Bivalency is Costly: Bivalent Stimuli Elicit Cautious Responding

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Abstract. When performing tasks in alternation, substantial slowing occurs when the stimuli have features relevant to both tasks (i.e., when stimuli are bivalent as opposed to univalent). One possible source of this slowing, herein called a bivalency cost, is that encountering bivalent stimuli leads to a more cautious response style. To investigate this, we employed a paradigm that required performing three simple tasks, with bivalent stimuli occasionally encountered on one task. The results show that regardless of the feature overlap among the stimuli used for the different tasks, the introduction of bivalent stimuli slowed responding on all tasks and it was accompanied by a decrease in response errors. Overall, it appears that bivalent stimuli recruit a more cautious approach to task-switching performance.

Key words: task switching, task alternation, bivalency cost, bivalent stimuli, top-down processes, endogenous processes

Under most conditions, a task is carried out more slowly when it must be performed in alternation with another task rather than alone.[1] Previous research has shown that this cost is substantially larger when the tasks involve bivalent materials; that is, stimuli whose features are relevant to multiple tasks (Allport, Styles, & Hsieh, 1994; Rogers & Monsell, 1995). For a concrete example, consider one task that requires naming the color of letters printed in color, and another that requires making case-decisions about the same letters. In this context, colored letters are *bivalent* stimuli, whereas colored bars or uncolored letters would be *univalent* stimuli. Our goal is to advance understanding of the slowing in performance that is produced by bivalent stimuli. To learn about this slowing, herein called the *bivalency cost*, the present study explored how performing a sequence of tasks with univalent stimuli is affected by the addition of a few trials with bivalent stimuli.

How do bivalent as opposed to univalent stimuli affect task performance? A critical difference between univalent and bivalent stimuli is that a univalent stimulus has one relevant feature or property (e.g., color) and implicates one simple property-response map (e.g., a map that links the ink color red to responding with the word red). By contrast, a bivalent stimulus has two relevant properties (e.g., the ink color and case of letters), and thus implicates two property-response maps. If we assume that each property-response map is instantiated as a set of IF-THEN rules (e.g., if the color is red, then say red), it follows that a set of simple IF-THEN rules is sufficient to cover the property-response map of a univalent stimulus, but a set of conjunction rules would be necessary for a bivalent stimulus. In the latter case, an additional rule is required for determining which property-response map is relevant on a given trial (e.g., if the stimulus appears on the top half of the screen, make color decisions). By these assumptions, it is possible that slowing occurs with bivalent

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[1] Under some conditions, a task can be performed as quickly in alternation with another task as under repetition conditions. This outcome occurs, for example, when tasks involve univalent stimuli with univalent responses and no bivalent stimuli have been presented on previous trials (Allport & Wylie, 2000; Jersild, 1927; Wylie & Allport, 2000).

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stimuli because the application of conjunction rules demands more processing time and resources, relative to the application of the simple rules that guide responding to univalent stimuli. This kind of interpretation seems consistent with the task-cueing/task-set reconfiguration account by Monsell and colleagues (Monsell, Yeung, & Azuma, 2000; Rogers & Monsell, 1995).

Another possibility is that bivalency costs occur because of dynamic influences across trials. A univalent stimulus elicits only one property-response map that is unique to that stimulus, whereas with bivalent stimuli, each elicits two property-response maps that may overlap the map of another stimulus. When working with bivalent stimuli, the task performed on Trial *n* requires activating one map (e.g., the one for naming the color of letters) while at the same time inhibiting or suppressing another map (e.g., the one for making case decisions). If the inhibited or negatively primed map is relevant on Trial $n + 1$, however, additional time is required to reactivate it and this results in a performance cost. This type of negative priming notion seems to form the core of the account proposed by Allport and colleagues (Allport et al., 1994; Allport & Wylie, 2000).

The task-cueing and negative priming accounts have dominated previous research on the costs associated with task switching (e.g., Allport & Wylie, 2000; Monsell et al., 2000). Aspects of these accounts (e.g., negative priming and task cueing) are based on processes that are initiated primarily from the bottom-up in response to stimuli or their properties. In contrast to these accounts, however, a recent pilot study in our laboratory produced results that are difficult to interpret within this context. We found slower performance on tasks with univalent stimuli that appeared among tasks with bivalent stimuli even when there was no property overlap between the univalent and bivalent stimuli, and this outcome does not fit either the task-cueing or negative priming view. Instead, our findings implicate additional higher-order processes that are initiated from the top-down.

The main objective of the present study was to investigate the slowing of performance on tasks with univalent stimuli whose properties either do or do not overlap with those of bivalent stimuli. As in the pilot study, we required participants to perform sequences of three different speeded tasks: making parity (odd/even) decisions about digits, naming the display colors of familiar symbols (e.g., #) and making case decisions about letters. These three tasks were always administered in the same predictable sequence. We created bivalent stimuli by displaying colored letters on some case-decision trials. By this manipulation, some of the stimuli used for the color-naming task and for the case-decision task had color as a shared property. This property was always relevant for the color-naming task and never relevant for the case-decision task. The digits used for the parity-decision task shared no relevant properties with any of the other stimuli. Therefore, on the assumption that bivalency costs reflect processes that are initiated and guided from the bottom up by properties of specific stimuli, we expected that the introduction of bivalent stimuli would slow performance on the color-naming task and on the case-decision task. However, because the stimuli used for the parity-decision task did not share their properties with any other stimuli, bottom-up accounts would not predict slowing on this task.

Method

Participants

The participants were 24 undergraduate volunteers (9 men and 15 women) from the University of British Columbia. They participated in return for course credit.

Materials

We prepared the following univalent stimuli, all displayed in 60-point Times New Roman font on a 17-inch color monitor. For the parity-decision task, we used the numerals 1 through 8, always displayed in black. For the color-naming task, we presented a string of three number-signs (i.e., ###) either in blue or in red. For the case-decision task, the stimuli were the following four consonant-vowel-consonant trigrams: BAF, DER, LOM, and TUJ. They were always displayed in black, either in upper- or lower-case letters. We also prepared a set of eight bivalent stimuli in 60-point Times New Roman font by displaying each of the above trigrams either in blue or in red.

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 color of symbols, and making case decisions about trigrams. After giving consent, each participant was instructed to say "odd" or "even" for the parity task, "red" or "blue" for the color task, and "upper" or "lower" for the case task. Then a total of 160 trials were presented, arranged into a practice block with 40 trials

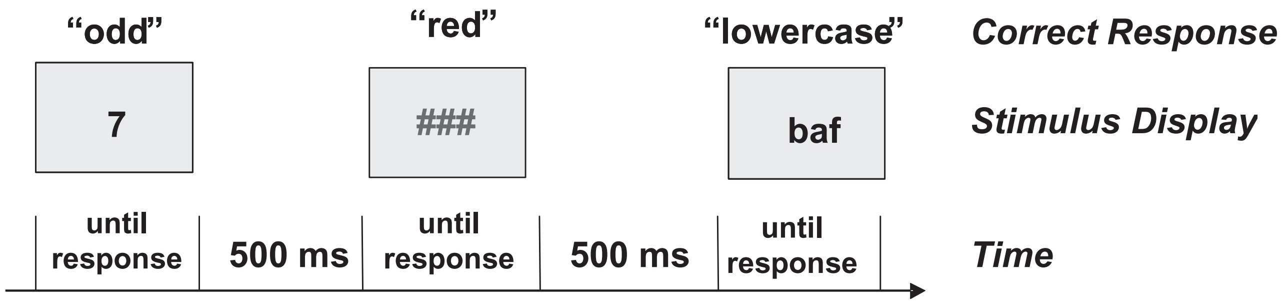

Figure 1. The figure shows an example of the sequence of events for one complete trial. Participants carried out three different tasks: making parity decisions about digits, naming the color of symbols, and making case decisions about trigrams. Each participant was instructed to respond "odd" or "even" for the parity task, "red" or "blue" for the color task, and "upper" or "lower" for the case task.

followed by 3 experimental blocks, each with exactly 40 trials. Each trial required making a parity-, a color-, and a case-decision, and these three tasks appeared always in the same order, as illustrated in Figure 1. The target stimulus for each task was displayed until the subject responded to it. Doing so blanked the screen for 500 ms, and then the stimulus for the next task appeared. Subjects' responses were recorded via microphone. Immediately after each trial, the experimenter typed the subject's triplet of responses on the keyboard (e.g., o / r / u), and this action initiated the next trial.

After receiving instructions, the practice block and three experimental blocks were presented without a break. For the first and third experimental (post-practice) blocks, only univalent stimuli were presented. For the second block, colored trigrams (i.e., bivalent stimuli) were presented on 20% of the case-decision tasks. These were distributed randomly among the 40 trials of the block. The entire experiment lasted about 15 minutes.

Results

Responses for which the microphone reacted to extraneous noise or failed to record a response were excluded from further analyses, and any responses longer than 3000 ms or shorter than 200 ms were also excluded. Less than 1% of all responses had to be excluded for these reasons. For each task and block, Table 1 shows the mean response time computed on the remaining, valid trials in each condition, as well as the mean percentage of response errors, with the associated standard deviations. The data shown are for univalent trials only.[2] The alpha level was set at .05 for all statistical analyses, and one-tailed t tests were used with hypothesized slower and more accurate responses in Block 2.

The objective of this study was to examine how performance on tasks with univalent stimuli is affected by the insertion of a small number of bivalent stimuli into a large series of trials. For this purpose, we compared performance on univalent trials in Block 2, where a small number of bivalent trails had been inserted, with performance on univalent trials in Blocks 1 and 3, where none of the tasks involved bivalent stimuli. A repeated-measures analysis of variance (ANOVA) of the response times showed significant main effects for task type, $F(2, 46) = 64.46$, $p < .001$, $MSE = 23236.39$, and for blocks, $F(2, 46) = 8.13$, $p < .001$, $MSE = 4818.19$. The interaction between blocks and task type was not significant, $F(4, 92) = 0.82$, $p = .46$, $MSE = 1763.17$. The effect due to task type reflects the slower responses on the parity-decision task than on either the color-naming or case-decision tasks. More interestingly, further analyses of the effect due to blocks revealed a significant quadratic component, $F(1, 23) = 16.15$, $p < .001$, $MSE = 4399.71$. The linear component was not significant, $F(1, 23) = 1.40$, $p = .25$, $MSE = 5236.68$. The quadratic component reflects the slower responses that were made in Block 2 than in either Block 1 or 3. The results of t tests confirmed that Block 2 response times were significantly slower than those in Block 1, $t(23) = 2.61$, $p < .01$, $MSE = 5205.36$, and that Block 2 response times were significantly slower than those in block 3, $t(23) = 4.32$, $p < .001$, $MSE = 4012.54$.

We conducted the same type of analysis on the error data that are listed in the bottom half of Table 1. The ANOVA showed significant main effects for block, $F(2, 46) = 38.19$, $p < .001$, $MSE = 4.87$, and task type, $F(2, 46) = 112.41$, $p < .001$, $MSE = 4.68$.

[2] As discussed in the Method section, 20% of the stimuli presented for the case-decision task in Block 2 were bivalent, and response times ($M = 703$ ms, $SD = 162$ ms) were significantly slower than in the neutral condition, $t(23) = 3.26$, $p < .005$. The mean error rate was 15% for the bivalent stimuli.

Table 1. Mean response times and mean percentage of errors (standard deviations in parentheses) on trials with univalent stimuli.

	TASK TYPE		
Block	Parity	Color	Case
Response Times			
Block 1	827 (209)	563 (95)	611 (97)
Block 2	871 (288)	586 (90)	638 (117)
Block 3	814 (213)	555 (110)	590 (91)
Decision Errors			
Block 1	8.44 (3.71)	3.21 (1.83)	0.80 (1.54)
Block 2	2.35 (2.70)	0.55 (1.10)	0.68 (1.68)
Block 3	7.27 (2.51)	3.27 (1.21)	0.77 (1.46)

Note. The means are based on 40 trials, except for Block 2 of the case-decision task where only 32 trials with univalent stimuli were presented.

The interaction effect between blocks and task type was also significant, $F(4, 92) = 38.19$, $p < .001$, $MSE = 3.29$. Follow-up analyses of the block effect revealed a significant quadratic component for the parity-decision task, $F(1, 23) = 85.72$, $p < .001$, $MSE = 5.57$, and for the color-decision task, $F(1, 23) = 148.04$, $p < .001$, $MSE = 0.78$, but not for the case-decision task, $F(1, 23) = .07$, $p = .80$, $MSE = 2.40$. The corresponding linear components were not significant. The quadratic components reflect the lower error rates achieved in Block 2 than in either Blocks 1 or 3. The results of *t* tests confirmed that in Block 2, errors were significantly fewer than in Block 1, $t(23) = 7.58$, $p < .001$, $MSE = 5.48$, and that in Block 2, errors were significantly fewer than in Block 3, $t(23) = 10.74$, $p < .001$, $MSE = 2.07$.

Due to the fact that only the parity decision stimuli do not share properties with the bivalent stimuli, a focused analysis was carried out on this task only. For the response-time data, a significant main effect of block was observed, $F(1, 23) = 4.15$, $p < .03$, $MSE = 5239.20$, and *t* tests resulted in significant differences between Block 1 and Block 2, $t(23) = 1.86$, $p < .05$, $MSE = 6793.50$, and Block 3 and Block 2, $t(23) = 2.75$, $p < .01$, $MSE = 5241.50$. The same analysis carried out on error data resulted in a significant main effect of block, $F(1, 23) = 34.85$, $p < .001$, $MSE = 7.20$, and *t* tests resulted in significant differences between Block 1 and Block 2, $t(23) = 6.93$, $p < .001$, $MSE = 9.30$, and Block 3 and Block 2, $t(23) = 9.02$, $p < .001$, $MSE = 3.56$.

Discussion

The main objective of the present study was to investigate how performance on tasks involving univalent stimuli is affected by the addition of a small number of tasks with bivalent stimuli. The response data on the univalent tasks revealed three relevant findings. First, subjects were slower to respond on tasks with univalent stimuli when they occurred in a series of trials containing a small number of bivalent stimuli (i.e., in Block 2 of the experiment). Second, subjects' responses were slower on all univalent stimuli, highlighting that performance was not influenced by whether or not the univalent stimuli had any properties in common with the bivalent stimuli. Third, the error data showed the same pattern of influence as the response-time data. Specifically, the insertion of a small number of bivalent stimuli into a large series of trials with mostly univalent stimuli produced a decrease in errors on the parity-decision task and on the color-naming task.

Although our study is the first to highlight bivalency costs, this outcome replicates and extends the results of previous investigations. For example, in a task-switching paradigm, Rogers and Monsell (1995; see neutral condition of Experiment 1) found slower responses to univalent stimuli that appeared intermixed with bivalent stimuli. Slower responding also has been observed under task repetition conditions when a series of tasks contained a few switch trials with bivalent stimuli (see De Jong, 2000, Experiment 2; Fagot, 1994, Experiments 3 and 4; Kray & Lindenberger, 2000; Mayr, 2001, Experiment 2).[3]

The finding of a bivalency cost on all three tasks we used in the present experiment is a challenge for the theoretical accounts that have dominated previous investigations in this area (e.g., Allport & Wylie, 2000; Monsell et al., 2000). The task-cueing account is consistent with the finding of slower responses on the case-decision task in Block 2 of our experiment, but it fails to explain the slowing of responding on either the parity-decision task or the color-naming task. Similarly, the negative priming view is consistent with the finding of slower responses on the color-naming task in Block 2 of our experiment, but it gives no insight into the slowing of responses on the parity-decision task. Moreover, neither of these accounts illuminates the pattern of errors that occurred on the parity-decision task or on the color-naming task.

The response speed and error data raise another possible interpretation, namely that in Block 2 of our experiment subjects adjusted their criterion and opted for a more cautious response style. This gene-

[3] The confounding of bivalency costs with switch costs proper should be minimal for the AABB design of Rogers and Monsell (1995). This is because the repetition control conditions (A**A**B**B**) are couched within bivalent task switching trials (**AAB**B); therefore, the bivalency effect may exert relatively equal influence on both the switching and repetition trials, and would therefore be cancelled out when switch costs are computed.

ral notion has previously been suggested to explain "mixing costs"; that is, performance changes on repeated tasks when a mixture of different stimulus types rather than only one type was used (e.g., 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 where the need for task scheduling has been assumed to elicit either a daring or cautious style of responding (e.g., Schumacher et al., 2001). If subjects behaved more cautiously in Block 2 of our experiment, this would have produced the speed-accuracy trade-off that we observed; that is, slower responses and a decrease in the error rate (see data in Table 1). Gopher and colleagues (Gopher, Armony, & Greenshpan, 2000) have observed that instruction-based control requirements (e.g., focus on accuracy vs. focus on speed) lead participants to develop a response style that influences all switch trials, irrespective of their specific attributes. It is feasible that encountering bivalent stimuli invokes an accuracy-oriented response style similar to that induced by instructional manipulations.

Our study was not designed to investigate the extent to which bivalency costs are under the influence of the perceptual and cognitive processes that are featured by the task cueing, negative priming, or response-style accounts. Instead, our goal was to demonstrate that processes that are initiated and guided by stimuli or by their properties are not sufficient to explain the performance costs associated with the introduction of a few tasks with bivalent stimuli. The results show that this situation recruits endogenous factors; that is, processes that are initiated and guided from the top down.

These preliminary results cannot rule out other interpretations of the data. For example, task order was not manipulated, and the task on which bivalent stimuli occurred was not manipulated. Therefore, some as of yet unknown interactions may be present. In particular, the three tasks varied in difficulty, and level of difficulty appears to interact with switching costs such as negative priming (Allport et al., 1994; Allport & Wylie, 2000), so could also conceivably interact with the magnitude of the bivalency cost.

The present research was not intended as the final word on bivalency costs. Instead, we were motivated by a more modest goal: to document the need for considering endogenous factors that influence generalized performance under task alternation conditions. We hope that our work will provoke future investigations in this area, especially research focused on top-down influences on task switching performance as well as on the interplay between endogenous and exogenous factors.

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