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Objects and Events as Determinants of Parallel Processing in Dual Tasks: Evidence From the Backward Compatibility Effect

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The backward-compatibility effect (BCE) is a major index of parallel processing in dual tasks and is related to the dependency of Task 1 performance on Task 2 response codes (Hommel, 1998). The results of four dual-task experiments showed that a BCE occurs when the stimuli of both tasks are included in the same visual object (Experiments 1 and 2) or belong to the same perceptual event (Experiments 3 and 4). Thus, the BCE may be modulated by factors that influence whether both task stimuli are included in the same perceptual event (objects, as studied in cognitive experiments, being special cases of events). As with objects, drawing attention to a (selected) event results in the processing of its irrelevant features and may interfere with task execution.

Keywords: dual task, parallel processing, event perception, attention, Gestalt

When a person tries to perform two choice-response tasks at nearly the same time, responses to one or both tasks are delayed and less accurate. A common method to study dual-task performance is to present stimuli for two tasks (S1 and S2) in rapid succession, requiring rapid responses to each stimulus (R1 and R2, respectively). In most cases, Task 1 responses are affected little, if at all, by the interval between the onsets of S1 and S2, an interval termed the stimulus-onset asynchrony (SOA). In contrast, Task 2 responses are slower at shorter SOAs than at longer SOAs. The observed slowing of Task 2 responses as SOA decreases is known as the psychological refractory period, or PRP, effect (Meyer & Kieras, 1997; Pashler, 1994; Pashler & Johnston, 1989; Telford, 1931; Welford, 1952, 1959). Several theories and models have been proposed to account for this PRP effect (Byrne & Anderson, 2001; Logan & Gordon, 2001; Meyer & Kieras, 1997; Navon & Miller, 2002; Tombu & Jolicœur 2003). Perhaps the most influential model of PRP is the response-selection bottleneck (RSB) theory suggested by Pashler and his colleagues (Pashler, 1994; Pashler & Johnston, 1989). According to this theory, noncentral processing stages can be performed in parallel without interference between the tasks (e.g., peripheral perceptual and motor processes), but a central-processing stage—responsible for the translation of the stimulus into a relevant response (S-R translation)—cannot occur simultaneously in two tasks because of structural limitations, thus acting as a bottleneck.

Several recent studies have challenged the RSB theory (e.g., Caessens, Hommel, Reynvoet, & van der Goten, 2004; Hommel, 1998; Hommel & Eglau, 2002; Lien & Proctor, 2000; Logan & Delheimer, 2001; Logan & Gordon, 2001; Logan & Schulkind, 2000). These studies have provided evidence of parallel S-R translation, which is called the backward compatibility effect (BCE). For example, Hommel (1998, Experiment 1) presented a single-letter stimulus in each trial that was either an H or S colored green or red. Task 1 was to press a left or right key according to the color of the letter, and Task 2 was to say the words "left" or "right" based on the identity of the letter. R1 was quicker and more accurate when the appropriate responses for R1 and R2 were compatible (e.g., pressing the right key and then saying the word "right") rather than incompatible (e.g., pressing the right key and then saying the word "left"). In Experiments 2 through 4 of Hommel's study, the compatibility was between S1 (stimulus color) and R2 (color-naming response). Task 1 was to press a left or right key according to the color of the letter, and Task 2 was to say the words "red" or "green" based on identity of the letter. Again, R1 was quicker and more accurate when S1 and R2 were compatible (e.g., S1 was red and R2 was saying "red") rather than incompatible (e.g., S1 was red and R2 was saying "green"). This BCE decreased as SOA increased (Experiment 3); it even occurred when R2 was not performed in close temporal proximity to R1 (Experiment 4) and on trials when no R2 needed to be performed (Experiment 5; see also Hommel & Eglau, 2002, Experiment 3). These findings suggest that the BCE is an automatic process (Hommel, 1998; Lien & Proctor, 2000).

To reconcile the BCE phenomenon with the RSB theory (Pashler, 1994), Hommel (1998) suggested that S-R translation is effectively composed of two distinct processes: response activation and response selection (the decision about which response to make among a set of activated responses; see also Hübner & Druey, 2006). According to this model, response activation for both tasks begins automatically and proceeds in parallel, but response selection is made serially (see also Schubert, Fischer, & Stelzel, 2008). Thus, Task 2 responses are activated concurrently with Task 1 responses, producing the BCE.

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Conditions Promoting Serial Versus Parallel Processing

There is wide agreement that the BCE indicates some degree of parallel task processing. Because a BCE does not always occur (see below), it provides an invaluable window to the conditions under which processing becomes serial rather than parallel. In the present work, we focused on the boundary conditions for the BCE and attempted to identify the general conditions that promote parallel versus serial processing.

Currently, there are three suggested boundary conditions for the BCE. According to Hommel (1998), the temporal overlap between Task 1 and Task 2 modulates the BCE because a greater temporal overlap increases the likelihood that automatically activated R2 codes will influence R1 response selection. This theory is supported by BCE reduction at long SOAs, but it may be incomplete because the BCE was absent even at the maximum temporal overlap (SOA = 0 ms), which occurred when participants had to switch between tasks in Logan and Schulkind's (2000) and Logan and Gordon's (2001) experiments.

Logan and Schulkind (2000) suggested a second boundary condition in their study of the BCE. In Experiment 2, participants were presented with two digits with varying SOAs and were asked to perform either the same task for each digit (two successive magnitude judgments or two successive parity judgments) or different tasks (magnitude judgment on one digit and parity judgment on the other digit). Their results showed that R1 was affected by the compatibility relationship between Task 1 and Task 2 when the task sets applied to both digits (there was a task repetition) but not when different task sets were applied in S1 and S2 (there was a task switch between Task 1 and Task 2). Correspondingly, Hübner and Druey (2008) only observed the BCE in task-repetition blocks, and Luria and Meiran (2005) showed more parallel processing in the PRP paradigm with task repetitions than with task switches. Accordingly, Logan and colleagues (Logan & Delheimer, 2001; Logan & Gordon, 2001; Logan & Schulkind, 2000) argued that the BCE is restricted to situations in which the same task set is applied in both S1 and S2. Logan and Gordon (2001) presented a quantitative model that explains the BCE results. This model assumes that, when a task repetition occurs, the same response categorizations serve both Task 1 and Task 2; therefore, Task 2 stimuli can activate the response categorizations of Task 1. In contrast with Logan's argument, however, the experiments of Hommel and others (e.g., Caessens et al., 2004; Ellenbogen & Meiran, 2008) found the BCE even when the participants had to switch between tasks (i.e., the categorizations were no longer shared). Hübner and Druey (2006, Experiment 1) used the same magnitude and parity judgments employed by Logan and Shulkind (2000) and observed a small BCE that did not interact with task switching. These considerations suggest that task repetition may determine parallel processing in some situations, but it may be an insufficient condition in other situations.

Finally, according to Ellenbogen and Meiran (2008), the BCE is modulated by working memory (WM) load. When WM capacity is available, the mapping rules for both tasks are simultaneously held in WM. These rules map categorizations (such as "colors related to green") to responses (key presses). Once placed in WM, the rules operate reflexively, like a prepared reflex (Cohen-Kdoshay & Meiran, 2007, 2009; Hommel, 2000; Woodworth, 1938), and generate the response codes. When WM capacity is exhausted by Task 1 rules, Task 2 rules cannot be held in WM while Task 1 is executed, and Task 2 response codes cannot be generated in parallel with Task 1 processing.

A Hypothesis Concerning a Fourth Boundary Condition

Despite their differences, both Hommel (1998) and Logan and Gordon (2001) assume that the BCE requires S1 and S2 information to be attended at the same time or within the same time window. We use the term "attention" to denote the selection for processing of a stimulus designed as a target according to task demands. As will be seen, this simple, undisputed and rather intuitive principle leads to some quite surprising predictions and results.

In Hommel's (1998) theory, simultaneous attention to S1 and S2 would increase the chances that Task 2 codes would overlap in time with Task 1 performance. In Logan and Gordon's (2001) theory, a feature-catch parameter determines how much the stimulus is present in the attentional window ("caught" in the sample of features, using their terms). In their simulations, it was assumed that both S1 and S2 are present inside the attentional window. Thus, the task-repetition boundary was determined based on the fact that both stimuli were attended; however, the role of including the stimuli in the same attentional window was not examined, only assumed.

To examine the above-mentioned principle, we conducted four dual-task experiments. In Experiments 1 and 2, we manipulated factors that were likely to influence the inclusion of S1 and S2 in the same visual object as defined by Gestalt principles of spatial proximity and common region. In both experiments, S1 and S2 were presented simultaneously. Experiment 3 examined whether this experimental design feature, namely the simultaneous presentation of S1 and S2, is critical. The results of this experiment suggest that simultaneous presentation is not critical. One way to interpret the results of this experiment is that S1 and S2 must belong to the same perceptual event. In Experiment 4, we provided converging evidence for this interpretation by manipulating a variable shown to affect event segmentation: goal sharing.

Before detailing our exact predictions, we should briefly mention a methodological consideration that guided us in the design of our experiments. One of the problems with the PRP procedure is that participants sometimes seem to engage in the strategy of response grouping (see Borger, 1963; De Jong, 1993; Knight & Kantowitz, 1976; Ruthruff, Pashler, & Hazeltine, 2003; Ruthruff, Pashler, & Klaassen, 2001). On trials with response grouping, participants select R1 but hold it in waiting until R2 has been selected and is ready to be initiated; the participants then perform R1 and R2 simultaneously. This strategy is more likely to be adopted when R1 and R2 both require manual responses because motor control is easier when two responses are emitted simultaneously rather than in close temporal succession (e.g., Rinkenauer, Urlich, & Wing, 2001).

The fact that the BCE did not interact with the interresponse interval (IRI) could be used to demonstrate that the BCE was not caused by a subset of trials in which R1 was delayed until Task 2 (Lien & Proctor, 2000). However, we did not want to rely too heavily on this logic and thus wanted to minimize the possibility of response grouping. For this reason, Task 1 and Task 2 did not share output modality and, as in most PRP experiments, we asked participants to respond to Task 1 as soon as it was selected without withholding the response (see Creamer, 1963; Wenke & Frensch, 2005). Although it is well known that dual-task interference still occurs with equal-task emphasis (Ruthruf et al., 2003), it was critical to ensure a uniform task order in our experiments. Finally, we also excluded trials with a short IRI from the core analyses because they seemed to indicate grouping. Unlike most previous investigators who excluded trials with IRI <100 ms, we were especially cautious and excluded trials with IRI <120 ms. This exclusion did not change the pattern of results, as will be seen below.

Experiment 1

The Gestalt psychologists argued that the perception of objects is based on grouping processes sensitive to factors such as the proximity of visual elements (Wertheimer, 1923/1950). Moreover, it is widely agreed that Gestalt principles operate at the early stages of visual perception, possibly preattentively (but see e.g., Ben-Av, Sagi, & Braun, 1992; Mack, Tang, Tuma, Kahn, & Rock, 1992; Moore & Egeth, 1997), to form objects that then attract attention (e.g., Dodd & Pratt, 2005; Duncan, 1984; Duncan & Humphreys, 1989; Kahneman & Henik, 1981; Kimchi, Yeshurun, & Cohen-Savransky, 2007; Treisman, 1986; see Scholl, 2001, for review).

There is an important cost associated with paying attention to objects. It has been argued that, when objects attract attention, their task-irrelevant features are automatically processed. This processing leads to enhanced interference from these irrelevant elements when they come from the same object or from the same element group (e.g., Driver & Baylis, 1989; Kahneman & Henik, 1981; Kramer & Jacobson, 1991; Lamers & Roelofs, 2007; Prinzmetal & Banks, 1977; see Remington & Folk, 2001, as well as the related controversy, e.g., Chen & Cave, 2006). In addition, when an object such as a word is ignored and only a subpart of it (a letter) is attended, the object itself can effectively be ignored. For example, if participants pay attention to the color in which a letter is written, they can effectively ignore the word that includes the letter (e.g., Besner, Stoltz, & Boutilier, 1997).

Based on the accounts of the BCE presented above, we gathered that conditions that make it difficult to ignore irrelevant information in tasks like the Stroop (1935) task are also likely to promote a BCE. (In the Stroop task, participants are asked to name the ink in which color words are written and are asked to ignore the words). When executing Task 1 in a dual-task paradigm, S2 represents irrelevant information that should be ignored; however, if S2 is presented in a manner that makes it difficult to ignore, the chances that it might influence Task 1 performance (and generate a BCE) increase. Accordingly, we suggest that, if S2 is included in the same object or the same group of objects as S1, the BCE will be enhanced relative to conditions in which S1 and S2 come from different objects or grouped elements.

In the grouped (or "object") condition of this experiment, a colored letter was presented and participants reported the color (Task 1) and the identity (Task 2) of a red or green H or X. In the less-grouped (or "separate objects") condition, a colored rectangle (red or green, S1) was presented simultaneously with a white letter (an H or an X, S2; Figure 1). This manipulation explicitly con-

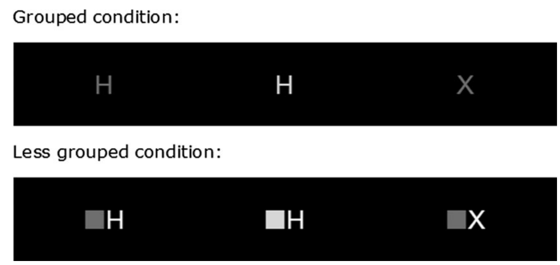

Figure 1. Stimulus displays in Experiment 1.

founded location-based (e.g., Posner, 1980) and object-based attention, as well as the integral nature of the stimuli. These confounds will be addressed in the next experiment.

Both groups made manual responses (R1), pressing keys with their left and right hands in response to the color task (Task 1), and made vocal responses (R2), saying the Hebrew words for "left" and "right" in response to letter identity (Task 2). R1 and R2 were compatible when both responses included the same response code (pressing the right key and saying "right" or pressing the left key and saying "left") and were incompatible when each response included a different response code (pressing the right key and saying "left" or pressing the left key and saying "right"). We predicted quicker and more accurate Task 1 responses in the compatible condition relative to the incompatible condition (indicating the BCE). This BCE was predicted to be larger in the grouped condition relative to the less-grouped condition.

Fagot and Pashler (1992, Experiments 1–3) asked participants to respond to two dimensions of the same object. Their results indicate a PRP effect typical in these conditions, suggesting serial processing of the object's two dimensions. A comparison between single object and two-object conditions (Fagot & Pashler, 1992, Experiment 2) yielded very similar SOA functions for RT2. The only difference between the conditions was observed with relatively long SOAs, which produced slower RTs in the single-object condition. The authors argued that this difference could not stem from response selection. However, they did not examine the BCE.

Because Task 1 and Task 2 involved different perceptual dimensions in the present experiment, and because Fagot and Pashler (1992) did not observe response grouping under these conditions, we did not expect grouping of R1 and R2—even in the grouped condition. However, we still tested whether grouping occurred. If response grouping occurred instead of stimulus grouping, the IRI should be shorter in the grouped condition than in the less-grouped condition.

Method

Participants. Forty undergraduate students from Ben-Gurion University of the Negev participated in this experiment in return for course credit. The participants reported having normal or corrected to normal vision. They were assigned to one of the two grouping conditions according to the order in which they entered the experiment.

Apparatus and stimuli. The stimuli were presented using a desktop computer with a 17" monitor controlled by software written in E-Prime (Schneider, Eschman, & Zuccolotto, 2002). A white asterisk served as a fixation mark. In the less-grouped condition, stimuli for Task 1 were red or green squares (S1) and stimuli for Task 2 were the uppercase letters H and X (S2) presented in white color. In the grouped condition, stimuli for both tasks were the uppercase letters H and X (S2), presented in red or green color (S1). All stimuli were presented at the center of a black screen. From a viewing distance of about 60 cm stimuli were 0.67° (width) × 0.67° (height) of the visual angle. In the less-grouped condition S2 was presented 0.09° on the right side of S1. The characters were presented in Arial font in bold.

Design and procedure. The experiment consisted of a single session, made of one practice block and four experimental blocks. Each block was composed of five replications of each of the four combinations of letter identity and color, randomly intermixed (2 colors × 2 letters). That is, there were 80 experimental trials for each group.

The procedure for any given trial was as follows. After an inter-trial interval of 1 sec, the fixation mark appeared for 1 sec followed by a blank interval of 250 ms. Then, the targets, a colored letter in the grouped condition or a colored square with a white letter in the less-grouped condition, were presented until both responses were given or until 2,500 ms had elapsed. For both groups, manual responses to color (S1) were performed by pressing the *a* (left) and *l* (right) keys of a QWERTY keyboard with index fingers of both hands (R1) and vocal responses to letter identity (S2) consisted of saying the words "smol" and "yamin," the Hebrew words for "left" and "right," respectively (R2). A microphone collected the vocal responses for reaction time (RT) and the experimenter who sat behind the participant entered the correctness scoring of these responses during the intertrial interval. Participants of both groups were required to perform the two responses in strict serial order (respond to S1 and then to S2) as quickly as possible while maintaining high accuracy. Errors were followed by the feedback of a beep consisting of a 400 Hz tone presented for 50 ms.

Results and Discussion

Premature Task 1 responses (RT1 $<$ 100 ms, 0.002%), R1 and/or R2 error trials (0.05%) and trials with potential response grouping (IRI $<$ 120 ms, 16.99%) were excluded from data analyses. Responses that reversed the instructed order (e.g., responding vocally to S2 and then manually to S1) were excluded from the RT analyses and considered errors (0.031%). Mean RT and the Proportion of Errors (PE) for this experiment are presented in Figure 2.

Task 1 RT. The analysis of variance (ANOVA) on RT1 yielded a significant main effect of Compatibility, $F(1, 38) = 30.90$, $p < .0001$, $MSE = 4{,}835.22$. Responses were slower when the relationship between R1 and R1 was incompatible (830 ms) rather than compatible (743 ms), indicating a BCE. More importantly, the Grouping × Compatibility interaction was significant, $F(1, 38) = 5.66$, $p < .03$, $MSE = 4{,}835.22$. Planned comparisons showed a significant simple BCE of 124 ms in the grouped condition, $F(1, 38) = 31.51$, $p < .0001$, and a significant simple BCE of 50 ms in the less-grouped condition, $F(1, 38) = 5.05$, $p < .03$, both *MSE*s = 4,835.22.

Task 1 PE. The ANOVA on PE1 yielded a similar pattern: A significant main effect of Compatibility, $F(1, 38) = 13.50$, $p < .001$, and a significant Grouping × Compatibility interaction, $F(1, 38) = 4.65$, $p < .03$, both *MSE*s = 0.0007. Responses were less accurate when the relationship between R1 and R2 was incompatible rather than compatible. Planned comparisons showed a significant simple BCE in the grouped condition, $F(1, 38) = 17.00$, $p < .0005$, and a nonsignificant simple BCE in the less-grouped condition, $F(1, 38) = 1.15$, $p = .29$, both *MSE*s = 0.0007.

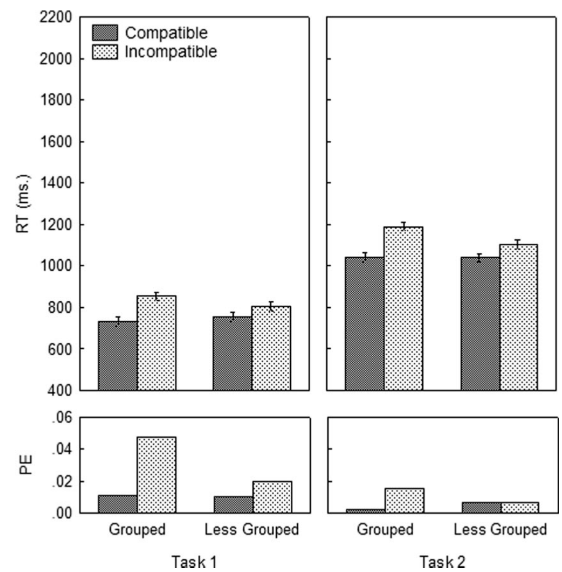

Figure 2. Reaction times (RT, ms) and proportion of errors (PE) for Tasks 1 and Task 2 according to compatibility and grouping, Experiment 1. Error bars indicate a 95% confidence interval computed for the contrast examining the compatibility effect.

Task 2 RT. The ANOVA on RT2 yielded a significant main effect of Compatibility, $F(1, 38) = 32.00$, $p < .0001$, $MSE = 7{,}242.33$. Responses were slower when the relationship between R1 and R2 was incompatible (1,147 ms) rather than compatible (1,039 ms), indicating a compatibility profile similar to the BCE on RT1. The Grouping × Compatibility interaction was also significant, $F(1, 36) = 4.90$, $p < .03$, $MSE = 7{,}242.33$. Planned comparisons showed a significant simple Compatibility effect of 150 ms in the grouped condition, $F(1, 38) = 30.97$, $p < .0001$, and a significant simple Compatibility effect of 66 ms in the less-grouped condition, $F(1, 38) = 5.92$, $p < .02$, both *MSE*s = 7,242.33.

Task 2 PE. The ANOVA on PE2 yielded a similar pattern: A significant main effect of Compatibility, $F(1, 38) = 15.91$, $p < .0003$, and a significant Grouping × Compatibility interaction, $F(1, 38) = 15.91$, $p < .0003$, both *MSE*s = 0.00006. Responses were less accurate when the relationship between R1 and R2 was incompatible rather than compatible. Planned comparisons showed a significant simple Compatibility effect in the grouped condition, $F(1, 38) = 31.82$, $p < .0001$, $MSE = 0.00006$, and a nonsignificant simple Compatibility effect in the less-grouped condition ($F < 1$).

IRI analyses. Trials with IRI $<$ 120 ms were additionally included in this analysis. The mean IRI was 325 ms in the grouped condition and 294 ms in the less-grouped condition. The ANOVA on IRI with Compatibility and Group as independent variables showed a significant main effect of Compatibility and a significant interaction between Compatibility and Group, $F(1, 38) = 10.51$, 13.73, $p < .003$, .0007, respectively, both *MSE*s = 635.15. The IRI was not shorter in the grouped condition relative to the less-grouped condition, as would be expected from a response-grouping account. In fact, the IRI in the grouped condition was non-significantly longer ($F < 1$). In addition, a comparison of the proportion of potential grouped-response trials (IRI < 120) showed that response grouping was more likely to occur in the less-grouped condition (5.69%) than in the grouped condition (4.80%). This result is contrary to what one would expect if our manipulation of task grouping resulted in response grouping or, alternately, stimulus grouping to one stimulus that required a one-response selection stage.

As we predicted, the BCE was larger when S1 and S2 came from the same object and spatial location relative to when they came from two objects and occupied two locations. Our result mirrors previous results that showed it is more difficult to ignore irrelevant information when it comes from the same object or location as the relevant information (e.g., Baylis & Driver, 1992; Hommel, 1995; Kahneman & Henik, 1981).

Experiment 2

We already noted that our grouping manipulation used in Experiment 1 confounded spatial attention and object attention. Specifically, when S1 and S2 came from the same object, participants could not focus their gaze to filter S2 information while executing Task 1 (see Bundesen, 1990, for a discussion of this strategy).

To determine the importance of grouping S1 and S2 in a single object, we changed our grouping manipulation to one based on the Gestalt principle of common region (Palmer, 1992; Palmer, Brooks, & Nelson, 2003). This manipulation allowed us to vary objecthood while keeping the spatial arrangement of S1 and S2 equivalent in the two grouping conditions. The common region was manipulated by including three stimuli and requiring participants to perform three tasks on these stimuli; however, we still focused on the first two stimuli and tasks. Specifically, the participants were asked to perform the same two tasks as Experiment 1 (color in Task 1 and letter identity in Task 2) with an additional task stimulus (fraction, S3). The three stimuli were presented as a colored rectangle, letter and fraction going from left to right, respectively. In detail, a colored rectangle (red or green, S1) was presented with a white letter (an H or an X, S2) and a fraction ([1/2] or [3/4], S3) simultaneously (Figure 3). The grouping of the colored rectangle and the letter (S1 and S2) was manipulated between participants according to the principle of common region. We either placed S1 and S2 inside a frame (grouped S1-S2 condition) or placed S2 and S3 inside a frame (less-grouped S1-S2 condition). The tasks and responses in Task 1 and Task 2 were the same as those used in Experiments 1 and 2. In Task 3, the participants were asked to press the space bar once or twice using both thumbs. We adopted this response mode in order to avoid using spatially defined responses, a feature that could have created compatibility with Tasks 1 and 2. As in the previous experiment, we predicted a larger BCE (from Task 2 to Task 1) in the grouped condition relative to the less-grouped condition.

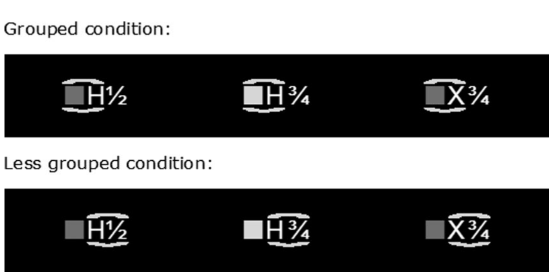

Figure 3. Stimulus displays in Experiment 2.

Method

Participants. Forty undergraduate students of similar characteristics to those in the previous experiment participated in this experiment. The participants were assigned to one of the two grouping conditions according to the order in which they entered the experiment.

Apparatus, stimuli, design, and procedure. S1 and S2 were the same as in Experiment 1, but there was also S3 which was a fraction ([1/2] or [3/4]). For this stimulus, participants were asked to press once for [1/2] or twice for [3/4] on the space key with both thumbs. From a viewing distance of about 60 cm, stimuli subtended a visual angle of 0.86° (height) × 0.86° (width) with distance of 0.09° between stimuli. The final modification was the inclusion of a frame made of two sky blue brackets of 1.72° (width) × 0.17° (thickness) that were presented above and below S1 and S2 (grouped) or S2 and S3 (less-grouped). Each block was composed of five replications of each of the six combinations of color, letter identity, and fraction, randomly intermixed (2 colors × 2 letters × 2 fractions). That is, there were 160 experimental trials for each group. Participants of both groups were required to respond to S1, then to S2, and then to S3.

Results and Discussion

Trials with premature Task 1 responses (RT1 < 100 ms, 0.002%) or incorrect R1, R2, or R3 (0.26%) were excluded from data analyses, as were trials with potential R1 and R2 response grouping (IRI < 120 ms, 14.27%). Responses made in the wrong order (0.01%) were considered incorrect responses. Mean RT and PE for this experiment are presented in Figure 4.

Task 1 RT. The ANOVA on RT1 yielded a significant main effect of Compatibility, $F(1, 38) = 23.59$, $p < .0001$, $MSE = 532.41$. Responses were slower when R1 and R2 were incompatible (895 ms) rather than compatible (870 ms), indicating a BCE. More importantly, the Grouping × Compatibility interaction was also significant, $F(1, 38) = 18.11$, $p < .0001$, $MSE = 532.41$. Planned comparisons showed a significant simple BCE of 47 ms in the grouped condition, $F(1, 38) = 41.54$, $p < .0001$, *MSE*s = 532.41 and a nonsignificant simple BCE of 3 ms in the less-grouped condition, $F < 1$.

Task 1 PE. The ANOVA on PE1 yielded a significant main effect of Compatibility, $F(1, 38) = 4.31$, $p < .04$, $MSE = 0.0001$). Responses were less accurate when the relationship between R1 and R2 was incompatible rather than compatible. The Grouping × Compatibility interaction was not significant, $F(1, 38) = 2.06$, $p <$ .15, $MSE = 0.00002$, but planned comparisons showed a significant simple BCE in the grouped condition, $F(1, 38) = 6.17$, $p <$ .001, $MSE = 0.00002$, and a non-significant simple BCE in the less-grouped condition, $F < 1$.

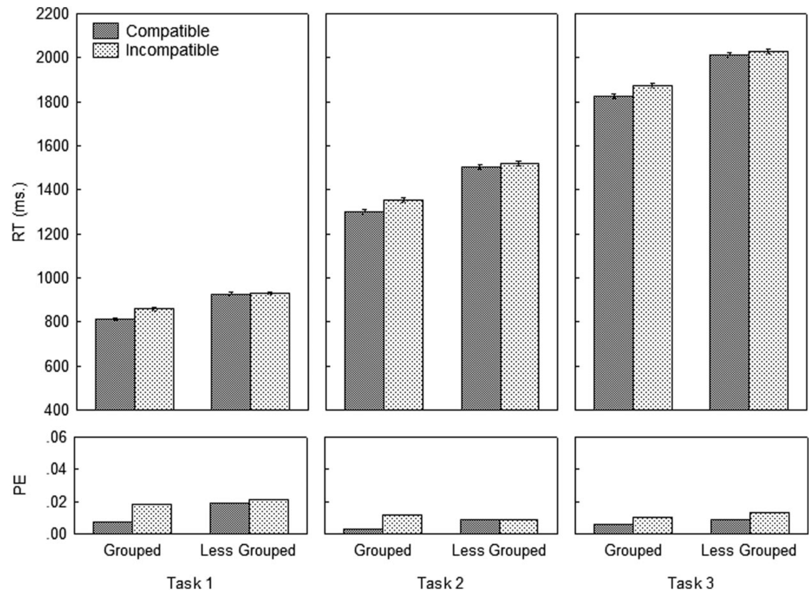

Figure 4. Reaction times (RTs, ms) and proportion of errors (PE) for Tasks 1, 2, and 3 according to compatibility and grouping, Experiment 2. Error bars indicate a 95% confidence interval computed for the contrast examining the compatibility effect.

Task 2 RT. The ANOVA on RT2 yielded a significant main effect of Compatibility, $F(1, 38) = 14.68$, $p < .0004$, $MSE = 1{,}464.70$. Responses were slower when R1 and R2 were incompatible (1,435 ms) rather than compatible (1,402 ms), a result similar to the BCE on RT1. More importantly, the Grouping × Compatibility interaction was significant, $F(1, 38) = 4.55$, $p < .04$, $MSE = 1{,}464.70$. Planned comparisons showed a significant simple Compatibility effect of 53 ms in the grouped condition, $F(1, 38) = 17.78$, $p < .0001$, and a non-significant simple Compatibility effect of 15 ms in the less-grouped condition, $F(1, 38) = 1.44$, $p < .24$, both MSEs = 1,464.70.

Task 2 PE. The ANOVA on PE2 yielded a significant main effect of Compatibility, $F(1, 38) = 4.25$, $p < .04$, $MSE = 0.0001$. Responses were less accurate when the relationship between R1 and R2 was incompatible rather than compatible. The Grouping × Compatibility interaction was also significant, $F(1, 38) = 4.25$, $p < .04$, $MSE = 0.0001$. Planned comparisons showed a significant simple Compatibility effect in the grouped condition, $F(1, 38) = 8.50$, $p < .006$, $MSE = 0.0001$, and a nonsignificant simple Compatibility effect in the less-grouped condition, $F < 1$.

Task 3 RT. The ANOVA on RT3 yielded a significant main effect of Compatibility, $F(1, 38) = 13.43$, $p < .0007$, and an almost significant Grouping × Compatibility interaction, $F(1, 38) = 3.81$, $p = .06$, both MSEs = 1,481.09. Responses were slower when R1 and R2 were incompatible (1,952 ms) rather than compatible (1,920 ms).

Task 3 PE. The ANOVA on PE3 yielded only a significant main effect of Compatibility, $F(1, 38) = 8.12$, $p < .01$. Responses were less accurate when R1 and R2 were incompatible rather than compatible.

IRI analysis. Trials with IRI < 120 ms were additionally included in this analysis. The mean IRI was 509 ms in the grouped condition and 588 ms in the less-grouped condition. The ANOVA on IRI with Compatibility and Group as independent variables yielded no significant effects.

As in Experiment 1, the BCE was larger when S1 and S2 were grouped. However, the BCE was generally smaller than in Experiment 1 and, unlike Experiment 1, the less-grouped condition produced a non-significant BCE. Experiment 3 addressed this issue in greater depth.

Experiment 3

In this experiment, we considered several explanations for the presence of the BCE in the less-grouped condition in Experiment 1 but not in Experiment 2. According to the first hypothesis, this discrepancy may be related to the higher WM load in Experiment 2 caused by the additional Task 3 rules (Ellenbogen & Meiran, 2008). However, this hypothesis is probably incorrect because the relevant comparison is between the less-grouped condition in Experiment 1 (BCE = 50 ms) and the grouped condition in Experiment 2 (BCE = 47 ms). When only two stimuli are presented adjacently, as in Experiment 1, they may be grouped according to the Gestalt principle of proximity. Because there were three objects in Experiment 2, there was little or no grouping of S1 and S2 (the less-grouped condition). The BCE data in conditions characterized by grouping suggests that WM load may not be the answer. Nonetheless, this analysis suggests the importance of grouping by proximity.

It is likely, however, that grouping according to proximity is insufficient and other conditions may also need to be met. We considered two additional conditions that may be grossly characterized as "bottom-up" on the one hand and "top-down" or strategic on the other hand. The bottom-up factors include temporal-code overlap (Hommel, 1998) and/or grouping according to the Gestalt principle of synchronicity (e.g., Fahle, 1993; Usher &

Donnelley, 1998; see Blake & Lee, 2005, for review). The latter possibility is supported by the literature on the Stroop effect, showing that grouping based on common fate determined the degree of interference caused by an irrelevant word stimulus in a color-naming task (Lamers & Roelofs, 2007). This point is emphasized by the fact that Lamers and Roelofs interpreted asynchronous presentation of stimuli as causing Gestalt breakage.

In contrast to the bottom-up factors, there were two strategic top-down processes that we considered. First, Miller, Ulrich, and Rolke's (2009) recent theory suggests that parallel processing in the dual-task paradigm reflects strategic resource allocation. Crucially, the theory states that participants choose to process stimuli in parallel when all or most of the SOAs are short. When S1 and S2 tend to arrive serially (SOA $>$ 0 ms), it makes little sense to divide the limited resources between the two tasks (letting the resources reserved for Task 2 be idle while Task 1 is executed) instead of allowing these resources to participate in Task 1 execution. This inefficient use of resources would not occur when S1 and S2 are presented simultaneously. Miller et al. supported their model using experiments that varied the proportion of short SOAs. Their indices of parallel processing were the PRP effect (shallow RT2-SOA slopes indicating parallel processing) and RT1 (relatively prolonged RT1 indicating parallel processing, see more below). However, they did not examine the BCE.

Another strategic account is related to the participants' ability to predict S2 onset correctly when the SOA is blocked. In the previous experiments, the SOA was 0 ms and, hence, S2 onset was perfectly predictable. If the SOA varies unpredictably between trials, S2 onset becomes much less predictable; unlike S2, SOA blocking does not influence the predictability of S1 because S1 comes after a constant inter-trial interval. The predictability of S2 may be important because S2 is processed relatively efficiently if it comes at a predictable time. This efficiency, in turn, leads to relatively strong influences from Task 2 onto Task 1. There is some evidence to support the role of S2 predictability in producing the BCE. Studies with two different stimuli and varied SOA have found no BCE even at short SOAs (e.g., Hübner & Druey, 2008; Lien, McCann, Ruthruff, & Proctor, 2005, Experiments 1–3) or have found a small BCE of about 10 ms only at short SOAs (Lien et al., 2005, Experiment 4; Lien, Ruthruff, Hsieh, & Yu, 2007). The BCE of 70 ms measured by Lien and Proctor (2000) in an exception. In contrast, the BCE is much more robust with a constant SOA of 0 ms (e.g., Ellenbogen & Meiran, 2008; Hommel, 1998; Hommel & Eglau, 2002) or with a constant SOA of 75 ms (Caessens et al., 2004).

In Experiment 3, we tried to distinguish between the bottom-up and the top-down accounts while holding proximity constant, thus ensuring that it does not come into play. In all the relevant conditions in this experiment, there were only two stimuli presented relatively close to one another. The participants in this experiment were asked to perform the same two tasks as the less-grouped condition of Experiment 1. In both groups, a colored rectangle (red or green, S1) was presented along with a white letter (an H or an X, S2). In this experiment, S1 and S2 were always presented simultaneously (SOA of 0 ms) in the grouped condition, as in the less-grouped condition of Experiment 1. In the less-grouped condition, S1 and S2 were separated by a variable SOA (0, 100, 300, and 900 ms). We were primarily interested in the results when SOA $=$ 0 ms, as this interval created a condition physically identical with the grouped condition, a similarity that makes it especially useful for investigating temporal code overlap and grouping based on synchronicity. The crucial difference between the groups was the proportion of SOA $=$ 0 ms, which was 1.00 in the grouped condition and .25 in the less-grouped condition. In order to make the conditions comparable, the number of trials with SOA $=$ 0 ms was the same in the two groups. The potential confound associated with the fact that there was more practice in the less-grouped condition is addressed below.

We reasoned that if the BCE depends on the formation of a Gestalt from S1 and S2 based on the principle of synchronicity or temporal code overlap, the BCE should be moderate and roughly equivalent to the less-grouped condition of Experiment 1. In addition, we predicted that the BCE would be equal in the two groups. However, if the critical factor is strategic in nature, associated with the effective division of processing resources between Task 1 and Task 2 and/or with the predictability of S2 onset, then the BCE should be larger in the grouped condition (constant SOA $=$ 0 ms) relative to the less-grouped condition (SOA $=$ 0 in the context of a variable SOA).

Method

Participants. Forty undergraduate students of similar characteristics to those in the previous experiments participated in this experiment. The participants were assigned to one of the two grouping conditions according to the order in which they entered the experiment.

Apparatus, stimuli, design, and procedure. These were the same as in the less-grouped condition of Experiments 1. In the grouped condition, S2 was presented simultaneously with S1 in each trial. In the less- grouped condition, S2 was presented simultaneously with S1 (SOA $=$ 0 ms) or 100, 300, or 900 ms after S1 onset. Each block was composed of five replications of each of the four or sixteen combinations of color, letter identity and SOA, randomly intermixed (2 colors $\times$ 2 letters, or 2 colors $\times$ 2 letters $\times$ 4 SOA, in the grouped and less-grouped condition, respectively). Thus, there were 80 or 320 experimental trials in the grouped and the less-grouped conditions, respectively, and therefore, 80 trials with SOA $=$ 0 ms in both conditions. Participants of both groups were required to respond to S1 and then to S2.

Results and Discussion

To ensure comparable conditions for the two groups, only the SOA $=$ 0 ms results from the less-grouped condition were included in the following analyses.

The premature Task 1 responses (RT1 $<$ 100 ms, 0.19%), R1 and/or R2 error trials (0.18%) and trials with potential response grouping (IRI $<$ 120 ms, 14.27%) were excluded from data analyses. Responses made in the incorrect order were excluded from the RT analyses and were considered errors (0.01%). Mean RT and PE for this experiment are presented in Figure 5.

Task 1 RT. The ANOVA on RT1 yielded two significant main effects: Grouping, $F(1, 38) = 24.70$, $p < .0001$, $MSE =$ 37,758.44, and Compatibility, $F(1, 38) = 36.47$, $p < .0001$, $MSE =$ 1,455.10. Responses were slower in the grouped condition (784 ms) than in the less-grouped condition (568 ms) and when the relationship between R1 and R2 was incompatible (701 ms) rather

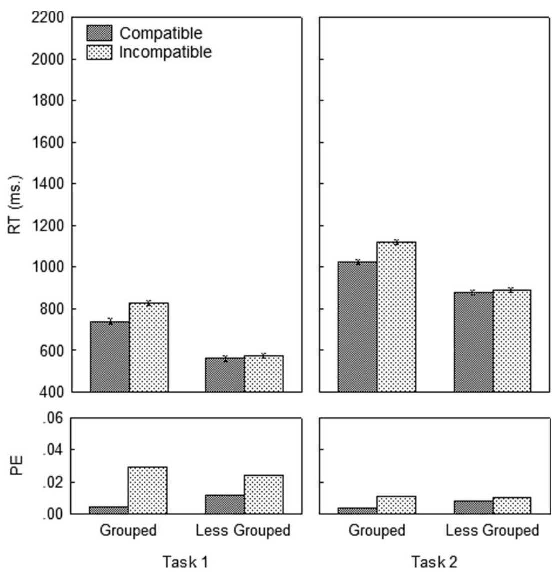

Figure 5. Reaction times (RTs, ms) and proportion of errors (PE) for Tasks 1 and Task 2 according to compatibility and grouping, Experiment 3. The data in the less grouped come only from trials with stimulus-onset asynchrony (SOA) of 0 ms. Error bars indicate a 95% confidence interval computed for the contrast examining the compatibility effect.

than compatible (650 ms). More importantly, the Grouping × Compatibility interaction was significant, $F(1, 38) = 18.89$, $p < .0001$, $MSE = 1{,}455.10$. Planned comparisons showed a significant simple BCE of 88 ms in the grouped condition, $F(1, 38) = 53.93$, $p < .0001$, and a non-significant simple BCE of 15 ms in the less-grouped condition, $F(1, 38) = 1.43$, $p = .24$, both *MSE*s = 1,455.10.

The lack of a BCE in the less-grouped condition may be caused by task practice, as there were more trials in the less-grouped condition. In order to rule out this possibility, we ran an additional analysis on the results of the less-grouped condition. In this analysis, we compared the BCE with SOA = 0 ms in the first quarter of trials to the BCE in all the trials in the grouped condition. The BCE in the less-grouped condition (first [1/4] of the trials) was actually reversed (−16 ms). This analysis clearly showed that the differential practice was not responsible for the difference between the conditions.

Task 1 PE. The ANOVA on PE1 yielded only a significant main effect of Compatibility, $F(1, 38) = 28.55$, $p < .0001$, and an almost significant Grouping × Compatibility interaction, $F(1, 38) = 3.52$, $p = .06$, both *MSE*s = 0.0002. The responses were less accurate when the relationship between R1 and R2 was incompatible rather than compatible. Planned comparisons showed a significant simple BCE in both grouping conditions, $F(1, 38) = 26.07, 6.01$, $p < .0001, .02$, respectively, both *MSE*s = 0.0002.

Task 2 RT. The ANOVA on RT2 yielded two significant main effects: Grouping, $F(1, 38) = 15.87$, $p < .0003$, $MSE = 44{,}789.41$, and Compatibility, $F(1, 38) = 21.52$, $p < .0001$, $MSE = 2{,}515.81$. Responses were slower in the grouped condition (1,072 ms) relative to the less- grouped condition (883 ms), and when the relationship between R1 and R2 was incompatible (1,004 ms) rather than compatible (952 ms). More importantly, the Grouping × Compatibility interaction was significant, $F(1, 38) = 13.43$, $p < .001$, $MSE = 2{,}515.81$. Planned comparisons showed a significant simple Compatibility effect of 93 ms in the grouped condition, $F(1, 38) = 34.47$, $p < .0001$, $MSE = 2{,}515.81$, and a non-significant simple Compatibility effect of 11 ms in the less-grouped condition, $F < 1$.

Task 2 PE. Similarly, the ANOVA on PE2 yielded a significant main effect of Compatibility, $F(1, 38) = 8.00$, $p < .007$, $MSE = 0.00006$. The responses were less accurate when the relationship between R1 and R2 was incompatible rather than compatible. The Grouping × Compatibility interaction was not significant, $F(1, 38) = 2.00$, $p = .16$, $MSE = 0.00006$, but planned comparisons showed a significant simple Compatibility effect in the grouped condition, $F(1, 38) = 9.00$, $p < .004$, $MSE = 0.00006$, and nonsignificant simple Compatibility effect in the less-grouped condition ($F = 1$).

Task 1 distributional analysis. The BCE is often increased with longer RTs (Ellenbogen & Meiran, 2008; Hommel, 1998), and in this experiment the BCE was absent in the less-grouped condition, which had quicker Task 1 RTs than the grouped condition. In order to show that the absent BCE in the less-grouped condition did not result from the quick RTs in this condition, we performed a Vincentizing procedure (Ratcliff, 1979) on RT1. For each participant and cell in the design, the 5th, 25th, 50th, 75th and 95th RT percentiles were computed. As can be seen in Figure 6, the BCE was absent in the less-grouped conditions for RTs that showed a BCE in the grouped condition (from 600 ms to 800 ms). Despite the comparable overall RTs, planned comparisons indicated a significant BCE in the medians of the grouped condition, $F(1, 38) = 24.62$, $p < .0001$, $MSE = 2{,}104.77$, but a nonsignificant BCE in the 75th percentile of RT in the less-grouped condition, $F(1, 38) = 1.32$, $p = .26$, $MSE = 4{,}472.07$. These results suggest that the quick RTs in the less-grouped condition were not responsible for the absent BCE.

SOA effects, Task 1, the less-grouped condition. Because SOA varied in the less-grouped condition, we could examine the presence of the usual PRP effect. The 2-way ANOVA on RT1 yielded only two significant main effects: SOA, $F(1, 19) = 5.42$, $p < .002$, $MSE = 3{,}507.62$, and Compatibility, $F(1, 19) = 8.54$, $p < .008$, $MSE = 715.36$. As can be seen in Figure 7, responses were 568, 548, 526, and 574 ms at SOA 0, 100, 300, and 900 ms,

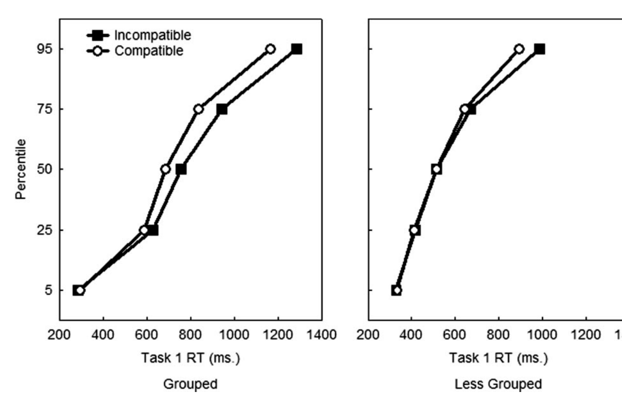

Figure 6. Mean reaction time1 (RT1) percentiles according to compatibility and grouping: Experiment 3.

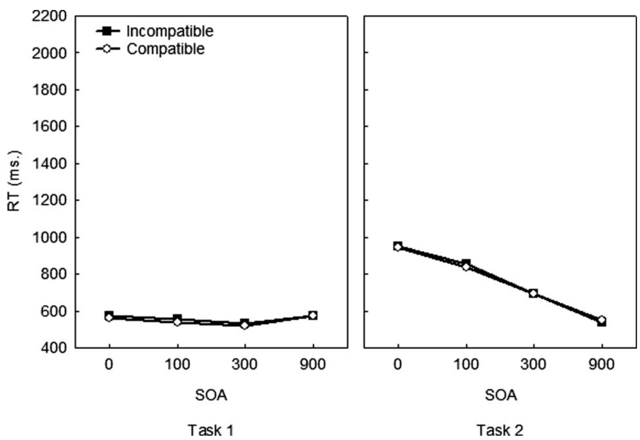

Figure 7. Mean reaction time (RT) in the less-grouped condition: Experiment 3, according to task, compatibility, and stimulus-onset asynchrony (SOA).

respectively, and they were slower when the relationship between R1 and R2 was incompatible (560 ms) rather than compatible (548 ms). The Grouping × Compatibility interaction was not significant, $F(1, 19) = 1.65$, $p < .18$, $MSE = 514.22$, and planned comparisons showed a significant simple BCE (17 ms) when the SOA was 300 ms, $F(1, 19) = 9.505$, $p < .006$, $MSE = 287.45$, and non-significant effects when the SOA was 0, 100, and 900 ms, $F(1, 19) = 2.75$, $p = .11$, $MSE = 757.53$, $F(1, 19) = 4.24$, $p = .06$, $MSE = 904.21$, and F < 1, 15, 19 and 1 ms, respectively. These results indicate a non-monotonic and relatively small (albeit significant) SOA effect.

SOA effects, Task 2, the less-grouped condition. The ANOVA on RT2 yielded only a significant main effect of SOA, $F(1, 19) = 394.95$, $p < .0001$, $MSE = 3{,}269.11$. As can be seen in Figure 7, responses became quicker as SOA increased. RT2 was almost the same in the incompatible condition (759 ms) and the compatible condition (756 ms). The Grouping × Compatibility interaction was not significant, $F(1, 19) = 2.02$, $p = .12$, $MSE = 816.61$, and planned comparisons showed non-significant simple Compatibility effects at all the SOAs (Fs < 1). These results indicate a typical PRP effect. Because we could not perform a similar analysis on the other group, we cannot tell if the PRP effect was less robust in the grouped condition (as predicted for parallel response selection according to the RSB model).

IRI analysis. Trials with IRI < 120 ms were additionally included in this analysis. The mean IRI was 290 ms in the grouped condition and 316 ms in the less-grouped condition. The ANOVA on IRI with Compatibility and Group as independent variables on trials with SOA = 0 ms yielded no significant effects. The IRI was not significantly shorter in the grouped condition than in the less-grouped condition, $F(1, 38) = 1.36$, $p = .25$, $MSE = 9{,}147.77$.

The results of the present experiment do *not* favor the hypothesis that grouping by synchronicity or temporal code overlap played an important role in the BCE observed in our experiment. They also show that grouping by proximity is insufficient to produce a BCE. Despite the proximity and the synchronous presentation of stimuli, the BCE was not significant in the less-grouped condition of this experiment. So far, the results favor the strategic hypothesis, which is based on making efficient use of resources (Miller et al., 2009) and/or the temporal expectancy of S2.

Before proceeding, it is important to discuss a piece of evidence that could favor the resource-sharing interpretation: the slowed RT1 in the grouped condition. This slowing is predicted by capacity-sharing models (Navon & Miller, 2002; Tombu & Jolicœur 2003). According to these theories, if Task 2 is processed in parallel with Task 1, fewer resources are available for Task 1 and it is processed relatively slowly. However, this pattern was not found in Experiments 1 and 2 and the raw trend of means was actually reversed in Experiment 2. Thus, the resource-sharing account does not seem to provide a unitary account of our results.

To further examine this issue and characterize the type of expectancy involved, we ran an additional analysis that examined how the BCE in the less-grouped condition was influenced by the preceding SOA. Technically, the SOA = 0 ms condition was not strictly identical in the two groups because the trials were always preceded by trials with SOA = 0 ms when the SOA was blocked. In contrast, when the SOA varied randomly, only ¼ of the trials with SOA = 0 ms were preceded by trials with SOA = 0 ms. Thus, these new analyses enabled us to examine the BCE in trials that matched those in the blocked condition more closely: those trials with SOA = 0 ms that were preceded by SOA = 0 ms.

More substantially, this analysis permitted us to distinguish two accounts explained below. Both of these accounts assume that participants form "local" expectations based on the events of the preceding trial. Such expectations have been noted in studies focusing on relevant vs. irrelevant task dimensions (Gratton, Coles, & Donchin, 1992), the degree of conflict resolution required in task switching (Goschke, 2000, see also Brown, Reynolds, & Braver, 2007) and the anticipation of stimulus onset (Los & van den Heuvel, 2001, although on a different time scale than the SOAs that we used).

According to the first account, the critical factor in causing parallel processing is whether the SOA is predicted to be 0 ms. In such a case, participants would tend to employ parallel processing (Miller et al., 2009). Moreover, the SOA is predicted to be 0 ms if the preceding SOA was 0 ms, because of the local expectancy. According to the second account, parallel processing is enabled as more attention is devoted to S2, and that attention is partially related to S2 expectancy. Accordingly, if the SOA repeats the SOA from the preceding trial, S2 appears at a relatively expected time and is thus processed relatively efficiently. The crucial difference between the two accounts is therefore whether the BCE is found when *any* SOA repeats from the preceding trial or *only* when *a SOA = 0 ms* repeats from the previous trial.

We ran an ANOVA on RT1 using the independent variables SOA, Preceding SOA and Compatibility. The means for this analysis are presented in Figure 8. The results show a significant BCE of 50 ms when both the current SOA and the preceding SOA were 0 ms, $F(1, 19) = 8.59$, $p < .01$. Although there was a trend toward a BCE in some other combinations of SOA and Preceding SOA, this trend never reached statistical significance. The results of this analysis seem to favor the strategic account based on the extension of Miller et al.'s (2009) model. According to this account, participants expecting SOA to be 0 ms tend to favor parallel processing because of optimized resource allocation. However, as previously discussed, Miller et al.'s model fails to provide a

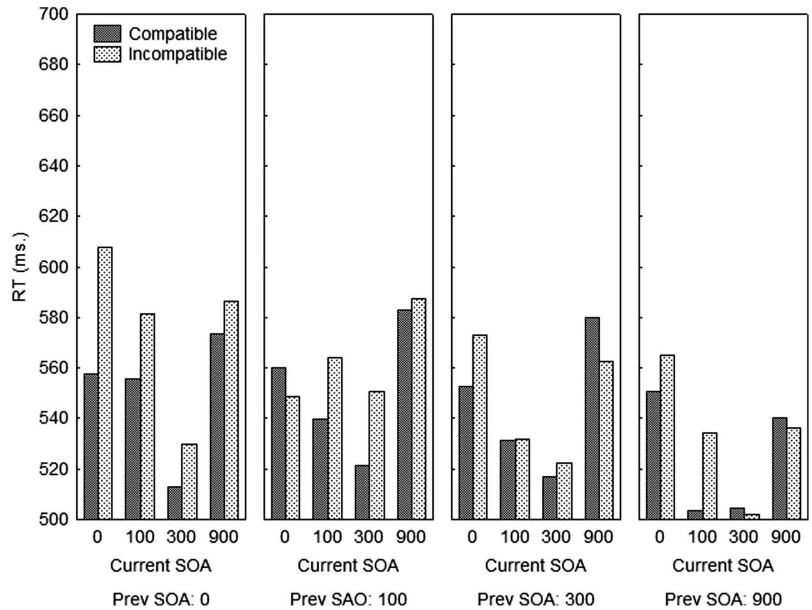

Figure 8. Reaction time (RT, ms) according to stimulus-onset asynchrony (SOA), Previous (=Prev.) SOA, and Compatibility for the less-grouped condition, Experiment 3.

unitary account of our results. Furthermore, a variant of the temporal overlap hypothesis could also account for our results if one assumes that both SOA expectancy and temporal overlap need to be present for a BCE to be observed. Thus, while the results of this analysis tended to support our extension of Miller et al.'s model, this extension fails elsewhere. We therefore considered another account of the results in Experiment 4.

Experiment 4

The account that we offer is based on the notion of spatial and temporal segmentation of incoming sensory information. Spatial perception depends on the segmentation of the visual scene into objects, while temporal perception segments time into events (Gepshtein & Kubovy, 2000; Zacks & Tversky, 2001; see also Cutting, 1981). More precisely, the temporal segmentation takes into account both events and objects but also adds a fourth dimension: time. In both spatial and temporal perception, a guiding principle is discontinuity. In space, it is easy to see how discontinuity is reflected, for example, in the Gestalt principles of grouping and common region. It appears that a similar principle governs events in time: the violation of continuity-based *expectancies* signal the end of one event and the beginning of the next (Zacks & Sargent, 2010). Thus, we suggest that a single principle may underlie the results of all the three experiments. This principle is that both S1 and S2 need to belong to the same perceptual event and that belonging to the same perceptual object (Experiments 1 and 2) is only a special case. Note that the term "object" is not a special case of the term "event." However, paying attention to objects without interruption, at least as studied in cognitive experiments, consists of an event. We hypothesize that, as with objects, drawing attention to a selected event results in the processing of its irrelevant features and causes S2 to interfere with Task 1.

According to the event-based account of Experiment 3, when the SOA was blocked and was 0 ms, participants needed to predict the onset of a single event which involved the presentation of both S1 and S2. Thus, S1 and S2 belonged in a single event. When the SOA varied, S1 and S2 tended to appear asynchronously and were thus probably treated as separate events. Moreover, there was another factor that distinguished the stimuli, and possibly caused the participants to treat them as belonging to separate events. It was the fact that, while S1 onset was predictable, S2 onset was not. Thus, in most of the trials, participants needed to predict S2 onset after S1 was presented. Experiment 4 was performed to provide support for the event-segmentation account by using a converging operation, described in the next paragraphs.

The attentional blink (AB) phenomenon may be taken as a performance-based marker for event segmentation in time (see especially Akyürek, Toffanin, & Hommel, 2008). The AB paradigm is a widely studied dual-task paradigm (see Olivers & Meeter, 2008; Visser, Bischof, & Di Lollo, 1999, for reviews). The paradigm involves rapid, serial, visual presentation of stimuli that are either targets (T1 and T2), such as digits, or distracters, such as letters. The participant's task is to report the identity of the targets after the serial presentation of stimuli ends. The AB phenomenon is related to decreased T2 detection when T2 follows T1 in close temporal succession, a decrease usually described in terms of lag. This decrement is described in terms of the mind's "blinking" and can therefore be regarded as an empirical marker of event segmentation (Akyürek et al.).

To provide converging evidence for the role of attention to events in the BCE, we chose a manipulation based on Hommel et al.'s (2006) suggestion that an attentional blink (and event segmentation) would *not* occur if the participant has not achieved the task goal after T1 and needs to await T2. Importantly, Hommel et al.'s idea fits well with the literature on event segmentation (see Zacks & Swallow, 2007, for review), which is largely based on subjective reports rather than performance. This literature suggests that events are occasionally defined in terms of goals such that goal completion signals the end of one event and the beginning of the next. Direct support for Hommel et al.'s hypothesis comes from both Ferlazzo, Lucido, Di Nocera, Fagioli, and Sdoia (2007) and Ferlazzo, Fagioli, Sdoia, and Di Nocera (2008). These authors showed that, when T1 and T2 served a common goal (participants were asked to report the sum of T1 and T2, which were digits), AB was reduced (there was less "blinking" and, we would argue, less segmentation) relative to when T1 and T2 served separate goals (report the identity of T1 and T2).

In this experiment, we used a manipulation analogous to the one used by Ferlazzo et al. (2008, 2007) while holding three variables constant to ensure they do not come into play. These variables included S2-onset predictability, the presence of three stimuli and tasks (as in Experiment 2), and the fact that S1 and S2 were *not* included in a common region. We reasoned that if the goal remains the same, there should not be event segmentation between S1 and S2, and these stimuli should belong to the same (perceived) and uninterrupted perceptual event.

In this experiment, participants in the ungrouped condition were told that they would have to make three responses to three stimuli (Figure 9). In each trial, a red or green square was displayed accompanied by a white digit on its right (S1 and S2, respectively). After making two responses (R1 and R2, respectively), these two stimuli were replaced by a digit (S3). Task 1 was to respond to a square (S1) according to color (red or green). Task 2 was to respond if the digit (S2) was greater or less than 5, and Task 3 was to add or subtract S3 (a digit) from S2 (also a digit), i.e., to calculate S2 + S3 or S2 − S3. To show which arithmetic operation to execute, addition or subtraction, a plus sign (+) or a minus sign (−) was displayed below S3. S2, but not S1, served as part of Task 3 in this condition. In contrast, participants in the grouped condition were told that they would have to perform a single task. They were told that, in each trial, a digit would be displayed and they would have to add it or subtract it from another digit. They were also told that the number would be accompanied by a colored square that would indicate whether the trial was an addition or subtraction trial. Furthermore, they were told that, in order to ensure that they perceived the cues correctly, they would have to respond as to whether the colored square was red or green and whether the digit was greater or less than 5. Responding to task cues has recently been incorporated into task-switching designs (Arrington, Logan, & Schneider, 2007). In both the grouped condition and the ungrouped condition, S1 (colored square) and S2 (digit) were the same except for their relatedness. In the ungrouped condition, S1 and S2 belonged to different task goals; however, in the grouped condition, S1 was the cue indicating how to treat S2. Moreover, the task executed on S3 was also the same in both conditions, and the slight perceptual difference between the conditions (the presentation of a "+" or "−" below S3) took place after R2, the last response and the one that was included in the core analyses (see below). Thus, apart from the perception of S1 and S2 as belonging or not belonging to the same goal, the conditions in the two groups were strictly comparable.

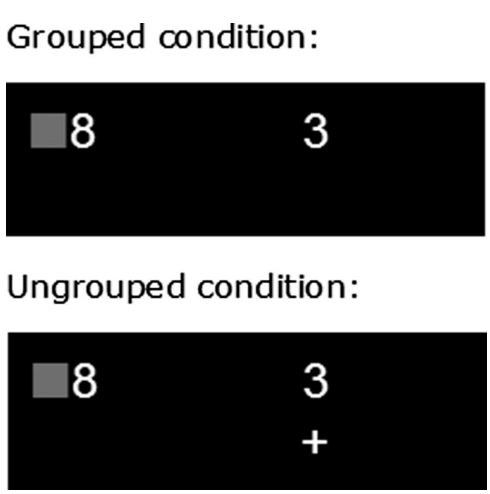

Figure 9. Stimulus displays used in Experiment 4.

To measure BCE, participants in both groups responded manually to S1 by pressing a right or left key on a keyboard, responded vocally to S2 by saying the words "right" and "left," and responded vocally to S3 by saying the result of S2 + S3 or S2–S3. In both conditions, R1 and R2 could thus be compatible (e.g., saying "right" and pressing the right key) or incompatible (e.g., saying "right" and pressing the left key). The BCE would be reflected in a quicker and more accurate R1 when R1 and R2 were compatible relative to when R1 and R2 were incompatible. We predicted that the BCE would be larger in the grouped condition than in the ungrouped condition. Note that we examined the BCE for Task 1 and Task 2 but not for Task 3 and Task 2. Because the BCE was computed for Task1 and Task 2, we took special care to make R1 and R2, as well as S1 and S2, identical in the two groups. S3 was slightly different in the two conditions, but this difference is less critical because Task 3 was unimportant for our question.

Method

Participants. Twenty undergraduate students similar to those who took part in the previous experiments took part in the experiment. They were assigned to one of the two grouping conditions according to the order in which they entered the experiment.

Apparatus and stimuli. A white asterisk served as a fixation mark. For both groups, the stimuli for Task 1 (S1) were the same as in the previous experiments. The stimuli for the second task (S2) were the digits 1, 2, 3, 4, 6, 7, 8, and 9 (5 excluded), presented in white color, and stimuli for the third task (S3) were the digits 1, 2, 3, 4, 5, 6, 7, 8, and 9, also presented in white color. In the ungrouped condition, S3 was accompanied by a plus sign (+) or a minus sign ([minus], also presented in white color. For both task grouping conditions, S2 was presented to the right of S1, while S3 was presented on a different slide which was presented only after the responses to both S1 and S2 were given. All the stimuli were presented on a black screen and the characters were presented in Arial font in bold. From a viewing distance of about 60 cm the stimuli occupied the visual angle of 0.67° (width) × 0.67° (height). The distance between S1 and S2 was 0.09°. In the ungrouped condition, in which S3 was composed of a number and either a plus or minus sign, the sign was presented 0.30° below the digit.

Design and procedure. The experiment consisted of a single session, comprising one practice block and five experimental blocks. Each block was composed of five replications of each of the 16 combinations of color and number, randomly intermixed (2 colors × 8 numbers). That is, there were 80 experimental trials for each group. Participants of both groups were required to respond to S1, then to S2, and then to S3.

The procedure for any given trial was as follows. After an intertrial interval of 1 s, the fixation mark appeared for 1 s followed by a blank interval of 250 ms, then, a colored square (S1) was presented with a number (S2) until both responses were made. After R1 and R2 were executed, another number (S3) was presented alone in the grouped condition, or with a plus or minus sign in the ungrouped condition, until a third response was made. Participants responded to S1 as in the preceding experiments. The response to S2 involved indicating if the digit was smaller or larger than 5 by saying the words "smol" and "yemin," respectively (left and right in Hebrew). R3 was vocal, saying the results of the addition or subtraction of S2 and S3 (R3).

Results and Discussion

Trials with premature responses (RT1 < 100 ms, 0.21%) or incorrect responses (1.44%) were excluded from data analysis, as well as trials with potential R1 and R2 response grouping (IRI < 120 ms, 6.10%). Responses made in the wrong order were considered incorrect responses (0.94%). Mean RT and PE for this experiment are presented in Figure 10.

Task 1 RT. The ANOVA on RT1 yielded a significant main effect of Compatibility, $F(1, 18) = 40.98$, $p < .0001$, $MSE = 901.62$. Responses were slower when R1 and R2 were incompatible (855 ms) rather than compatible (795 ms), indicating a BCE. More importantly, the Grouping × Compatibility interaction was significant, $F(1, 18) = 13.34$, $p < .002$, $MSE = 901.62$. Planned comparisons showed a significant simple BCE of 95 ms in the grouped condition, $F(1, 18) = 50.55$, $p < .0001$, and a non-significant simple BCE of 26 ms in the ungrouped condition, $F(1, 18) = 3.77$, $p = .07$, both *MSE*s = 901.62. Given the numerical size of the non-significant simple BCE in the ungrouped condition, we do not argue that the effect was absent; however, it was significantly smaller than the BCE in the grouped condition, as indicated by the significant interaction.

Task 1 PE. The ANOVA on PE1 yielded a significant main effect of Compatibility, indicating a BCE, $F(1, 18) = 4.44$, $p < .04$, and a significant Grouping × Compatibility interaction, $F(1, 18) = 12.93$, $p < .002$, both *MSE*s = 0.0001. Responses were less accurate when the relationship between R1 and R2 was incompatible rather than compatible. Planned comparisons showed a significant simple BCE in the grouped condition, $F(1, 18) = 16.27$, $p < .0008$, and a non-significant simple BCE in the ungrouped condition, $F(1, 18) = 1.107$, $p = .31$, both *MSE*s = 0.0001.

Task 2 RT. The ANOVA on RT2 yielded a significant main effect of Compatibility, $F(1, 18) = 55.15$, $p < .0001$, $MSE = 981.79$. Responses were slower when R1 and R2 were incompatible (1,278 ms) rather than compatible (1,204 ms), a pattern similar to the BCE on RT1. More importantly, the Grouping × Compatibility interaction was significant, $F(1, 18) = 15.16$, $p < .001$, $MSE = 981.79$. Planned comparisons showed a significant simple Compatibility effect of 112 ms in the grouped condition, $F(1, 18) = 64.07$, $p < .0001$,) and a simple Compatibility effect of 35 ms in the ungrouped condition, ($F(1, 18) = 6.23$, $p < .02$, both *MSE*s = 981.79.

Task 2 PE. The ANOVA on PE2 yielded a significant main effect of Compatibility, $F(1, 18) = 4.78$, $p < .04$, $MSE = 0.0001$. Responses were less accurate when the relationship between R1

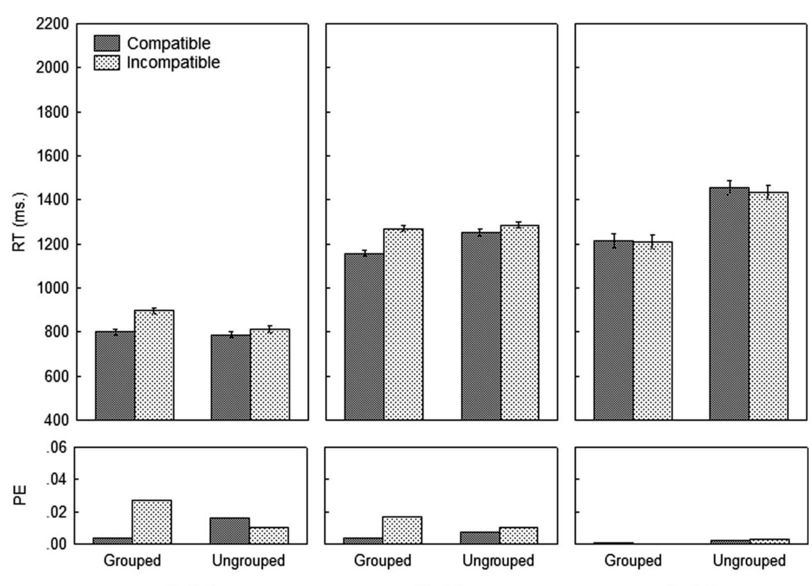

Figure 10. Mean reaction time (RT, ms) and proportion of errors (PE) according to task, compatibility, and grouping, Experiment 4. Error bars indicate a 95% confidence interval computed for the contrast examining the compatibility effect.

and R2 was incompatible rather than compatible. The Grouping × Compatibility interaction was not significant, $F(1, 18) = 1.87$, $p = .18$, $MSE = 0.0001$, but planned comparisons showed a significant simple Compatibility effect in the grouped condition, $F(1, 18) = 6.31$, $p < .02$, $MSE = 0.0001$, and a non-significant simple Compatibility effect in the ungrouped condition, $F < 1$.

Task 3 RT and PE. The ANOVA on RT3 and the ANOVA on PE3, both using Compatibility and Grouping as independent variables, did not reveal any significant effects.

IRI analysis. Trials with IRI < 120 ms were additionally included in this analysis. The mean IRI was 422 ms in the grouped condition and 410 ms in the less-grouped condition. The ANOVA on IRI with Compatibility and Group as independent variables yielded only a marginally significant effect of Compatibility, $F(1, 18) = 3.25$, $p = .09$, $MSE = 503.97$. The IRI tended increase in the incompatible condition as compared to the compatible condition. Importantly, this analysis does not suggest that response grouping mediated our effects.

As we expected, R1 was quicker and more accurate when R1 and R2 were compatible rather than incompatible, indicating a BCE. Importantly, this BCE was larger when S1 and S2 were directed toward a common goal. This result supports our hypothesis that variables influencing event segmentation, such as goal completion, also modulate the BCE. Both Logan and Schulkind (2000) and Logan and Gordon (2001) suggested that parallel processing (measured by the BCE) is modulated by task-switching. However, they argued that the critical component of task-switching is the sharing of categorizations between tasks. Here we showed that task switching modulated the BCE in conditions whose categorizations did not differ.

Task 2 Compatibility Effects, Experiments 1–4

As seen in the results of all four experiments, the compatibility effects were similar in Task 1 and Task 2 despite the use of different modalities for R1 and R2. To investigate this phenomenon, we performed a combined analysis of the two responses with three-way ANOVAs using the independent variables of the preceding ANOVAs and an additional independent variable: Task (Task 1 vs. Task 2). The three-way interaction examines whether the influence of Grouping on the compatibility effect was similar in the two tasks. This triple interaction did not approach significance for Experiments 1–3, Fs < 1, indicating comparable effects in Task 1 and Task 2. In Experiment 4, the interaction approached significance, $F(1, 18) = 4.00$, $p = .051$. We cannot offer an explanation for this discrepancy, but we can conclude that, in almost every case, all the Task 1 and the Task 2 effects were similarly influenced by Grouping. According to the RSB model, the fact that the compatibility effect was fully propagated from Task 1 to Task 2 is consistent with the notion that BCE is related to prebottleneck or bottleneck processes in Task 1 and that response selection was serial. In such a case, response selection of Task 2 must wait until response selection of Task 1 in completed. Postponing the completion of the response selection of Task 1 therefore results in greater slack and consequent identical slowing in RT2 (see further Pashler, 1994).

General Discussion

The present experiments investigated the boundary conditions for parallel processing in dual-task performance using the BCE as the main index. In Experiment 1, we found that the BCE was larger when S1 and S2 belonged to the same perceptual object and occupied the same position in space relative to when S1 and S2 belonged to two different objects. In Experiment 2, we employed a manipulation based on the Gestalt principle of common region. We showed that if stimuli belonged to the same object, even if they did not occupy the same position in space, it was sufficient to produce a BCE. Some of our findings could be interpreted as evidence for the role of bottom-up factors, including temporal code overlap (Hommel, 1998) and grouping by synchronicity and proximity, as well as top-down factors, including predictable S2 onset and the efficient allocation of resources (Miller et al., 2009). To distinguish between these factors, we used Experiment 3 to compare a constant SOA of 0 ms to an SOA = 0 ms in the context of variable SOA. The results showed a BCE with a constant SOA but not with variable SOA. These results suggest the influence of top-down factors because the BCE was absent with a variable SOA. However, they may be caused by the inclusion of S1 and S2 in the same perceptual event. To determine the role of this factor, we used a manipulation in Experiment 4 in which the task goal did not complete before both S1 and S2 were processed. The results of this experiment indicated a significant BCE when S1 and S2 belonged to the same goal (and event) and a small and nonsignificant effect when the stimuli did not belong to the same goal.

Before discussing the theoretical implications of these findings, it is important to discuss a potential alternative explanation of our results. In dual-task experiments, participants might delay the Task 1 response and group it with the Task 2 response (e.g., Hübner & Druey, 2006, 2008; Lien et al., 2005; Lien & Proctor, 2000; Miller, 2006; Miller & Alderton, 2006). To minimize response grouping, we instructed participants to avoid withholding R1 and to perform it before Task 2, even when S1 and S2 were presented simultaneously. We also excluded trials in which R1 and R2 were emitted in close temporal succession and adopted a very stringent criterion of 120 ms. In addition, while the mean IRI in our experiments was similar in both grouping conditions, the BCE was larger in the grouped condition relative to the less-grouped (or ungrouped) condition, suggesting that the BCE is not a result of response grouping. This finding is in line with Schubert et al. (2008), who observed no interaction between the BCE and IRI.

What Are the Boundary Conditions for the BCE?

The literature suggests three boundary conditions for the BCE: task repetition (Logan & Gordon, 2001; Logan & Schulkind, 2000), temporal overlap (Hommel, 1998), and retention of Task 2 rules in WM during Task 1 execution (Ellenbogen & Meiran, 2008). The results of the present work suggest another factor: uninterrupted attention to both S1 and S2 that occurs when they belong to the same event or object.

The present results not only add a fourth boundary condition, but also challenge the boundary conditions previously suggested. Temporal code overlap (Hommel, 1998) seems logically required to produce the effect. To appreciate this point, simply consider an absurd situation in which Task 1 has already completed well before Task 2 has begun. In this case, it would be extremely unlikely to find a BCE. Although some degree of temporal overlap appears necessary to generate BCE, this condition is insufficient. The limits of temporal overlap are shown most clearly in Experiments 2, 3, and 4. In all of these experiments, the grouped and less-grouped (or ungrouped) conditions had equivalent conditions that were characterized by the simultaneous presentation of S1 and S2. Nonetheless, a BCE was found in some, but not all, of these conditions. Thus, while temporal overlap may be a necessary condition for the BCE, it is not a sufficient condition.

Task repetition has also been suggested as a boundary condition (Logan & Gordon, 2001; Logan & Schulkind, 2000). As in previous studies (e.g., Hommel, 1998), we found a reliable BCE in conditions involving a task switch in Experiments 1–3. Task repetition may have also played a role in the BCE in Experiment 4 because BCE was found only when S1 and S2 belonged to the same task. However, this modulation was not caused by the sharing of response categorizations, the boundary factor suggested by Logan and Gordon (2001) to be critical. Instead, it was due to the sharing of a task goal. Fischer, Miller, and Schubert (2007), who also observed a BCE under task-switching conditions, concluded that greater resource availability is critical in task-repetition conditions.

Finally, we (Ellenbogen & Meiran, 2008) suggested that WM load is a factor that can eliminate the BCE. However, in the present experiments, we found that the BCE could be produced or eliminated in conditions with relatively equal WM loads. Moreover, in Experiment 4, the grouped condition required greater information retention than the ungrouped condition and still produced a larger BCE. Importantly, Ellenbogen and Meiran argued that extreme WM loads must be used in order to observe WM modulation of the BCE. None of the conditions in this study met this requirement.

In the present work, we relied on the BCE as an index of parallel processing and did not employ other indices. Other indices have been derived from the RSB model and have previously been used for this exact purpose (e.g., Luria & Meiran, 2005). However, other investigators have just examined the PRP effect and RT1 (e.g., Miller et al., 2009), relying on the logic that parallel processing would be reflected in shallower PRP effects and slower RT1. The latter is expected because when some resources are used by Task 2 while Task 1 is underway, fewer resources are available for Task 1 and its execution is slowed.

Of the aforementioned indices, only RT1 data are available from the present experiments. Our results indicate a reliable effect in the expected direction (quicker RT1 for the less-grouped or ungrouped condition) only in Experiment 3. In other experiments, the trend was not significant and often reversed. The prediction that RT1 will slow in parallel processing is based on theories that view response selection as a continuous limited resource (Navon & Miller, 2002; Tombu & Jolicœur, 2003). Because this prediction regarding RT1 was *not* borne out in three out of four experiments, it suggests that the BCE and the variables influencing it are related to other processing stages. Thus, our results favor the theory that the BCE is related to a processing stage preceding response selection: response activation (Hommel, 1998; Schubert et al., 2008). This intriguing hypothesis should be examined in future work combining multiple parallel-processing indices.

The present results imply that attention to (selected) events operates in a manner analogous to attention to (selected) objects. Our results show that, once an event is selected, its features—including those irrelevant to the task at hand—are processed and may interfere with task execution. This phenomenon was reflected in Experiments 3 and 4. In these experiments, S2, which was irrelevant for Task 1, still interfered with Task 1 processing when S1 and S2 belonged to the same event. We were unable to locate any precedence for this finding, which should be explored in greater depth in future studies.

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