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# The Bivalency Effect in Task Switching: General and Enduring

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The purpose of this study was to investigate the generality and temporal endurance of the bivalency effect in task switching. This effect refers to the slowing on univalent stimuli that occurs when bivalent stimuli appear occasionally. We used a paradigm involving predictable switches between 3 simple tasks, with bivalent stimuli occasionally occurring on one of the tasks. The generality of the bivalency effect was investigated by using different tasks and different types of bivalent stimuli, and the endurance of this effect was investigated across different intertrial intervals (ITIs) and across the univalent trials that followed trials with bivalent stimuli. In 3 experiments, the results showed a general, robust, and enduring bivalency effect for all ITI conditions. Although the effect declined across trials, it remained significant for about 4 trials following one with a bivalent stimulus. Our findings emphasise the importance of top–down processes in task-switching performance.

*Keywords:* task switching, univalent stimuli, bivalent stimuli, bivalency effect

Switching between tasks is costly when the tasks involve bivalent stimuli (e.g., Allport & Wylie, 1999; Jersild, 1927), that is, stimuli with features relevant to more than one task. More curiously, however, task-switching performance is also slowed on univalent stimuli when bivalent stimuli occur occasionally amongst them (Rogers & Monsell, 1995; Woodward, Meier, Tipper, & Graf, 2003; Woodward, Metzak, Meier, & Holroyd, 2008). We have proposed that the latter slowing of performance, hereinafter called the *bivalency effect*, stems from a cautious response style that is adopted to deal with the perceived "trickiness" of bivalent stimuli occurring amongst univalent stimuli (Woodward et al., 2003, 2008). The primary purpose of the present study was to investigate the generality and temporal endurance of the bivalency effect.

In our previous studies, participants had to perform a predictable sequence of three simple tasks, each of which required a binary decision: a parity decision (odd vs. even), a colour decision (red vs. blue), and a case decision (uppercase vs. lowercase). For most of the trials, we presented univalent stimuli (i.e., black numbers for the parity decision task, coloured shapes for the colour decision task, and black letters for the case decision task), but on a few trials, the letters for the case decision task were presented in colour, thus turning them into bivalent stimuli. The results showed that, on subsequent trials with only univalent stimuli, performance was slowed for all tasks, including the parity decision task, which did not share any features with the bivalent stimuli (i.e., the letters used for the case decision task). This finding—the bivalency effect—suggests that, in addition to triggering a bottom–up influence on performance, the occurrence of a few bivalent stimuli amongst the univalent stimuli produces a top–down effect that endured across subsequent trials.

The bivalency effect challenges current task-switching theories that focus primarily on the exogenous influences produced by bivalent stimuli, that is, on processes that are initiated and guided from the bottom up by stimuli or their properties (Allport & Wylie, 2000; Monsell, Yeung, & Azuma, 2000; Rogers & Monsell, 1995). Although these theories can readily account for the slowing of performance we observed on the colour and case decision tasks, they are not able to accommodate the finding of slower responding on the parity decision task, which involved stimuli that had no features in common with the stimuli used for the colour task or case decision task. However, our finding is consistent with a recent account by Kray and Lindenberger (2000). They suggested that, because bivalent stimuli permit different actions, they create uncertainty and slowing may occur because of the need to make a decision about which action is context appropriate. More important, it may be that, once initiated, this autonomous decision-making process remains primed for some time and thusly slows performance even on a subsequent trial with a univalent stimulus, thereby giving rise to the bivalency effect.

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The present study was designed to examine whether the bivalency effect reflects either a process of recovering from task uncertainty, as implied by Kray and Lindenberger (2000), or a cautious response style of the sort proposed by Woodward et al. (2003, 2008). We assumed that task uncertainty in response to bivalent stimuli would be relatively short lived and that recovery would occur quickly either with longer intertrial intervals (ITIs) or across a few trials with univalent stimuli. By contrast, we reasoned that, if the bivalency effect reflects the adoption of a more cautious response style (i.e., a method for dealing with a tricky situation) after encountering bivalent stimuli, there is no reason to expect that it would diminish with longer ITIs or that it would disappear very quickly across a few trials with univalent stimuli.

In our original study (Woodward et al., 2003), participants were required to respond verbally, and their responses were recorded by the experimenter after each sequence of three tasks. The inter stimulus interval (ISI) was fixed, but the length of the ITI (i.e., the interval between sequences of three tasks) was variable, because it was determined by the speed with which the experimenter recorded errors. In the present study, we required participants to respond by key presses (left vs. right), thereby permitting us to manipulate and control the length of the ITI and to investigate the temporal endurance of the bivalency effect. We hypothesised that, if the bivalency effect reflects an autonomous process of recovering from the uncertainty induced by bivalent stimuli, the magnitude of the bivalency effect should be smaller with longer ITIs. Alternatively, we expected that, if the bivalency effect is due to the adoption of a more cautious response style, the ITI manipulation should not affect the magnitude of the effect.

To investigate the endurance of the bivalency effect, we used ITIs of 1,000 ms and 2,000 ms for Experiment 1 and ITIs of 1,000 ms, 3,000 ms and 5,000 ms for Experiment 3. To further investigate the temporal endurance of the bivalency effect, we explored its persistence across trials with univalent stimuli that immediately followed trials with a bivalent stimulus. Finally, to examine the generality of the bivalency effect, we used different tasks and materials. In Experiment 1, we required participants to switch between visually presented parity, colour, and case decisions, and bivalency was induced by adding colour to some of the letters used for the case decision tasks. In Experiment 2, the same tasks were used but the stimuli for the parity task were presented auditorily. In Experiment 3, participants switched between size, parity, and letter decisions, and bivalency was induced by varying the size of some of the letters used for the letter decision task. We expected to find the bivalency effect in each experiment.

## Experiment 1

### Method

*Participants.* Participants were 40 volunteers from the University of Bern. Six participants were excluded because their accuracy on decisions with bivalent stimuli was less than 66%, leaving a final sample size of 34 (21 women, 13 men), 17 for each experimental condition.

*Materials.* For the parity decision task, the stimuli were the numerals 1 through 8, each displayed in black and in triplicate (e.g., 777). For the colour-naming task, the stimuli were the symbols $, %, &, and #, displayed in triplicate (e.g., &&&), and either in blue or in red. For the case decision task, the stimuli were triplicates of the consonants p, n, s, and d, shown in black, either in upper- or lowercase. The bivalent stimuli used were the same four consonants (p, n, s, and d), displayed in either blue or red and in either upper- or lowercase. All stimuli were presented in the centre of the computer screen in 60-pt. Times New Roman font.

*Procedure.* Participants were tested individually. They were seated in front of a computer and informed that the experiment involved three different tasks: making parity decisions about digits, naming the colour of symbols, and making case decisions about letters. After giving consent, the same number of participants ($n = 17$) were pseudorandomly assigned to each of the ITI conditions (1,000 vs. 2,000 ms). To make their responses, participants were instructed to press one of two keys (*b* and *n*) on the keyboard with their left and right index fingers, respectively, for each of the three tasks. They practised the tasks to become familiar with the stimulus–response mappings. The mapping information, printed on paper, was displayed below the computer screen for the duration of the experiment. Participants were further informed that they would be shown coloured letters for some of the case decision trials. They were specifically instructed to ignore colour information and to keep making case decisions.

After these instructions, a block of 30 trials was presented for practise. Each trial required making a parity decision, a colour decision, and a case decision, always in the same order, as illustrated in Figure 1. The stimulus for each task was displayed until the participant responded. Doing so blanked the screen for 500 ms, and then the next stimulus appeared. After each trial sequence, an additional blank interval was included that differed according to experimental condition. In the 1,000-ms ITI condition, the additional blank screen remained for 500 ms (resulting in a 1,000-ms ITI), and in the 2,000-ms ITI condition, the additional blank screen was 1,500 ms (resulting in a 2,000 ms ITI). After the practise block and a brief break, each participant completed three experimental blocks, each with 30 trials, without a break between blocks.

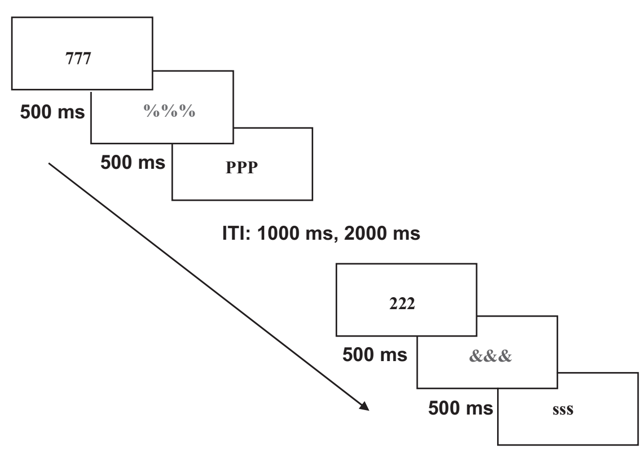


*Figure 1.* Example of the sequence of events for two consecutive univalent trials (Experiment 1). Participants carried out three different tasks: Making parity decisions about digits, making colour decisions about symbols (the symbols were presented either in blue or red), and making case decisions about letters. On a bivalent trial (not pictured here), the letters were presented in colour (either blue or red). ITI = intertrial interval.

For the first and third blocks, only univalent stimuli were presented. For the second block, coloured letters (i.e., bivalent stimuli) were presented on 20% of the case decision task trials. The specific letter selected for this purpose was determined randomly and without replacement from amongst the 16 possible letters (4 letters × 2 case formats × 2 colours). Trials with bivalent stimuli were evenly interspersed amongst the 30 trials of the block; they occurred on every fifth trial, specifically Trials 3, 8, 13, 18, 23, and 28. The entire experiment lasted about 15 min.

### *Results*

An alpha level of 0.05 was used for all statistical tests. Effect sizes are expressed as partial $\eta^2$ values. A preliminary analysis showed that accuracy was high on all tasks, which is consistent with the instruction for participants to respond as quickly and accurately as possible. For univalent stimuli, the average error rate was 2.9%, 3.1%, and 3.1% for Blocks 1, 2, and 3, respectively, and it was 2.3%, 3.6%, and 3.1%, respectively, for the parity, colour, and case decision tasks. The means in each set were not significantly different from each other ($F$s $< 1.3$, $p$s $> .05$, $\eta^2 < .04$).

For each participant, the median decision time (DT) was computed for each of the three tasks, separately for each block. For Block 2, median DTs for univalent and bivalent case decisions were computed separately. In the top part of Table 1, the means of the individual median DTs together with the associated standard errors are shown for univalent stimuli. The bottom part of Table 1 shows the mean DT for accurate case decisions made on the trials with bivalent stimuli in Block 2. The combined findings show that case decisions were made substantially more slowly with bivalent than with univalent stimuli, an observation that was borne out by a two-factorial analysis of variance (ANOVA). This ANOVA of the case task DTs from Block 2, with stimulus valence as a within-participant factor and ITIs as a between-participants factor, revealed a main effect due to stimulus valence, $F(1, 32) = 24.7$, $p < .01$, $\eta^2 = .44$, but no other significant main or interaction effects.

Our main objective was to examine the impact on trials with univalent stimuli that is produced by occasionally encountering trials with bivalent stimuli. The most relevant results, summarised in the top part of Table 1 and depicted in Figure 2, are the latencies from the univalent stimuli in Block 2 versus those from the univalent trials in Blocks 1 and 3. To account for practise effects, we averaged the data from Blocks 1 and 3. A mixed three-factorial ANOVA with block (average of Blocks 1 and 3 vs. Block 2) and task (parity, colour, case) as within-subject factors and ITI (1,000 ms, 2,000 ms) as a between-subject factor revealed a significant main effect of block, $F(1, 32) = 24.6$, $p < .01$, $\eta^2 = .43$, due to slower responding on univalent stimuli of Block 2, compared with the average of Blocks 1 and 3. The analysis also showed a significant effect for task, $F(2, 64) = 13.4$, $p < .01$, $\eta^2 = .29$, due to faster responding on the case decision task than the parity or colour decision task. Neither the main effect due to ITI, $F(1, 32) = 1.14$, $p = .29$, nor any interaction effects reached significance; all $F$s $< 3$, $p$s $> .05$ (the observed power for the null effect of the ITI × Block interaction was .162). For the 1,000-ms ITI condition, the bivalency effect was 58 ms, 66 ms, and 64 ms for the parity, colour, and letter tasks, respectively. For the 2,000-ms ITI condition, the bivalency effect was 87 ms, 85 ms, and 78 ms for the parity, colour, and case decisions, respectively. This pattern provides clear evidence that a similar bivalency effect was present in both ITI conditions.

To further assess the temporal endurance of the bivalency effect, we also examined whether participants were slower to respond to univalent stimuli that occurred on the trials immediately following one with a bivalent stimulus. For this purpose, we computed the median DTs for each of the trials following those with a bivalent stimulus. Specifically, we presented a bivalent stimulus on every fifth trial in Block 2, and for the purpose of the present analysis, we designated this trial with the label N, with succeeding trials labelled N + 1, N + 2, N + 3, and N + 4. The data from these trials, as well as the data from the corresponding Block 1 and 3 trials, combined across the ITI conditions, are summarised in Table 2.

A four-factorial ANOVA with block, trial, and task as within-subjects factors and with ITI as a between-subjects factor revealed significant main effects for block, $F(1, 32) = 26.85$, $p < .01$, $\eta^2 = .46$; for trial, $F(3, 96) = 8.56$, $p < .01$, $\eta^2 = .21$; and for task, $F(2, 64) = 15.33$, $p < .01$, $\eta^2 = .32$. More important, there was also a significant Block × Trial interaction, $F(3, 96) = 3.52$, $p < .05$, $\eta^2 = .10$, a finding that is depicted in Figure 3, which underscores the gradual decrease of the bivalency effect across a series of trials with purely univalent stimuli. No other effect was significant. In a

Table 1
*Experiment 1: Mean Decision Times (and Standard Errors) on Trials With Univalent and Bivalent Stimuli*

| | 1,000-ms ITI | | | | 2,000-ms ITI | | | |
|---|---|---|---|---|---|---|---|---|
| Stimulus and block | Parity | Colour | Case | Total | Parity | Colour | Case | Total |
| Univalent | | | | | | | | |
| Block 1 | 817 (53) | 802 (43) | 738 (47) | 786 (44) | 979 (81) | 820 (49) | 785 (62) | 861 (60 |
| Block 2 | 843 (55) | 848 (43) | 760 (47) | 817 (45) | 998 (79) | 881 (54) | 815 (71) | 898 (62) |
| Block 3 | 753 (41) | 762 (38) | 654 (30) | 723 (32) | 843 (48) | 772 (42) | 690 (38) | 769 (35) |
| Total | 804 (46) | 804 (38) | 717 (39) | 775 (45) | 940 (43) | 824 (43) | 764 (55) | 843 (45) |
| Bivalent | | | | | | | | |
| Block 2 | | | 1,149 (126) | | | | 1,235 (171) | 1,192 (105) |

*Note.* Decision times are given in milliseconds. For univalent stimuli, means are based on individual median decision times of correct responses out of 30 decisions for Blocks 1 and 3. For the case decisions of Block 2, only 24 decisions with univalent stimuli were presented. For bivalent stimuli, means are based on individual median decision times of correct responses out of 6 decisions. ITI = intertrial interval.

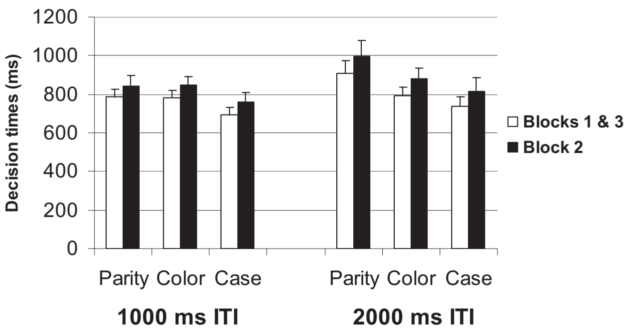


*Figure 2.* Experiment 1: Mean decision times averaged across univalent Blocks 1 and 3 (white bars) and univalent stimuli from Block 2 (black bars). Error bars represent standard errors.

follow-up three-factorial ANOVA in which only the data from trial N + 4 were included, the effect due to blocks was still significant, $F(1, 32) = 5.38$, $p < .05$, $\eta^2 = .14$; thereby documenting the temporal endurance of the bivalency effect.

### *Discussion*

The primary goal of Experiment 1 was to examine the temporal endurance of the bivalency effect. Our results show that the bivalency effect endures across different ITIs (1,000 vs. 2,000 ms), as well as across several trials with purely univalent stimuli. Although the bivalency effect declined across the four trials that followed a trial involving a bivalent stimulus, it was still significant four trials after the occurrence of a trial containing a bivalent stimulus.

These results replicate and extend our previous findings. In addition, they undermine the possibility raised by Kray and Lindenberger (2000) that the bivalency effect might be due to a temporary, short-lived task uncertainty (about which task needs to be performed on a particular trial) that is caused by encountering an occasional bivalent stimulus. We speculated that this uncertainty and its effects on performance would have been more pronounced on trials with relatively short ITIs than on trials with longer ITIs, but the results from Experiment 1 showed no significant difference in DTs between ITI conditions.

Table 2
*Experiment.1: Mean Decision Times (and Standard Errors) on Univalent Trials Immediately Following Trials With Bivalent Case Decisions in Block 2 and the Corresponding Trials From Blocks With Only Univalent Stimuli*

| Block and trial | Parity | Colour | Case |
|---|---|---|---|
| Blocks 1 and 3 averaged | | | |
| Trial N + 1 | 858 (38) | 826 (32) | 753 (41) |
| Trial N + 2 | 877 (44) | 820 (33) | 722 (32) |
| Trial N + 3 | 866 (39) | 785 (26) | 730 (31) |
| Trial N + 4 | 871 (46) | 797 (31) | 709 (33) |
| Block 2 | | | |
| Trial N + 1 | 1,126 (85) | 967 (52) | 841 (53) |
| Trial N + 2 | 937 (58) | 955 (65) | 819 (51) |
| Trial N + 3 | 928 (58) | 873 (45) | 802 (49) |
| Trial N + 4 | 942 (57) | 856 (44) | 765 (43) |

*Note.* Decision times are given in milliseconds. Trial N refers to the sequence trial containing a bivalent stimulus in Block 2. Subsequent trials are labelled N + 1, N + 2, N + 3, and N + 4, respectively.

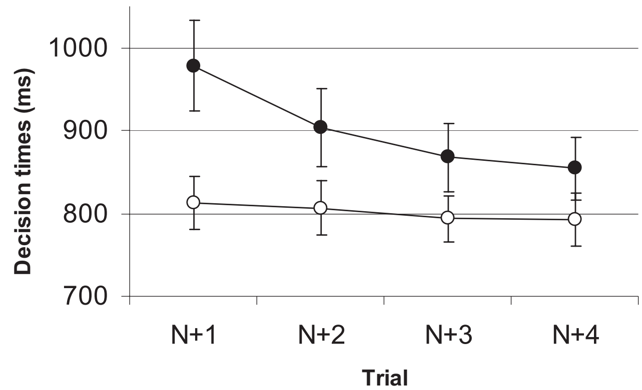


*Figure 3.* Endurance of the bivalency effect in Experiment 1: Mean decision times for trials following trials with a bivalent case decisions in Block 2 (closed circles) compared with the corresponding trials where no bivalent stimuli occurred. Error bars represent standard errors. Trial N refers to the sequence trial containing a bivalent stimulus in the bivalent block; subsequent trials (represented here) are labelled N + 1, N + 2, N + 3, and N + 4, respectively.

The finding that the bivalency effect endured for at least the four trials following a trial with a bivalent stimulus is additional evidence against Kray and Lindenberger's (2000) temporary task uncertainty proposal. Each trial in Experiment 1 took, on average, approximately 5 s (required for making three decisions, each requiring approximately 750 ms, plus two 500-ms ISIs, plus the 1,000-ms or 2,000-ms ITI, respectively); thus, our findings indicate that the occasional occurrence of a bivalent stimulus was sufficient to slow down decision making on univalent stimuli for as long as 20 s. Such a long-lasting effect cannot be attributed to temporary task uncertainty. Instead, the finding supports our view that the bivalency effect is triggered by an endogenous process—more specifically, by a cautious response style.

## Experiment 2

In all of our previous experiments (Woodward et al., 2003, 2008), we manipulated bivalency as we did in Experiment 1; that is, we used colour to create bivalent letters. We proceeded on the assumption that the black digits we used for the parity decision task and the black letters we used for the case decision task would not be affected by this manipulation (cf. Gilbert & Shallice, 2002; Masson, Bub, Woodward, & Chan, 2003; Meiran, 2000). However, recent work by Masson and colleagues suggests, at least indirectly, that this assumption may not be warranted (Masson, Bub, & Ishigami, 2007). Specifically, their findings suggest that, in the context of one task that draws attention to colour information, any other task that involves visual stimuli may invite an automatic evaluation of colour information. Consistent with this possibility, the insertion of a few trials with colour-induced bivalent stimuli might transform the black stimuli we used for the parity and case decision tasks into functionally bivalent stimuli, and this transformation might be the cause of the bivalency effect.

Experiment 2 was designed to test this hypothesis. We used the same three tasks as in Experiment 1. However, whereas the stimuli for the colour and case decision tasks were presented visually, as in Experiment 1, the stimuli for the parity decision task were presented auditorily. As in Experiment 1, bivalent stimuli were created by presenting some of the letters for the case decision task in colour, thus turning them into bivalent stimuli. Although it is still possible to argue that the black stimuli we used for the case decision task may trigger an automatic evaluation of colour information (cf. Masson et al., 2007), this line of reasoning does not seem pertinent to the univalent, auditory stimuli we used for the parity decision task. We reasoned, therefore, that if a bivalency effect occurs even with univalent auditory stimuli, it cannot be attributed to an automatic colour evaluation mechanism of the sort stipulated by Masson et al.

## Method

*Participants.* Participants were 16 volunteers from the University of Bern (10 women, 6 men). All participants were accurate on at least 66% of the decisions with bivalent stimuli; therefore, all data were retained.

*Materials.* For the colour and case decision tasks, we used the same stimuli as in Experiment 1 and presented them in the same manner as in Experiment 1. However, for the parity decision task, we recorded the monosyllabic numerals 1, 2, 3, 4, 5, 6, 8, and 9 and saved each as a .wav file. The same bivalent stimuli were used as in Experiment 1, that is, the four consonants (p, n, s, and d), displayed either in blue or in red and either in upper- or lowercase.

*Procedure.* The procedure was identical to that used in Experiment 1, except that participants wore headphones to hear the auditory stimuli we used for the parity decision task and that only the 2,000-ms ITI condition was administered.

## Results

A preliminary analysis showed that, on univalent stimuli, incorrect decisions were made on 5.7%, 6.0%, and 4.5% of the trials in Blocks 1, 2, and 3, respectively, and on 3.4%, 6.9%, and 5.9% of the trials requiring parity, colour, and case decisions, respectively. A two-way ANOVA with block and task as within-participant factors revealed a significant main effect of task, $F(2, 76) = 5.29$, $p < .01$, $\eta^2 = .28$. Pairwise comparisons revealed significant differences between parity and colour decision task performance, $t(15) = 3.2$, and between parity and case decision task performance, $t(15) = 2.2$, but not between colour and case decision task performance. No other effect was significant.

For each participant, we computed the median time for correct decisions made on each task and for each block. For Block 2, median DTs for univalent and bivalent case decisions were computed separately. In Table 3, the means of the individual median DTs together with the associated standard errors are shown for univalent stimuli, as well as for accurate case decisions made on Block 2 trials with bivalent stimuli. A *t* test showed that case decisions were made substantially more slowly with bivalent than with univalent stimuli, $t(15) = 3.85$, $p < .01$.

To examine the overall impact on trials with univalent stimuli that is produced by occasionally encountering trials with bivalent stimuli, we carried out a two-way ANOVA with block (average of Blocks 1 and 3 vs. Block 2) and task (parity, colour, case) as within-participant factors. It revealed a significant effect for block, $F(1, 15) = 9.33$, $p < .01$, $\eta^2 = .38$, indicating slower responding to univalent stimuli in Block 2, compared with Blocks 1 and 3. The analysis also showed a significant main effect for task, $F(2, 30) = 53.72$, $p < .01$, $\eta^2 = .78$, as well as a significant Block × Task interaction effect, $F(2, 30) = 3.60$, $p < .05$), $\eta^2 = .19$. These results are depicted in Figure 4.

Table 3
*Experiment 2: Mean Decision Times (and Standard Errors) on Trials With Univalent and Bivalent Stimuli*

| Stimulus and block | Parity | Colour | Case | Total |
|---|---|---|---|---|
| Univalent | | | | |
| Block 1 | 1,000 (43) | 614 (61) | 513 (24) | 715 (36) |
| Block 2 | 1,021 (55) | 720 (70) | 570 (33) | 770 (48) |
| Block 3 | 928 (51) | 603 (53) | 516 (21) | 682 (35) |
| Total | 984 (48) | 646 (58) | 533 (24) | 721 (38) |
| Bivalent | | | | |
| Block 2 | | | 675 (49) | |

*Note.* Decision times are given in milliseconds. For univalent stimuli, means are based on individual median decision times of correct responses out of 30 decisions for Blocks 1 and 3. For the case decisions of Block 2, only 24 decisions with univalent stimuli were presented. For bivalent stimuli, means are based on individual median decision times of correct responses out of 6 decisions.

A separate ANOVA of the bivalency effect (i.e., the difference between the average of Blocks 1 and 3 vs. Block 2) revealed a larger bivalency effect on the colour decision task (111 ms) than on the parity decision task (55 ms) or the case decision task (56 ms). Direct comparisons between the average of Blocks 1 and 3 versus Block 2 revealed that the bivalency effect was statistically significant for each task: For parity decision, $t(15) = 2.12$, for colour decision, $t(15) = 3.13$, and for case decision, $t(15) = 2.81$.

To examine the temporal endurance of the bivalency effect across trials, we computed median DTs for each of the trials following those with a bivalent stimulus. As in Experiment 1, every fifth trial in Block 2 involved a bivalent stimulus, and we designated this trial with the label N, with subsequent trials labelled N + 1, N + 2, N + 3, and N + 4. The mean DT data are presented in Table 4. A three-factorial ANOVA with block, trial, and task as within-participant factors revealed significant main effects for block, $F(1, 15) = 14.02$, $p < .01$, $\eta^2 = .48$, for trial, $F(3, 45) = 5.33$, $p < .01$, $\eta^2 = .26$, and for task, $F(2, 30) = 52.03$, $p < .01$, $\eta^2 = .77$. In addition, there was also a significant Block × Task interaction, $F(2, 30) = 3.56$, $p < .05$, $\eta^2 = .19$, and a marginal Block × Trial interaction, $F(3, 45) = 2.31$, $p = .089$, $\eta^2 = .13$. The latter interaction is depicted in Figure 5. Follow-up ANOVAs revealed a significant effect of block for Trials N + 1, N + 2, and N + 3, all *F*s > 6.9, *p*s < .05. For Trial N + 4, the main effect of block was marginal, $F(1, 15) = 3.82$, $p = .069$.

## Discussion

The goal of Experiment 2 was to replicate and extend the core findings from Experiment 1 and to examine the possibility that the bivalency effect occurs because of a tendency to overinterpret the bivalent potential of univalent stimuli or, more concretely,

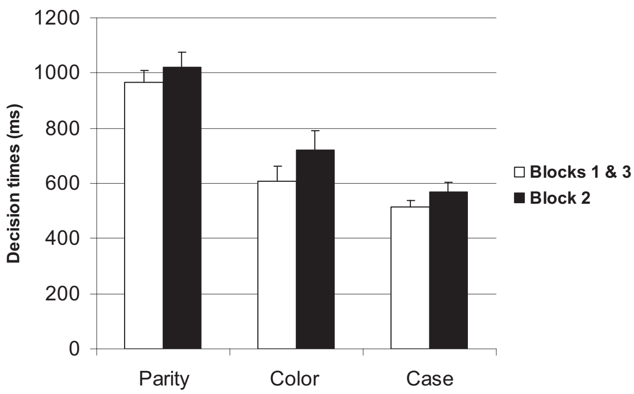


*Figure 4.* Experiment 2: Mean decision times averaged across univalent Blocks 1 and 3 (white bars) and univalent stimuli from Block 2 (black bars). Error bars represent standard errors.

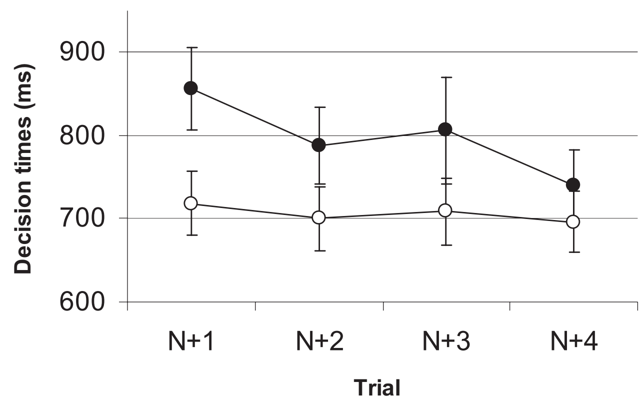


*Figure 5.* Endurance of the bivalency effect in Experiment 2: Mean decision times for trials following trials with a bivalent case decisions (closed circles) compared with the corresponding trials where no bivalent stimuli occurred. Error bars represent standard errors. Trial N refers to the sequence trial containing a bivalent stimulus in the bivalent block; subsequent trials (represented here) are labelled N + 1, N + 2, N + 3, and N + 4, respectively.

because after an encounter with a bivalent visual stimulus, every univalent visual stimulus comes to function, to a limited extent, as a bivalent stimulus (cf. Masson et al., 2007). To address this possibility, we used both visual and auditory univalent stimuli on the assumption that, in the context of bivalent visual stimuli, univalent visual stimuli might be treated as having bivalent properties but that this tendency to overinterpret properties would not apply to stimuli presented auditorily. However, the finding of a significant bivalency effect for all of our univalent stimuli (i.e., visual and auditory) suggests that this effect is not an overinterpretation artefact of the sort implied by the work of Masson et al.

Our results revealed a larger bivalency effect on the colour decision task than on either the parity or case decision task. We assume that this difference in effect magnitude is a methodological artefact that may have been caused in our experiment by the need to switch between modalities.

The results of Experiment 2 also further illuminate the temporal endurance of the bivalency effect by documenting its persistence across several trials with univalent stimuli. By contrast to Experiment 1, however, a detailed inspection of the results revealed that, for the parity decision task, there was no evidence of a bivalency effect on the fourth trial with univalent stimuli. This finding, in contrast to the parity decision task findings from Experiment 1, raises the possibility that a switch between modalities interacts with the endurance of the bivalency effect.

Table 4
*Experiment 2: Mean Decision Times (and Standard Errors) on Univalent Trials Immediately Following Trials With Bivalent Case Decisions in Block 2 and the Corresponding Trials From Blocks With Only Univalent Stimuli*

| Block and trial | Parity | Colour | Case |
|---|---|---|---|
| Blocks 1 and 3 averaged | | | |
| Trial N + 1 | 990 (56) | 634 (63) | 530 (27) |
| Trial N + 2 | 957 (49) | 621 (65) | 521 (28) |
| Trial N + 3 | 975 (58) | 627 (58) | 525 (27) |
| Trial N + 4 | 988 (58) | 594 (52) | 505 (25) |
| Block 2 | | | |
| Trial N + 1 | 1,138 (67) | 817 (70) | 615 (40) |
| Trial N + 2 | 1,052 (65) | 747 (71) | 565 (34) |
| Trial N + 3 | 1,055 (80) | 813 (107) | 550 (36) |
| Trial N + 4 | 976 (59) | 697 (73) | 545 (33) |

*Note.* Decision times are given in milliseconds. Trial N refers to the sequence trial containing a bivalent stimulus in Block 2. Subsequent trials are labeled N + 1, N + 2, N + 3, and N + 4, respectively.

## Experiment 3

Experiment 3 was designed to further investigate the temporal endurance and generality of the bivalency effect, and more important, to examine the possibility that this effect might be specifically linked to our use of colour information for creating bivalent stimuli. In the pursuit of these goals, the experiment involved sequences of three tasks: making size decisions about symbols, making parity decisions about single-digit numbers, and making consonant/vowel decisions about letters. We created bivalent stimuli by varying the size of the letters presented for the consonant/vowel decision task. In Experiment 3, we also counterbalanced the order of presenting blocks with univalent and bivalent stimuli to examine whether the bivalency effect is influenced by the participants' familiarity with the decision tasks.

### Method

*Participants.* Participants were 72 undergraduate students (64 women) from the University of Bern. All participants were accurate on at least 66% of the decisions with bivalent stimuli; therefore, all data were retained.

*Materials.* For the size decision task, the stimuli were the symbols #, %, &, and $, presented either in 20-pt. font or in 180-pt. font. For the parity decision task, the stimuli were the numerals 1 through 4, each displayed in 60-pt. font. For the consonant/vowel decision task, the stimuli were the uppercase letters A, P, T, and U, each displayed in 60-pt. font. We created bivalent stimuli by presenting the four letters (A, P, T, and U) in either 20-pt. or 180-pt. font. On the display monitor, stimuli in 20-pt. font covered about 2% of the vertical extent of the monitor, whereas the 180-pt. stimuli covered about 20%. All stimuli were displayed in the centre of the computer screen in black Times New Roman font.

*Procedure.* The procedure was similar to that used in Experiments 1 and 2, except for the ITI manipulation, the specific task instructions, and the ordering of the blocks. Participants were assigned to one of three ITI conditions: 1,000 ms, 3,000 ms, or 5,000 ms. They were instructed to press one of two keys (*b* and *n*) on the keyboard with their left and right index fingers, respectively, for each of the three tasks: making size decisions about symbols, making parity decisions about digits, and making consonant/vowel decisions about letters. Participants were further informed that, on some of the consonant/vowel decision trials, the size of the letters would vary. They were specifically instructed to ignore the size of the letters and to focus on making consonant/vowel decisions.

After these instructions, a block of 30 trials was presented for practise. Then, after a short break, a total of 60 trials were presented, consisting of two experimental blocks each with 30 trials, without a break between blocks. Each trial required making a size decision, a parity decision, and a consonant/vowel decision, always in the same order, as illustrated in Figure 6. The stimulus for each decision was displayed until the participant responded. Doing so blanked the screen for 500 ms, and then the next stimulus appeared. After each trial sequence, an additional blank interval was included, which differed across conditions. In the 1,000-ms ITI condition, the additional blank screen remained for 500 ms; in the 3,000-ms ITI condition, the additional blank lasted 2,500 ms; and in the 5,000-ms ITI condition, the additional blank lasted 4,500 ms.

Block order was counterbalanced in each ITI condition to explore the possibility that practise might be contributing to the bivalency effect. For half of the participants, the block with univalent stimuli only (i.e., the univalent block) was presented first, and for the other half, the block including bivalent stimuli was presented first (i.e., the bivalent block). Selection of the bivalent stimuli was random without replacement from the set of eight bivalent stimuli (4 letters × 2 sizes). Trials with bivalent stimuli were distributed evenly amongst the 30 trials and occurred on every fifth trial, specifically on Trials 3, 8, 13, 18, 23, and 28. Depending on the ITI condition, the entire experiment lasted between 15 and 25 min.

### Results

A preliminary examination showed that the average error rate for univalent stimuli was 1.6%, 3.3%, and 1.8%, respectively, for the size, parity, and consonant/vowel decision tasks. A three-way ANOVA with the factors type of block (univalent, bivalent), task (size, parity, consonant/vowel), and ITI condition (1,000 ms, 3,000 ms, 5,000 ms) revealed a significant main effect for task, $F(2, 138) = 11.1$, $p < .05$, $\eta^2 = .14$. No other main effect and no interactions were significant.

For each participant, we computed the median DT for correct responses on each of the three tasks and for each block. For the bivalent block, median DTs for univalent and bivalent consonant/vowel decisions were computed separately. To explore the occurrence of practise effect, univalent trials from the bivalent block and those from the univalent block were first analysed in a mixed four-factorial ANOVA with type of block and task as within-

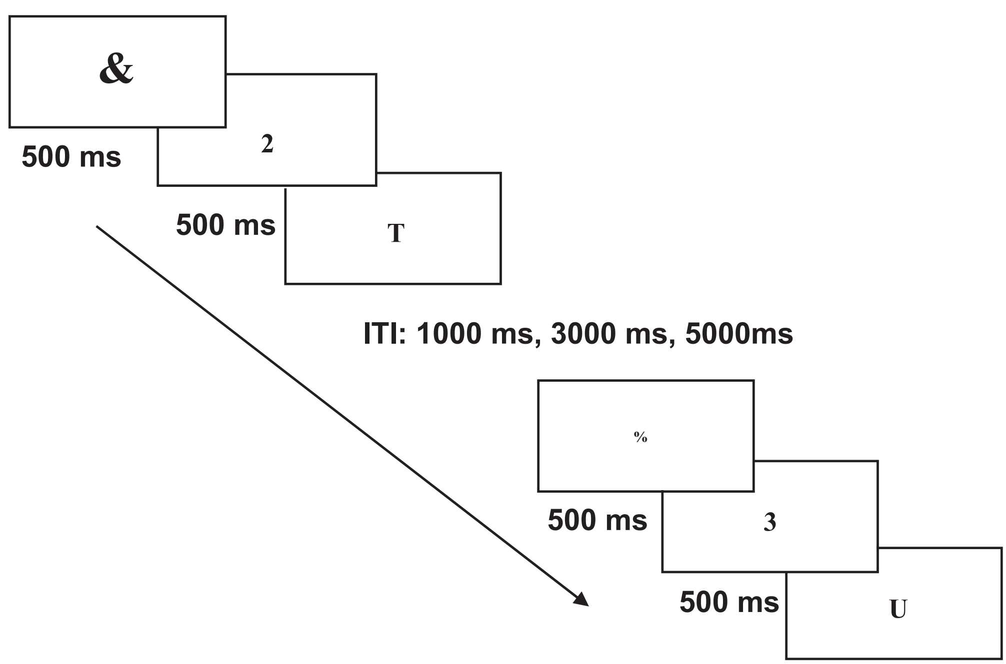


*Figure 6.* Example of the sequence of events for two consecutive univalent trials (Experiment 3). Participants carried out three different tasks: making size decisions about symbols, making parity decisions about digits, and making vowel/consonant decisions about letters. On a bivalent trial (not pictured here), the size of the letters was varied.

participant factors and block order and ITI condition as between-participants factors. There was a significant Type of Block × Block Order interaction, $F(1, 66) = 4.92$, $p < .05$, $\eta^2 = .07$, reflecting the fact that the bivalency effect was smaller when the univalent block occurred before rather than after the bivalent block. Specifically, DTs for the univalent block were 640 ms when presented first and 621 ms when presented second, and DTs for the bivalent block were 684 ms when presented first and 661 when presented second. This result provides evidence that DTs were influenced by familiarity with the tasks. However, no other interaction with block order was significant. Therefore, the data were collapsed across block order for subsequent analyses.

In Table 5 the means of the individual median DTs together with the associated standard errors are shown for each ITI condition. The findings show that consonant/vowel decisions were made substantially more slowly with bivalent than with univalent stimuli in the bivalent block. This observation was confirmed by a mixed two-way ANOVA revealing main effects due to stimulus valence, $F(1, 69) = 60.0$, $p < .01$, $\eta^2 = .46$, and ITI condition, $F(2, 69) = 8.6$, $p < .01$, $\eta^2 = .20$, as well as a significant interaction between these factors, $F(2, 69) = 6.36$, $p < .01$, $\eta^2 = .16$. Post hoc tests of the difference between these univalent and bivalent consonant/vowel decisions revealed that the cost of adding bivalency was higher for the 1,000-ms condition (225 ms), compared with both the 3,000-ms and the 5,000-ms conditions (85 ms and 99 ms, respectively), with $t$s > 2.64, whereas the latter two conditions did not differ.

Of primary interest was the size of the bivalency effect, which we examined by means of a three-factorial ANOVA with type of block (univalent, bivalent) and task (size, parity, consonant/vowel) as within-subject factors and ITI condition (1,000 ms, 3,000 ms, 5,000 ms) as a between-subjects factor. The analysis revealed a significant effect due to type of block, $F(1, 69) = 20.4$, $p < .01$, $\eta^2 = .23$, because of longer DTs on univalent stimuli that occurred in the bivalent versus the univalent block. There was also a significant main effect of task, $F(2, 138) = 31.6$, $p < .01$, $\eta^2 = .31$, a main effect due to ITI, $F(2, 69) = 4.46$, $p < .05$, $\eta^2 = .11$; and a significant Task × ITI interaction, $F(4, 138) = 2.66$, $p < .05$, $\eta^2 = .07$. Separate two-way ANOVAs with type of block and tasks revealed that the interaction was due to a significant effect of task for the 3,000-ms and the 5,000-ms ITI conditions, with $F(2, 46) = 18.3$, $p < .01$, $\eta^2 = .447$, and $F(2, 46) = 18.3$, $p < .01$, $\eta^2 = .447$, respectively, whereas task was not significant in the 1,000-ms ITI condition, $F(2, 46) = 1.98$, *ns*. No interaction involving type of block approached significance (all $F$s < 1, $p$s > .05; observed power for the null effect of ITI × Type of Block was .119).

We also used the DTs to examine the endurance of the bivalency effect across the univalent trials that followed a trial with a bivalent stimulus. As for the preceding experiments, we computed a median DT for each of the trials following those with a bivalent stimulus. The data from these trials, as well as the data from the corresponding univalent block trials, combined across the ITI conditions, are summarised in Table 6. A four-factorial ANOVA with type of block, trial, and task as within-participant factors and ITI as a between-participants factor revealed a significant Type of Block × Trial interaction, $F(3, 207) = 6.59$, $p < .01$, $\eta^2 = .09$. No other effects approached significance. To illustrate this interaction, Figure 7 highlights the gradual decrease of the bivalency effect across a series of purely univalent trials. In a subsequent three-factorial ANOVA in which only the data from trial N + 4 were included, the effect due to type of block was still significant, $F(1, 69) = 7.38$, $p < .01$, $\eta^2 = .10$.

Table 5
*Experiment 3: Mean Decision Times (and Standard Errors) on Trials With Univalent and Bivalent Stimuli*

| ISI, stimulus, and block | Size | Parity | Consonant/ vowel | Total |
|---|---|---|---|---|
| 1,000-ms ITI | | | | |
| Univalent stimuli | | | | |
| Univalent block | 682 (26) | 705 (35) | 649 (36) | 679 (28) |
| Bivalent block | 732 (28) | 758 (40) | 708 (44) | 733 (33) |
| Bivalent stimuli | | | | |
| Bivalent block | | | 934 (70) | |
| 3,000-ms ITI | | | | |
| Univalent stimuli | | | | |
| Univalent block | 665 (29) | 683 (31) | 560 (24) | 636 (25) |
| Bivalent block | 708 (34) | 716 (37) | 585 (31) | 670 (30) |
| Bivalent stimuli | | | | |
| Bivalent block | | | 670 (45) | |
| 5,000-ms ITI | | | | |
| Univalent stimuli | | | | |
| Univalent block | 585 (17) | 646 (28) | 500 (15) | 577 (16) |
| Bivalent block | 635 (26) | 678 (41) | 536 (20) | 616 (26) |
| Bivalent stimuli | | | | |
| Bivalent block | | | 635 (44) | |

*Note.* ITI = intertrial interval.

### Discussion

The goal of Experiment 3 was to replicate and generalise the findings from the preceding experiments. The results showed that the bivalency effect generalises across different kinds of materials, is not linked to the specific bivalent stimuli we used in the preceding experiments, and remains robust even across an ITI of 5,000 ms. The results once more highlight the temporal endurance of the bivalency effect by showing that, although it declines across trials, it is still significant four trials after the occurrence of a bivalent stimulus.

## General Discussion

The first goal of the present study was to examine the temporal endurance of the bivalency effect and to ascertain whether this effect is caused by task uncertainty induced by bivalent stimuli, as suggested by Kray and Lindenberger (2000), or by the adoption of a cautious response style, as proposed in our previous work (Woodward et al., 2003, 2008). According to the former account, bottom–up effects induced by bivalent stimuli are sufficient to explain the bivalency effect, whereas, according to the latter account, processes that are initiated from the top down would be necessary. Under the assumption that task uncertainty would be relatively short lived, the bivalency effect would disappear quickly across time. In contrast, the adoption of a cautious response style would imply that the bivalency effect would be more persistent. We manipulated the ITI and examined the persistence of the bivalency effect across trials with univalent stimuli that

Table 6
*Experiment 3: Mean Decision Times (and Standard Errors) on Univalent Trials Immediately Following Trials With Bivalent Case Decisions in the Bivalent Block and the Corresponding Trials From Blocks With Only Univalent Stimuli*

| Block and trial | Size | Parity | Consonant–vowel |
|---|---|---|---|
| Univalent block | | | |
| Trial N + 1 | 667 (19) | 688 (20) | 614 (24) |
| Trial N + 2 | 638 (18) | 674 (21) | 580 (17) |
| Trial N + 3 | 653 (19) | 691 (20) | 573 (17) |
| Trial N + 4 | 655 (20) | 702 (23) | 575 (20) |
| Bivalent block | | | |
| Trial N + 1 | 798 (32) | 788 (28) | 661 (25) |
| Trial N + 2 | 709 (20) | 755 (27) | 602 (18) |
| Trial N + 3 | 693 (19) | 723 (26) | 611 (23) |
| Trial N + 4 | 697 (20) | 715 (23) | 617 (23) |

*Note.* Trial N refers to the sequence trial containing a bivalent stimulus in the bivalent block. Subsequent trials are labeled N + 1, N + 2, N + 3, and N + 4, respectively.

immediately followed trials with a bivalent stimulus. In three experiments, we demonstrated that the bivalency effect remained intact across ITIs from 1,000 ms to 5,000 ms and that it persisted across several trials with univalent stimuli that immediately followed trials with a bivalent stimulus. These results support the view that the bivalency effect is triggered by a cautious response style (Woodward et al., 2003, 2008). A task uncertainty account that assumes a quick recovery from the need for making a decision about which action is context appropriate, as suggested by Kray and Lindenberger (2000), is not sufficient to explain the endurance of the bivalency effect.

The second goal was to examine the generality of the bivalency effect across different tasks and stimuli. In Experiment 1, we required participants to switch between visually presented parity, colour, and case decisions. Bivalency was induced by adding colour to some of the case decision tasks. With this design, the basic finding of a bivalency effect was replicated. Admittedly, we proceeded on the assumption that the black digits we used for the parity decision task and the black letters we used for the case decision task would be processed as univalent stimuli. However, it is possible that, if any of the tasks in a task set draws attention to colour information, any other task that involves visual stimuli may invite an automatic evaluation of colour information. Therefore, in Experiment 2, the same tasks were used as in Experiment 1, but the stimuli for the parity task were presented auditorily. The results showed a consistent bivalency effect for all tasks. This finding demonstrates the generality of the bivalency effect, ruling out the possibility that our previous findings may have been due to the spreading of bivalency from the colour-induced bivalent stimuli to the black stimuli we used for the parity and case decision tasks. In Experiment 3, participants switched between size, parity, and consonant/vowel decisions, and bivalency was induced by varying the size of some of the letters used for the consonant/vowel decision task. Again, we found a consistent bivalency effect, thusly demonstrating that its occurrence is not dependent on the presence of colour in the task set but that it is a rather general phenomenon that occurs across a variety of tasks and types of stimuli.

Current task-switching theories focus primarily on the exogenous influences produced by bivalent stimuli (e.g., Allport & Wylie, 2000; Monsell et al., 2000). These theories can account for the slowing of performance on the stimuli that share features with the bivalent stimuli, but they are not able to accommodate the finding of slower responding on tasks with stimuli that have no overlapping features with the bivalent stimuli. To explain the endogenous influence produced by bivalent stimuli that are presented occasionally amongst univalent stimuli on subsequent trials with purely univalent stimuli a different explanation is necessary. We have argued that a change in task orientation (i.e., the adoption of a cautious response style) in response to bivalent stimuli is sufficient to explain the general slowing that can be seen across ITI conditions and that fades out slowly across subsequent trials.

The adoption of a cautious response style when encountering bivalent stimuli may be functional for maintaining accurate task-switching performance. Slowing the pace of responding can be seen as a response to the trickiness associated with bivalent stimuli without sacrificing accuracy. This general notion has previously been associated with *mixing costs* to explain performance changes on repeated tasks when a mixture of different stimulus types, rather than only one stimulus type, was presented (Los, 1999; Lupker, Brown, & Colombo, 1997; Monsell, Patterson, Graham, Hughes, & Milroy, 1992). A similar notion has also been used to account for dual-task performance in which task scheduling has been said to fit either a daring or cautious style (Schumacher et al., 2001). Although they have not been highlighted in previous studies, our findings replicate results reported by others. For example, Rogers and Monsell (1995; see neutral condition of Experiment 1) found slower task-switching responses to univalent stimuli that appeared intermixed with bivalent stimuli. Slower responding also has been observed under repetition conditions when a series of tasks contained bivalent switch trials (De Jong, 2000; Fagot, 1994; Kray & Lindenberger, 2000; Mayr, 2001; Rubin & Meiran, 2005).

The results of the present study indicate that a comprehensive account of task switching must include endogenous processes (e.g., task orientation or response style) that operate in addition to processes engaged by the specific features of the stimuli presented for each task to be performed. A promising starting point may be the account put forward recently by Waszak, Hommel, and Allport (2003; cf. Mayr & Kliegl, 2000). They have suggested that stimuli

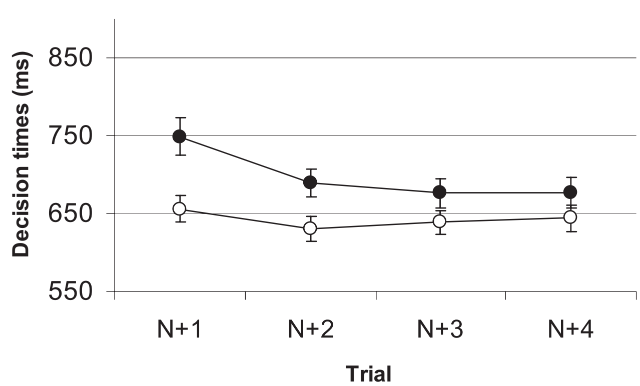


*Figure 7.* Endurance of the bivalency effect in Experiment 3: Mean decision times for trials immediately following trials with a bivalent consonant/vowel decisions (closed circles) compared with the corresponding trials where no bivalent stimuli occurred. Error bars represent standard errors.

acquire a history during an experiment, that is, they acquire associations with the tasks in which they occur. Our results suggest that it is not only the specific episodic binding between tasks and stimuli but also the general experience of trickiness in a specific context that affects performance. As a consequence, task interference effects are neither stimulus nor task specific, but rather extend to the context in which they occur. Such a proposal may be even testable with newly developed computational models (Altmann & Gray, 2008; Meiran, Kessler, & Adi-Japha, 2008).

It is important to note that the specific influence of bivalency on task-switching performance explored in the present study is not observed with paradigms in which only two types of task are used. Nevertheless, the cost of bivalency as identified with a paradigm involving switching between three tasks may contribute substantially to the switch cost observed with other task-switching paradigms. Further research is necessary to determine the relative contribution of the bivalency effect to switch costs in other task-switching paradigms.

To summarise, the results of the present study replicate and extend previous work. In three experiments with different tasks and types of bivalent stimuli, we consistently found that the bivalency effect is general and enduring. This demonstration provides further support for the importance of top–down influences on task-switching performance.

## Résumé

L'objectif de cette étude était d'examiner la généralité et l'endurance temporelle de l'effet de bivalence dans l'alternance de tâche. Cet effet fait référence au ralentissement observé sur les stimuli univalents survenant lorsque des stimuli bivalents apparaissent occasionnellement. Nous avons eu recours à un paradigme impliquant des permutations prévisibles entre trois tâches simples, avec des stimuli bivalents survenant occasionnellement au cours d'une des tâches. La généralité de l'effet de bivalence a été testée en utilisant différents types de tâches et de stimuli bivalents alors que son endurance a été examinée avec différents intervalles inter-essai (IIE) et avec les essais univalents suivant les essais avec des stimuli bivalents. Dans trois expériences, les résultats ont montré un effet de bivalence général, robuste et endurant pour toutes les conditions d'IIE. Même si l'effet diminue au fil des essais, il demeure significatif pour environ quatre essais suivant un essai avec stimulus bivalent. Nos résultats font ressortir l'importance qu'ont les processus dirigés par les concepts pour expliquer la performance aux permutations de tâches.

*Mots-clés* : alternance de tâche, stimuli univalents, stimuli bivalents, effet de bivalence

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