045$, $\eta^2=0.138$, $\epsilon=0.84$ can be explained by the finding that the incongruent bivalency effect elicited greater amplitude differences than the congruent ($p=0.01$) and the unexpectedness ($p<0.05$) effects, but that the congruent and unexpectedness effects did not differ from each other ($p=0.76$). A significant interaction between block-set type and order was also revealed, $F(2,32)=2.84$, $p=0.04$, $\eta^2=0.151$, $\epsilon=0.84$. All three of the block-set types (incongruent, congruent, and unexpected) showed smaller effects in the second block-set compared to the first block-set (Fig. 2); however, these practice effects differed across block-set type as follows. The congruent bivalency effect in the first block-set was greater than the congruent ($p<0.01$) and unexpected ($p<0.01$) effects but not the incongruent bivalency effect

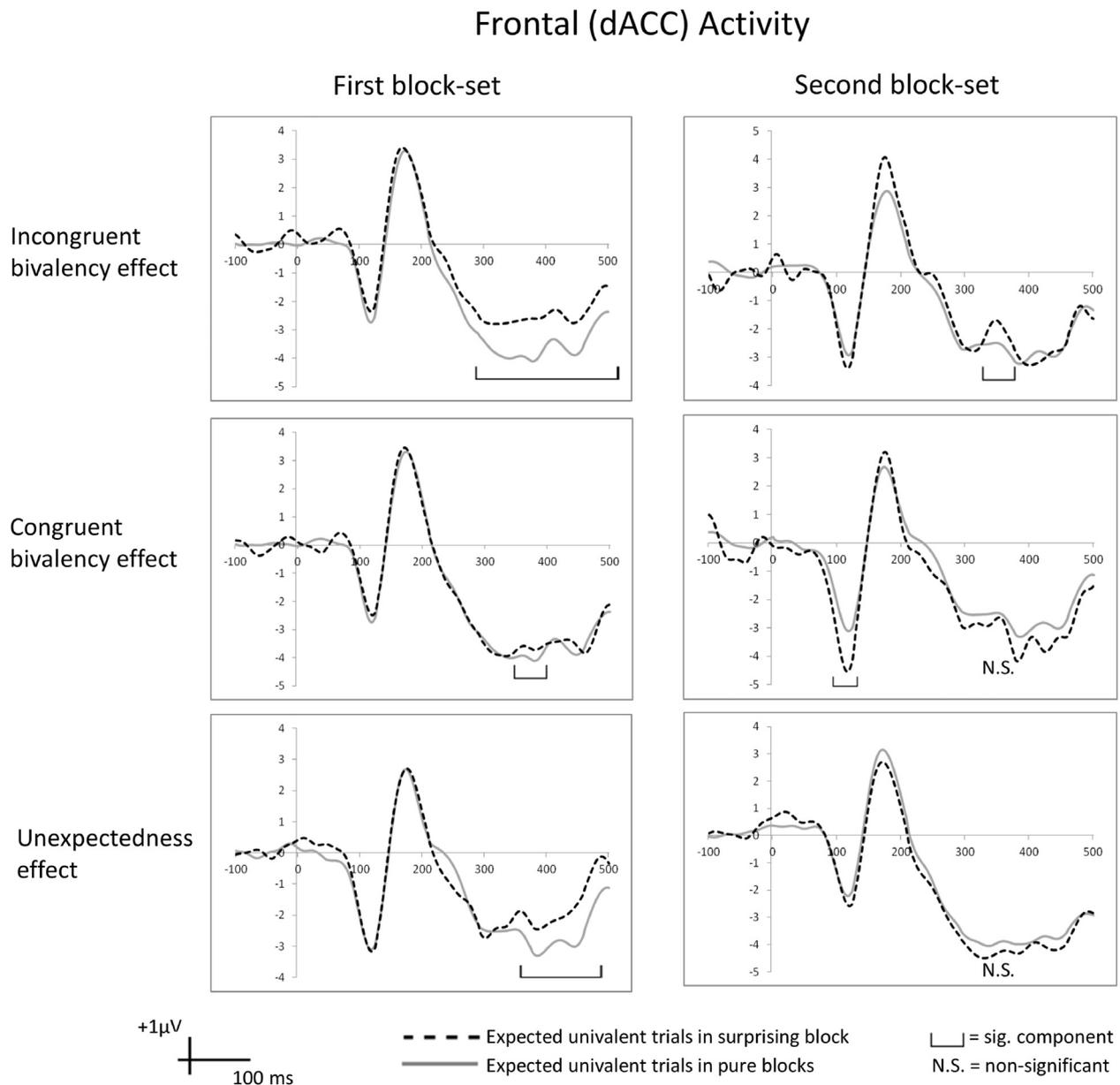


Fig. 4. Event-related potentials (localized to dACC) capturing processing differences between expected univalent stimuli that appeared in pure vs. bivalent/unexpected blocks. There were two sets of three blocks; each block set consisted of one bivalent/unexpected block containing univalent trials (dashed line) plus occasional surprising trials (not graphed), flanked by two blocks containing purely univalent trials (solid line). There were three types of surprising trials (incongruent bivalent, congruent bivalent, and unexpected), producing the incongruent bivalency effect (top row), the congruent bivalency effect (middle row), and the unexpected effect (bottom row). First block set: represents first encounter with the block set. Second block set: represents performance on the second set of blocks following practice with the first set of blocks.

($p=0.94$) in the second block-set. Likewise, the unexpected effect in the first block-set was greater than the congruent ($p=0.04$) and unexpected ($p=0.02$) effects but not the incongruent bivalency effect ($p=0.99$) in the second block-set. The incongruent bivalency effect was greater in the first block-set compared to all other conditions ($ps < 0.05$). The incongruent amplitude differences appear to be less susceptible to practice, consistent with the behavioural findings presented above (see Fig. 2).

3.5. Congruent bivalency effect amplitude differences (350–390 ms)

For the congruent bivalency effect, amplitude differences between trials that followed congruent bivalent stimuli compared to trials in purely univalent blocks appeared within the first block set between 350 and 390 ms. Responses to univalent trials that followed congruent bivalent stimuli showed a less negative

amplitude than trials in pure blocks ($-3.43 \mu\text{V}$ vs. $-3.97 \mu\text{V}$), $t(8) = -2.10$, $p = 0.039$. 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 ($-4.36 \mu\text{V}$ vs. $-3.60 \mu\text{V}$), $t(8) = 1.30$, $p = 0.232$. To increase confidence in our assertion that this frontal activity reflects processing differences at the dACC, we used BESA to performed source analysis. Principle components analysis (PCA) was first used to determine the number of dipoles needed for each time window (dipoles accounting for less than 2% of the variance are not reported); the software then automatically calculated the locations of each dipole. Note that EEG data do not have sufficient spatial resolution to estimate precise Talairach coordinates; these should be considered as rough estimates of dipole location (see Section 2.4 above). Two principle components were needed to account for 97.5% of the variance in the ERP difference scores. The estimated source for the first dipole (accounting for 94.9% of the

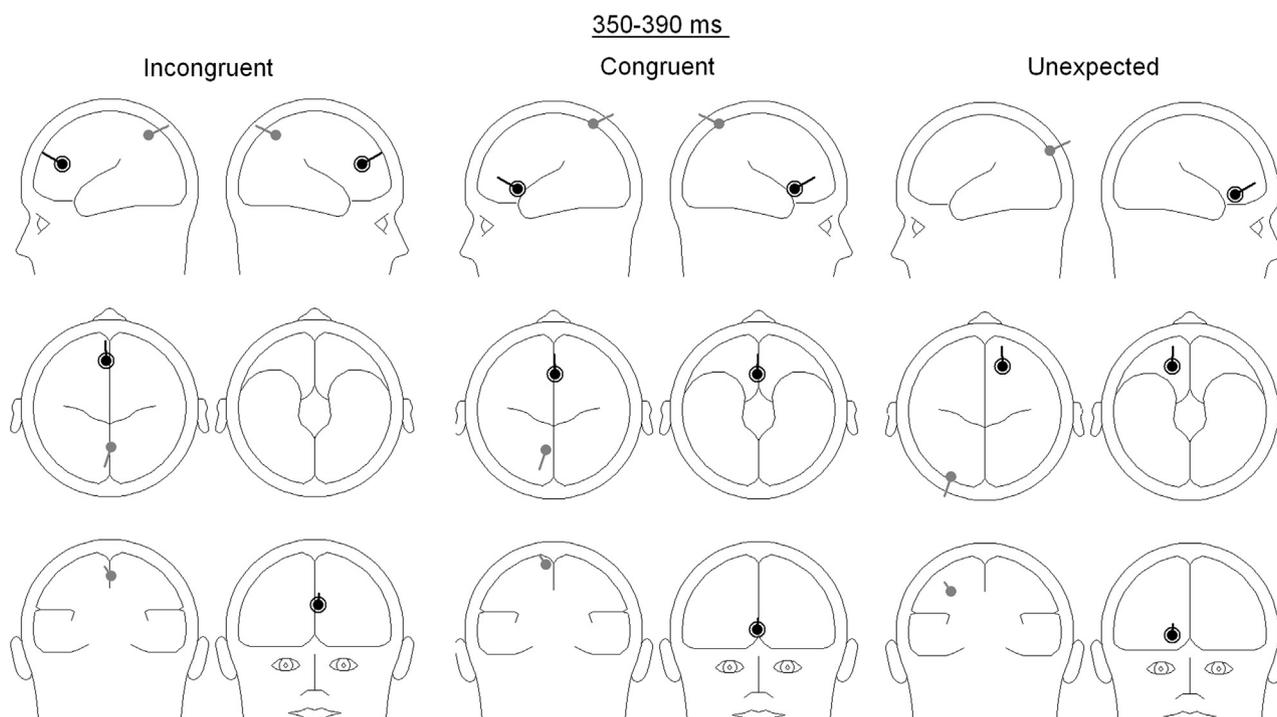


Fig. 5. Source analysis for the late ERP component (350–390 ms) associated with the incongruent bivalency effect, the congruent bivalency effect, and the unexpectedness effect. For each effect, the first dipole accounting for most of the variance (96% for incongruent, 98% for congruent, and 87% for unexpected) is shown in black, and the second dipole is shown in grey. Our source analyses place the generators of these primary dipoles near the anterior cingulate cortex (ACC) in each case.

variance) was consistent with the ACC. The estimated source of the second dipole was consistent with Brodmann area 7, and accounted for only 2.6% of the variance. See Fig. 5 for source diagram.

3.6. Unexpectedness effect amplitude differences (350–500 ms)

For the unexpectedness effect, amplitude differences between trials that followed unexpected univalent stimuli compared to trials in purely univalent blocks appeared within the first block set between 350 and 500 ms. Less negative amplitudes were revealed for univalent trials that followed unexpected stimuli than univalent trials in pure blocks ($-1.76 \mu\text{V}$ vs. $-3.20 \mu\text{V}$), $t(8)=2.28$, $p=0.025$. No differences within this time frame were found when univalent trials in the unexpected block appeared in the second block set ($-4.56 \mu\text{V}$ vs. $-3.84 \mu\text{V}$), $t(8)=0.82$, $p=0.441$. Two principle components were needed to account for 97.1% of the variance in the ERP difference scores. The first dipole (accounting for 87.3% of the variance) was consistent with a source in the ACC. The estimated source of the second dipole was consistent with Brodmann area 19, and accounted for only 9.8% of the variance. See Fig. 5 for source diagram.

3.7. Incongruent bivalency effect amplitude differences (300–550 ms)

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. Univalent trials that followed incongruent bivalent stimuli showed a less negative amplitude than trials in pure blocks, ($-2.17 \mu\text{V}$ vs. $-3.97 \mu\text{V}$), $t(8)=2.72$, $p=0.013$. Unlike the congruent bivalency effect and the unexpectedness effect, the incongruent bivalency effect in the second block set captured processing differences at

325–390 ms after stimulus onset. Less negative amplitude was observed for univalent trials that followed incongruent bivalent stimuli than trials in pure blocks, ($-2.19 \mu\text{V}$ vs. $-2.84 \mu\text{V}$), $t(8)=1.94$, $p=0.040$ (see Fig. 4). Two principle components were needed to account for 98.5% of the variance in the ERP difference scores. The first dipole (accounting for 96.2% of the variance) was consistent with a source in the ACC. The estimated source of the second dipole was consistent with Brodmann area 7, and accounted for only 2.3% of the variance. See Fig. 5 for source diagram.

The time-windows of the present study are consistent with the original Grundy et al. (2013) study. Grundy et al. collapsed across congruent and incongruent bivalent stimuli, so that the ERPs that corresponded to the congruent bivalency effect and the incongruent bivalency effect were summated; in that paper, the late ERP components were within the time window 300–550 ms and activity was localized to ACC. Fig. 6 shows a direct comparison between the averaged congruent and incongruent conditions for the Grundy et al. (2013) study and the present study, illustrating the similarity across these late ERP components.

It is notable that the latency differences of the waveforms appear to be related to the behavioural RTs of the surprising stimulus types. Specifically, the behavioural incongruent bivalency effect was the largest (59 ms), incongruent bivalent stimuli elicited the longest RTs (800 ms), and the time window of ERP responses was the longest (300–550 ms). The behavioural congruent bivalency effect was the smallest (21 ms), congruent bivalent stimuli elicited the shortest RTs (702 ms), and the time window of the ERP responses was the shortest (350–390 ms). The unexpected condition fell in-between on all these measures: the behavioural unexpectedness effect was 33 ms, the mean RT was 741 ms, and the time window of ERP responses was 350–500 ms. Thus, the behavioural results appear to be related to the ERP latency differences. Future experiments could use a between-subjects design to increase the number of trials per condition for each observer to provide support for this hypothesis.

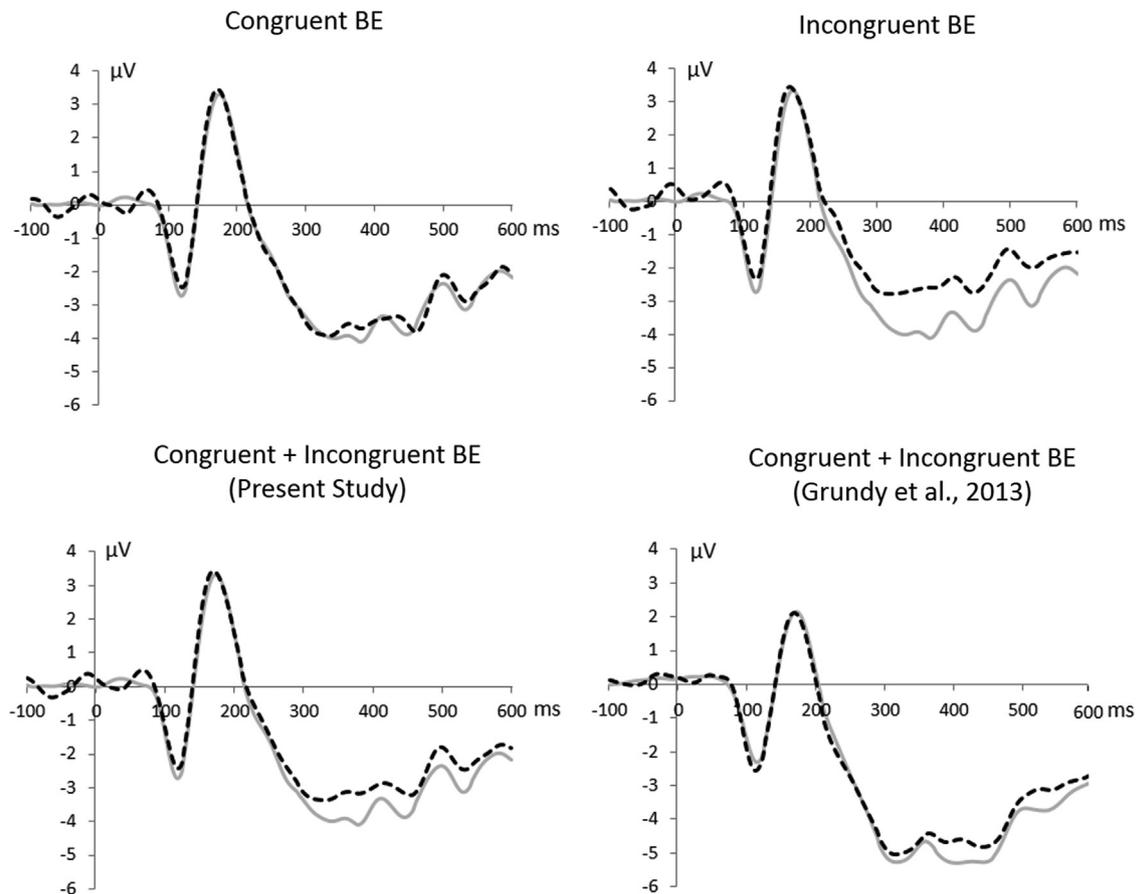


Fig. 6. The congruent bivalency effect, incongruent bivalency effect and the combination of the two effects in the present study compared to the original Grundy et al. (2013) bivalency effect waveforms at frontal electrodes associated with ACC activity. Notice that the overall waveforms in the present study are very similar to the Grundy et al. waveforms.

3.8. Electrophysiological results (100–120 ms)

The bivalency effects (congruent and incongruent), but not the unexpectedness effect, were captured by amplitude differences between 100 and 120 ms after stimulus onset at electrode clusters that we previously linked to TPJ activity³ (left hemisphere: P5, P7, and PO7; right hemisphere: P6, P8, PO8; see Figs. 7 and 8). Even though the PLS analysis did not highlight the TPJ area in this study, the significant effects at TPJ in our previous work (Grundy et al., 2013) makes it an important *a priori* focus of the current analyses.

A 2 (block-set order: bivalent first vs. unexpected first) \times 3 (block-set type: congruent vs. incongruent vs. unexpected) \times 2 (hemisphere: left vs. right) mixed measures ANOVA was performed and revealed a significant effect of block-set type, $F(2,32)=2.51$, $p < 0.05$, $\eta^2=0.191$, $\epsilon=0.89$. This can be explained by the finding that the congruent and incongruent bivalency effects showed larger amplitude differences than the unexpectedness effect, $t(17)=2.51$, $p=0.02$, and $t(17)=2.10$, $p=0.05$, but that the congruent and incongruent bivalency effects did not differ from each other, $t(17)=0.32$, $p=0.752$. No other effects reached significance (all $ps > 0.2$). Given that counterbalancing block-set order resulted in 9 participants per cell, future studies may look more closely at the interaction between block-set order and type to clarify whether there might be additional practice effects.

³ There was also a significant amplitude difference within this time window for univalent trials that followed congruent bivalent stimuli at the frontal cluster. However, our source analysis confirmed that this was likely a reflection of TPJ activity, consistent with our previous bivalency effect study (Grundy et al., 2013).

Source analysis confirmed that the components at 100–120 ms were likely a reflection of TPJ activity. For the congruent bivalency effect, two principle components were needed to account for 99.4% of the variance in the ERP difference scores. The first dipole (accounting for 93.9% of the variance) was located at $x, y, z = -37, -90, 30$; this roughly corresponds to the left TPJ. The second dipole (accounting for 5.5% of the variance) was located at $x, y, z = 40, -58, 61$, which roughly corresponds to the right TPJ.

For the incongruent bivalency effect, two principle components were needed to account for 99.6% of the variance in the ERP difference scores. The first dipole (accounting for 95.5% of the variance) was located at $x, y, z = -16, -85, 45$. The second dipole (accounting for 4.1% of the variance) was located at $x, y, z = -69, -30, 37$. Both of these dipoles are located around the left TPJ.

4. Discussion

In the present study we examined the influence of three different types of surprising stimuli in modulating behavioural and electrophysiological adjustments to subsequent univalent trials. The occasional presence of bivalent stimuli within a block of univalent trials is enough to elicit a 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 adjustment observed as the bivalency effect is believed to involve top-down cognitive control modulated by the dorsal anterior cingulate cortex (dACC; Grundy et al., 2013; Woodward et al., 2008), a center involved in conflict detection (Kerns et al., 2004; Kerns, 2006; Liu, Banich, Jacobson, &

Temporal Parietal Junction Activity

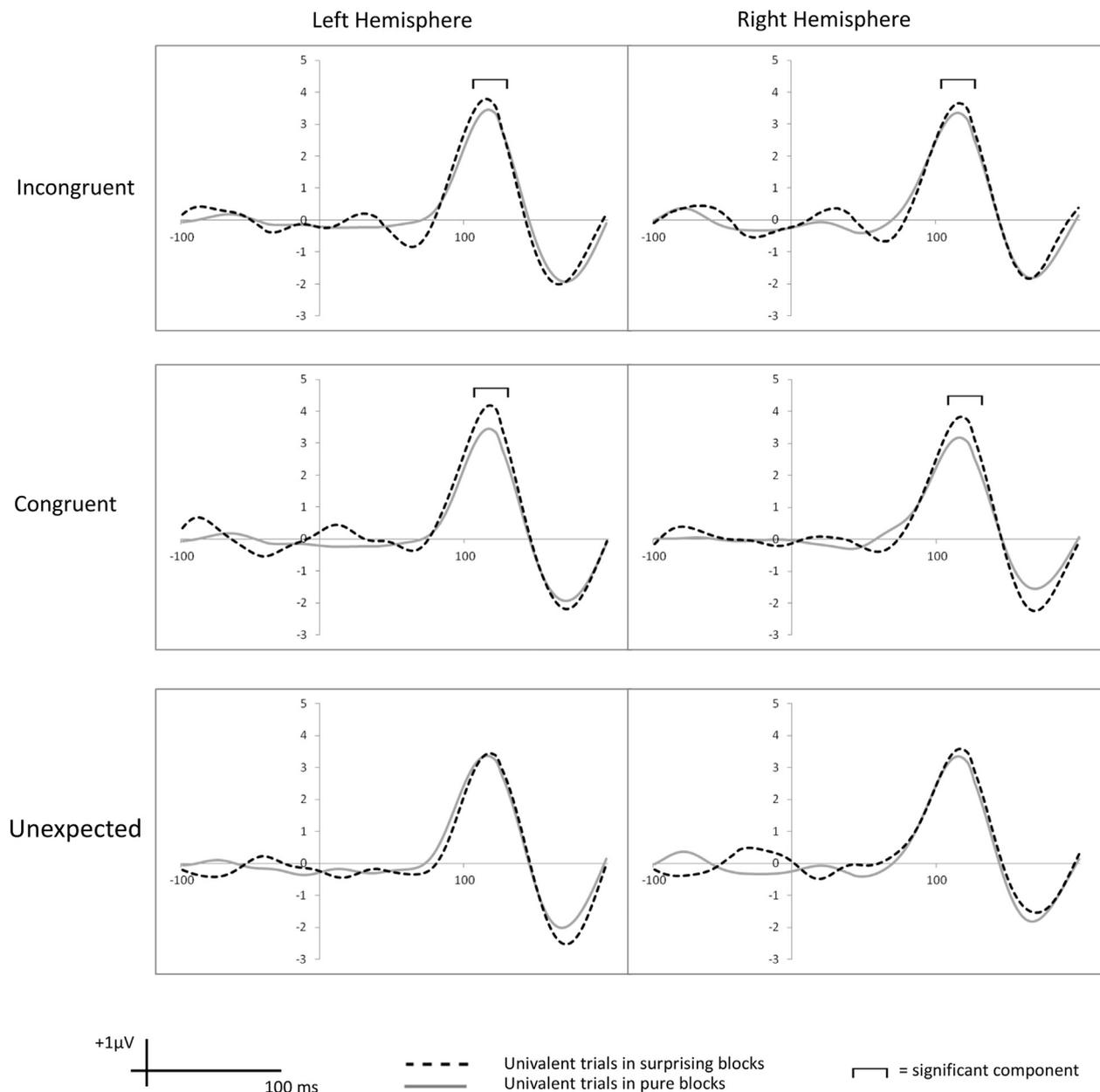


Fig. 7. Event-related potentials at posterior electrode sites capturing processing differences between the bivalency effects (congruent and incongruent) and the unexpectedness effect. The differences between the conditions were localized to temporal parietal junction activity using BESA source modeling.

Tanabe, 2004; Milham et al., 2001; 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). Here we provide support for the idea that the bivalency effect reflects a process by which the dorsal anterior cingulate cortex (dACC) maintains a continuously updated history of cognitive load in order to estimate the value of upcoming cognitive control. Furthermore, we show that the bivalency effect is differentiated from a simple violation of expectancy effect near the temporal parietal junction (TPJ), which might reflect additional extraction of visual features in response to the cueing of simultaneous task sets.

Two ERP components were sensitive to the bivalency and unexpectedness effects in revealing ways; an early component was observed between 100 and 120 ms, and a later component was observed between 300 and 550 ms. We used source modeling

to localize the early component to temporal parietal junction (TPJ) activity and the later component to dACC activity; both time windows and locations are consistent with our previous work (Grundy et al., 2013). Importantly, the dACC activity was larger and more robust for trials that followed incongruent bivalent trials than those that followed congruent bivalent or unexpected univalent stimuli, demonstrating an increase in the dACC response to the higher levels of conflict produced by incongruent bivalent stimuli. Moreover, the electrophysiological activity localized to the area of the TPJ captured differences relevant to the type of surprising stimulus, showing sensitivity to both congruent and incongruent bivalency effects, but not to the unexpectedness effect.

The bivalency effect is difficult to explain by most theories of dACC function. For instance, the conflict monitoring theory

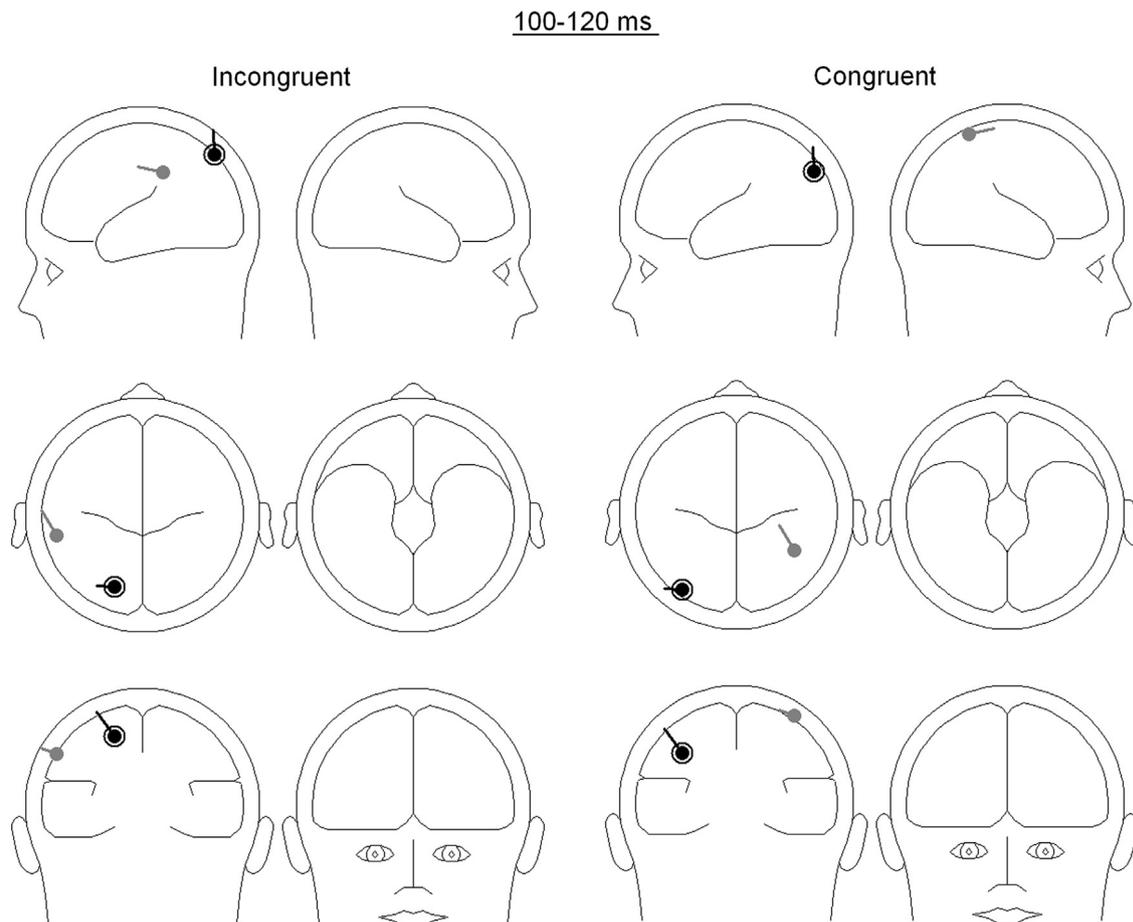


Fig. 8. Source analysis for the early ERP component (100–120 ms) associated with the incongruent bivalency effect and the congruent bivalency effect. For each effect, the first dipole accounting for most of the variance (94% for incongruent and 96% for congruent) is shown in black, and the second dipole is shown in grey. Our source analyses place the generators of these primary dipoles near the left temporal parietal junction (TPJ) in each case.

(Botvinick et al., 2001a, 2001b, 2004; Botvinick, 2007; Van Veen et al., 2001) and outcome evaluation models (Eisenberger et al., 2003; Gehring & Willoughby, 2002; Nieuwenhuis et al., 2004; Yeung & Sanfey, 2004) rely on an overlap of conflicting processing pathways and negative outcomes, but the dACC is also active on univalent trials following conflict and in the absence of negative outcomes (Grundy et al., 2013; Woodward et al., 2008).

Here, we support a recent model of dACC function that predicts the behavioural and electrophysiological responses that underlie the bivalency effect. The model proposes that the dACC maintains a continuously updated account of predicted cognitive demand (Sheth et al., 2012). When bivalent stimuli (that by definition involve conflict) are encountered, the dACC is activated in response to the conflict generated by bivalent stimuli, and slower response times are observed on these trials. Importantly, univalent trials that *follow* bivalent stimuli also show greater dACC activity than trials in purely univalent blocks (Grundy et al., 2013; Woodward et al., 2008). We suggest that the dACC encodes the conflict produced by the bivalent stimulus and this raises the predicted cognitive load for upcoming trials; when subsequent univalent trials appear, this prediction leads to response slowing.

The model also predicts differences due to level of conflict produced by the surprising stimulus. In contrast to the incongruent bivalent stimulus, neither the congruent bivalent nor the unexpected univalent stimuli contain response conflict. The additional conflict carried by the incongruent bivalent stimulus leads to a larger estimate of upcoming cognitive load, reflected by a

stronger dACC signal and greater slowing of behavioural responses following the incongruent stimulus.

The history-dependent predictive model of the dACC can also account for the response slowing observed on trials that share no features with bivalent stimuli (i.e. on parity decision trials), a finding that has been problematic for cognitive control theories that rely on overlapping stimulus and response properties, including negative priming (D'Angelo & Milliken, 2012; Milliken, Thomson, Bleile, MacLellan, & Giammarco, 2012; Tipper, Weaver, Cameron, Brehaut, & Bastedo, 1991; Tipper, 2001), task-decision process (Braverman & Meiran, 2010; Meiran & Kessler, 2008; Meiran et al., 2008; Monsell et al., 2000; Rubinstein et al., 2001; Sohn & Anderson, 2001), and conflict monitoring (Botvinick et al., 2001a, 2001b, 2004; Botvinick, 2007; Van Veen et al., 2001) accounts. A history-dependent predictive 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.

It is important to understand how the present theoretical account fits with a recent model of the bivalency effect, *episodic context binding* (Meier et al., 2009; Meier & Rey-Mermet, 2012a, 2012b; Meier et al., 2013; Rey-Mermet & Meier, 2012a, 2012b, 2013; Rey-Mermet et al., 2013). Critically, we suggest that these models are not mutually exclusive. Rather, they work well in explaining different levels of processing within the bivalency effect. According to the episodic context binding account, the slowing observed as the bivalency effect is the result of retrieving a demanding context created by the occasional appearance of

bivalent stimuli. This context is bound to all trials that appear within a bivalent block and this leads to a response slowing when retrieved upon subsequent presentations of univalent stimuli within the block. However, as Meier and Rey-Mermet (2012a) have recently pointed out, “To answer the question how exactly the context is established further research is necessary” (p. 7). Here we propose an answer to that question by suggesting that the demanding context is a function of predicted upcoming cognitive load, which varies as a function of the most recently encountered conflict-loaded stimulus.

It is notable that the TPJ was implicated in the incongruent and congruent bivalency effects but not the unexpectedness effect; this suggests that the cueing of two task sets, beyond the influence of violations of expectancy, might be necessary to recruit TPJ processes in this task. Amplitude differences at TPJ electrode sites have been associated with visual extraction of stimulus features (Evans, Shedden, Hevenor, & Hahn, 2000), and we previously hypothesized that this early component might represent feature extraction triggered by task-set cueing on bivalent trials when task demands become uncertain (Grundy et al., 2013). Critically, this distinction did not obtain for the unexpectedness effect, suggesting that this additional feature extraction at early stages distinguishes bivalent processes (which cue two tasks, one of which is irrelevant) from more generic responses to unexpected features (which are surprising but do not cue two tasks).

5. Conclusion

In sum, we provide evidence for the notion that the bivalency effect reflects a process involving dACC by which future cognitive load is predicted based on current and recent cognitive demands. Furthermore, the TPJ appears to contribute to the bivalency effect, but not to a violation of expectancy effect; this might reflect an enhanced focus on features of subsequent univalent trials that is triggered by simultaneously cueing different task sets.

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