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The Bivalency Effect: Evidence for Flexible Adjustment of Cognitive Control

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When bivalent stimuli (i.e., stimuli with features for two different tasks) appear occasionally, performance is slower on subsequent univalent stimuli. This "bivalency effect" reflects an adjustment of cognitive control arising from the more demanding context created by bivalent stimuli. So far, it has been investigated only on task switch trials, but not on task repetition trials. Here, we used a paradigm with predictable switches and repetitions on three tasks, with bivalent stimuli occasionally occurring on one task. In three experiments, we found a substantial bivalency effect for all trials with at least one source of conflict. However, this effect was reduced for the repetition trials sharing no features with bivalent stimuli, that is, for those without conflict. This confirms that the bivalency effect reflects an adjustment of cognitive control. The news is that this adjustment of cognitive control is sensitive to the presence of conflict, but neither to its amount nor to its source.

Keywords: task switching, switch costs, repetition trial, bivalent stimuli, episodic binding

Cognitive control is the ability to maintain current goal representations in the face of conflict. It enables us to flexibly select goal-relevant features while suppressing distracting ones (Botvinick, Braver, Barch, Carter, & Cohen, 2001; Botvinick, Cohen, & Carter, 2004). Cognitive control is necessary, for example, when switching between different tasks. In particular, cognitive control is required when responding to bivalent stimuli (i.e., stimuli with features that are relevant to more than one task). Moreover, recent studies have shown that even the occasional occurrence of bivalent stimuli triggered an "across the border" adjustment of cognitive control. That is, a general performance slowing occurred on several subsequent univalent trials, and even on those, which shared no relevant feature with the bivalent stimulus (Meier, Woodward, Rey-Mermet, & Graf, 2009; Rey-Mermet & Meier, 2011; Woodward, Meier, Tipper, & Graf, 2003; Woodward, Metzak, Meier, & Holroyd, 2008; see also Rogers & Monsell, 1995; Wylie & Allport, 2000). This general slowing was coined the "bivalency effect." While the previous studies have focused on task switching trials, the purpose of the present study was to test whether the bivalency effect is differentially engaged in task switching and task repetition trials.

So far, four studies have explored the bivalency effect (Meier et al., 2009; Rey-Mermet & Meier, 2011; Woodward et al., 2003, 2008). In the initial study by Woodward et al. (2003), participants performed three binary tasks in a given order: a parity decision (odd vs. even numerals), a color decision (red vs. blue symbols), and a case decision (uppercase vs. lowercase letters). Most stimuli were univalent (i.e., black numerals for the parity decision, colored shapes for the color decision, and black letters for the case decision). However, for a few case decisions, the letters were presented in color, thus turning them into bivalent stimuli. Performance was slower for all tasks following bivalent stimuli, including those with stimuli that shared no relevant features with the bivalent stimuli (i.e., parity decisions). Woodward et al. noted that this result is a challenge for task-switching theories that focus primarily on bottom-up processes, that is, processes initiated and guided by the stimuli and their particular features (e.g., Allport & Wylie, 2000; Meiran, 2008; Monsell, Yeung, & Azuma, 2000; Rogers & Monsell, 1995). These theories can account for the slowing in response to univalent stimuli, which share a relevant feature with the bivalent stimuli (i.e., those used for case and color decisions). However, they cannot account for the slowing in response to univalent stimuli, which share no features with the bivalent stimuli (i.e., those used for the parity decisions). Rather, the results seem to be compatible with the explanation that participants adjusted control and opted for a more cautious response style when encountering bivalent stimuli.

In a second study using functional MRI (fMRI), Woodward et al. (2008) explored the neural correlates of the bivalency effect. The results showed that the bivalency effect was associated with activation in the dorsal anterior cingulate cortex (dACC), a brain area recruited for the adjustment of cognitive control (see Botvinick et al., 2001). Woodward et al. interpreted this result as support

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for the "breaking inertia" account with higher dACC activation reflecting a change in the environment that may require the adjustment of responses (Behrens, Woolrich, Walton, & Rushworth, 2007; Paus, 2001).

In a third study, Meier et al. (2009) investigated the generality and endurance of the bivalency effect for different types of tasks (parity, color, case, size, letter), for different types of bivalent stimuli (colored or large/small letters) and for different modalities (visual, auditory). Furthermore, they tested its endurance across longer intertrial intervals and across several trials with univalent stimuli. The results showed a reliable bivalency effect across all experimental conditions, thus enduring for more than 20 s. To account for these findings, Meier et al. proposed an extension of an "episodic context binding" explanation put forward by Waszak, Hommel, and Allport (2003). According to this explanation, stimuli acquire a history during an experiment; that is, they acquire associations with the tasks in which they occur. If the binding goes beyond tasks and stimuli, and extends to the particular context (i.e., among purely univalent stimuli or among univalent stimuli *and* occasionally occurring bivalent stimuli), univalent stimuli and tasks might be bound to the more demanding context created by bivalent stimuli. Accordingly, the bivalency effect might be the result of episodic context binding.

In a fourth study, Rey-Mermet and Meier (2011) examined whether the bivalency effect might result from overlapping response sets or from episodic context binding. Because so far the same response set (e.g., the keys *b* and *n*) has been used for all three tasks, responding to univalent stimuli may have activated bivalent stimulus features, which may have slowed performance. Rey-Mermet and Meier tested one group of participants with an overlapping response set (i.e., the same two response keys for all three tasks) and another group with a nonoverlapping response set (i.e., six response keys, that is, two keys for each task). Irrespective of the response set (overlapping vs. nonoverlapping), a comparable bivalency effect was found on all univalent trials. Thus, the bivalency effect is not the result from overlapping response sets. Rather, it stems from episodic context binding.

Together, these studies suggest that the bivalency effect reflects an adjustment of cognitive control, which is recruited to fine-tune performance according to the more demanding context created by bivalent stimuli. However, all of them have involved univalent trials with at least one source of conflict. One source of conflict stems from the necessity to switch tasks. As switch trials require the inhibition of the previously relevant task and the activation of the newly relevant task, they inherently involve a conflict (see, e.g., Allport & Wylie, 2000; Rogers & Monsell, 1995). A second source of conflict arises from the feature overlap between univalent and bivalent stimuli. Encountering univalent stimuli sharing relevant features with the bivalent stimuli activates the bivalent stimulus features, and results in a conflict (see, e.g., Allport & Wylie, 2000; Meiran, 2008; Waszak et al., 2003).

The previous studies showed a comparable bivalency effect for trials with two sources of conflict (*switch* trials sharing *relevant* features with the bivalent stimuli) and for trials with only one source of conflict (*switch* trials sharing no features with the bivalent stimuli). Thus, they are inconsistent with the notion that more conflict always triggers more cognitive control (e.g., Botvinick et al., 2001, 2004). Moreover, the previous findings also challenge the assumption that the adjustment of cognitive control recruited by one source of conflict cannot affect the resolution of conflict arising from any other sources (cf., Akçay & Hazeltine, 2008; Egner, 2008; Egner, Delano, & Hirsch, 2007; Funes, Lupiáñez, & Humphreys, 2010; Notebaert & Verguts, 2008). While this is consistent with the slowing on the trials with stimuli sharing *relevant* features with the bivalent stimuli, it fails to explain the result of the *switch* trials sharing *no relevant* features with the bivalent stimuli. This indicates that the adjustment of cognitive control triggered by the occasional occurrence of bivalent stimuli is not specific to the resolution of the conflict that is associated with the bivalent stimuli (i.e., the conflict on the trials for which the univalent stimuli shared relevant features with the bivalent stimuli). In contrast, it is also relevant for the resolution of conflict from at least one other source (i.e., switching tasks; see Freitas, Bahar, Yang, & Banai, 2007; Kunde & Wühr, 2006).

So far, it is unknown whether the bivalency effect occurs when no source of conflict is present on the univalent trial. However, this information would be particularly important in order to determine the flexibility of the adjustment of cognitive control underlying the bivalency effect. Hence, in the present work, we included univalent repetition trials. We adapted the paradigm used in the previous studies by asking participants to perform repeatedly two size decisions (small vs. large), two parity decisions (even vs. odd), and two letter decisions (vowel vs. consonant). In one block (the purely univalent block), all stimuli were univalent. In the other (the mixed block), bivalent stimuli (e.g., small or large letters for the letter decisions) were occasionally presented.

Theoretically, the bivalency effect might be insensitive to the presence or absence of conflict on a particular univalent trial. In this case, the magnitude of the bivalency effect would be similar for all switch and repetition trials. Accordingly, the bivalency effect would reflect an adjustment of cognitive control, which is neither sensitive to the presence of conflict nor to its amount or its source. Alternatively, the bivalency effect might depend on the presence or absence of conflict on a particular univalent trial. In trials including a conflict, such as switch trials or those repetition trials, which share relevant features with the bivalent stimuli, the bivalency effect would occur. In contrast, in trials with no conflict, such as repetition trials that have no relevant features in common with bivalent stimuli, the bivalency effect would be reduced, or even absent. In this case, the bivalency effect would reflect a flexible adjustment of cognitive control, which is sensitive to the presence of conflict, but neither to its amount nor to its source.

The question whether the bivalency effect would have a differential impact on switch and repetition trials is also important for the interpretation of switch costs (i.e., the slower performance on switch compared with repetition trials). One interpretation of switch costs is that they reflect executive control processes that reconfigure the cognitive system in order to switch tasks (e.g., Meiran, 1996; Rogers & Monsell, 1995). Another interpretation is that they arise from binding processes (e.g., Allport & Wylie, 2000; Waszak et al., 2003). Both interpretations are concerned with what switch costs represent, making it important to understand which factors affect them in task-switching procedures. Moreover, if the bivalency effect contributes to switch costs, it would reflect a so far neglected component of switch costs.

In the present study, we performed three experiments. In Experiment 1, we asked participants to perform repeatedly two size decisions, two parity decisions, and two letter decisions. Bivalent stimuli were small or large letters, occasionally appearing in the letter decision. The results showed a substantial bivalency effect for the trials with at least one source of conflict. Critically, this effect was reduced for the repetition trials sharing no relevant features with the bivalent stimuli, that is, the trials without conflict. In Experiment 2, we generalized the previous findings, using bivalent stimuli for the parity decision. Accordingly, we asked participants to perform repeatedly two size decisions, two letter decisions, and two parity decisions. Bivalent stimuli were small or large digits, occasionally appearing in the parity decision. In Experiment 3, we tested whether the reduction of the bivalency effect observed in the repetition trials sharing no relevant features with the bivalent stimuli was caused by a passive decay. In both previous experiments, these repetition trials appeared on the fourth position of the trial sequence and thus were distant from bivalent stimuli, possibly explaining the reduction of the bivalency effect. Accordingly, we presented the repetition trials sharing no relevant features with the bivalent stimuli on the second position of the trial sequence. Specifically, we asked participants to perform repeatedly two letter decisions, two parity decisions, and two size decisions. Bivalent stimuli were small or large digits, occasionally appearing in the size decision. This experiment again replicated our previous results.

Experiment 1

Method

Participants. Forty undergraduates students (4 men, mean age = 22.7, *SD* = 5.1) from the University of Bern participated in return for course credit.

Materials. We used the same materials as Meier et al. (2009; Experiment 3). For the size task, stimuli were the symbols #, %, &, and $, presented either in 20-point font or in 180-point font. For the parity task, stimuli were the numerals 1 through 4, each displayed in 60-point font. For the letter task, stimuli were the uppercase letters A, P, T, and U, each displayed in 60-point font. We created bivalent stimuli by presenting the four letters (A, P, T, and U) in either 20-point or 180-point font. Stimuli in 20-point font covered about 2% of the vertical extent of the display monitor whereas the 180-point stimuli covered about 20%. All stimuli were displayed at the center of the computer screen in black Times New Roman font.

Procedure. Participants were tested individually. They were informed that the experiment involved three different tasks: size decisions (small vs. large) about symbols, parity decisions (odd vs. even) about numerals, and letter decisions (vowel vs. consonant) about letters. They were instructed to press one of two computer keys (*b* and *n*) with their left and right index fingers respectively, for each of the three tasks. The mapping information, printed on paper, was presented below the computer screen throughout the experiment. Participants were informed that, for some of the letter decisions, the size of the letters would vary. They were specifically instructed to ignore the size of the letters and to focus on making letter decisions.

After these instructions, a block of 30 trial sequences was presented for practice. Each trial sequence required making two size decisions in succession, two parity decisions in succession and two letter decisions in succession, as illustrated in Figure 1. Within the trial sequence, the first decision of each pair was, therefore, a switch trial and the second decision of each pair, a repetition trial. Within each pair, the particular stimulus was determined randomly and did not repeat. The stimulus for each trial was displayed until the participant responded. Then, the screen blanked for 500 ms and then the next stimulus appeared. After each trial sequence, an additional blank interval of 500 ms was included. After the practice block and a brief break, each participant completed a purely univalent block and a mixed block without any break between blocks. Block order was counterbalanced across participants. The first block included 32 trial sequences, with the first two trial sequences serving as "warm-up" sequences which were discarded from the analyses. The second block had 30 trial sequences.

For the purely univalent blocks, only univalent stimuli were presented. For the mixed block, stimuli were univalent except on 10% of the letter decisions in which bivalent stimuli (i.e., large or small letters) appeared. Bivalent stimuli were determined randomly from among the 8 possible letters (4 letters × 2 sizes). For counterbalancing, they appeared on switch trials for half of the participants and on repetition trials for the other half. Trial sequences with bivalent stimuli were evenly interspersed among the 30 trial sequences of the block; occurring in every fifth trial sequence, specifically in the 3rd, 8th, 13th, 18th, 23th, and 28th sequences. The entire experiment lasted about 20 min.

Data analysis. For each participant, the accuracy rates and the median decision times (DTs) for correct responses were computed for each trial type (switch and repetition), each task, and each block. For the mixed block, accuracy rates and median DTs for univalent and bivalent letter decisions were computed separately. To account for general training effects, we collapsed the data across block order for each block type, task, and trial type. Switch costs were calculated for the purely univalent block and the mixed block (univalent trials only) separately and for each task. An alpha level of 0.05 was used for all statistical tests. Greenhouse-Geisser corrections are reported where appropriate and effect sizes are expressed as partial η^2 values.

Results

Performance on bivalent stimuli. In the mixed block, participants were significantly slower on bivalent stimuli (i.e., the large or small letters for the letter decisions) than on the corresponding univalent stimuli (i.e., the letters with standard size) when bivalent stimuli were presented on switch trials, $t(19) = 3.46$, $p < .01$ ($M_{\text{bivalent}} = 886$ ms, $SE = 82$; $M_{\text{univalent}} = 637$ ms, $SE = 33$), and when they were presented on repetition trials, $t(19) = 2.58$, $p < .05$ ($M_{\text{bivalent}} = 692$ ms, $SE = 77$; $M_{\text{univalent}} = 530$ ms, $SE = 19$). Furthermore, participants responded less accurately on bivalent stimuli than on the corresponding univalent stimuli when bivalent stimuli were presented on switch trials ($M_{\text{bivalent}} = .92$, $SE = 0.025$; $M_{\text{univalent}} = .96$, $SE = 0.010$) and when they were presented on repetition trials ($M_{\text{bivalent}} = .94$, $SE = 0.025$; $M_{\text{univalent}} = .96$, $SE = 0.011$). However, these differences were not significant, $t < 1.71$, $p > .05$.

Performance on univalent stimuli. Our main objective was to examine the bivalency effect on repetition trials relative to switch trials across the different tasks. The most relevant results, depicted in Figure 2a (left panel), are the DTs from the univalent trials in the mixed block compared with those in the purely

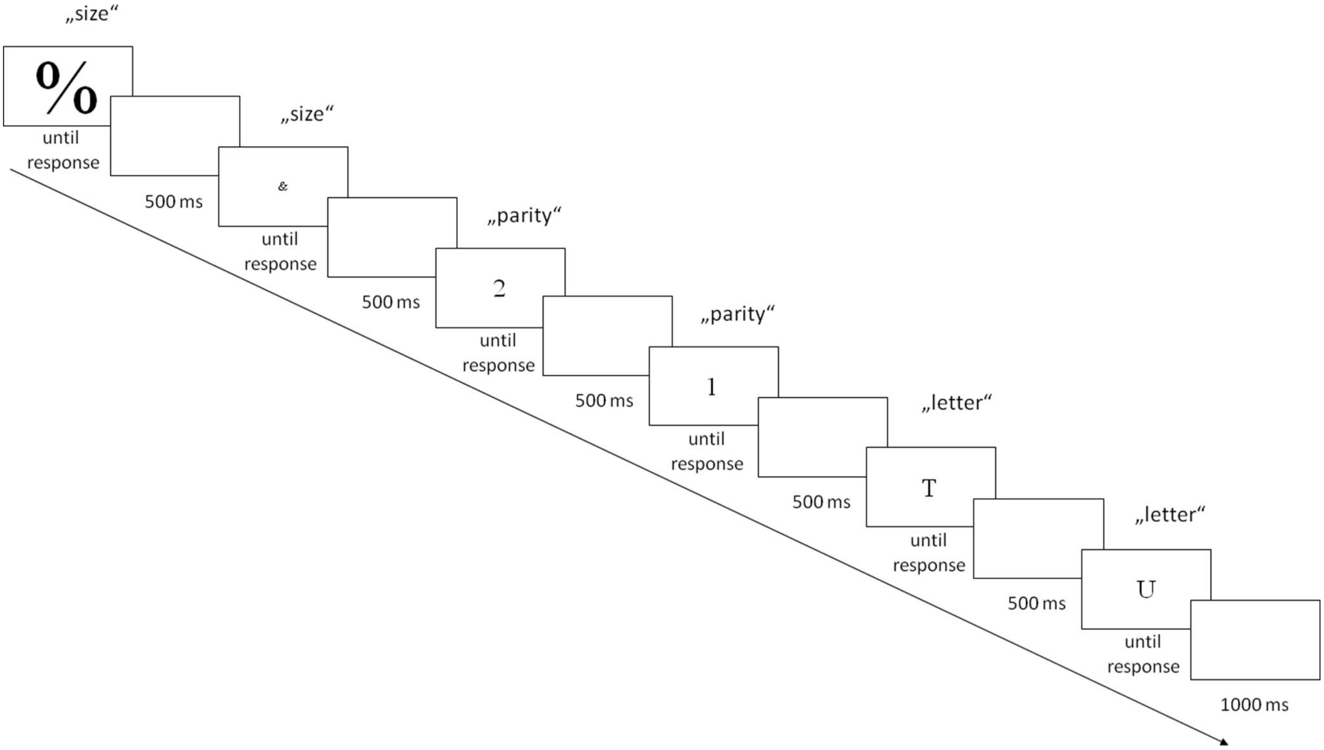

Figure 1. Experiment 1: Example of a univalent trial sequence. Participants carried out two size decisions (small vs. large) on symbols, two parity decisions (odd vs. even) on numerals, and two letter decisions (vowel vs. consonant) on letters. On a bivalent trial sequence (not pictured here), the size of the letters was varied.

univalent block for each trial type and task. We carried out a three-way repeated-measures analysis of variance (ANOVA) on the DTs of univalent trials, with the factors block (purely univalent, mixed), task (size, parity, letter), and trial type (switch, repetition). This analysis revealed a significant main effect of block, $F(1, 39) = 7.62$, $p < .01$, $\eta^2 = .16$, caused by slower responses on univalent trials in the mixed block than in the purely univalent block. This confirms the presence of the bivalency effect. The ANOVA also showed a significant main effect of task, $F(2, 78) = 32.69$, $p < .001$, $\eta^2 = .46$, and of trial type, $F(1, 39) = 76.85$, $p < .001$, $\eta^2 = .66$, as well as a significant interaction between these factors, $F(2, 78) = 13.30$, $p < .001$, $\eta^2 = .25$. This interaction reflects a larger difference between switch and repetition trials (i.e., a larger switch cost) for parity decisions than for size and letter decisions (Figure 2a, left panel).

Critically, the three-way interaction between block, task, and trial type was significant, $F(2, 78) = 3.46$, $p < .05$, $\eta^2 = .08$. To locate the source of this interaction, we conducted separate ANOVAs for the size-, the parity-, and the letter-decisions, with the factors block (purely univalent, mixed) and trial type (switch, repetition). These analyses showed that the main effect of block was significant for the size and parity decisions, $F(1, 39) = 11.83$, $p < .01$, $\eta^2 = .23$, and $F(1, 39) = 4.53$, $p < .05$, $\eta^2 = .10$, respectively, and approached significance for the letter decisions, $F(1, 39) = 3.26$, $p < .08$, $\eta^2 = .08$. More important, the ANOVAs also revealed a significant interaction between block and trial type for the parity decisions, $F(1, 39) = 5.85$, $p < .05$, $\eta^2 = .13$, but neither for the size nor for the letter decisions, $F\text{s} < 1.78$, $p\text{s} > .05$, $\eta^2 < .04$. Altogether, this suggests that the magnitude of the bivalency effect was similar for switch and repetition trials for the size decisions as well as for the letter decisions. In contrast, for the parity decisions the bivalency effect was present on switch trials, $t(39) = 2.67$, $p < .05$, but absent on repetition trials, $t(39) = 0.69$, $p = .49$ (Figure 2a, right panel).

Thus, switch costs were affected for the task with univalent stimuli sharing no relevant features with the bivalent stimuli (i.e., the parity decisions). Specifically, for the purely univalent block switch costs were 79 ms, 142 ms, and 85 ms for size-, parity-, and letter-decisions, respectively. For the univalent stimuli of the mixed block, the respective switch costs were 69 ms, 169 ms, and 103 ms for size-, parity-, and letter-decisions. Thus, the switch cost difference caused by the bivalency effect was 28 ms and larger for parity decisions, which had no shared features with the bivalent stimuli, than for those tasks with overlapping stimulus features (4 ms, size- and letter-decisions averaged).

We also conducted a three-way repeated-measures ANOVA on the accuracy of univalent trials, with the factors block (purely univalent, mixed), task (size, parity, letter) and trial type (switch, repetition). The ANOVA revealed a significant main effect of task, $F(1.71, 66.62) = 7.55$, $p < .01$, $\eta^2 = .16$, and a significant interaction between task and trial type, $F(1.59, 62.14) = 6.89$, $p < .01$, $\eta^2 = .15$. This interaction reflects a larger difference between switch and repetition trials for parity decisions (switch trial: $M = .94$, $SE = 0.009$; and repetition trial: $M = .96$, $SE = 0.006$) than for size decisions (switch trial: $M = .97$, $SE = 0.004$; and repe-

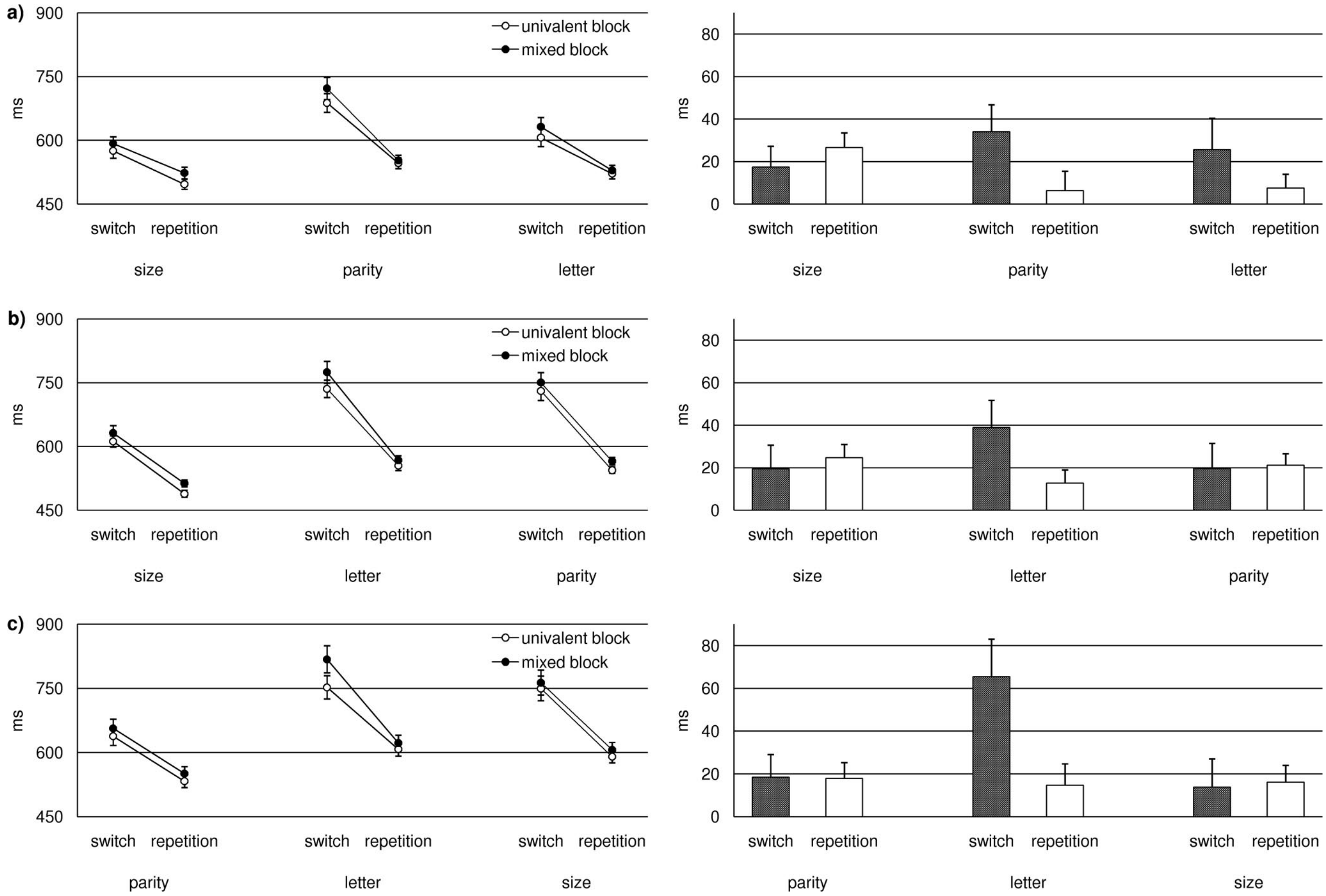

Figure 2. Results of (a) Experiment 1, (b) Experiment 2, and (c) Experiment 3. Left: Decision time data (i.e., performance on univalent stimuli for switch and repetition trials in purely univalent and mixed blocks). Right: Bivalency effect (i.e., decision times [DTs] difference between univalent trials from the purely univalent block and those from the mixed block).

tition trial: $M = .97$, $SE = 0.007$) and for letter decisions (switch trial: $M = .97$, $SE = 0.007$; and repetition trial: $M = .96$, $SE = 0.008$). It is interesting to note that the three-way interaction between block, task, and trial type was also significant, $F(2, 78) = 6.05$, $p < .01$, $\eta^2 = .13$. This reflects a slightly larger switch cost difference between the univalent trials of the mixed block and those of the purely univalent block for the size decisions (purely univalent block: $M = .007$, $SE = 0.006$; and mixed block: $M = -.007$, $SE = 0.010$) than for the letter decisions (purely univalent block: $M = .004$, $SE = 0.007$; and mixed block: $M = .013$, $SE = 0.013$) and for the parity decisions (purely univalent block: $M = .012$, $SE = 0.006$; and mixed block: $M = .006$, $SE = 0.009$). However, none of these differences was significantly different from zero, *t*s < 1.23, *p*s $> .05$. Thus, although these differences were affected differentially by the three tasks, they were not large enough to be significant. This suggests that no speed–accuracy trade-off compromised the critical DTs effects.

Discussion

The primary goal of Experiment 1 was to investigate the bivalency effect on repetition trials relative to switch trials across the three different tasks. The results showed a reliable bivalency effect and substantial switch costs. Critically, for the repetition trials of the parity decisions no bivalency effect occurred. While the bivalency effect was present for all switch trials and for those repetition trials whose stimuli had *relevant* features in common with the bivalent stimuli, it was absent for repetition trials in the task with stimuli that shared *no relevant* features with the bivalent stimuli. Thus, the bivalency effect occurred when at least one source of conflict was present on the univalent trial. This suggests an adjustment of cognitive control which is sensitive to the presence of conflict, but neither to its amount nor to its source.

To generalize these findings, we performed a second experiment in which we created bivalent stimuli for the parity decisions, rather than for the letter decisions. We asked participants to perform repeatedly two size decisions, two letter decisions, and two parity decisions, and the bivalent stimuli were small or large numerals that appeared occasionally in the parity decision. Accordingly, the size and parity decisions were the tasks whose univalent stimuli shared relevant features with the bivalent stimuli. In contrast, the letter decision was the task whose univalent stimuli did not share any relevant features with the bivalent stimuli. Again, we expected to find a substantial reduction of the bivalency effect on repetition trials relative to switch trials for the task, for which stimuli shared no relevant features with the bivalent stimuli (i.e., the letter decisions).

Experiment 2

Method

Participants. The participants were 72 different volunteers (30 men, mean age = 23.5, *SD* = 2.9) from the University of Bern.

Materials. For the size task, stimuli were the symbols #, %, and $, presented either in 20-point font or in 180-point font. For the letter task, stimuli were the uppercase letters A, E, N, P, T, and U, each displayed in 60-point font. For the parity task, stimuli were the numerals 1 through 6, each displayed in 60-point font. We created bivalent stimuli by presenting the six numerals (1 through 6) in either 20-point or 180-point font. Stimuli in 20-point font covered about 2% of the vertical extent of the display monitor whereas the 180-point stimuli covered about 20%. All stimuli were displayed at the center of the computer screen in black Times New Roman font.

Procedure. The procedure was identical to Experiment 1 except that participants performed two size decisions in succession, two letter decisions in succession, and two parity decisions in succession. Bivalent stimuli (i.e., small or large numerals) appeared on parity decisions in the 3rd, 8th, 13th, 18th, 23th, and 28th trial sequences of the mixed block. Participants were specifically instructed to ignore the size of the numerals and to focus on making parity decisions.

Data analysis. The data analysis was similar to Experiment 1.

Results

Performance on bivalent stimuli. In the mixed block, participants were significantly slower on bivalent stimuli (i.e., the small or large numerals for the parity decisions) than on the corresponding univalent stimuli (i.e., the numerals with standard size) when bivalent stimuli were presented on switch trials, $t(35) = 3.92$, $p < .001$ ($M_{\text{bivalent}} = 903$ ms, $SE = 66$; $M_{\text{univalent}} = 709$ ms, $SE = 30$), and when they were presented on repetition trials, $t(35) = 5.87$, $p < .001$ ($M_{\text{bivalent}} = 713$ ms, $SE = 30$; $M_{\text{univalent}} = 585$ ms, $SE = 13$). Furthermore, participants responded significantly less accurately on bivalent stimuli than on the corresponding univalent stimuli when bivalent stimuli were presented on switch trials, $t(35) = 2.06$, $p < .05$ ($M_{\text{bivalent}} = .92$, $SE = 0.017$; $M_{\text{univalent}} = .96$, $SE = 0.006$). However, when bivalent stimuli were presented on repetition trials, there was no difference between the bivalent stimuli and the corresponding univalent stimuli ($M_{\text{bivalent}} = .97$, $SE = 0.011$; $M_{\text{univalent}} = .97$, $SE = 0.006$), with $t(35) = 0.23$, $p = .98$.

Performance on univalent stimuli. Figure 2b (left panel) shows the means of the median DTs on univalent trials with the associated standard errors. To examine the bivalency effect on switch and repetition trials across tasks, we carried out a three-way repeated-measures ANOVA on the DTs of univalent trials, with the factors block (purely univalent, mixed), task (size, letter, parity) and trial type (switch, repetition). This analysis revealed a significant main effect of block, $F(1, 71) = 13.87$, $p < .001$, $\eta^2 = .16$, caused by slower responses on univalent trials in the mixed block than in the purely univalent block. This confirms the presence of the bivalency effect. The ANOVA also showed a significant main effect of task, $F(2, 142) = 51.92$, $p < .001$, $\eta^2 = .42$, and of trial type, $F(1, 71) = 153.22$, $p < .001$, $\eta^2 = .68$, as well as a significant interaction between these factors, $F(1.77, 125.83) = 16.57$, $p < .001$, $\eta^2 = .19$. This interaction reflects a larger difference between switch and repetition trials (i.e., a larger switch cost) for letter and parity decisions than for size decisions (Figure 2b, left panel).

Critically, the three-way interaction between block, task, and trial type was significant, $F(2, 142) = 3.09$, $p < .05$, $\eta^2 = .04$. To locate the source of this interaction, we conducted separate ANOVAs for the size-, the letter-, and the parity-decisions, with the factors block (purely univalent, mixed) and trial type (switch, repetition). These analyses showed a significant main effect of block for all three tasks (size: $F(1, 71) = 8.77$, $p < .01$, $\eta^2 = .11$; letter: $F(1, 71) = 13.24$, $p < .01$, $\eta^2 = .16$; and parity: $F(1, 71) = 7.48$, $p < .01$, $\eta^2 = .10$). More important, the ANOVAs also revealed that the interaction between block and trial type approached significance for the letter decisions, $F(1, 71) = 3.28$, $p < .07$, $\eta^2 = .04$, but neither for the size nor for the parity decisions Fs < 1, ps $> .05$, $\eta^2 < .004$. Altogether, this indicates that the magnitude of the bivalency effect was similar for switch and repetition trials for the size decisions as well as for the parity decisions. In contrast, for the letter decisions the bivalency effect was larger on switch trials than on repetition trials (Figure 2b, right panel). This effect remains significant on both trial types, with $t(71) = 3.02$, $p < .01$ for switch trials, and $t(71) = 2.05$, $p < .05$ for repetition trials.

Thus, switch costs were affected for the task with univalent stimuli sharing no relevant features with the bivalent stimuli (i.e., the letter decisions). Specifically, for the purely univalent block switch costs were 123 ms, 181 ms, and 186 ms for size-, letter-, and parity-decisions, respectively. For the univalent stimuli of the mixed block, the respective switch costs were 118 ms, 207 ms, and 185 ms for size-, letter-, and parity-decisions. Thus, the switch cost difference caused by the bivalency effect was 26 ms and larger for letter decisions, which had no shared features with the bivalent stimuli, than for those tasks with overlapping stimulus features (−3 ms, size- and parity-decisions averaged).

We also conducted a three-way repeated-measures ANOVA on the accuracy of univalent trials, with the factors block (purely univalent, mixed), task (size, letter, parity) and trial type (switch, repetition). The ANOVA revealed a significant main effect of task, $F(2, 142) = 4.20$, $p < .05$, $\eta^2 = .06$, and of trial type, $F(1, 71) = 17.75$, $p < .001$, $\eta^2 = .20$. Thus, participants made more correct responses on size and letter decisions ($M = .97$, $SE = 0.002$ and $M = .97$, $SE = 0.003$, respectively) than on parity decisions ($M = .96$, $SE = 0.002$). Furthermore, they made more correct responses on repetition trials ($M = .97$, $SE = 0.002$) than on switch trials ($M = .96$, $SE = 0.002$). No other main or interaction effects were significant, Fs < 1.87, ps $> .05$, $\eta^2 < .03$. Thus, no speed–accuracy trade-off compromised the critical DTs effects.

Discussion

The results of Experiment 2 replicated those of Experiment 1. They showed a reliable bivalency effect, substantial switch costs, and a reduction of the bivalency effect on the repetition trials for the task that shared no relevant features with the bivalent stimuli (i.e., the letter decisions). Thus, the bivalency effect was substantially reduced when no source of conflict was present on a particular univalent trial. This suggests that the bivalency effect reflects an adjustment of cognitive control, which is sensitive to the presence of conflict but neither to its amount nor to its source.

However, one might argue that the particular set-up of the previous experiments with the repetition trials of the tasks sharing no relevant features with the bivalent stimuli on the fourth position of the trial sequence may have favored the reduction of the bivalency effect. These repetition trials are distant from the bivalent stimuli. Thus, it is possible that the reduction was only caused by a passive decay of the effect (e.g., Altmann & Gray, 2002; see also Vandierendonck, Liefooghe, & Verbruggen, 2010). Therefore, we ran a third experiment to test this alternative interpretation. In Experiment 3, the bivalent stimuli were small or large numerals that appeared occasionally in the size decisions. We asked participants to perform repeatedly two letter decisions, two parity decisions, and two size decisions. Thus, we changed the order of the tasks such that the repetition trials of the letter decisions were presented on the second position of the trial sequence and those of the parity decisions were presented on the fourth position. If the bivalency effect would be reduced on repetition trials for the parity decisions, this would favor a "passive decay" interpretation. In contrast, if the bivalency effect would be reduced on repetition trials for the letter decisions, this would be consistent with a "flexible adjustment of cognitive control" interpretation.

Experiment 3

Method

Participants. The participants were 44 volunteers (19 men, mean age = 24, *SD* = 4.5) from the University of Bern.

Materials. The materials were identical to Experiment 2.

Procedure. The procedure was identical to Experiment 1 except that participants performed two letter decisions in succession, two parity decisions in succession, and two size decisions in succession. Bivalent stimuli (i.e., small or large numerals) appeared on size decisions in the 3rd, 8th, 13th, 18th, 23th, and 28th trial sequences of the mixed block. Participants were specifically instructed to ignore the parity of the numerals and to focus on making size decisions.

Data analysis. The data analysis was similar to Experiment 1.

Results

Performance on bivalent stimuli. In the mixed block, participants were significantly slower on bivalent stimuli (i.e., the small or large numerals for the size decisions) than on the corresponding univalent stimuli (i.e., the small or large symbols) when bivalent stimuli were presented on switch trials, $t(21) = 6.17$, $p < .001$ ($M_{\text{bivalent}} = 1123$ ms, $SE = 86$; $M_{\text{univalent}} = 670$ ms, $SE = 30$), and when they were presented on repetition trials, $t(21) = 4.30$, $p < .001$ ($M_{\text{bivalent}} = 944$ ms, $SE = 103$; $M_{\text{univalent}} = 553$ ms, $SE = 26$). Furthermore, participants responded significantly less accurately on bivalent stimuli than on the corresponding univalent stimuli when bivalent stimuli were presented on switch trials, $t(21) = 3.60$, $p < .01$ ($M_{\text{bivalent}} = .89$, $SE = 0.026$; $M_{\text{univalent}} = .97$, $SE = 0.008$), and when they were presented on repetition trials, $t(21) = 2.28$, $p < .05$ ($M_{\text{bivalent}} = .92$, $SE = 0.026$; $M_{\text{univalent}} = .98$, $SE = 0.007$).

Performance on univalent stimuli. Figure 2c (left panel) shows the means of the median DTs on univalent trials with the associated standard errors. To examine the bivalency effect on switch and repetition trials across tasks, we carried out a three-way repeated-measures ANOVA on the DTs of univalent trials, with the factors block (purely univalent, mixed), task (parity, letter, size) and trial type (switch, repetition). This analysis revealed a significant main effect of block, $F(1, 43) = 11.48$, $p < .01$, $\eta^2 = .21$, caused by slower responses on univalent trials in the mixed block than in the purely univalent block. This confirms the presence of the bivalency effect. The ANOVA also showed a significant main effect of task, $F(2, 86) = 46.06$, $p < .001$, $\eta^2 = .52$, and of trial type, $F(1, 43) = 79.88$, $p < .001$, $\eta^2 = .65$, as well as a significant interaction between these factors, $F(2, 86) = 8.50$, $p < .001$, $\eta^2 = .16$. This interaction reflects a larger difference between switch and repetition trials (i.e., a larger switch cost) for parity and letter decisions than for size decisions (Figure 2c, left panel). Moreover, the interaction between block and task was significant, $F(1.74, 74.88) = 4.54$, $p < .05$, $\eta^2 = .10$, indicating a larger bivalency effect on letter decisions (40 ms) than on parity and size decisions (15 ms and 18 ms, respectively).

Critically, the three-way interaction between block, task, and trial type was significant, $F(2, 86) = 4.78$, $p < .05$, $\eta^2 = .10$. To locate the source of this interaction, we conducted separate ANOVAs for the parity-, letter-, and size-decisions, with the factors block (purely univalent, mixed) and trial type (switch, repetition). These analyses showed that the main effect of block approached significance for the parity decisions, $F(1, 43) = 3.32$, $p < .08$, $\eta^2 = .07$, and was significant for the letter and size decisions, $F(1, 43) = 15$, $p < .001$, $\eta^2 = .26$, and $F(1, 43) = 5.21$, $p < .05$, $\eta^2 = .11$, respectively. More important, the ANOVA also revealed a significant interaction between block and trial type for the letter decisions, $F(1, 43) = 6.67$, $p < .05$, $\eta^2 = .13$, but neither for the size nor for the letter decisions, $F\text{s} < 1$, $p\text{s} > .05$, $\eta^2 < .001$. Altogether, this indicates that the magnitude of the bivalency effect was similar for switch and repetition trials for the parity decisions as well as for the size decisions. In contrast, for the letter decisions the bivalency effect was present on switch trials, $t(43) = 3.73$, $p < .01$, but absent on repetition trials, $t(43) = 1.47$, $p = .15$ (Figure 2c, right panel).

Thus, switch costs were affected for the task with univalent stimuli sharing no relevant features with the bivalent stimuli (i.e., the letter decisions). Specifically, for the purely univalent block switch costs were 160 ms, 145 ms, and 105 ms for the parity-, letter-, and size-decisions, respectively. For the univalent stimuli of the mixed block, the respective switch costs were 157 ms, 195 ms, and 106 ms for parity-, letter-, and size-decisions. Thus, the switch cost difference caused by the bivalency effect was 51 ms and larger for letter decisions, which had no shared features with the bivalent stimuli, than for those tasks with overlapping stimulus features (−1 ms, parity- and size-decisions averaged).

We also conducted a three-way repeated-measures ANOVA on the accuracy of univalent trials, with the factors block (purely univalent, mixed), task (parity, letter, size) and trial type (switch, repetition). The ANOVA revealed a significant main effect of trial type, $F(1, 43) = 8.55$, $p < .01$, $\eta^2 = .17$. Thus, participants made more correct responses on repetition trials ($M = .98$, $SE = 0.003$) than on switch trials ($M = .97$, $SE = 0.004$). No other main or interaction effects were significant, $F\text{s} < 2.19$, $p\text{s} > .05$, $\eta^2 < .05$. These results indicate that no speed–accuracy trade-off compromised the critical DTs effects.

Discussion

The primary goal of Experiment 3 was to exclude an alternative explanation, namely that the reduction of the bivalency effect observed in the repetition trials of the univalent stimuli with no shared features in Experiments 1 and 2 was caused by a passive decay. The results showed a reliable bivalency effect and substantial switch costs. More important, they revealed again that the bivalency effect was reduced on repetition trials for the letter decisions, but not for the parity decisions. Thus, the bivalency effect was reduced for the repetition trials sharing no relevant features with the bivalent stimuli, even when these repetition trials were very close to the bivalent stimuli. These results cannot be accounted by a passive decay of the effect (cf., Altmann & Gray, 2002; Vandierendonck et al., 2010). They rather support the view that the bivalency effect is sensitive to the presence or absence of conflict on a particular univalent trial.

General Discussion

The purpose of the present study was to investigate the bivalency effect on repetition trials relative to switch trials in order to test the flexibility of the adjustment of cognitive control thought to underlie the bivalency effect. Hence, we used a paradigm with predictable switches and repetitions on three tasks, with bivalent stimuli occasionally occurring in one task. Thus, the present design contained univalent trials with two sources of conflict (i.e., *switch* trials sharing *relevant* features with the bivalent stimuli), with one source of conflict (repetition trials sharing *relevant* features with the bivalent stimuli, or *switch* trials sharing no relevant features with the bivalent stimuli), and without conflict (i.e., repetition trials sharing no relevant features with the bivalent stimuli).

In three experiments, we found a reliable bivalency effect, that is, a performance slowing for univalent trials after bivalent stimuli occurred. In addition, we found a performance slowing on switch trials relative to repetition trials, demonstrating the presence of switch costs. More critically, the bivalency effect for switch and repetition trials was similar in those tasks whose stimuli shared *relevant* features with the bivalent stimuli. In contrast, in the task for which univalent stimuli shared *no relevant* features with the bivalent stimuli, the bivalency effect was present on switch trials, but reduced on repetition trials. Thus, the bivalency effect endured across subsequent univalent trials depending on the presence or absence of conflict on the particular trial. When a trial involved conflict, such as *switch* trials and those *repetition* trials which had *relevant* features in common with the bivalent stimuli, a substantial bivalency effect was found. In contrast, when a particular trial involved no conflict, such as those *repetition* trials that had *no relevant* features in common with the bivalent stimuli, the bivalency effect was reduced.

The results support the view that the bivalency effect reflects an adjustment of cognitive control which is sensitive to the presence of conflict, but neither to its amount nor to its source. Thus, some types of conflict, such as the occasional occurrence of bivalent stimuli, induce an adjustment of control that is sufficient to deal with situations without additional sources of conflict at no cost (i.e., for repetitions of a task with nonoverlapping stimulus features). Concurrently, when coping with additional conflict, from one or more sources, this seems to come at a similar cost. These results challenge a prominent hypothesis in cognitive control research, that is, the hypothesis that adjustment of cognitive control is always sensitive to the amount and to the source of conflict (e.g., Botvinick et al., 2001; 2004; Egner, 2008).

Recently, we have put forward an "episodic context binding" account to explain the bivalency effect (Meier et al., 2009; Rey-Mermet & Meier, 2011). Based on the finding that stimuli acquire associations with the tasks in which they occur (Waszak et al., 2003), we have proposed that the binding goes beyond tasks and stimuli, and extends to the particular context. Accordingly, univalent stimuli and tasks might be bound to the more demanding context created by bivalent stimuli. This episodic context binding would interfere with performance for all tasks, irrespective of whether univalent trials share or do not share features with the bivalent stimuli. As a consequence, performance would be slowed for all subsequent univalent trials. According to this explanation, the bivalency effect is the result of interference caused by episodic context binding. It is interesting to note that the results of the present study suggest that this episodic context binding is engaged flexibly, depending on the presence or absence of conflict in the univalent trial. Specifically, the presence of a conflict in the univalent trials strengthens episodic context binding, whereas the absence of conflict weakens it (see Verguts & Notebaert, 2008, 2009, for a similar argument). Thus, this account can predict in which situations cognitive control processes are enforced (i.e., on univalent trials with at least one source of conflict) and how they are triggered (i.e., by binding stimuli and tasks with the context in which they occur).

Moreover, the present results also showed that switch costs were affected only for the particular task that involved univalent stimuli sharing *no relevant* features with the bivalent stimuli. This indicates that for typical task-switching studies that are carried out with two tasks and with bivalent stimuli that have shared stimulus features by design, the bivalency effect is levelled out by calculating switch costs as the difference between DTs on switch and repetition trials. Only for univalent stimuli without shared stimulus features, the bivalency effect was smaller on repetition trials relative to switch trials and thus larger switch costs emerged. Therefore, the processes related to the bivalency effect, such as episodic context binding, may contribute to switch costs.

In sum, the findings of the present study demonstrate that the magnitude of the bivalency effect depends on the presence or absence of conflict on each particular univalent trial. Therefore, they confirm that the bivalency effect arises from an adjustment of cognitive control. The news is that this adjustment of cognitive control is certainly sensitive to the presence of conflict, but neither to its amount nor to its source.

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